The Fukushima Daiichi Accident

Report by the Director General

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

REPORT BY THE DIRECTOR GENERAL

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

REPORT BY THE DIRECTOR GENERAL

GC(59)/14

FOREWORD

By Yukiya Amano
Director General

This report presents an assessment of the causes and consequences of the accident at the Fukushima Daiichi nuclear power plant in Japan, which began on 11 March 2011. Caused by a huge tsunami that followed a massive earthquake, it was the worst accident at a nuclear power plant since the Chernobyl disaster in 1986.

The report considers human, organizational and technical factors, and aims to provide an understanding of what happened, and why, so that the necessary lessons learned can be acted upon by governments, regulators and nuclear power plant operators throughout the world. Measures taken in response to the accident, both in Japan and internationally, are also examined.

The immense human impact of the Fukushima Daiichi accident should not be forgotten. More than 100 000 people were evacuated because of the release of radionuclides to the environment. At the time of writing, in 2015, many of them were still unable to return to their homes.

I visited the Fukushima Daiichi plant a few months after the accident and saw for myself the powerful and destructive impact of the tsunami. It was a shocking and sobering experience.

But I was deeply impressed by the courage and dedication of those workers and managers who remained at their posts after the tsunami struck and who struggled, in appalling conditions, to bring the stricken reactors under control. They had to improvise a response in circumstances for which they had not been trained, often lacking appropriate equipment. They deserve our respect and admiration.

A major factor that contributed to the accident was the widespread assumption in Japan that its nuclear power plants were so safe that an accident of this magnitude was simply unthinkable. This assumption was accepted by nuclear power plant operators and was not challenged by regulators or by the Government. As a result, Japan was not sufficiently prepared for a severe nuclear accident in March 2011.

The Fukushima Daiichi accident exposed certain weaknesses in Japan's regulatory framework. Responsibilities were divided among a number of bodies, and it was not always clear where authority lay.

There were also certain weaknesses in plant design, in emergency preparedness and response arrangements and in planning for the management of a severe accident. There was an assumption that there would never be a loss of all electrical power at a nuclear power plant for more than a short period. The possibility of several reactors at the same facility suffering a crisis at the same time was not considered. And insufficient provision was made for the possibility of a nuclear accident occurring at the same time as a major natural disaster.

Since the accident, Japan has reformed its regulatory system to better meet international standards. It gave regulators clearer responsibilities and greater authority. The new regulatory framework will be reviewed by international experts through an IAEA Integrated Regulatory Review Service mission. Emergency preparedness and response arrangements have also been strengthened.

Other countries responded to the accident with measures that included carrying out 'stress tests' to reassess the design of nuclear power plants against site specific extreme natural hazards, installing additional backup sources of electrical power and supplies of water, and strengthening the protection of plants against extreme external events.

Although nuclear safety remains the responsibility of each individual country, nuclear accidents can transcend national borders. The Fukushima Daiichi accident underlined the vital importance of effective international cooperation. The IAEA is where most of that cooperation takes place. Our Member States adopted the IAEA Action Plan on Nuclear Safety a few months after the accident and have been implementing its far-reaching provisions to improve global nuclear safety.

The IAEA, which provided technical support and expertise to Japan after the accident and shared information about the unfolding crisis with the world, has reviewed and improved its own arrangements for responding to a nuclear emergency. Our role during a nuclear emergency has been expanded to include providing analysis of its potential consequences and presenting possible scenarios on how a crisis could develop.

IAEA safety standards embody an international consensus on what constitutes a high level of safety. They were reviewed after the accident by the Commission on Safety Standards. A few amendments were proposed and adopted. I encourage all countries to fully implement IAEA safety standards.

IAEA peer reviews have a key role to play in global nuclear safety, enabling countries to benefit from the independent insights of leading international experts, based on the common reference frame of the IAEA safety standards. They address issues such as operational safety at nuclear power plants, the effectiveness of nuclear regulators and the design of nuclear power plant sites against specific hazards. We have strengthened our peer review programme since the accident and will continue to do so.

I am confident that the legacy of the Fukushima Daiichi accident will be a sharper focus on nuclear safety everywhere. I have seen improvements in safety measures and procedures in every nuclear power plant that I have visited. There is widespread recognition that everything humanly possible must be done to ensure that no such accident ever happens again. This is all the more essential as global use of nuclear power is likely to continue to grow in the coming decades.

There can be no grounds for complacency about nuclear safety in any country. Some of the factors that contributed to the Fukushima Daiichi accident were not unique to Japan. Continuous questioning and openness to learning from experience are key to safety culture and are essential for everyone involved in nuclear power. Safety must always come first.

I express my gratitude to the experts from many countries and international organizations who contributed to this report, and to my colleagues at the IAEA who drafted and reviewed it. I hope that the report, and the accompanying technical volumes, will prove valuable to all countries that use, or plan to use, nuclear power in their continuous efforts to improve safety.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from the report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this report made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

CONTENTS

EXECUTIVE SUMMARY 1
SUMMARY REPORT 19

1. INTRODUCTION 19

1.1. THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT 20

2. THE ACCIDENT AND ITS ASSESSMENT 23

2.1. DESCRIPTION OF THE ACCIDENT 23
2.1.1. Initiating event and response 23
2.1.2. Progression of the accident 33
2.1.3. Stabilization efforts 44
2.2. NUCLEAR SAFETY CONSIDERATIONS 48
2.2.1. Vulnerability of the plant to external events 48
2.2.2. Application of the defence in depth concept 52
2.2.3. Assessment of the failure to fulfil fundamental safety functions 55
2.2.4. Assessment of beyond design basis accidents and accident management 59
2.2.5. Assessment of regulatory effectiveness 63
2.2.6. Assessment of human and organizational factors 67
2.3. OBSERVATIONS AND LESSONS 70

3. EMERGENCY PREPAREDNESS AND RESPONSE 74

3.1. INITIAL RESPONSE IN JAPAN TO THE ACCIDENT 75
3.1.1. Notification 76
3.1.2. Mitigatory actions 77
3.1.3. Management of the emergency 79
3.2. PROTECTING EMERGENCY WORKERS 81
3.2.1. Protection of personnel at the plant following the earthquake and tsunami 82
3.2.2. Protective measures for emergency workers 82
3.2.3. Designation of emergency workers 83
3.2.4. Medical management of emergency workers 84
3.3. PROTECTING THE PUBLIC 84
3.3.1. Urgent protective actions and relocation 85
3.3.2. Protective actions relating to food, drinking water and agriculture 89
3.3.3. Public information 90
3.3.4. International trade 91
3.3.5. Waste management in the emergency phase 91
3.4. TRANSITION FROM THE EMERGENCY PHASE TO THE RECOVERY PHASE AND ANALYSES OF THE RESPONSE 92
3.4.1. Transition from the emergency phase to the recovery phase 92
3.4.2. Analyses of the response 93
3.5. RESPONSE WITHIN THE INTERNATIONAL FRAMEWORK FOR EMERGENCY PREPAREDNESS AND RESPONSE 94
3.6. OBSERVATIONS AND LESSONS 96

4. RADIOLOGICAL CONSEQUENCES 100

4.1. RADIOACTIVITY IN THE ENVIRONMENT 106
4.1.1. Releases 106
4.1.2. Dispersion 107
4.1.3. Deposition 111
4.1.4. Consumer products 112
4.2. PROTECTING PEOPLE AGAINST RADIATION EXPOSURE 116
4.2.1. Restriction of public exposure 116
4.2.2. Restriction of occupational exposure, including exposure of emergency workers 119
4.3. RADIATION EXPOSURE 120
4.3.1. Public exposures 121
4.3.2. Occupational exposures 127
4.4. HEALTH EFFECTS 130
4.4.1. Early radiation induced health effects 131
4.4.2. Potential late radiation induced health effects 132
4.4.3. Radiation effects in children 133
4.4.4. Prenatal radiation induced health effects 134
4.4.5. Psychological consequences 134
4.5. RADIOLOGICAL CONSEQUENCES FOR NON-HUMAN BIOTA 136
4.6. OBSERVATIONS AND LESSONS 137

5. POST-ACCIDENT RECOVERY 140

5.1. OFF-SITE REMEDIATION OF AREAS AFFECTED BY THE ACCIDENT 140
5.1.1. Establishment of a legal and regulatory framework for remediation 141
5.1.2. Remediation strategy adopted 142
5.1.3. Progress in remediation 143
5.2. ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING 147
5.2.1. Strategic plan 148
5.2.2. Preparations for decommissioning 148
5.2.3. Management of contaminated water 149
5.2.4. Removal of spent fuel and fuel debris 152
5.2.5. Decommissioning end state for the site 153
5.3. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE 154
5.3.1. Managing the waste 154
5.3.2. Off-site activities 154
5.3.3. On-site activities 157
5.4. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT 158
5.4.1. Socioeconomic consequences 158
5.4.2. Revitalization 159
5.4.3. Engagement of and communication with stakeholders 160
5.5. OBSERVATIONS AND LESSONS 161

6. THE IAEA RESPONSE TO THE ACCIDENT 164

6.1. IAEA ACTIVITIES 164
6.1.1. Initial activities 164
6.1.2. IAEA missions to Japan 166
6.1.3. IAEA Ministerial Conference on Nuclear Safety 166
6.1.4. The IAEA Action Plan on Nuclear Safety 167
6.1.5. Cooperation with Fukushima Prefecture 168
6.1.6. Fukushima Ministerial Conference on Nuclear Safety 169

6.2. MEETINGS OF THE CONTRACTING PARTIES TO THE CONVENTION ON NUCLEAR SAFETY 170
6.2.1. Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety 170
6.2.2. Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety 171
6.2.3. Diplomatic Conference and the Vienna Declaration on Nuclear Safety 171

REFERENCES 173
ABBREVIATIONS 191
CONTRIBUTORS TO DRAFTING AND REVIEW 193
INTERNATIONAL TECHNICAL ADVISORY GROUP 204
MEETINGS 205
COPYRIGHT NOTICE 207
EDITORIAL NOTE 208

THE FUKUSHIMA DAIICHI ACCIDENT

EXECUTIVE SUMMARY

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed, over 6000 were injured and, at the time of writing of this report[1], around 2500 people were still reported to be missing. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant, operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site, and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units[2] as well as at the spent fuel pools. The four other nuclear power plants[3] along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi nuclear power plant to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people were still living outside the areas from which they were evacuated.

Following stabilization of the conditions of the reactors at the Fukushima Daiichi nuclear power plant[4], work to prepare for their eventual decommissioning began. Efforts towards the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

---

[1] March 2015. In some cases, information was available up to June 2015 and has been included, where possible.

[2] Of the six units of the Fukushima Daiichi nuclear power plant, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.

[3] The Higashidori, Onagawa, Fukushima Daini and Tokai Daini nuclear power plants.

[4] On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi nuclear power plant. Its definition differs from the terminology used by the IAEA and others.

In the immediate aftermath of the accident, the IAEA discharged its emergency response role. It activated its Incident and Emergency System, coordinated the inter-agency response and initiated a series of briefings with Member States and the media.

The Director General visited Japan immediately and the IAEA dispatched several missions to Japan, including an international fact finding mission and peer review missions on decommissioning and remediation.

The IAEA organized an International Ministerial Conference on Nuclear Safety in June 2011, which resulted in a Ministerial Declaration on Nuclear Safety. This declaration outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken.

The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety (the Action Plan)[5], in consultation with Member States. The Action Plan, which defined a programme of work to strengthen the global nuclear safety framework, was unanimously endorsed by the 55th IAEA General Conference in 2011.

The IAEA also undertook cooperative activities in Fukushima through a memorandum of cooperation between the IAEA and Fukushima Prefecture. This provided the basis for cooperation on radiation monitoring and remediation, human health, and emergency preparedness and response.

The IAEA also facilitated and organized a number of international conferences and meetings of its Member States and the Contracting Parties to the Convention on Nuclear Safety. Many of these activities took place under the Action Plan.

Since the accident at the Fukushima Daiichi nuclear power plant, there have been many analyses of its causes and consequences, as well as detailed considerations of its implications for nuclear safety, by IAEA Member States and international organizations and by States party to international nuclear safety instruments, in particular the Convention on Nuclear Safety. An extraordinary meeting of the Contracting Parties to the Convention on Nuclear Safety was held in August 2012 to review and discuss the initial analyses of the accident and the effectiveness of the Convention.

The Contracting Parties to the Convention on Nuclear Safety, at the 6th Review Meeting in March–April 2014, reported on the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; the enhancement of power systems to improve reliability; the re-evaluation of site specific external natural hazards and multi-unit events; the improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and the improvement of severe accident management provisions and guidelines.

In February 2015, the Contracting Parties to the Convention on Nuclear Safety, at a Diplomatic Conference convened by the IAEA Director General, adopted the Vienna Declaration on Nuclear Safety, which includes principles for the implementation of the third objective of the Convention,

[5] The Action Plan defined a programme of work to strengthen the global nuclear safety framework. The Action Plan consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; the protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For more details, see Section 6.1.

which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".

The report on the Fukushima Daiichi accident is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review of the report. Additional internal and external review mechanisms were also instituted.

This Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved. The report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the Action Plan, and it highlights the main observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

NUCLEAR SAFETY CONSIDERATIONS

Vulnerability of the plant to external events

The earthquake on 11 March 2011 caused vibratory ground motions, which shook the plant structures, systems and components. It was followed by a series of tsunami waves, one of which inundated the site. Both the recorded ground motions and the heights of the tsunami waves significantly exceeded the assumptions of hazards that had been made when the plant was originally designed. The earthquake and the associated tsunami impacted on multiple units at the Fukushima Daiichi nuclear power plant.

The seismic hazard and tsunami waves considered in the original design were evaluated mainly on the basis of historical seismic records and evidence of recent tsunamis in Japan. This original evaluation did not sufficiently consider tectonic-geological criteria, and no re-evaluation using such criteria was conducted.

Prior to the earthquake, the Japan Trench was categorized as a subduction zone with a frequent occurrence of magnitude 8 class earthquakes; an earthquake of magnitude 9.0 off the coast of Fukushima Prefecture was not considered to be credible by Japanese scientists. However, similar or higher magnitudes had been registered in different areas in similar tectonic environments in the past few decades.

There were no indications that the main safety features of the plant were affected by the vibratory ground motions generated by the earthquake on 11 March 2011. This was due to the conservative approach to earthquake design and construction of nuclear power plants in Japan, resulting in a plant

that was provided with sufficient safety margins. However, the original design considerations did not provide comparable safety margins for extreme external flooding events, such as tsunamis.

The vulnerability of the Fukushima Daiichi nuclear power plant to external hazards had not been reassessed in a systematic and comprehensive manner during its lifetime. At the time of the accident, there were no regulatory requirements in Japan for such reassessments, and relevant domestic and international operating experience was not adequately considered in the existing regulations and guidelines. The regulatory guidelines in Japan on methods for dealing with the effects of events associated with earthquakes, such as tsunamis, were generic and brief, and did not provide specific criteria or detailed guidance.

Before the accident, the operator had conducted some reassessments of extreme tsunami flood levels, using a consensus based methodology developed in Japan in 2002, which had resulted in values higher than the original design basis estimates. Based on the results, some compensatory measures were taken, but they proved to be insufficient at the time of the accident.

In addition, a number of trial calculations were performed by the operator before the accident, using wave source models or methodologies that went beyond the consensus based methodology. Thus, a trial calculation using the source model proposed by the Japanese Headquarters for Earthquake Research Promotion in 2002, which used the latest information and took a different approach in its scenarios, envisaged a substantially larger tsunami than that provided for in the original design and in estimates made in previous reassessments. At the time of the accident, further evaluations were being conducted, but in the meantime, no additional compensatory measures were implemented. The estimated values were similar to the flood levels recorded in March 2011.

Worldwide operating experience has shown instances where natural hazards have exceeded the design basis for a nuclear power plant. In particular, the experience from some of these events demonstrated the vulnerability of safety systems to flooding.

— **The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of nuclear power plants is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.**
— **The safety of nuclear power plants needs to be re-evaluated on a periodic basis to consider advances in knowledge, and necessary corrective actions or compensatory measures need to be implemented promptly.**
— **The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on a nuclear power plant. The assessment of natural hazards also needs to consider their effects on multiple units at a nuclear power plant.**
— **Operating experience programmes need to include experience from both national and international sources. Safety improvements identified through operating experience programmes need to be implemented promptly. The use of operating experience needs to be evaluated periodically and independently.**

Application of the defence in depth concept

Defence in depth is a concept that has been applied to ensure the safety of nuclear installations since the start of nuclear power development. Its objective is to compensate for potential human and equipment failures by means of several levels of protection. Defence is provided by multiple and independent means at each level of protection.

The design of the Fukushima Daiichi nuclear power plant provided equipment and systems for the first three levels of defence in depth: (1) equipment intended to provide reliable normal operation; (2) equipment intended to return the plant to a safe state after an abnormal event; and (3) safety systems intended to manage accident conditions. The design bases were derived using a range of postulated hazards; however, external hazards such as tsunamis were not fully addressed. Consequently, the flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems at each of the three levels.

The common cause failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices and the insufficiency of operating procedures made it impossible to arrest the progression of the accident and to limit its consequences.

The failure to provide sufficient means of protection at each level of defence in depth resulted in severe reactor damage in Units 1, 2 and 3 and in significant radioactive releases from these units.

— **The defence in depth concept remains valid, but implementation of the concept needs to be strengthened at all levels by adequate independence, redundancy, diversity and protection against internal and external hazards. There is a need to focus not only on accident prevention, but also on improving mitigation measures.**
— **Instrumentation and control systems that are necessary during beyond design basis accidents need to remain operable in order to monitor essential plant safety parameters and to facilitate plant operations.**

Assessment of the failure to fulfil fundamental safety functions

The three fundamental safety functions important for ensuring safety are: the control of reactivity in the nuclear fuel; the removal of heat from the reactor core and spent fuel pool; and the confinement of radioactive material. Following the earthquake, the first fundamental safety function — control of reactivity — was fulfilled in all six units at the Fukushima Daiichi nuclear power plant.

The second fundamental safety function — removing heat from the reactor core and the spent fuel pool — could not be maintained because the operators were deprived of almost all means of control over the reactors of Units 1, 2 and 3 and the spent fuel pools as a result of the loss of most of the AC and DC electrical systems. The loss of the second fundamental safety function was, in part, due to the failure to implement alternative water injection because of delays in depressurizing the reactor pressure vessels. Loss of cooling led to overheating and melting of the fuel in the reactors.

The confinement function was lost as a result of the loss of AC and DC power, which rendered the cooling systems unavailable and made it difficult for the operators to use the containment venting system. Venting of the containment was necessary to relieve pressure and prevent its failure. The operators were able to vent Units 1 and 3 to reduce the pressure in the primary containment vessels. However, this resulted in radioactive releases to the environment. Even though the containment vents for Units 1 and 3 were opened, the primary containment vessels for Units 1 and 3 eventually failed. Containment venting for Unit 2 was not successful, and the containment failed, resulting in radioactive releases.

— **Robust and reliable cooling systems that can function for both design basis and beyond design basis conditions need to be provided for the removal of residual heat.**
— **There is a need to ensure a reliable confinement function for beyond design basis accidents to prevent significant release of radioactive material to the environment.**

Assessment of beyond design basis accidents and accident management

Safety analyses conducted during the licensing process of the Fukushima Daiichi nuclear power plant, and during its operation, did not fully address the possibility of a complex sequence of events that could lead to severe reactor core damage. In particular, the safety analyses failed to identify the vulnerability of the plant to flooding and weaknesses in operating procedures and accident management guidelines. The probabilistic safety assessments did not address the possibility of internal flooding, and the assumptions regarding human performance for accident management were optimistic. Furthermore, the regulatory body had imposed only limited requirements for operators to consider the possibility of severe accidents.

The operators were not fully prepared for the multi-unit loss of power and the loss of cooling caused by the tsunami. Although TEPCO had developed severe accident management guidelines, they did not cover this unlikely combination of events. Operators had therefore not received appropriate training and had not taken part in relevant severe accident exercises, and the equipment available to them was not adequate in the degraded plant conditions.

In September 2012, the Nuclear Regulation Authority (NRA) was established. The NRA formulated new regulations for nuclear power plants to protect the people and the environment, which came into force in 2013. These regulations strengthened countermeasures to prevent simultaneous loss of all safety functions due to common causes, including re-evaluation of the impact of external events such as earthquakes and tsunamis. New countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive material were also introduced.

— **Comprehensive probabilistic and deterministic safety analyses need to be performed to confirm the capability of a plant to withstand applicable beyond design basis accidents and to provide a high degree of confidence in the robustness of the plant design.**
— **Accident management provisions need to be comprehensive, well designed and up to date. They need to be derived on the basis of a comprehensive set of initiating events and plant conditions and also need to provide for accidents that affect several units at a multi-unit plant.**
— **Training, exercises and drills need to include postulated severe accident conditions to ensure that operators are as well prepared as possible. They need to include the simulated use of actual equipment that would be deployed in the management of a severe accident.**

Assessment of regulatory effectiveness

The regulation of nuclear safety in Japan at the time of the accident was performed by a number of organizations with different roles and responsibilities and complex inter-relationships. It was not fully clear which organizations had the responsibility and authority to issue binding instructions on how to respond to safety issues without delay.

The regulatory inspection programme was rigidly structured, which reduced the regulatory body's ability to verify safety at the proper times and to identify potential new safety issues.

The regulations, guidelines and procedures in place at the time of the accident were not fully in line with international practice in some key areas, most notably in relation to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture.

— **In order to ensure effective regulatory oversight of the safety of nuclear installations, it is essential that the regulatory body is independent and possesses legal authority, technical competence and a strong safety culture.**

Assessment of human and organizational factors

Before the accident, there was a basic assumption in Japan that the design of nuclear power plants and the safety measures that had been put in place were sufficiently robust to withstand external events of low probability and high consequences.

Because of the basic assumption that nuclear power plants in Japan were safe, there was a tendency for organizations and their staff not to challenge the level of safety. The reinforced basic assumption among the stakeholders about the robustness of the technical design of nuclear power plants resulted in a situation where safety improvements were not introduced promptly.

The accident at the Fukushima Daiichi nuclear power plant showed that, in order to better identify plant vulnerabilities, it is necessary to take an integrated approach that takes account of the complex interactions between people, organizations and technology.

— **In order to promote and strengthen safety culture, individuals and organizations need to continuously challenge or re-examine the prevailing assumptions about nuclear safety and the implications of decisions and actions that could affect nuclear safety.**
— **A systemic approach to safety needs to consider the interactions between human, organizational and technical factors. This approach needs to be taken through the entire life cycle of nuclear installations.**

EMERGENCY PREPAREDNESS AND RESPONSE

Initial response in Japan to the accident

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at a nuclear power plant (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national Government would then assess the situation and determine whether it was to be categorized as a 'nuclear emergency'[6]. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections.

Based on a report from the Fukushima Daiichi nuclear power plant, the Prime Minister declared a nuclear emergency on the evening of 11 March and issued orders for protective actions for the public. The response at the national level was led by the Prime Minister and senior officials at the Prime Minister's Office in Tokyo.

[6] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006, hereinafter referred to as the Nuclear Emergency Act.

The consequences of the earthquake and tsunami, and increased radiation levels, made the on-site response extremely difficult. The loss of AC and DC electrical power, the presence of a huge amount of rubble that hindered on-site response measures, aftershocks, alerts of further tsunamis and increased radiation levels meant that many mitigatory actions could not be carried out in a timely manner. The national Government was involved in decisions concerning mitigatory action on the site.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi nuclear power plant, was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions.

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**
— **The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.**

Protecting emergency workers

At the time of the accident, the national legislation and guidance in Japan addressed measures to be taken for the protection of emergency workers, but only in general terms and not in sufficient detail.

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. However, there were no arrangements in place to integrate into the response those emergency workers who had not been designated prior to the accident.

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected, and major efforts were required to meet the needs of on-site emergency workers.

Members of the public, referred to as ‘helpers’, volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.

— **Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, be given adequate training and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency, and helpers who volunteer to assist in the emergency response.**

Protecting the public

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary, using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). The arrangements did not envisage that

decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no criteria for relocation.

Protective actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi nuclear power plant began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km of the plant to 3 km and then to 10 km. By the evening of 12 March, it had been extended to 20 km. Similarly, the area in which people were ordered to shelter was extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20–30 km radius of the nuclear power plant, the public was ordered to shelter until 25 March, when the national Government recommended voluntary evacuation. Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

On 22 April, the existing 20 km evacuation zone was established as a ‘Restricted Area’, with controlled re-entry. A ‘Deliberate Evacuation Area’ was also established beyond the ‘Restricted Area’ in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made regarding protective actions in the agricultural area and restrictions on the consumption and distribution of food and consumption of drinking water. In addition, a certification system for food and other products intended for export was established.

Several channels were used to keep the public informed and to respond to people’s concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material.

— **Arrangements need to be in place to allow decisions to be made on the implementation of predetermined, urgent protective actions for the public, based on predefined plant conditions.**
— **Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.**
— **Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.**

— **Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.**

Transition from the emergency phase to the recovery phase and analysis of the response

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection (ICRP).

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), and two investigation committees created by the Government and the Parliament, respectively.

After the accident, national emergency preparedness and response arrangements in Japan were, in many cases, revised to take account of the findings of these analyses and of relevant IAEA safety standards in the area of emergency preparedness and response.

— **Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and for transition to the recovery phase.**
— **Timely analysis of an emergency and the response to it, drawing lessons and identifying possible improvements, enhances emergency arrangements.**

Response within the international framework for emergency preparedness and response

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements.[7]

At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the inter-agency response.

The international response to the accident involved many States and a number of international organizations.

The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point. The IAEA also sent expert missions to Japan and coordinated the inter-agency response.

[7] The primary international legal instruments are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The international safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 and No. GS-G-2.1. Safety Series No. 115 also included elements related to emergency preparedness and response. The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET) and Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

Different States[8] either took or recommended different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.

Relevant organizations participating in the Inter-Agency Committee on Radiological and Nuclear Emergencies regularly exchanged information. Joint press releases were also issued.

— **The implementation of international arrangements for notification and assistance needs to be strengthened.**
— **There is a need to improve consultation and sharing of information among States on protective actions and other response actions.**

RADIOLOGICAL CONSEQUENCES

Radioactivity in the environment

The accident resulted in the release of radionuclides to the environment. Assessments of the releases have been performed by many organizations using different models. Most of the atmospheric releases were blown eastward by the prevailing winds, depositing onto and dispersing within the North Pacific Ocean. Uncertainties in estimations of the amount and composition of the radioactive substances were difficult to resolve for reasons that included the lack of monitored data on the deposition of the atmospheric releases on the ocean.

Changes in the wind direction meant that a relatively small part of the atmospheric releases were deposited on land, mostly in a north-westerly direction from the Fukushima Daiichi nuclear power plant. The presence and activity of radionuclides deposited in the terrestrial environment were monitored and characterized. The measured activity of radionuclides decreases over time due to physical decay, environmental transport processes and cleanup activities.

In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi nuclear power plant directly into the sea at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.

Radionuclides such as iodine-131, caesium-134 and caesium-137 were released and found in drinking water, food and some non-edible items. Restrictions to prevent the consumption of these products were established by the Japanese authorities in response to the accident.

— **In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**

[8] The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment.

Protecting people against radiation exposure

Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations[9]. The application of some of the protective measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.

There were some differences between the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**
— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**

Radiation exposure

In the short term, the most significant contributors to the exposure of the public were: (1) external exposure from radionuclides in the plume and deposited on the ground; and (2) internal exposure of the thyroid gland, due to the intake of iodine-131, and internal exposure of other organs and tissues, mainly due to the intake of caesium-134 and caesium-137. In the long term, the most important contributor to the exposure of the public will be external radiation from the deposited caesium-137.

The early assessments of radiation doses used environmental monitoring and dose estimation models, resulting in some overestimations. For the estimates in this report, personal monitoring data provided by the local authorities were also included to provide more robust information on the actual individual doses incurred and their distribution. These estimates indicate that the effective doses incurred by members of the public were low and generally comparable with the range of effective doses incurred due to global levels of natural background radiation.

In the aftermath of a nuclear accident involving releases of iodine-131 and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of iodine-131 was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes

[9] International recommendations on radiation protection are issued by the ICRP. These recommendations are taken into account in the establishment of international safety standards, including radiation protection standards (the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards, or BSS)), which were developed and established by several international organizations and issued under the aegis of the IAEA. The BSS are used worldwide in the development of national regulations for the protection of people and the environment from the potential detrimental effects of exposure to ionizing radiation. The 2007 ICRP recommendations provided a revised framework for radiation protection. These included introducing reference levels for protection strategies. At the time of the accident, the BSS were being revised, inter alia, to take account of these recommendations.

immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.

By December 2011, around 23 000 emergency workers had been involved in the emergency operations. The effective doses incurred by most of them were below the occupational dose limits in Japan. Of this number, 174 exceeded the original criterion for emergency workers and 6 emergency workers exceeded the temporarily revised effective dose criterion in an emergency established by the Japanese authority. Some shortcomings occurred in the implementation of occupational radiation protection requirements, including during the early monitoring and recording of radiation doses of emergency workers, in the availability and use of some protective equipment and in associated training.

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**
— **While dairy products were not the main pathway for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**
— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**

Health effects

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) to the United Nations General Assembly.[10] UNSCEAR found that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" (which was reported within the context of the health implications related to "levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami").[11] Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence."[12]

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of

[10] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/68/46, UN, New York (2013).

[11] The World Health Organization (WHO) also published a health risk assessment in 2013 on the basis of preliminary estimated doses. The results are presented in this report.

[12] See footnote 10.

diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children's thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents' exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure".[13]

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey's Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that "The most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation."[14]

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation if levels of exposure are similar to the global average background levels of radiation.**
— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**
— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought".[15]**

---

[13] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/67/46, UN, New York (2012).

[14] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[15] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.**

Radiological consequences for non-human biota

No observations of direct radiation induced effects in plants and animals have been reported, although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences, but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism, and of the use of natural resources.**

POST-ACCIDENT RECOVERY

Off-site remediation of areas affected by the accident

The long term goal of post-accident recovery[16] is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation[17] of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011.[18] It assigned responsibilities to the national and local governments, the operator and the public, and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

---

[16] Post-accident recovery includes: the remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

[17] Remediation is defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

[18] Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110, 2011.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

Following the accident, the authorities in Japan adopted a 'reference level' as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations.

Two categories of contaminated areas were defined on the basis of additional annual doses estimated in the autumn of 2011. The national Government was assigned responsibility for formulating and implementing remediation plans in the first area (the 'Special Decontamination Area') — within a radius of 20 km of the Fukushima Daiichi site and in areas where additional annual doses arising from contamination on the ground were projected to exceed 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the 'Intensive Contamination Survey Area'), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

— **Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.**
— **Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.**
— **As part of the remediation strategy, the implementation of rigorous testing and controls on food is necessary to prevent or minimize ingestion doses.**
— **Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.**

On-site stabilization and preparations for decommissioning

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged nuclear power plant was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised to reflect the experience gained and an improved understanding of the conditions of the damaged nuclear power plant, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures towards decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and was stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge to the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.

Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began.[19] A conceptual model of future activities for removing fuel debris was developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

— **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.**
— **Retrieving damaged fuel and characterizing and removing fuel debris necessitate solutions that are specific to the accident, and special methods and tools may need to be developed.**

Management of contaminated material and radioactive waste

Stabilization of a damaged nuclear power plant and the on-site decontamination and remediation efforts in the surrounding areas result in large quantities of contaminated material and radioactive waste. On the site, large amounts of contaminated solid and liquid material, as well as radioactive waste, have been generated following various recovery activities.[20] The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. At the time of writing, several hundred temporary storage facilities had been established in local communities and efforts to establish an interim storage facility were continuing.

— **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**

[19] Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.

[20] The distinction between contaminated material and radioactive waste depends upon the radionuclides and the activity concentrations associated with the materials.

Community revitalization and stakeholder engagement

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communication improved in the aftermath of the accident, and the affected population became increasingly involved in decision making and remediation measures.

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**
— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**

THE FUKUSHIMA DAIICHI ACCIDENT

SUMMARY REPORT

1. INTRODUCTION

The Great East Japan Earthquake occurred on 11 March 2011. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate. A section of the Earth's crust, estimated to be about 500 km in length and 200 km wide, was ruptured, causing a massive earthquake with a magnitude of 9.0 and a tsunami which struck a wide area of coastal Japan, including the north-eastern coast, where several waves reached heights of more than ten metres. The earthquake and tsunami caused great loss of life and widespread devastation in Japan. More than 15 000 people were killed and over 6000 injured and, at the time of writing of this report[21], around 2500 people were still reported to be missing [1]. Considerable damage was caused to buildings and infrastructure, particularly along Japan's north-eastern coast.

At the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO), the earthquake caused damage to the electric power supply lines to the site, and the tsunami caused substantial destruction of the operational and safety infrastructure on the site. The combined effect led to the loss of off-site and on-site electrical power. This resulted in the loss of the cooling function at the three operating reactor units[22] as well as at the spent fuel pools. The four other NPPs[23] along the coast were also affected to different degrees by the earthquake and tsunami. However, all operating reactor units at these plants were safely shut down.

Despite the efforts of the operators at the Fukushima Daiichi NPP to maintain control, the reactor cores in Units 1–3 overheated, the nuclear fuel melted, and the three containment vessels were breached. Hydrogen was released from the reactor pressure vessels, leading to explosions inside the reactor buildings in Units 1, 3 and 4 that damaged structures and equipment and injured personnel. Radionuclides were released from the plant to the atmosphere and were deposited on land and on the ocean. There were also direct releases into the sea.

People within a radius of 20 km of the site and in other designated areas were evacuated, and those within a radius of 20–30 km were instructed to shelter before later being advised to voluntarily evacuate. Restrictions were placed on the distribution and consumption of food and the consumption of drinking water. At the time of writing, many people were still living outside the areas from which they were evacuated.

Following stabilization of the conditions of the reactors at the Fukushima Daiichi NPP[24], work began to prepare for their eventual decommissioning. Efforts towards the recovery of the areas affected by the accident, including remediation and the revitalization of communities and infrastructure, began in 2011.

---

[21] March 2015. In some cases, information was available up to June 2015 and has been included, where possible.

[22] Of the six units of the Fukushima Daiichi NPP, Units 1, 2 and 3 were operating at the time of the accident; Units 4, 5 and 6 were in planned shutdown.

[23] The Higashidori, Onagawa, Fukushima Daini and Tokai Daini NPPs.

[24] On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi NPP. The definition differs from the terminology used by the IAEA and others.

1.1. THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned" [2].

The report on the Fukushima Daiichi accident is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review of the report. Additional internal and external review mechanisms were also instituted, as illustrated in Fig. 1.1.

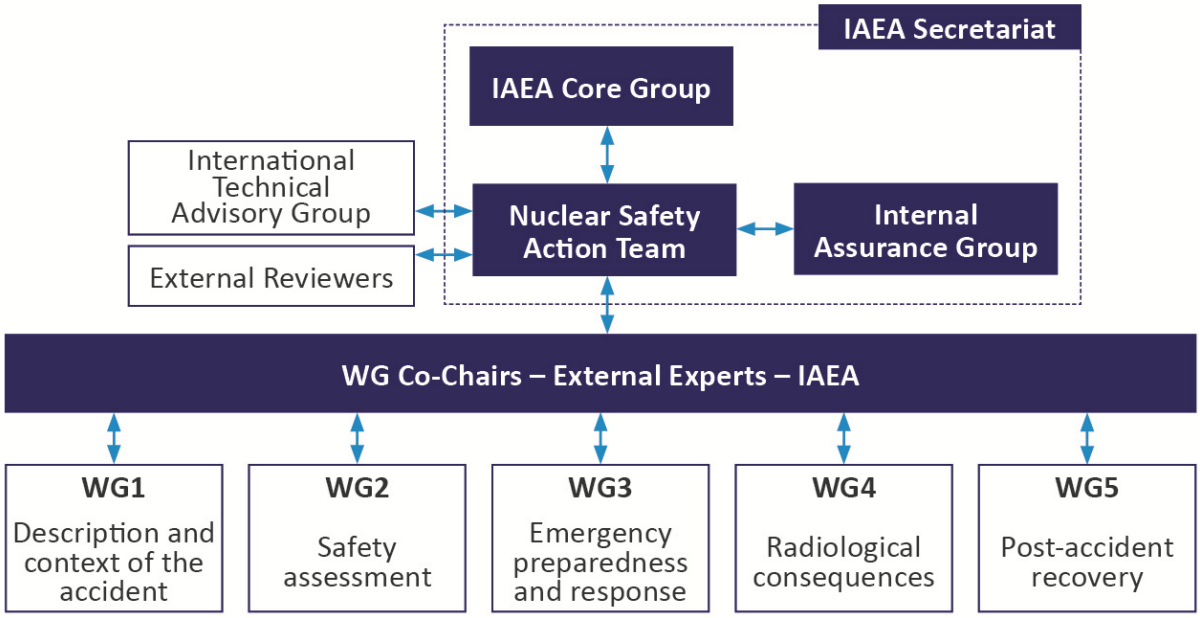


FIG. 1.1. IAEA organization structure for preparing the report on The Fukushima Daiichi Accident.

This Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved. The report provides a description of the accident and its causes, evolution and consequences, based on the evaluation of data and information from a large number of sources available up to March 2015, including the results of the work carried out in implementing the IAEA Action Plan on Nuclear Safety (the Action Plan)[25], and it highlights the main

[25] The Action Plan, unanimously endorsed by the 55th IAEA General Conference in 2011, defined a programme of work to strengthen the global nuclear safety framework. It consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For a detailed discussion of the Action Plan, see Section 6.1.

observations and lessons. Significant amounts of data were provided by the Government of Japan and other organizations in Japan.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, NPP operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

This Report by the Director General comprises the following six sections:

— Section 1: Introduction.
— Section 2: The accident and its causes, including a description of the sequence of events and an assessment of how extreme natural events led to the severe nuclear accident.
— Section 3: Emergency preparedness and response, including the arrangements for the protection of emergency workers and the public, and the implementation of these arrangements during and immediately after the accident.
— Section 4: The radiological consequences of the accident, including radiation exposure of workers and the public, and health and environmental effects.
— Section 5: Post-accident recovery activities, including decommissioning of the plant, remediation strategies for the off-site areas affected, waste management and strategies for revitalization.
— Section 6: An overview of the activities of the IAEA and the Contracting Parties to the Convention on Nuclear Safety in response to the accident.

Key observations and lessons arising from specific features of the accident are included in Sections 2–5. The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 1.2.

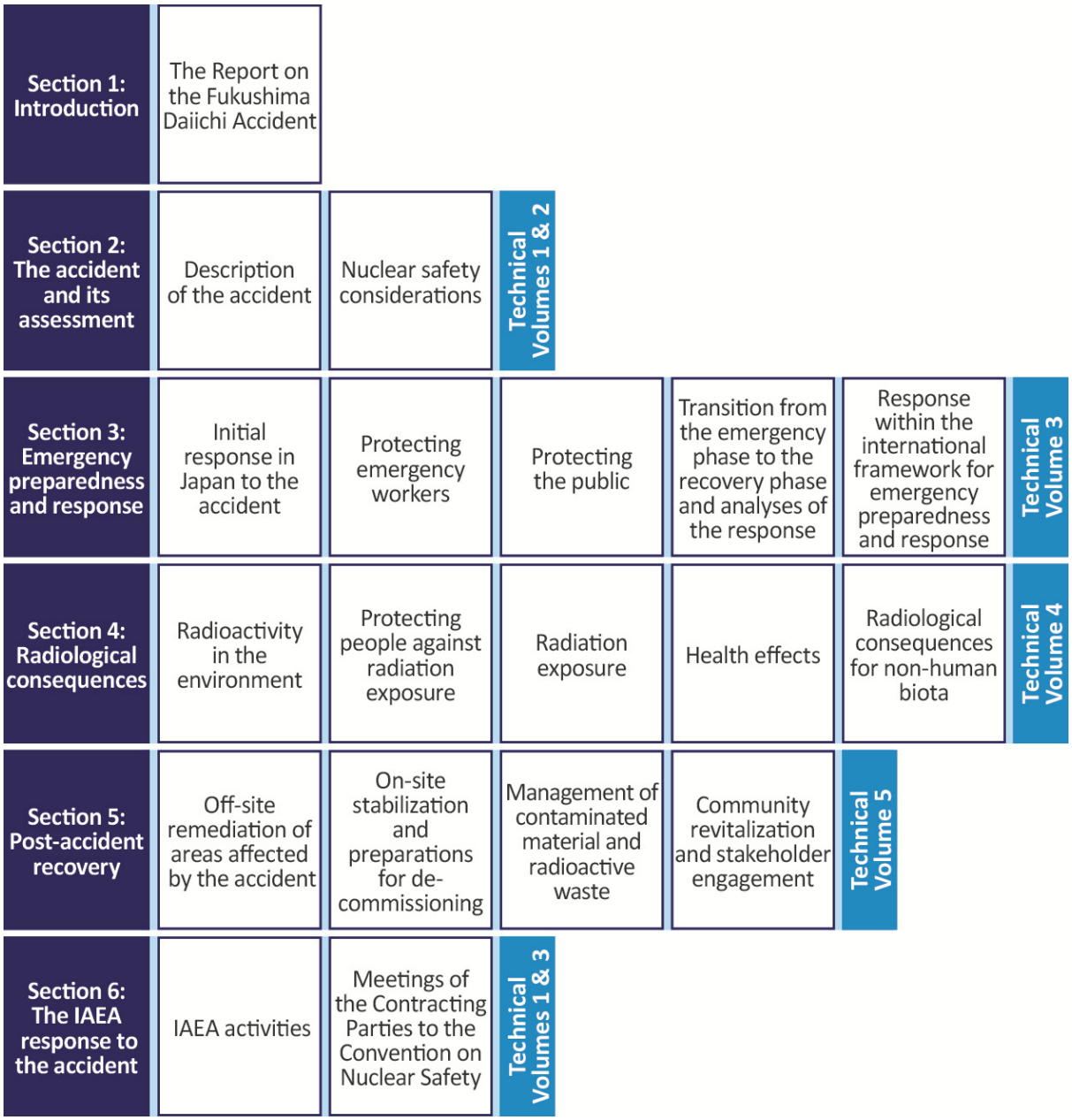


FIG. 1.2. Structure of the Summary Report and its relationship to the content of the technical volumes.

2. THE ACCIDENT AND ITS ASSESSMENT

This section provides a brief description of the accident at the Fukushima Daiichi NPP, followed by an assessment of factors that are considered to have contributed to its causes and consequences.

Section 2.1 describes the main events in chronological order, including the impact of the earthquake and tsunami and the subsequent events.

Section 2.2 assesses the causes of the accident. It begins with an evaluation of the vulnerability of the Fukushima Daiichi NPP to external hazards and deals with its design, the accident progression, the efforts of the operators to maintain fundamental safety functions and the actions taken by them. This section also considers the effectiveness of the regulatory framework in Japan as well as the impact of human and organizational considerations on nuclear safety.

2.1. DESCRIPTION OF THE ACCIDENT

The description that follows is mainly based on information provided by the Government of Japan to the IAEA [3, 4], reports of the investigation committees established by the Japanese Government [5, 6], the National Diet of Japan [7] and TEPCO [8], including updates and supplements by TEPCO [9, 10], the regulatory body [11] and the IAEA missions listed in Section 6. Other sources from which information has been taken are cited separately.

Events are presented in chronological order. Some of the main events occurred in parallel or had an impact on actions taken in other locations on-site.

2.1.1. Initiating event and response

The earthquake and the loss of off-site power

The Great East Japan Earthquake of 11 March 2011 occurred at 14:46 Japan Standard Time (JST), 05:46 UTC[26], off the eastern coast of Japan. It was caused by a sudden release of energy at the interface where the Pacific tectonic plate forces its way under the North American tectonic plate (Fig. 2.1). The main shock, with a magnitude of 9.0 [12], lasted for more than two minutes, with several significant pulses and aftershocks. This event was among the largest recorded earthquakes, most of which also occurred in areas along the Pacific tectonic plate: the earthquakes of 1960 and 2010 in Chile, with a magnitude of 9.5 and 8.8, respectively, and those in Alaska (1964) and Sumatra (2004), both with a magnitude of 9.2.

[26] Universal Time Coordinated, which is nine hours behind JST. Unless indicated, the report uses JST for all times.



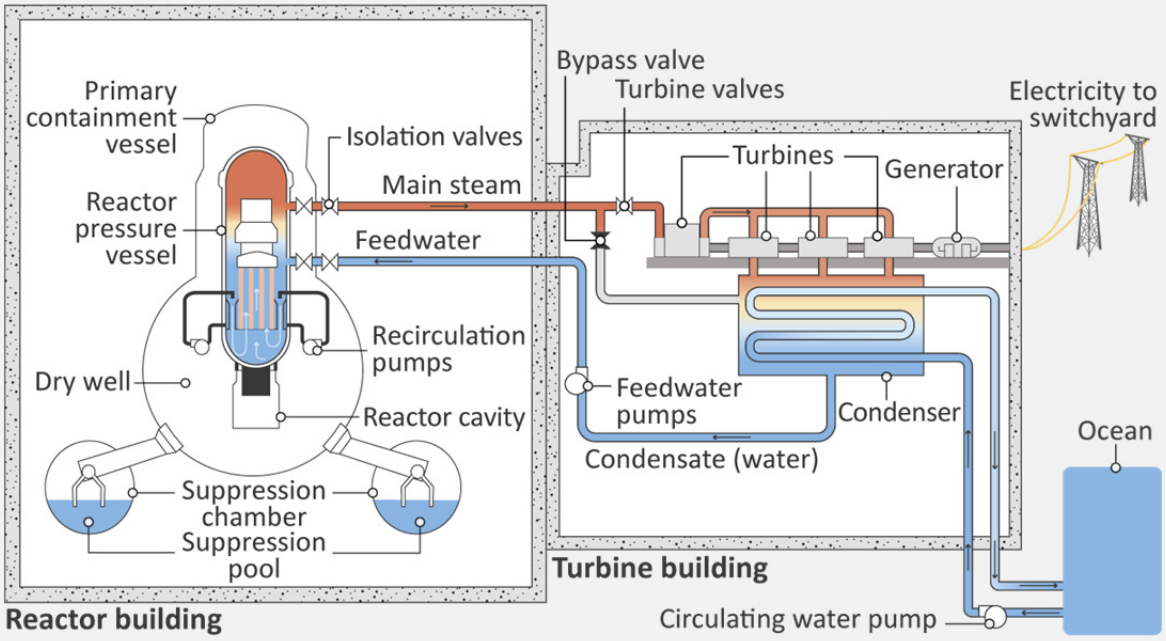
FIG. 2.1. The epicentre of the Great East Japan Earthquake and the NPPs nearby.

When the earthquake occurred, three of the six boiling water reactors (Box 2.1) at the Fukushima Daiichi NPP [13] were operating at full power and three were shut down for refuelling and maintenance. The operating reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. This automatic action achieved control of reactivity.

When shut down, the reactor cores continued to generate heat (known as decay heat). To prevent the nuclear fuel from overheating, this heat had to be removed by cooling systems that were mainly run or controlled by electrical power. The earthquake caused damage to on-site switchyard equipment, off-site substation equipment, and the power lines supplying off-site AC power to the plant, leading to the loss of all off-site electrical power. The on-site replacement power facilities — emergency diesel generators — which were designed to deal with such loss of off-site power situations, automatically started in order to restore AC power in all six units.

Box 2.1. Boiling water reactors

Boiling water reactors use a closed, direct steam cycle loop, as shown schematically below. The working fluid is water that is used both as the coolant to remove heat and the moderator for controlling reactivity. Coolant water boils in the reactor core at a pressure of approximately 7 MPa, and the steam that is generated is used to drive turbines to generate electricity. After passing through the turbines, the steam is condensed back to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feedwater.



Units 1–3 were automatically isolated from their turbine systems due to the power interruption, resulting in increases in the temperature and pressure of the reactors due to the decay heat. The cooling of these reactors following isolation was accomplished by means of the following design and operational provisions (Box 2.2):

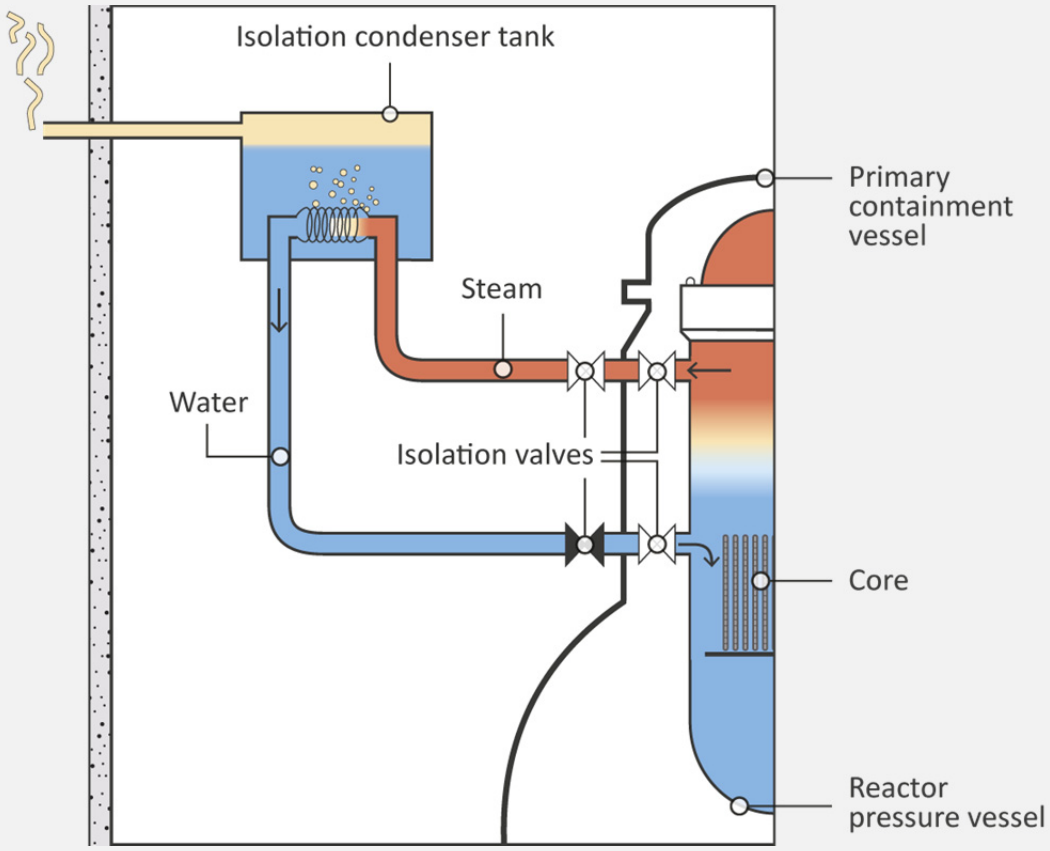
— In Unit 1, as the reactor pressure increased, both loops of the isolation condenser system started automatically and continued to cool the reactor. The operation of both isolation condenser loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the reactor pressure vessel. Afterwards, only one of the loops was used by the operators to control the cooling rate[27] in a range prescribed by the procedures.
— In Units 2 and 3, the increase in reactor pressure automatically activated safety relief valves, which were designed to protect the reactor from overpressurization by releasing steam from the reactor vessel to the suppression pool section of the primary containment vessel. This resulted in a decrease in the reactor water levels. The operators manually activated the reactor core isolation cooling system in accordance with procedures.

[27] In boiling water reactors, the cooling rate is monitored and controlled by the reduction in reactor pressure, which, in turn, corresponds to the decrease in reactor temperature.

Box 2.2. Systems for cooling the core when the reactor is isolated from the turbines

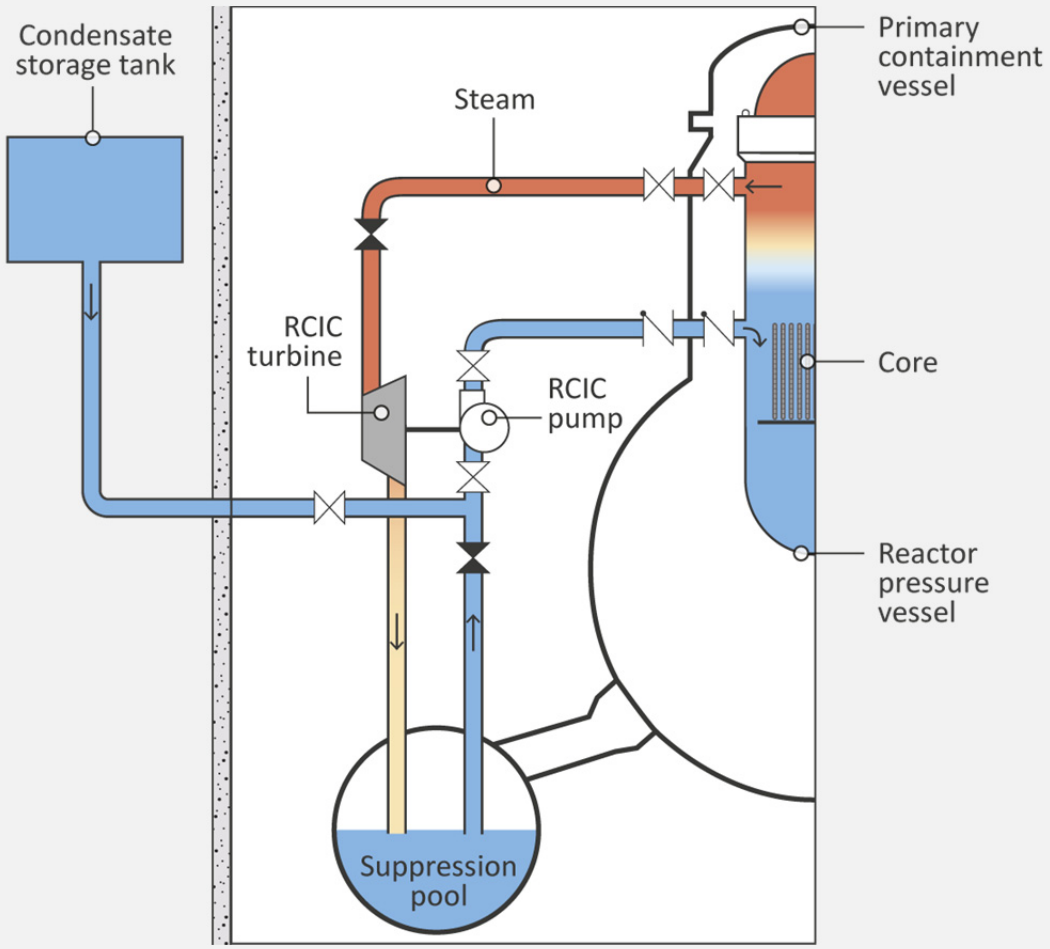
Normal shutdown cooling of boiling water reactors at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 2.1). However, when the reactor is isolated, this path is not available and core cooling is provided by the systems designed for an isolated reactor under high pressure conditions which exist after reactor shutdown. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser (IC) system for Unit 1 (the earlier design) and the reactor core isolation cooling (RCIC) system for Units 2–6.

Isolation condenser. In the Unit 1 design, there were two separate and redundant isolation condenser loops. In these closed loops, the primary side of the isolation condenser received steam generated in the reactor and condensed it by cooling inside the heat exchanger tubes that were submerged in colder water tanks (isolation condenser pools) located outside the primary containment vessel. Condensed steam was then sent as cold water back to the reactor by gravity (see the diagram below). Without mixing with the radioactive primary side water, the secondary side water in the isolation condenser pools boiled, and the evaporated steam was vented to the atmosphere, which served as the heat sink. The secondary side water volume of the isolation condenser (both trains together) was sufficient for eight hours of cooling before requiring replenishment from a dedicated water source.



Reactor core isolation cooling. In the design of Units 2–6, there were open cycle cooling systems that needed a source for adding water to the reactor system. In the reactor core isolation cooling systems, the steam from the reactor drove a small turbine which, in turn, ran a pump that injected water into the reactor at high pressure. The steam that ran the turbine was discharged and accumulated in the suppression pool section of the primary containment vessel, which served as the heat sink for absorbing waste heat. The water lost from the reactor was replenished by taking fresh water from the condensate storage tank (see the diagram below). When the tank emptied or the suppression pool became full, the water that accumulated in the suppression pool could be used, making the system essentially a closed loop cycle. The reactor core isolation cooling was designed to operate for at least four hours.

Box 2.2. Systems for cooling the core when the reactor is isolated from the turbines (cont.)



The decay heat from the nuclear fuel in Units 4–6 also had to be removed:

— In Unit 4, the equipment for cooling and refilling of spent fuel pool water[28] stopped working as a result of the loss of off-site power. The Unit 4 spent fuel pool, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among all the spent fuel pools of the units.
— In Unit 5, the reactor pressure, which was being kept elevated by the use of a pump for pressure testing purposes at the time of the earthquake, initially dropped when the pump stopped as a result of the loss of off-site power. The pressure started to rise due to decay heat, but unlike in Units 2 and 3, it remained well below the levels to activate the safety relief valves.
— In Unit 6, the reactor was near atmospheric pressure and room temperature with fuel in the core, and the decay heat was low.

[28] The spent fuel pools, which store the used and new fuel assemblies, are filled with water, providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

In the spent fuel pools of all units and the common spent fuel pool[29], which lost cooling and refilling capabilities upon the loss of off-site power, the temperatures of the pool water started to increase due to decay heat.

In response to the earthquake and the loss of off-site power, the operators activated the 'event based' abnormal operating procedures in all three main control rooms of the six units.[30] An earthquake emergency response team was activated at the on-site emergency response centre located within the seismically isolated building.[31] The Site Superintendent was responsible for directing the site response and for coordination with on-site and off-site organizations, as the head of TEPCO's on-site emergency response centre. Three shift superintendents in each of the main control rooms were responsible for directing the actions in their units under the command of the Site Superintendent.

The units at the Fukushima Daiichi NPP responded to the initiating event — the earthquake and the concurrent loss of off-site power — as intended by the designers and as stipulated in the operating procedures (except for some operator actions that were restricted or delayed by the aftershocks) (Fig. 2.2).

[29] As a shared auxiliary facility among the units, the common spent fuel pool, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[30] Each pair of units shared a common main control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[31] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and was put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

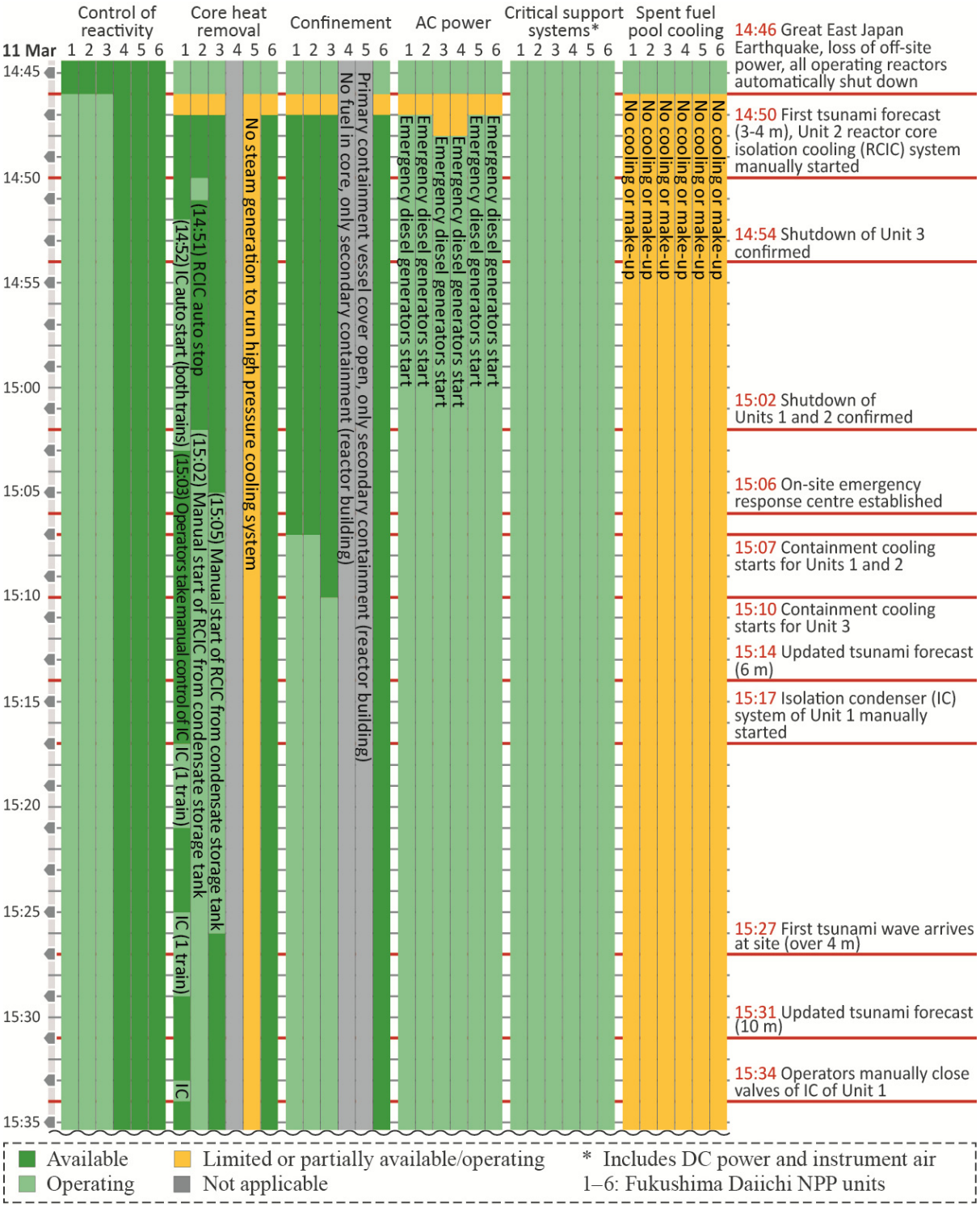


FIG. 2.2. Response of the Fukushima Daiichi NPP to the earthquake and the loss of off-site power.

The tsunami and the station blackout

In addition to causing the strong ground motion, the earthquake displaced a massive amount of water, giving rise to a series of large tsunami waves [14]. When these tsunami waves reached the coast, they had a devastating effect over a wide area (Fig. 2.3).

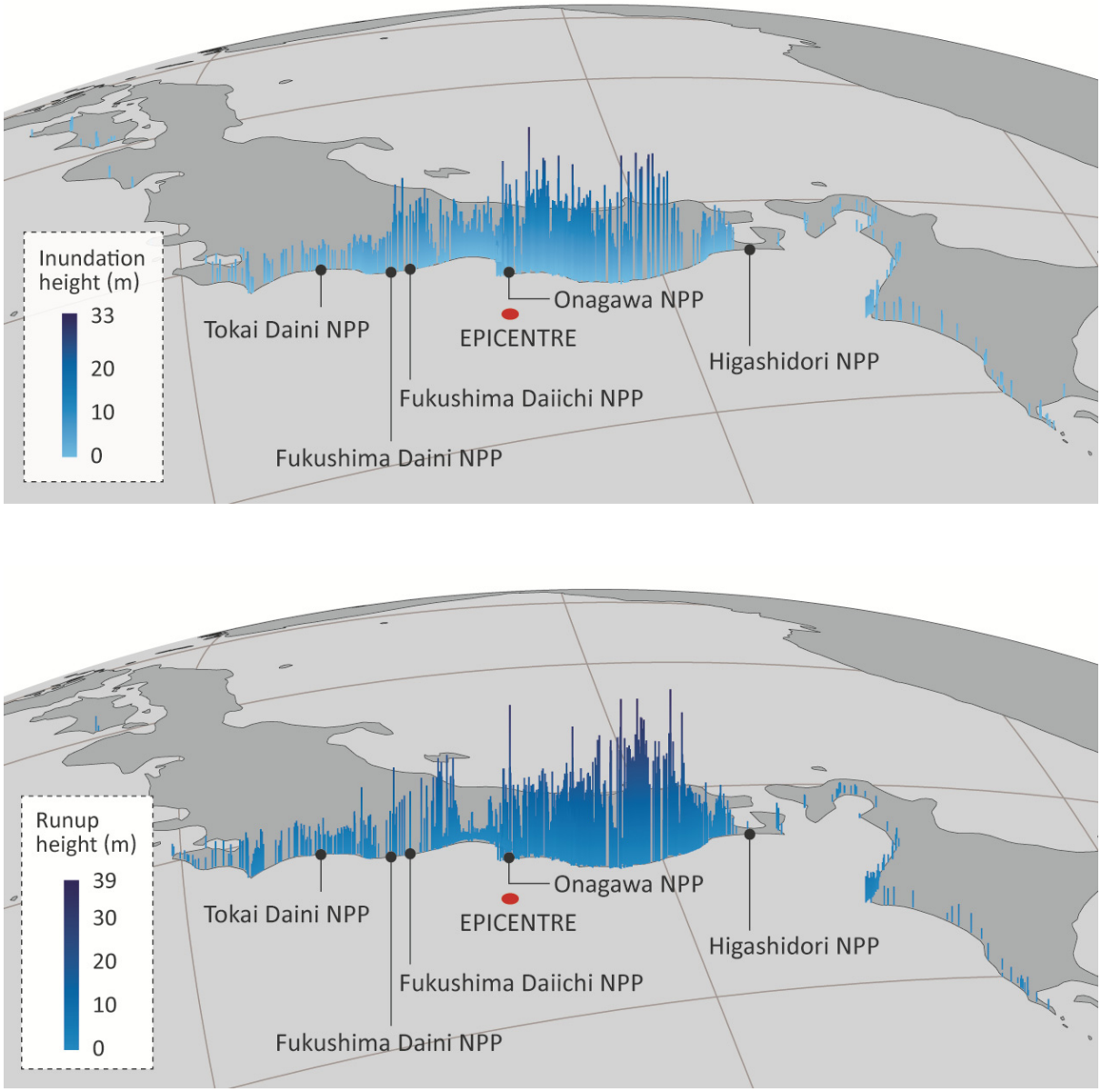


FIG. 2.3. The variation of tsunami wave impact, inundation (top) and runup (bottom)[32], based on the coastal geography and topography [15].

The tsunami waves started reaching the Fukushima Daiichi NPP about 40 minutes after the earthquake. The site was protected from the first wave, which had a 4–5 m runup height, by the

[32] Runup height is the height of the wave at the furthest inland point, and inundation height is the crest height of a wave compared to the sea level.

tsunami barrier seawalls that were designed to protect against a maximum tsunami height of 5.5 m [16]. However, about 10 minutes after the first wave, the second and largest wave, with a runup height of 14–15 m, overwhelmed the seawalls and inundated the site. It engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations[33] (Fig. 2.4), causing the following sequence of events:

— The wave flooded and damaged the unhoused seawater pumps and motors at the seawater intake locations on the shoreline. This meant that essential plant systems and components, including the water cooled emergency diesel generators[34], could not be cooled to ensure their continuous operation.
— The wave flooded and damaged the dry cask storage building located near the seashore between Units 1–4 and Units 5–6. There were no significant impacts on the casks or the fuel stored in them, as was later confirmed [17].
— Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the emergency diesel generators or their associated power connections, which resulted in the loss of emergency AC power. Only one of the air cooled emergency diesel generators — that of Unit 6 — was unaffected by the flooding[35]. It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout.

Because of the station blackout in Units 1–5, the emergency operating procedures for 'loss of all AC power' [18] were initiated. A 'specific event', as defined in the regulations associated with the Act on Special Measures Concerning Nuclear Emergency Preparedness [19], hereinafter referred to as the Nuclear Emergency Act, based on the condition of 'some safety systems becoming unavailable', was declared by the Site Superintendent, who was the head of the on-site emergency response centre of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

The Fukushima Daiichi NPP units, similar to other plants of the same age, were designed to withstand a station blackout for eight hours, based on the capacity of the DC batteries in the reactor units[36].

---

[33] The administration buildings and the seismically isolated building that contained the on-site emergency response centre were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[34] Each unit had a pair of emergency diesel generators, and Unit 6 had an additional generator. Of those 13 emergency diesel generators, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

[35] The air cooled emergency diesel generators of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be unaffected by the flooding. However, the components (i.e. switchgears, power centres, panels etc.) of the air cooled emergency diesel generators of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[36] NPPs are generally equipped with on-site DC and additional backup AC power sources (i.e. gas turbine generators or diesel engines) to withstand a station blackout for a limited period of time, varying between 4 and 72 hours. The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

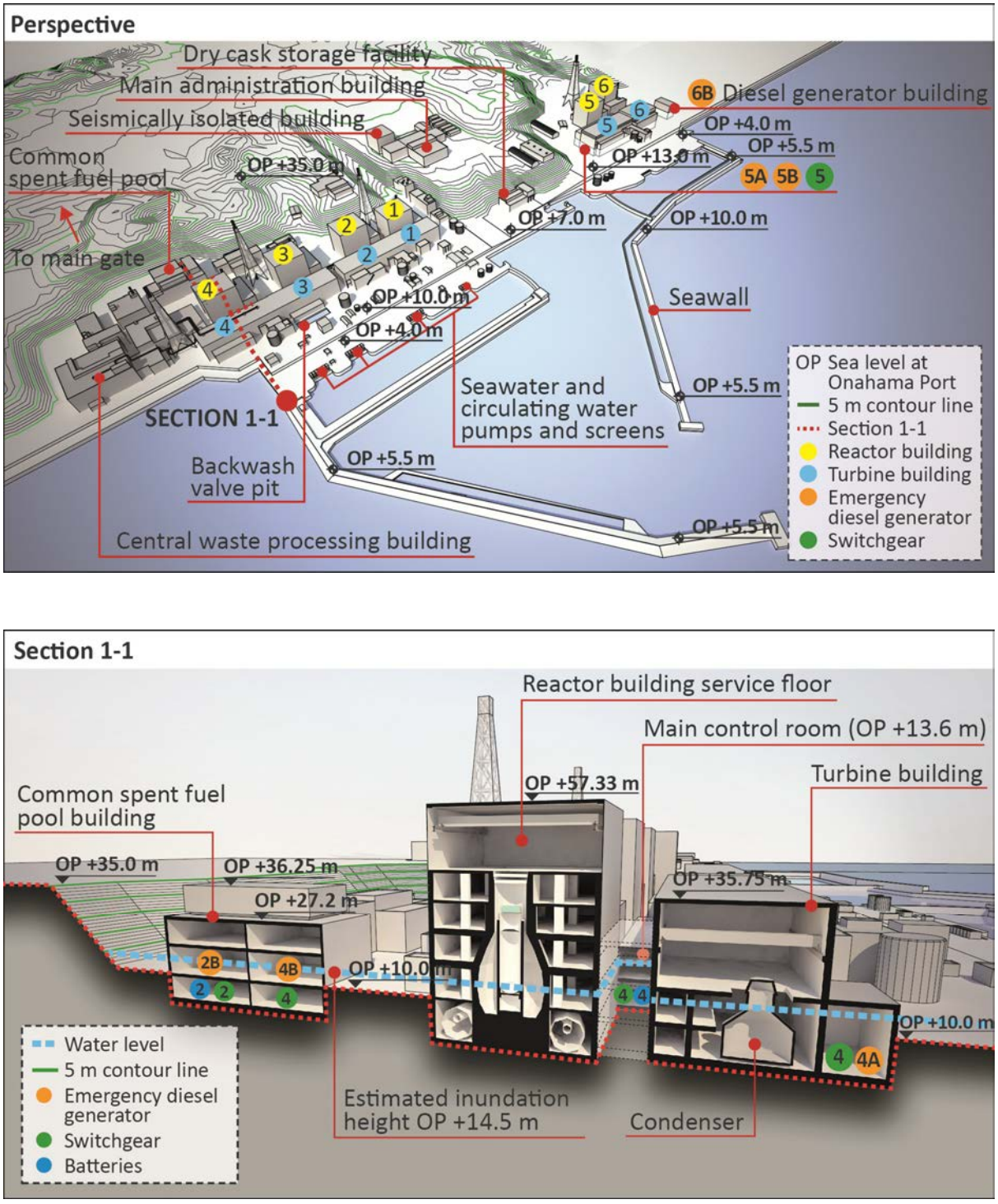


FIG. 2.4. The elevations and locations of structures and components at the Fukushima Daiichi NPP [20].

Loss of DC power in Units 1, 2 and 4

All units at the Fukushima Daiichi NPP were equipped with on-site DC sources as an emergency power supply, but the flooding also affected this equipment in Units 1, 2 and 4, inundating the DC batteries, power panels or connections. Consequently, DC power was gradually lost in Units 1, 2 and 4 during the first 10–15 minutes of the flooding, making it difficult to cope with the station blackout.

Due to the loss of all AC and DC power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the spent fuel pools in all units was already lost following the loss of off-site power. The additional loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the spent fuel pools of these units.

In the absence of procedures addressing the loss of all AC and DC power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with a station blackout under these conditions. The operators and emergency response centre staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

Response in Units 3, 5 and 6

Units 3, 5 and 6 maintained power enabling the operators to observe the plant status as the main control room indications and controls were functioning. This allowed the operators to continue with their 'symptom based' emergency operating procedures in response to the events:

— In Unit 3, the safety relief valves automatically opened to protect the reactor vessel from overpressurization, and the operators manually restarted the reactor core isolation cooling system, controlling and monitoring the reactor water injection with the available DC power. They also shut off other non-critical equipment to maximize the availability of the DC batteries in order to extend the period of time for coping with the station blackout.
— DC power was also available in Unit 5. The reactor was not generating steam, so residual heat removal by a high pressure cooling system was not possible. Alternative options to depressurize the reactor vessel to enable coolant injection by low pressure systems were tried unsuccessfully, and the reactor vessel, which was pressurized and filled with water, continued to heat up and pressurize.
— Unit 6 did not experience a station blackout, since AC power was available from one operating emergency diesel generator. Here, the efforts focused on maintaining fundamental safety functions in response to the loss of off-site power. The reactor was at atmospheric pressure, making it possible to utilize the low pressure systems to inject cooling water; however, some of the necessary components of those systems were damaged by the flooding and required restoration.

2.1.2. Progression of the accident

The nuclear emergency in Units 1 and 2

As all electrical power was lost in Units 1 and 2, there were no indications available to the operators to determine whether the safety systems were operating properly, or operating at all, in order to maintain the fundamental safety functions[37]. Unable to determine the water level in the reactor and the operational status of the cooling systems, plant operators declared that the core cooling fundamental safety function was lost. Consequently, the on-site emergency response centre reported to the off-site organizations, TEPCO Headquarters and relevant government authorities, that nuclear emergency conditions for Units 1 and 2 existed on the basis of the 'inability of water injection of the emergency core cooling system', as defined in regulations [21].

[37] The fundamental safety function of reactivity control had been confirmed before the station blackout by indications showing that the control rods were inserted and the fission reaction had stopped.

Establishing the severe accident management strategy

The staff in the on-site emergency response centre started following the established severe accident management guidelines, and the operators in the common main control room of Units 1 and 2 activated the severe accident operating procedure. Since the core cooling appeared to be compromised, the accident management strategy focused on injecting water into the reactors in order to prevent, or mitigate, potential damage to the nuclear fuel. Two options for injecting water into the reactors were identified:

— The use of systems that could inject water directly into the reactors, even at high pressures, which required the restoration of AC power.
— The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection lines to inject water into the core.[38]

The on-site emergency response centre adopted a core cooling strategy that used the stationary diesel driven fire pump and the fire engines via the fire protection system to inject water into the reactors, in addition to connecting temporary power sources.

This accident strategy was given the highest priority for Units 1 and 2 and was applicable to all other units with some variations. For example, in Unit 5, the accident management action was to restore AC power using the available interconnecting line[39] to the operating emergency diesel generator in Unit 6.

Status of core cooling in Units 1 and 2

Just before the tsunami struck, the Unit 1 isolation condenser was stopped by the operators in accordance with established operating procedures to control the reactor cooling rate. This was accomplished by closing the valves (located outside the primary containment vessel and DC operated, as shown in Box 2.2). About 2.5 hours after the loss of indications, at 18:18 on 11 March, some of the status lamps for those valves were found to be functioning, confirming that the control valves were closed. The operators attempted to start the isolation condenser by opening those valves. However, the isolation condenser did not function, indicating that the AC powered isolation valves inside the primary containment vessel were closed.[40] Thus, the fundamental safety function of core cooling at Unit 1 was lost when the isolation condenser was stopped by the operators just before the tsunami, and the Unit 1 core heated up from that time.

Additionally, local measurements (in the reactor building) at 20:07 indicated that the reactor was still near the operating pressure of 70 bar (7 MPa), which prevented water injection by alternative methods that would only be possible below 8 bar (0.8 MPa).

[38] The fire protection system was designed primarily for fire suppression and flooding of the containment vessel, not for injection of water into the reactor.

[39] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management. Sharing the functioning emergency power of Unit 6 was only possible for Unit 5, since these interconnections had been installed only between pairs of units, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[40] The valve positions were not clear to the operators owing to the uncertain timing and sequence of each type of power loss that would determine the status of isolation valves. All the isolation condenser valves would keep their position when the AC power was lost, but the AC powered isolation valves would close, by design, if the control power (i.e. DC power) was lost.

After several reports from the on-site emergency response centre on the status of Unit 1 and the other units, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March.[41]

In Unit 2, which was also without any indications of operation of the core cooling system and core pressure and temperature, the operators assumed the worst case scenario that the reactor core isolation cooling system was not operating and the Unit 2 core was heating up. At 21:01, the on-site emergency response centre informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Following this prediction, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order at 21:23 on 11 March for the evacuation of the public within 3 km, and for sheltering within 3–10 km, of the site[42].

The uncovering of the Unit 1 core was indicated when high radiation levels were encountered in the Unit 1 reactor building by a team that was dispatched at 21:51 to confirm the status of the operation of the isolation condenser.[43] This was an indication of the severity of the conditions at the Unit 1 reactor and of possible core damage.

Deterioration in conditions in Unit 1 confinement

Following the confirmation of the loss of core cooling in Unit 1, further challenges to the other fundamental safety function — the confinement — became evident when the first reading of the containment vessel pressure became possible at 23:50 on 11 March. The containment vessel pressure had exceeded the maximum pressure considered in its design, and this information prompted the Site Superintendent to order preparations for venting of the Unit 1 containment vessel. This situation also warranted an emergency notification, based on an 'abnormal rise in primary containment vessel pressure', as defined in the regulations associated with the Nuclear Emergency Act [19].

The measurements of Unit 1's containment pressure recorded the highest values at 02:30 and 02:45 on 12 March.

Confirmation of Unit 2's status and focus on recovery of Unit 1's safety function

At 02:10 on 12 March, a team was able to enter the room where Unit 2's reactor core isolation cooling system equipment was located and read the parameters to determine the system's status. The operating status was communicated to the on-site emergency response centre at 02:55 on 12 March and served to clarify the previously unknown condition of Unit 2 core cooling about 11 hours after the loss of monitoring in the main control room. On confirmation of Unit 2 core cooling, and with the acute challenge to the confinement function of Unit 1, the Site Superintendent decided to focus the accident management on venting efforts at Unit 1.

While the venting plans were being developed, the accident management strategy to restore Unit 1's core cooling using the fire pump for water injection proved to be impossible to implement because the pump was discovered to be inoperable at 01:48 on 12 March. The alternative, using fire trucks connected to the injection port in the turbine building, which had been installed the previous year as a

[41] At the same time, the Nuclear Emergency Response Headquarters, located at the Prime Minister's Office, was established, and the Prime Minister assumed responsibilities as the Director General, directing the national nuclear emergency response.

[42] Earlier, at 20:50, the local government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

[43] Their personal dosimeters recorded levels as high as 0.8 mSv in about ten seconds of their stay in the building.

fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake, was then put into action.

Heating up of Unit 5 and restoration of AC power

At about the same time, a Unit 5 safety relief valve automatically opened for the first time approximately 10 hours after the station blackout because the reactor pressure reached its opening set value, at 01:40 on 12 March. The valve automatically opened and closed several times to maintain the pressure in a range determined by the design because the Unit 5 reactor had continued to heat up in the absence of heat removal measures.

The safety relief valves were operating automatically to limit pressure, but could not be used to reduce pressure, since most of them had had their depressurization function disabled for the test carried out before the accident. Reducing pressure by opening a small valve (the head vent nozzle) on the reactor vessel was considered as an alternative because DC power was available for this purpose. Later, at 06:06 on 12 March, approximately 14.5 hours after the station blackout, the head vent nozzle was remotely opened and left open to depressurize the water-filled reactor vessel. In addition, the power connection between Unit 5 and the operating emergency diesel generator in Unit 6 was completed nearly 16.5 hours after the station blackout, enabling some AC power to be connected to the Unit 5 equipment, such as the pumps and valves needed for reactor heat removal.

Alternative cooling of the Unit 1 core

Meanwhile, the Unit 1 reactor pressure became low enough[44] to allow alternative water injection. An alternative cooling method, that is, freshwater injection from the fire engines into the Unit 1 reactor to restore core cooling, started at 04:00 on 12 March, about 12.5 hours after the station blackout. Water injection from a single one-tonne truck continued intermittently for approximately 5.5 hours with the truck having to return to the freshwater tank periodically to be refilled. At the same time, work on establishing a direct line from the tank continued. Later, just over 17.5 hours after the station blackout, continuous freshwater injection into Unit 1 started directly from the tank.

Venting of the Unit 1 containment

The measurement of Unit 1's containment pressure at 04:19 on 12 March showed that pressure in the containment had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Furthermore, the radiation levels measured at the main gate shortly afterwards showed an increase[45]. This was also an indication of some uncontrolled radioactive release from the primary containment, i.e. degraded confinement. The deteriorating radiological conditions at the site, combined with the elevated containment pressure in Unit 1, caused the Government to expand the evacuation zone to 10 km at 05:44 on 12 March.

The activities to configure venting of Unit 1's containment were set to start at 09:00 on 12 March. As soon as confirmation was received from the Fukushima Prefecture authorities, at 09:02, of the completion of evacuation of Okuma Town[46], the teams were activated to start manipulation of the valves in order to arrange the path for the venting of Unit 1's containment. After 5.5 hours of efforts,

[44] Reactor depressurization had occurred without any operator or plant system actions, indicating that an unknown path provided pressure relief.

[45] An increase of around tenfold (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23).

[46] Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.

the venting path (Box 2.3) was established when the final valve on the path was opened at around 14:00 on 12 March. The success of the venting operation was confirmed by a decrease in containment pressures, as measured at 14:30[47], and was reported to the relevant government authorities. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29[48] by one of the site monitors located near the site boundary to the north-west of Unit 1.

Loss of normal core cooling and start of emergency core cooling in Unit 3

While the containment venting of Unit 1 was being established, the station blackout response in Unit 3 had to be modified when the reactor core isolation cooling system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation. The operators tried unsuccessfully to restart the system several times, and the water in the reactor therefore continued to boil and evaporate and the reactor water level continued to decrease.

When the water level reached the point at which the high pressure coolant injection system — an emergency core cooling system — was activated automatically, at 12:35, this system automatically maintained the reactor water level in the predetermined range. However, the operators took manual control to avoid repeated automatic starts and stops of the system in order to preserve DC power for longer, in accordance with station blackout response procedures.

Seawater injection and power supply line-up for Unit 1

After approximately 11 hours of water injection into the Unit 1 core, the fresh water in the fire protection water tank was almost completely depleted. As a result, freshwater injection into Unit 1 was stopped at 14:53 on 12 March. The Site Superintendent then decided to inject sea water into the Unit 1 reactor from the Unit 3 backwash valve pit, where sea water had pooled after the tsunami, as it was the only available source of water at that time. The arrangements for seawater injection were completed in just over half an hour.

Around the same time, work to connect the mobile voltage power supplies[49] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized at 15:30 on 12 March.

Nearly 24 hours after the station blackout, seawater injection and AC power supply were connected to Unit 1. However, within minutes of connection, an explosion in the Unit 1 reactor building damaged both of these arrangements before they could be put in use.

---

[47] Overall, it took 14.5 hours from the Site Superintendent's order (around midnight) to start venting. This was a result of high radiation levels around the suppression chamber where valves had to be manually manipulated, and the lack of compressed air supply to operate the valves.

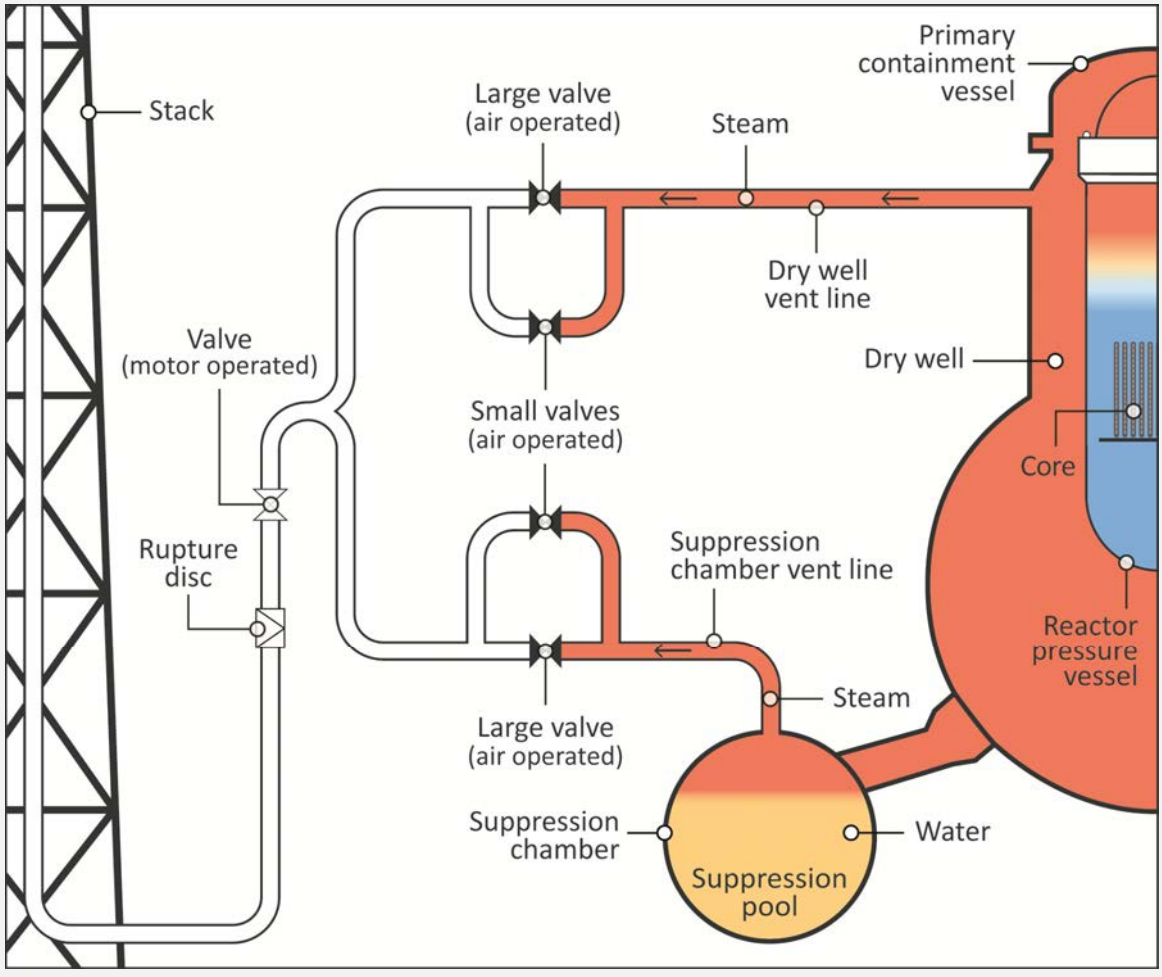
[48] At 16:17, it was noted by the emergency response centre that the radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h, and the authorities were notified at 16:27 since the value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

[49] Almost one hour after the station blackout on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPPs. The first vehicle, from Tohoku Electric, arrived around 22:00 on 11 March, i.e. nearly six hours after the station blackout. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Force arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

Box 2.3. Containment venting

As a measure to improve the ability to cope with severe accidents, 'hardened vents' (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [22, 23]. The aim was to prevent overpressurization of the primary containment by allowing venting (see the figure below). Although the preferred path of venting was from the suppression chamber, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the dry well. Either path could be aligned by manipulating valves from the main control room, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to break when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment.



Explosion in the Unit 1 reactor building

At 15:36 on 12 March, an explosion occurred on the service floor of the Unit 1 reactor building, causing damage to the upper building structure and injuring workers. Although the explosion did not seem to damage the primary containment, there was extensive damage to the secondary containment (the reactor building). The cause of the explosion was unknown to the plant staff, but it was suspected

that hydrogen had been released from the core and had escaped from the primary containment via an unknown path. Consequently, the on-site emergency response centre requested evacuation of staff from the areas in and around Units 1–4, including the two main common control rooms, except for the three most senior level staff.

Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Injection of sea water into Unit 1

The explosion in Unit 1 not only caused serious damage to the seawater injection and temporary electrical power line assemblies, but also hindered their repair because of the rubble scattered around the site and the locally high dose rates from contaminated rubble. After an evacuation lasting about two hours, teams returned to repair or replace damaged equipment.

After the repair and replacement of damaged equipment, water injection into the Unit 1 reactor, using fire engines and sea water from the Unit 3 backwash valve pit, started at 19:04 on 12 March and continued[50] afterwards. Boric acid was added later to address re-criticality concerns for ensuring the fundamental safety function of reactivity control. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

Loss of Unit 3 core cooling

While Unit 1 was assigned the highest priority with respect to the maintenance of the fundamental safety functions during the first day and a half after the earthquake and the tsunami, the core cooling situation in Unit 3 became a cause of concern on the morning of Sunday 13 March.

After 14 hours of continued operation of the emergency high pressure coolant injection system, the Unit 3 operators became concerned about the reliability and possible failure of the system's turbine powering the injection pump, which was by then operating at low reactor steam pressure. The concern was related to the possibility of turbine damage and the creation of a release path from the reactor vessel. This would result in an uncontrollable release of radioactive steam directly outside the primary containment. This concern was heightened when the turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure.

Consequently, the operators decided to stop the high pressure coolant injection system and instead use the alternative means of injection at low pressure (the diesel driven fire pump). The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below that of the diesel driven fire pump and could be kept low by the use of pressure relief valves. The Unit 3 emergency high pressure core injection system was therefore turned off by the operators, who then started their attempts to open the pressure relief valves.

However, all attempts to open the pressure relief valves failed, and reactor pressure quickly increased above the level at which the diesel driven fire pump could inject, stopping the cooling of the Unit 3 core about 35 hours after the station blackout. Faced with this setback, the operators tried for nearly 45 minutes to return to injection via the emergency high pressure coolant injection system but were unsuccessful. Without any capability to cool the reactor, an emergency report for 'loss of reactor cooling function' as defined in the regulations associated with the Nuclear Emergency Act [19] was

[50] On one occasion, according to the investigations [7], a TEPCO executive who was representing the company at the Prime Minister's Office asked the Site Superintendent on the telephone to stop the seawater injection into Unit 1. That directive was not followed, and seawater injection was not interrupted.

issued for Unit 3 at 05:10 on 13 March. The Unit 3 core remained without cooling for the hours that followed, and Unit 3 became the next unit to lose core cooling.

After the loss of cooling, an alternative water injection method to cool the Unit 3 core utilizing the fire engines was ordered by the Site Superintendent at 05:15. In view of the deteriorating conditions, he also ordered the Unit 3 containment venting path to be lined up.

Unit 3 alternative core cooling and containment venting

The fire engines from Units 5 and 6 were dispatched to Unit 3 and work began at 05:21 on 13 March to establish a line for injecting sea water into the Unit 3 core from the Unit 3 backwash valve pit through the fire protection lines. An additional fire engine arrived from the Kashiwazaki-Kariwa NPP at 06:30. The seawater injection line was completed within an hour. However, its use was postponed by the Site Superintendent as a result of a communication from TEPCO Headquarters[51]. As a result, the injection line was changed back to the borated freshwater source through the fire protection line using fire engines.

The efforts to reduce the reactor pressure below the fire engine pump pressure in order to maintain water injection required the activation of the pressure relief valves. This was achieved by use of DC batteries from cars, which were collected in the common main control room of Units 3 and 4.

Meanwhile, the Unit 3 venting line arrangement was also completed in a little more than three hours, at 08:41 on 13 March, but the containment pressure was still below the containment design pressure, not high enough to cause the bursting of the rupture disc as designed. As efforts continued to reduce the reactor pressure by opening the safety relief valve, the operators in the main control room observed a drop in the reactor pressure in the Unit 3 reactor at 09:08, although the valve status indicators did not conclusively show whether or not the valves were in the open position. Along with this depressurization of the reactor vessel, there was a pressure surge in the primary containment, indicating a discharge from the reactor vessel to the containment vessel. Eventually, at 09:20 on 13 March, the containment pressure exceeded the maximum design pressure of the containment and, subsequently, the containment pressure dropped rapidly, indicating that the venting of the Unit 3 containment had occurred as a result of the bursting of the rupture disc.

Following reactor depressurization, achieved by opening additional safety relief valves, the reactor pressure fell below the fire engine pump pressure, and injection of borated fresh water into the Unit 3 reactor started at 09:25, after more than four hours without cooling.

The venting of the Unit 3 containment was short lived when a valve on the vent line closed[52] because of the lack of sufficient air supply to keep it open. After 6.5 hours of effort, the valve was reopened by using a mobile compressor.

Unit 2 precautionary measures for fundamental safety functions

At around 10:15 on 13 March, as the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, the Site Superintendent ordered the containment

[51] A division director in the emergency Off-site Centre at TEPCO Headquarters who attended a meeting in the Prime Minister's Office earlier asked the Site Superintendent on the telephone whether there was any fresh water available. He informed the Site Superintendent of the views of meeting participants, who were inclined to continue freshwater injection as long as possible. The Site Superintendent interpreted this communication as a directive not to inject sea water as long as fresh water was available.

[52] As was discovered two hours later.

vent path for Unit 2 to be pre-emptively established. This was intended to take advantage of the still favourable radiological conditions, compared with the other units and site-wide trend[53], to conduct work in the Unit 2 reactor building where the valves were to be manipulated. The work was accomplished in 45 minutes, but venting did not occur because the pressure inside the Unit 2 containment was not high enough to burst the rupture disc.

At around 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's operating cooling system failed. For this purpose, fire engines were to be connected to the fire protection lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed.

Injection of sea water into Unit 3 and increase of radiation levels

As the fresh water from the fire protection tanks was depleted at 12:20 on 13 March, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started nearly one hour later, at 13:12.

At 14:15 on 13 March, a high radiation dose rate (nearly 1 mSv/h) was measured near the site boundary, and the relevant government agencies were notified at 14:23 of an 'abnormal site boundary radiation level increase' as defined in the regulations associated with the Nuclear Emergency Act [19]. Fifteen minutes later, the radiation dose rate exceeded 100–300 mSv/h at the entry doors of the Unit 3 reactor building. As the dose rates measured on the Unit 3 side of the common main control room of Units 3 and 4 exceeded 12 mSv/h, the shift team moved to the Unit 4 side.

The on-site emergency response centre inferred from these dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common main control room of Units 3 and 4 and from the areas in the vicinity of Unit 3.

The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

Establishment of core cooling in Unit 5

Meanwhile, the power from the Unit 6 emergency diesel generator was connected at 20:48 on 13 March to the pump of Unit 5's normal, low pressure, heat removal system, and was activated at 20:54. A reactor water injection line to the reactor of Unit 5 through one of the two residual heat removal systems was lined up and interconnecting pipe valves to the makeup water condensate system were opened, 53 hours after the station blackout. However, water injection did not occur, since the reactor pressure had gradually risen and exceeded the injection pressure. In response, a safety relief valve was opened, making use of available DC power and nitrogen supplies. This was successful in reducing the pressure in the reactor pressure vessel and allowed water injection into the Unit 5 reactor at 05:30 on 14 March, which continued afterwards.[54]

---

[53] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km away from the reactor buildings of Units 1–4 near the main gate, indicating a possible breach of the containment vessel, although the source of the neutrons was unknown.

[54] In addition, the AC power to operate the system for controlling reactor building pressure was supplied from Unit 6's emergency diesel generator. A little over two days after the blackout, pressure in the reactor building was below atmospheric pressure, ensuring secondary confinement.

Loss of seawater cooling in Units 1 and 3

As the injection of sea water into Units 1 and 3 from the Unit 3 backwash valve pit continued into Monday, 14 March, the water in the pit fell to such a low level that injection had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3, which resumed two hours later. Unit 1 core cooling was postponed until the pit could be refilled.

In the following hours, the Unit 3 containment pressure was found to be increasing and the reactor water level indication continued to decrease. The reactor water level in Unit 3 went off-scale at 06:20 on 14 March, indicating to the operators that the core was uncovered. The Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the pit refilling activities.

The containment pressure in Unit 3 reached a maximum at 07:00, but was found to be slightly lower at 07:20. It subsequently remained stable below maximum design pressure. The Site Superintendent then decided to resume the work to establish a line to refill the backwash valve pit from the ocean. In the next two to four hours, the seawater injection lines for all units were re-established, and refilling of the pit commenced, utilizing two additional fire engines to pump water from the ocean and tanker trucks from the Japan Self-Defense Force, which arrived at the site at 10:26, to carry water to the pit.

Seawater injection into Unit 1 was ready to be resumed when all activities, including the ongoing seawater injection into the Unit 3 reactor, had to stop because of the explosion in Unit 3. This damaged the hoses and fire engines around the Unit 3 backwash valve pit and necessitated a temporary evacuation of workers from the outside areas.

Explosion in the Unit 3 reactor building

At 11:01 on 14 March, an explosion occurred in the upper part of the Unit 3 reactor building, destroying the structure above the service floor and injuring workers. In addition to the destruction of the alternative water injection arrangement, the capability to vent the containment in Unit 2 was also lost as a result of the explosion, which affected the previously set up Unit 2 containment venting path. After the explosion, the isolation valve on the Unit 2 vent line was discovered to be closed and could not be reopened.

Restart of seawater cooling in Units 1 and 3

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. After restoration of injection lines, seawater injection was recommenced first for Unit 3 in the afternoon of 14 March and later in the evening for Unit 1. The cores had been without cooling water injection for 5 hours in Unit 3 and for 18 hours in Unit 1.

Loss of cooling and seawater injection in Unit 2

At around 13:00 on 14 March, Unit 2 became the next unit to experience loss of cooling, with measurements showing that the reactor water level had decreased and that the reactor pressure had increased. This pointed to the possible failure of the Unit 2 reactor core isolation cooling system, as inferred by the unit operators and the on-site emergency response centre. As a result, a ‘loss of reactor cooling functions’ report as defined in the regulations associated with the Nuclear Emergency Act [19] was issued for Unit 2.

After the failure of the reactor core isolation cooling system, seawater injection through the fire protection system was attempted at 13:05, but the reactor pressure was too high for the fire engine

pumps. It seemed likely that, without water injection, the core would be uncovered very soon. It was therefore decided to use the relief valves to depressurize the reactor in order to enable water injection at low pressure, while recognizing the potential adverse impact on the confinement as a result of the release of steam from the reactor into the containment.[55]

After reactor vessel depressurization and refuelling of the fire engines, seawater injection into Unit 2 through the fire protection system began shortly before 20:00 on 14 March, first with one fire engine and soon afterwards with two.

Degradation of the Unit 2 confinement

At around 21:55 on 14 March, recently restored radiation monitoring equipment inside the containment indicated that the radiation levels in the Unit 2 containment had increased substantially since the previous measurements taken eight hours earlier.[56] Also, both the reactor and containment pressures showed an increasing trend after 22:30 on 14 March. The containment pressure exceeded the design pressure at 22:50, prompting an emergency declaration of an 'unusual rise of pressure in containment vessel' in accordance with the regulations associated with the Nuclear Emergency Act [19] for Unit 2. This condition was reported to the relevant government authorities at 23:39. Over the next three to four hours, more relief valves were opened to decrease reactor pressure in order to allow water injection into the Unit 2 reactor. As a consequence, the containment pressure increased further while the unit operations team tasked with establishing the venting line to relieve containment pressure was unable to open the vent valves. In order to protect the confinement function and permit venting as soon as possible, TEPCO staff at the emergency on-site and off-site centres agreed to vent directly from the dry well, recognizing that this would increase radioactive releases to the environment. However, it was not possible to open the valves on the dry well vent either, and consequently Unit 2 venting could not be accomplished.

At 04:17 on Tuesday 15 March, the relevant government agencies were notified that depressurization of the Unit 2 containment and of the reactor had not been effective and that containment pressure continued to increase.

Events in Units 2 and 4 followed by site evacuation

At 06:14 on 15 March, an explosion was heard on the site and tremors were felt in the common main control room of Units 1 and 2. This was followed by a drop in the pressure reading of the Unit 2 containment (suppression chamber). The staff in the main control room initially reported to the on-site emergency response centre that the Unit 2 suppression chamber pressure had dropped to near atmospheric pressure[57], indicating potential loss of the confinement function.

This information indicated a possible containment vessel failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site emergency response centre ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site emergency response centre was located. At about the same time as the event associated with the Unit 2

[55] The suppression chamber section of the primary containment vessel was already nearly saturated.

[56] A 5000-fold increase in radiation levels in the containment atmosphere (from 1.08 mSv/h to 5360 mSv/h) and a 40-fold increase in radiation levels in the suppression pool section of the containment (from 10.3 mSv/h to 383 mSv/h). Additionally, neutrons had been detected between 21:00 on 14 March and 01:40 on 15 March, again near the main gate. It was thought by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors.

[57] After rechecking the readings, it was confirmed that the suppression chamber pressure was off the scale, but the dry well section pressure had not decreased significantly in Unit 2.

suppression chamber, an explosion in the upper part of the Unit 4 reactor building was reported by the evacuating personnel.

Following the events in Units 2 and 4, all personnel except those required for monitoring and emergency response were instructed by the Site Superintendent to go to a radiologically safe location. Approximately 650 people understood this order as a site evacuation and evacuated to the Fukushima Daini NPP. An estimated 50–70 staff[58], including the Site Superintendent, remained at the Fukushima Daiichi site. The relevant government agencies were informed of the evacuation by the on-site emergency response centre at 07:00 on 15 March.

About two hours later, white smoke (or steam) was observed being released from the Unit 2 reactor building near the fifth floor. A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

During this sequence of events, fundamental safety functions of Units 1–3 were lost or severely degraded (Fig. 2.5), and efforts focused on damage assessment and restoration and stabilization of those functions.

2.1.3. Stabilization efforts

Replenishment of the spent fuel pool at Units 3 and 4

A remote visual inspection from a helicopter to address concerns about the status of the Unit 3 and 4 spent fuel pools was conducted in the afternoon of Wednesday, 16 March. The inspection confirmed that there was sufficient water in the Unit 4 spent fuel pool to cover the fuel assemblies; however, observations were not conclusive for Unit 3's spent fuel pool, making its replenishment a high priority.

The first supply of water to the Unit 3 spent fuel pool was made between 09:30 and 10:00 on 17 March, when helicopters dropped sea water. Fresh water was sprayed by water cannon trucks later on the same day between 19:05 and 20:07. Sea water or fresh water was sprayed into the Unit 4 spent fuel pool starting on 20 March[59].

Spraying into the pools using water cannon and fire engine trucks or concrete pump vehicles continued intermittently in March, to ensure that the spent fuel was not exposed. The fuel pool cooling and cleanup system was also utilized in April and well into May 2011.

Restoration of power supplies and end of the station blackout

Between 17 and 20 March, work was carried out to lay temporary power cables to Units 1 and 2. At 15:46 on Sunday 20 March, almost exactly nine days after the station blackout, off-site power was restored to Units 1 and 2 through this temporary AC power system, ending the blackout in Units 1 and 2.

---

[58] As noted by different investigation reports, the exact number of staff is not certain [6, 8]. It is also noted that the staff who evacuated to the Fukushima Daini NPP site started to return to the Fukushima Daiichi NPP site on the same day.

[59] The same approach was followed for adding water to the spent fuel pool of Unit 1. Since the Unit 2 reactor building was still covering the Unit 2 spent fuel pool, the spray method could not be used for Unit 2.

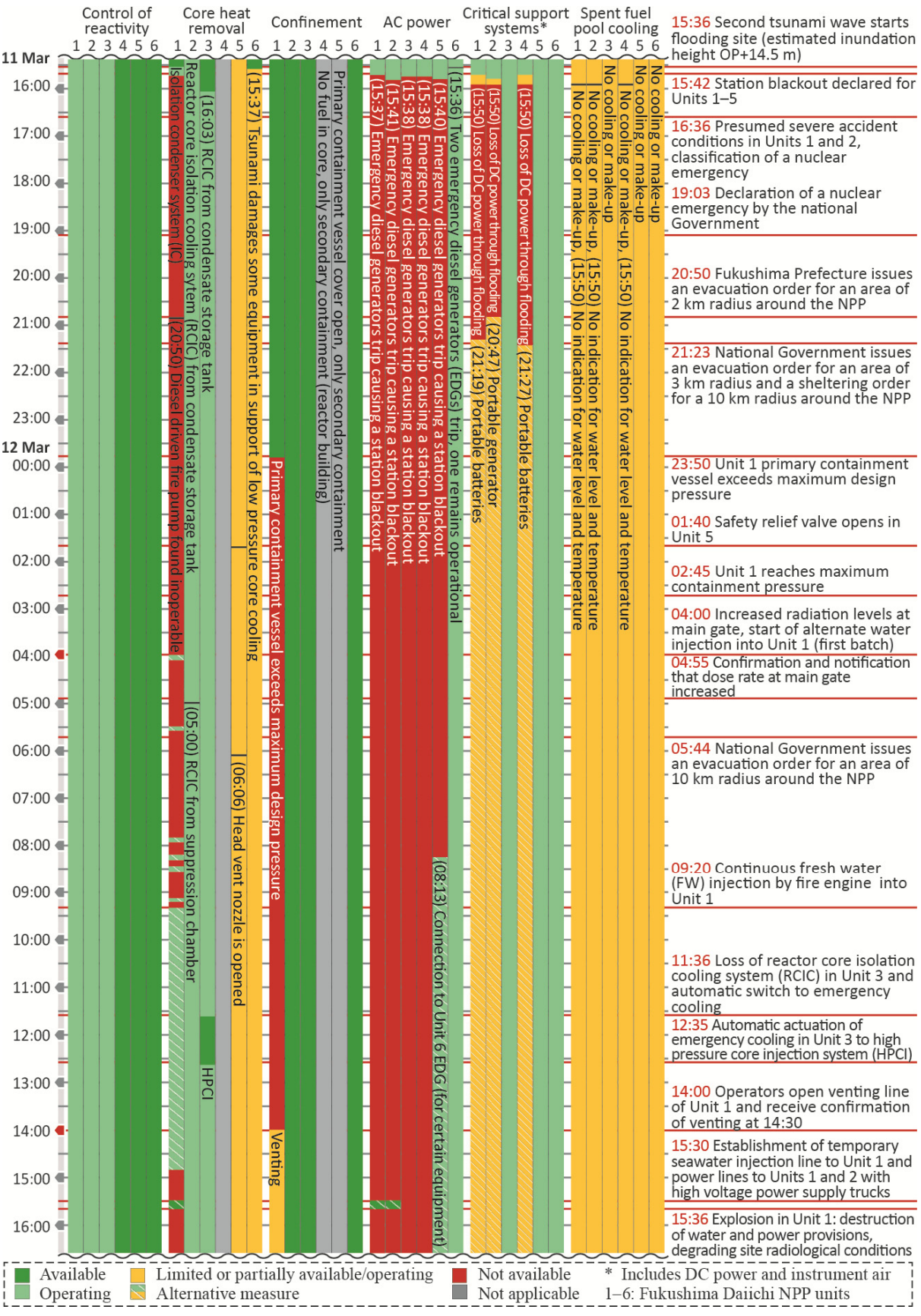


FIG. 2.5. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011).

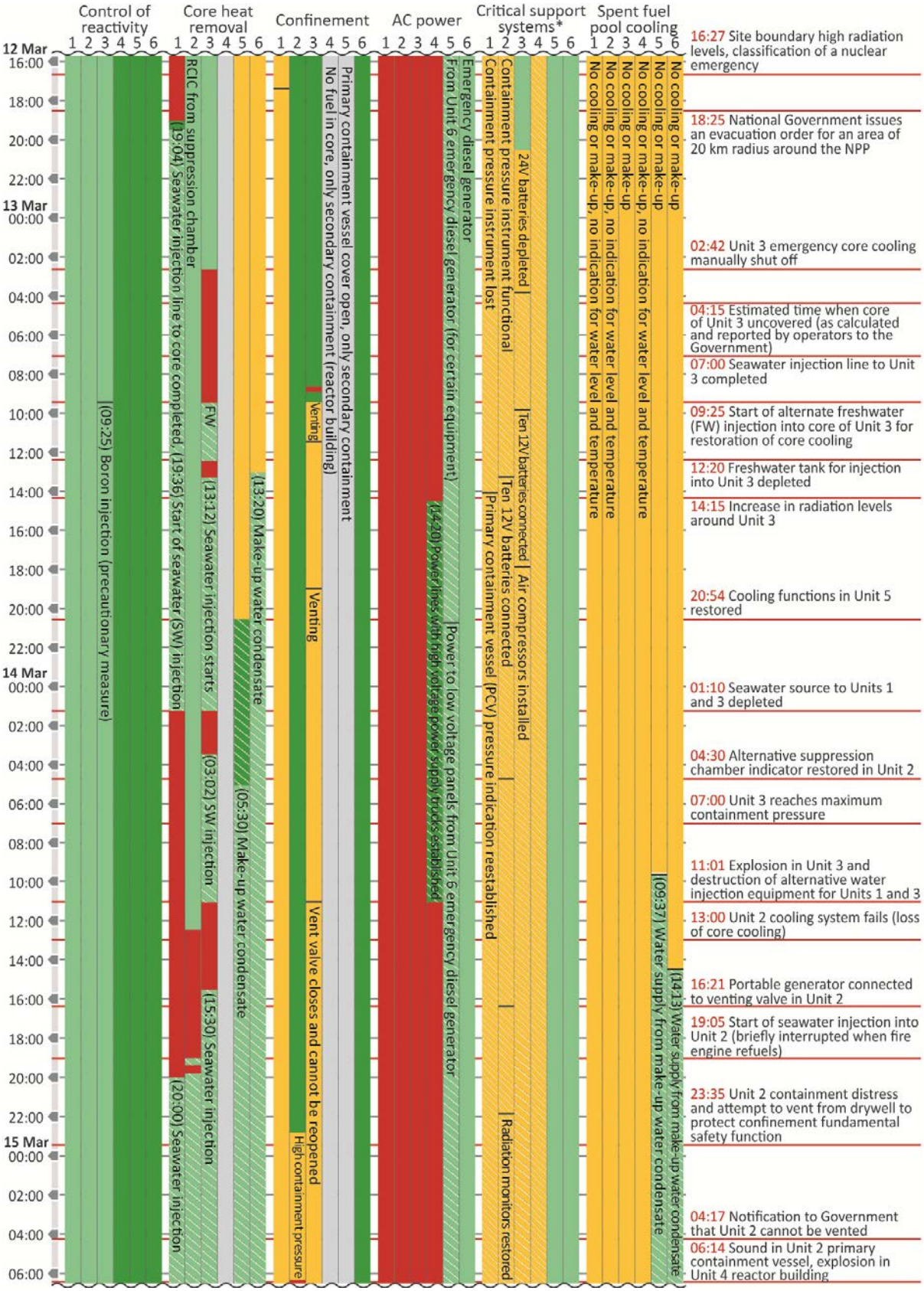


FIG. 2.5. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011) (cont.).

In Unit 6, power was restored to the cooling system of the second water cooled emergency diesel generator through a power line connected to the operating air cooled generator. The water cooled emergency diesel generator began operation again at 04:22 on 19 March, supplying AC power to Units 5 and 6.

The blackout at Units 3 and 4 ended after more than 14 days, when temporary off-site power to these two units was restored on 26 March.

Achieving stable conditions

Unit 5 was the first unit to reach cold shutdown mode when its normal residual heat removal system was put into service, at 12:25 on 20 March. The reactor temperature decreased below 100°C in approximately two hours, placing Unit 5 in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the beginning of the accident.

The normal residual heat removal system of Unit 6 was put back in service, in a manner similar to that at Unit 5, at 18:48 on the same day. The reactor temperature decreased below 100°C in less than one hour, placing Unit 6 in the cold shutdown mode at 19:27 on 20 March (Fig. 2.6).

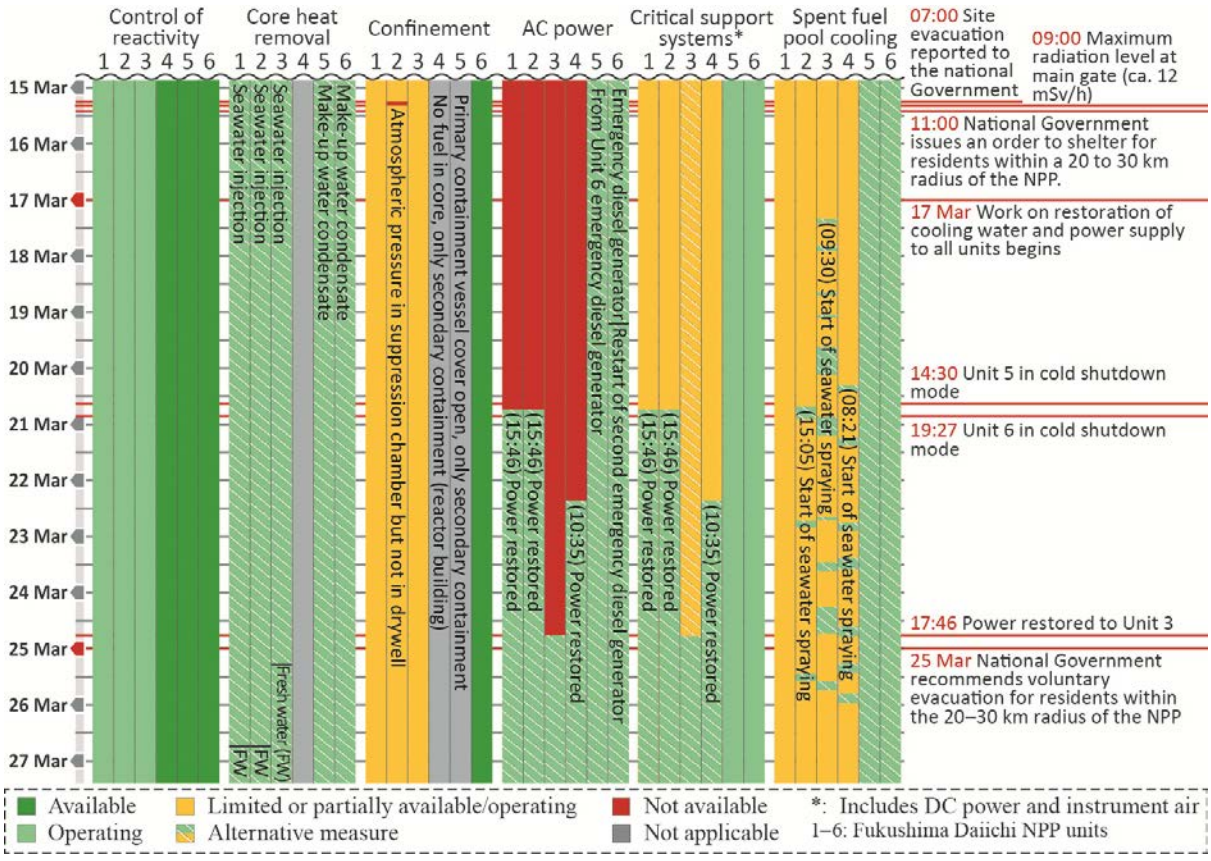


FIG. 2.6. Temporary restoration of fundamental safety functions at the Fukushima Daiichi NPP.

For Units 1–3, TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at the TEPCO Fukushima Daiichi Nuclear Power Station [24]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[60]: achievement of significant suppression of radiological releases and steady decline of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap. The Government of Japan and TEPCO announced on 19 July that the first condition had been achieved in Units 1–3 and, on 16 December 2011, that the second condition had been achieved for these units. This announcement officially[61] brought the 'accident' phase of events at the Fukushima Daiichi NPP to a close.

However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued. Additionally, challenges in the management of waste, such as difficulties in dealing with the accumulation of radioactive water due to groundwater ingress to the buildings and occasional failures of equipment, continued. At the time of writing, the Government of Japan considered the Fukushima Daiichi NPP a 'specified facility as an accident site'[62].

2.2. NUCLEAR SAFETY CONSIDERATIONS

2.2.1. Vulnerability of the plant to external events

The earthquake on 11 March 2011 caused vibratory ground motions that shook the plant structures, systems and components. It was followed by a series of tsunami waves, one of which inundated the site. Both the recorded ground motions and the heights of the tsunami waves significantly exceeded the assumptions of hazards that had been made when the plant was originally designed. The earthquake and the associated tsunami impacted on multiple units at the Fukushima Daiichi NPP.

The seismic hazard and tsunami waves considered in the original design were evaluated mainly on the basis of historical seismic records and evidence of recent tsunamis in Japan. This original evaluation did not sufficiently consider tectonic-geological criteria and no re-evaluation using such criteria was conducted.

Prior to the earthquake, the Japan Trench was categorized as a subduction zone with a frequent occurrence of magnitude 8 class earthquakes; an earthquake of magnitude 9.0 off the coast of Fukushima Prefecture was not considered to be credible by Japanese scientists. However, similar or higher magnitudes had been registered in different areas in similar tectonic environments in the past few decades.

There were no indications that the main safety features of the plant were affected by the vibratory ground motions generated by the earthquake on 11 March 2011. This was due to the conservative approach to earthquake design and construction of NPPs in Japan, resulting in a plant that was provided with sufficient safety margins. However, the original design considerations did not provide comparable safety margins for extreme external flooding events, such as tsunamis.

---

[60] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

[61] According to the criteria set by the Government of Japan at the time.

[62] In accordance with the definition of 'specified nuclear facility', i.e. a facility that would require special measures for safety or physical protection of specified nuclear material, established by the current regulatory body, the Nuclear Regulation Authority (NRA), on 7 November 2012.

The vulnerability of the Fukushima Daiichi NPP to external hazards had not been reassessed in a systematic and comprehensive manner during its lifetime. At the time of the accident, there were no regulatory requirements in Japan for such reassessments and relevant domestic and international operating experience was not adequately considered in the existing regulations and guidelines. The regulatory guidelines in Japan on methods for dealing with the effects of events associated with earthquakes, such as tsunamis, were generic and brief, and did not provide specific criteria or detailed guidance.

Before the accident, the operator had conducted some reassessments of extreme tsunami flood levels, using a consensus based methodology developed in Japan in 2002, which had resulted in values higher than the original design basis estimates. Based on the results, some compensatory measures were taken, but they proved to be insufficient at the time of the accident.

In addition, a number of trial calculations were performed by the operator before the accident, using wave source models or methodologies that went beyond the consensus based methodology. Thus, a trial calculation using the source model proposed by the Japanese Headquarters for Earthquake Research Promotion in 2002, which used the latest information and took a different approach in its scenarios, envisaged a substantially larger tsunami than that provided for in the original design and in estimates made in previous reassessments. At the time of the accident, further evaluations were being conducted, but in the meantime, no additional compensatory measures were implemented. The estimated values were similar to the flood levels recorded in March 2011.

Worldwide operating experience has shown instances where natural hazards have exceeded the design basis for an NPP. In particular, the experience from some of these events demonstrated the vulnerability of safety systems to flooding.

Box 2.4. Tsunamis [25]

A tsunami — in Japanese meaning a wave (‘nami’) in a harbour (‘tsu’) — is a series of travelling waves of long wave length (e.g. from kilometres to hundreds of kilometres) and period (e.g. several minutes to tens of minutes, and, exceptionally, hours), generated by deformation or disturbances of the sea floor (or, in generic terms, underwater floor). Earthquakes, volcanic phenomena, underwater and coastal landslides, rock falls or cliff failures can generate a tsunami. Tsunamis can occur in all oceanic regions and sea basins of the world and even in fjords and large lakes.

Tsunami waves propagate outward from the generating area in all directions, with the main direction of energy propagation determined by the dimensions and orientation of the generating source. During propagation of the tsunami in deep water, they proceed as ordinary gravity waves, with a speed depending on the depth of water. For example, in deep ocean, speeds could exceed 800 km/h, with a wave height generally less than a few tens of centimetres and, in the case of an earthquake source, with wave lengths often exceeding 100 km. During the propagation, submarine topography affects the speed and height of the tsunami wave. Refraction, reflection from a sea mount or its chain (archipelago) and diffraction are important factors affecting the propagation of tsunami waves in deep water.

Tsunami waves become steeper and increase in height on approaching shallow water because wave speed is reduced and wave length is shortened when the depth decreases. In a coastal zone, local topography and bathymetry, such as a peninsula or submarine canyon, may cause an additional increase in wave heights which can also be amplified by the presence of a bay, an estuary, a harbour or lagoon funnels as a tsunami moves inland. Several large waves may occur and the first may not be the largest. A recession of the sea may also occur before the first wave and between each consecutive flooding. A tsunami may cause inland inundation because its wave length is so long that a huge mass of water follows behind the wave front. This can have a destructive impact.

The IAEA safety standards in force at the time of the accident required that before the construction of an NPP, site specific external hazards, such as earthquakes and tsunamis, need to be identified, and the impacts of these hazards on the NPP need to be evaluated as part of a comprehensive and full characterization of the site [26]. Adequate design bases are required to be established to provide sufficient safety margins over the lifetime of the NPP [27]. These margins need to be sufficiently large to address the high level of uncertainty associated with the evaluation of external events. Site related hazards also need to be periodically reassessed in order to identify any need for change as a result of new information and knowledge during the life of the plant [26].

In the 1960s and 1970s, it was common international practice to use historical records when applying methods for estimating seismic and concomitant (e.g. tsunami) hazards. This common practice included increasing safety margins by increasing the maximum recorded historical seismic intensity or magnitude in the site region and assuming that such an event would occur at the closest distance to the site [28]. This was done to account for the uncertainties in the observations of intensities or magnitudes, as well as to compensate for the fact that the maximum potential values might not be attained in a relatively short period of observation when, typically, the observation period needs to include pre-historical data in order to provide robust estimates for the hazard assessment. However, the seismic hazard assessment for the design of Units 1 and 2 at the Fukushima Daiichi NPP was conducted mainly on the basis of regional historical seismic data without increasing the safety margins as described above. During the process of obtaining construction permits for the later units, a new methodology was applied using a combination of historical earthquake information and the geomorphological fault dimensions [16, 29].

The information regarding the ‘inland’ faults was taken from official sources as well as from specific surveys conducted by the operator, and conservative parameters were assumed in the analysis to predict the magnitude of a possible earthquake. For the Japan Trench, an earthquake of magnitude 8 class was originally estimated as the maximum event without (i) sufficient tectonic based justification and (ii) use of global analogues, and based largely on observed historical data.

Large magnitude earthquakes (M 9) had occurred elsewhere in the Pacific ‘ring of fire’, for example in Chile in 1960 and in Alaska in 1964, shortly before Fukushima Daiichi Unit 1 was given the construction licence. These earthquakes did not lead to a consensus among Japanese seismologists that such an event would be possible close to the shores of Japan in a tectonic environment similar to those that generated earthquakes in other areas of the Pacific tectonic plate.

In the original assessment of external flooding hazards used in the ‘Establishment Permit’ for the plant, the plant designers applied the methodology and criteria prevalent in Japan at the time, which were based on the study and interpretation of historical records of earthquakes and tsunamis. The distant tsunami that occurred following one of the world’s largest known earthquakes in Chile in 1960 was the event used for design purposes against external flooding. This event resulted in a tsunami height observed at Onahama Port in Fukushima Prefecture of 3.1 m above sea level.

With regard to the tsunami sources located at the Japan Trench off the eastern coast, there was a lack of historical records of tsunami flood levels at the location of the Fukushima Daiichi site, as well as a lack of evidence of the occurrence of earthquakes in the area offshore of the site. The absence of data on nearby tsunami sources supported the adopted maximum flood level of 3.1 m for design purposes. TEPCO did not consider large magnitude earthquakes that had occurred elsewhere and did not postulate them as a local tsunami source at the Japan Trench.

Despite the lack of regulatory requirements in Japan for conducting a reassessment of seismic hazards and tsunami hazards, TEPCO had conducted several reassessments over the lifetime of the Fukushima Daiichi NPP [30]. TEPCO and other operating organizations in Japan had reassessed tsunami flood levels using a methodology developed by the Japan Society of Civil Engineers and published in

2002 [31]. This methodology used a standard source model for near or local tsunamis, based on historical data, in which no earthquake generating a tsunami is assumed to occur along the Japan Trench offshore of the Fukushima Daiichi site. The assumption of the standard source model, as described above, was applied in all evaluations that were performed using this methodology.

The 2006 guidelines of the Nuclear Safety Commission of Japan (NSC) [32] required consideration of inter-plate earthquakes as well as inland crustal earthquakes. These guidelines on seismic safety and associated events were used for evaluating seismic hazards, but the guidelines on tsunami hazards included only generic and brief statements and did not provide specific requirements, criteria or methodology. These earthquakes were considered by TEPCO as magnitude 8 class during its 'back-checking' of seismic safety as requested by the Nuclear and Industrial Safety Agency (NISA). However, owing to the distance of the site from those inter-plate earthquakes, the approach provided smaller hazard values associated with this tectonic structure when compared with the inland seismogenic sources. Consequently, their impact on the ground motion hazard was not considered. At the time of the accident, TEPCO had not completed the re-assessment of the vulnerability of the plant to earthquakes and tsunamis.

In 2009, TEPCO estimated a value of 6.1 m for the maximum tsunami height, using the latest bathymetric and tidal data. As a result of this new estimate, some design changes were made at the Fukushima Daiichi NPP, notably raising the motors of the pumps used for the removal of residual heat. During the accident, this measure alone proved to be insufficient. No other safety measures had been implemented to enhance flood protection, such as measures to avoid the flooding of emergency diesel generators.

In addition to the reassessments employing the methodology of the Japan Society of Civil Engineers, trial calculations of the tsunami water flood levels were performed by TEPCO before the accident. One of these trial calculations [30] applied the source model proposed by the Headquarters for Earthquake Research Promotion, which used the latest information and considered different scenarios [30, 33]. This approach examined the potential of the Japan Trench off the coast of Fukushima Prefecture to cause tsunamis. It did not rely only on historical tsunami records for this part of the tectonic subduction zone.

The new approach, applied between 2007 and 2009, postulated an earthquake of magnitude 8.3 off the Fukushima coast. Such an earthquake could lead to a tsunami runup of around 15 m at the Fukushima Daiichi NPP (similar to the actual tsunami height on 11 March 2011), which would inundate the main buildings. On the basis of this new analysis, TEPCO, NISA and other organizations in Japan considered that further studies and investigations were needed. TEPCO and other electrical utilities requested the Japan Society of Civil Engineers to review the appropriateness of the tsunami source models; these efforts were in progress in March 2011.

TEPCO did not take interim compensatory measures in response to these increased estimates of tsunami height, nor did NISA require TEPCO to act promptly on these results [30].

Notwithstanding the difficulties and uncertainties in the seismic hazard assessment, the events at the Fukushima Daiichi NPP demonstrated the robustness of Japanese NPPs in relation to earthquake vibratory ground motions. On 11 March 2011, the maximum accelerations recorded at the base mat of the reactor buildings of Fukushima Daiichi Units 1–5 were significantly larger than had been estimated when the plant was designed. However, there were no indications that the ground motion caused notable damage to safety related structures, systems or components [34]. However, the defences against tsunami induced flooding proved inadequate against tsunami wave heights that were much larger than those used in the design of the Fukushima Daiichi NPP. A scenario involving simultaneous extreme natural hazards and affecting multiple units was not considered in the design of the Fukushima Daiichi NPP. The timely provision of resources for the implementation of severe

accident management actions at the Fukushima Daiichi NPP was compromised by the disruption off-site at the regional level due to the extensive damage caused to the infrastructure by the earthquake and the tsunami.

NPP operating experience in Japan and elsewhere in the 12 years prior to the accident showed the potential for severe consequences from flooding. The relevant operating experience included: a storm surge causing flooding at two reactors at the Le Blayais NPP in France in 1999; the Indian Ocean tsunami in 2004, which flooded seawater pumps at the Madras Atomic Power Station in India; and the Niigata-Chuetsu-Oki earthquake in Japan in 2007. The latter affected TEPCO's Kashiwazaki-Kariwa NPP, causing flooding of the reactor building of Unit 1 owing to the failure of the underground external fire extinguishing piping [35–38].

2.2.2. Application of the defence in depth concept

Defence in depth is a concept that has been applied to ensure the safety of nuclear installations since the start of nuclear power development. Its objective is to compensate for potential human and equipment failures by means of several levels of protection. Defence is provided by multiple and independent means at each level of protection.

The design of the Fukushima Daiichi NPP provided equipment and systems for the first three levels of defence in depth: (1) equipment intended to provide reliable normal operation; (2) equipment intended to return the plant to a safe state after an abnormal event; and (3) safety systems intended to manage accident conditions. The design bases were derived using a range of postulated hazards; however, external hazards such as tsunamis were not fully addressed. Consequently, the flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems at each of the three levels.

The common cause failures of multiple safety systems resulted in plant conditions that were not envisaged in the design. Consequently, the means of protection intended to provide the fourth level of defence in depth, that is, prevention of the progression of severe accidents and mitigation of their consequences, were not available to restore the reactor cooling and to maintain the integrity of the containment. The complete loss of power, the lack of information on relevant safety parameters due to the unavailability of the necessary instruments, the loss of control devices, and the insufficiency of operating procedures made it impossible to arrest the progression of the accident and to limit its consequences.

The failure to provide sufficient means of protection at each of level of defence in depth resulted in severe reactor damage in Units 1, 2 and 3 and in significant radioactive releases from these units.

The earthquake on 11 March 2011 caused major damage to the infrastructure in the region, including the loss of connections from the off-site power grid to the Fukushima Daiichi NPP. This resulted in a deviation from the normal operation of the plant (defence in depth Level 1). After the earthquake, power supply was successfully provided from on-site sources, and all safety systems at defence in depth Level 3 continued to function as designed. This indicated that the safety systems and equipment withstood the seismic hazard [8].

The plant was built close to sea level and protection against flooding hazards was not sufficient, as the risk of flooding was not appropriately estimated [27]. Key safety equipment was not protected in leaktight compartments or by locating it at higher elevations to provide protection from flooding. This led to the loss of provisions for residual heat removal and containment cooling at defence in depth Levels 1, 2 and 3.

Box 2.5. The concept of defence in depth applicable at the time of the accident [27]

The concept of defence in depth, as applied to all safety activities, whether organizational, behavioural or design related, ensures that they are subject to overlapping provisions, so that if a failure were to occur, it would be detected and compensated for or corrected by appropriate measures. The concept has been further elaborated since 1988 [39, 40]. Application of the concept of defence in depth throughout design and operation provides a graded protection against a wide variety of transients, anticipated operational occurrences and accidents, including those resulting from equipment failure or human action within the plant, and events that originate outside the plant.

Application of the concept of defence in depth in the design of a plant provides a series of levels of defence (inherent features, equipment and procedures) aimed at preventing accidents and ensuring appropriate protection in the event that prevention fails.

(1) The aim of the first level of defence is to prevent deviations from normal operation, and to prevent system failures. This leads to the requirement that the plant be soundly and conservatively designed, constructed, maintained and operated in accordance with appropriate quality levels and engineering practices, such as the application of redundancy, independence and diversity. To meet this objective, careful attention is paid to the selection of appropriate design codes and materials, and to the control of fabrication of components and of plant construction. Design options that can contribute to reducing the potential for internal hazards (e.g. controlling the response to a postulated initiating event), to reducing the consequences of a given postulated initiating event, or to reducing the likely release source term following an accident sequence contribute at this level of defence. Attention is also paid to the procedures involved in the design, fabrication, construction and in-service plant inspection, maintenance and testing, to the ease of access for these activities, to the way the plant is operated and to how operational experience is utilized. This whole process is supported by a detailed analysis which determines the operational and maintenance requirements for the plant.
(2) The aim of the second level of defence is to detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions. This is in recognition of the fact that some postulated initiating events are likely to occur over the service lifetime of an NPP, despite the care taken to prevent them. This level necessitates the provision of specific systems as determined in the safety analysis and the definition of operating procedures to prevent or minimize damage from such postulated initiating events.
(3) For the third level of defence, it is assumed that, although very unlikely, the escalation of certain anticipated operational occurrences or postulated initiating events may not be arrested by a preceding level and a more serious event may develop. These unlikely events are anticipated in the design basis for the plant, and inherent safety features, fail-safe design, additional equipment and procedures are provided to control their consequences and to achieve stable and acceptable plant states following such events. This leads to the requirement that engineered safety features be provided that are capable of leading the plant first to a controlled state, and subsequently to a safe shutdown state, and maintaining at least one barrier for the confinement of radioactive material.
(4) The aim of the fourth level of defence is to address severe accidents in which the design basis may be exceeded and to ensure that radioactive releases are kept as low as practicable. The most important objective of this level is the protection of the confinement function. This may be achieved by complementary measures and procedures to prevent accident progression, and by mitigation of the consequences of selected severe accidents, in addition to accident management procedures. The protection provided by the confinement may be demonstrated using best estimate methods.
(5) The fifth and final level of defence is aimed at mitigation of the radiological consequences of potential releases of radioactive materials that may result from accident conditions. This requires the provision of an adequately equipped emergency control (see Section 3 on Emergency Preparedness and Response).

A relevant aspect of the implementation of defence in depth is the provision in the design of a series of physical barriers to confine the radioactive material at specified locations. The number of physical barriers that will be necessary will depend on the potential internal and external hazards, and the potential consequences of failures. The barriers may, typically for water cooled reactors, be in the form of the fuel matrix, the fuel cladding, the reactor coolant system pressure boundary and the containment.

The flooding was the common cause of failure of the emergency power supply system, the near complete loss of systems providing DC power to measuring and control devices, and the destruction of the structures and components providing seawater cooling for the plant.

The objectives of defence in depth Level 4 are the prevention of accident progression and the mitigation of the consequences of a severe accident. For actions at Level 4, the operators needed to use all available means to supply water to the reactor in order to ensure the adequate removal of residual heat. This required the availability of instruments which provide reliable information on the key safety parameters and simple, reliable means for pressure relief in the reactor. In addition, the operators needed clear guidance and to be trained to be able to initiate accident management measures [41].

As the accident progressed, operators lost the ability to reliably measure important safety parameters from the control room. This information was needed to assess the reactor status and to take well informed decisions on unusual actions and methods to cool the reactors. Nevertheless, the operators gave high priority to reactor cooling and managed to quickly prepare water supply lines with the intention of injecting coolant into the reactors using available low pressure pumps. However, the attempts to relieve reactor pressure failed because no provisions had been made to carry out this function after a complete loss of power. The required control power could not be restored in time to prevent core damage [8].

The last physical barrier included in defence in depth Level 4 is the reactor containment. Its purpose is to mitigate the consequences of accidents by preventing large radioactive releases to the environment after reactor damage. Depending on the containment type, various systems or kinds of equipment are needed to protect the containment against physical phenomena associated with core damage accidents that could challenge the containment integrity. The units at the Fukushima Daiichi NPP included means for the controlled venting of the containment to relieve the overpressure that might be caused by a steam leakage from the reactor cooling circuit. In addition, the atmosphere inside the containment was filled with inert nitrogen in order to eliminate hydrogen burn and prevent possible explosions.

Measurements taken during the accident indicate that the containment pressures of Units 1, 2 and 3 at certain times increased to levels that were near, or higher than, those for which the respective containments had been designed. This increase in pressure was due to the loss of containment cooling systems and the generation of steam by the overheated reactor cores. Although some containment venting systems were successfully opened, indications are that the containments of Units 1, 2 and 3 failed, leading to the release of radioactive material and hydrogen. The nitrogen atmosphere inside the containments had effectively prevented hydrogen burn and explosions from occurring in that confined space. However, as hydrogen leaked from the containments to the reactor buildings, hydrogen explosions occurred at Units 1, 3 and 4 [8].

The Fukushima Daiichi accident demonstrated that extreme natural hazards have the potential to invalidate or impair multiple levels of defence in depth [42, 43]. A systematic identification and assessment of external hazards and robust protection against these hazards needs therefore to be considered for all levels of defence in depth. Furthermore, the accident showed that alternative design provisions and accident management capabilities could still ensure the supply of cooling water to the reactor even if all prime safety systems designed to protect the reactor against accidents were lost. However, the timely use of such provisions requires instruments that can provide reliable information on the key safety parameters and simple, reliable means to relieve the pressure in the reactor, so that any means can be used to supply cooling water to the reactor.

2.2.3. Assessment of the failure to fulfil fundamental safety functions

The three fundamental safety functions important for ensuring safety are: the control of reactivity in the nuclear fuel; the removal of heat from the reactor core and spent fuel pool; and the confinement of radioactive material. Following the earthquake, the first fundamental safety function — control of reactivity — was fulfilled in all six units at the Fukushima Daiichi NPP.

The second fundamental safety function — removing heat from the reactor core and the spent fuel pool — could not be maintained because the operators were deprived of almost all means of control over the reactors of Units 1, 2 and 3 and the spent fuel pools as a result of the loss of most of the AC and DC electrical systems. The loss of the second fundamental safety function was, in part, due to the failure to implement alternative water injection because of delays in depressurizing the reactor pressure vessels. Loss of cooling led to overheating and melting of the fuel in the reactors.

The confinement function was lost as a result of the loss of AC and DC power, which rendered the cooling systems unavailable and made it difficult for the operators to use the containment venting system. Venting of the containment was necessary to relieve pressure and prevent its failure. The operators were able to vent Units 1 and 3 to reduce the pressure in the primary containment vessels. However, this resulted in radioactive releases to the environment. Even though the containment vents for Units 1 and 3 were opened, the primary containment vessels for Units 1 and 3 eventually failed. Containment venting for Unit 2 was not successful, and the containment failed, resulting in radioactive releases.

Box 2.6. Fundamental safety functions

The three fundamental safety functions are:

(1) Control of the reactivity;

(2) Heat removal;

(3) Confinement of radioactive material.

Prior to the accident at the Fukushima Daiichi NPP, there were two accidents involving the failure to maintain one or more of the fundamental safety functions. The accident in 1979 at the Three Mile Island NPP in the United States of America occurred as a result of the loss of the second of these safety functions, but radioactive releases to the environment were successfully prevented by the third function, confinement of radioactive material by the containment vessel. The accident in 1986 at the Chernobyl NPP in the former Soviet Union occurred as a result of the loss of the first of these safety functions. This plant did not have a containment vessel. Consequently, the Chernobyl accident resulted in a very large radioactive release to the environment. The Fukushima Daiichi accident occurred because of the loss of the second and third of these safety functions following a combination of extreme external events.

Control of the reactivity of nuclear fuel in the reactor core

The safety systems for controlling the reactivity of nuclear fuel in the reactor core are the reactor protection and the control rod drive systems. Prior to the earthquake, Fukushima Daiichi Units 1–3 were operating; Units 4–6 were shut down for maintenance. The reactors of Units 1–3 were automatically shut down by their reactor protection systems, which were activated by the seismic event monitoring equipment. The insertion of reactor control rods by the control rod drive systems terminated the nuclear chain reaction in the nuclear fuel and brought the reactors to a shutdown condition.

Removal of heat from the nuclear fuel

Following the shutdown of Units 1–3, residual heat, produced by the ongoing decay of radioactive substances in the fuel, was removed by the reactor cooling systems. This maintained the second fundamental safety function. These cooling systems comprised both closed circulation loops to transfer heat to the sea water and various means to inject water at high and low pressure into the reactor cores to remove this residual heat (see Section 2.1).

Many of these systems needed AC power to operate, and all of them needed DC power to control their operation. Most sources of power were lost during the course of the accident; this part of the report focuses on the impact of this loss of power.

Unit 1

The isolation condenser (see Box 2.2) for cooling Unit 1 started automatically as the result of a high reactor vessel pressure signal. It opened the isolation valves in the condensate return lines (other isolation valves in the lines were open during normal operation) when the reactor shut down following the earthquake. As required by the operating procedures, the isolation condenser system was stopped and restarted several times by the operators to prevent the reactor from cooling down too quickly and causing thermal stress exceeding the reactor pressure vessel design values. This was done by opening and closing the isolation valves in the condensate return lines [8].

At the time the tsunami inundated the site and electrical power was lost, the operators had just stopped the isolation condenser system by closing a valve on the return line outside the primary containment vessel. Operators had no information available on the isolation condenser valve positions, and it was not until approximately three hours later that they first attempted to manually restart the isolation condenser. The operators were not fully trained to understand how the valves worked under these conditions. They ultimately made two unsuccessful attempts from the main control room to restart the isolation condenser by opening the outer isolation valves. The operators had no procedures to manually operate the isolation condenser. At the time of writing, the exact location of all of the valves in the isolation condenser system was unknown, but indications are that the isolation condenser did not function following the tsunami [8].

The steam turbine operated high pressure coolant injection system was not available because its DC power was lost.

Following the loss of the isolation condenser and the high pressure coolant injection system, an alternative means of injecting water into the reactor pressure vessel that relied on low pressure equipment was needed, such as that provided by the pumps for firefighting or fire trucks. The operators prepared the injection pathways in due time, but to be able to inject water at low pressure, it was also necessary to reduce the pressure inside the reactor pressure vessel using the safety relief valves. These valves could not be opened because of the loss of control power and high pressure air. The pressure in both the reactor vessel and in the containment was too high to allow the injection of sufficient water to cool the fuel without venting the containment and depressurizing the reactor pressure vessel. The alternative low pressure water injection systems were thus incapable of injecting water into the reactor pressure vessel.

The pressure in the reactor vessel remained high until the core was severely damaged. The most likely cause of pressure relief was a breach of the reactor pressure vessel due to melting [44]. The assumption that pressure relief was caused by a breach is supported by the pressure increase in the containment a few hours after indications had been received of severe core damage. The consequent reduction in pressure provided the conditions for the first injection of water into the reactor pressure

vessel about 12 hours after the tsunami. However, by this time, significant fuel damage had already occurred [8].

It is estimated that the damage to the reactor core occurred approximately 4–5 hours after the tsunami, and that the molten core breached the reactor vessel bottom about 6–8 hours after the tsunami. The first signs of radioactive release to the environment were observed about 12 hours after the tsunami, and a large release took place when the Unit 1 containment was vented to prevent its breach, because of the high pressure, about 23 hours after the tsunami. Chemical reactions between fuel cladding and water had generated large quantities of hydrogen, which passed from the reactor pressure vessel into the primary containment vessel and escaped further to the reactor building [8].

Unit 2

Unit 2 had a different design for removing residual heat from the reactor core. The reactor core isolation cooling system (see Box 2.2) used steam from the reactor pressure vessel to drive a turbine which pumped water into the reactor vessel. The Unit 2 reactor core isolation cooling system was manually started after off-site power was lost. To remotely operate this system, DC power was needed, and it was designed to operate for at least four hours. However, the system continued to operate in harsh conditions for about 68 hours without DC power and without operator interventions [8]. This system successfully maintained the water level in the reactor pressure vessel above the fuel and ensured the cooling function.

There are indications that, after about 68 hours, the reactor core isolation cooling system failed. It was therefore no longer possible to inject water into the reactor pressure vessel because it was at high pressure. The water level in the reactor pressure vessel was estimated to drop to the reactor core top in a few hours after the reactor core isolation cooling system stopped functioning. The operators relied on alternative equipment for the low pressure injection of water, similar to that available for Unit 1. After some initial difficulties, they succeeded in reducing the pressure in the reactor pressure vessel by using safety relief valves, although injection was too late to prevent the rapid heating of the fuel and damage to the reactor core.

The containment venting system failed to relieve the pressure at Unit 2. It is assumed that this failure occurred because the rupture disc did not break. It is estimated that the Unit 2 reactor core began to melt about 76 hours after the tsunami. Radioactive releases started about 89 hours after the tsunami, following the breach of the containment boundary as indicated by the rapid drop in containment pressure [45].

Unit 3

In Unit 3, DC power was available for about two days, in contrast to the situation in Units 1 and 2. This meant that the reactor core isolation cooling and the high pressure coolant injection systems using steam driven pumps were available. Initially, the operators were able to maintain water levels in the reactor core by injecting water with the reactor core isolation cooling system. They followed procedures that enabled them to maximize the battery life available for the reactor core isolation cooling system [8].

In addition, steam relief from the reactor pressure vessel to the suppression chamber was available, and the suppression chamber pressure could be controlled using spray water provided by fire pumps. This situation lasted for 20 hours, until the reactor core isolation cooling system stopped and could not be restarted. The high pressure coolant injection system started automatically injecting water into the reactor pressure vessel to maintain the water level.

The high pressure coolant injection system is intended to rapidly refill the reactor pressure vessel following a leak in the reactor coolant system. This system was very effective in reducing pressure in the reactor pressure vessel. However, this led to a situation where inlet steam pressure to the pump turbine dropped below the pump's specifications, and the efficiency of the pump decreased significantly. The operators decided to shut down the system after about 14 hours because of concerns that the system could fail and begin to leak radioactive material outside the containment.

Following the shutdown of the high pressure coolant injection system, operators prepared an injection line to the reactor vessel and were prepared to inject sea water into the reactor vessel. However, due to the high reactor pressure, it was not possible to inject sea water until the reactor was depressurized. Therefore, because of the delay in injecting sea water into the reactor vessel, the water level continued to drop close to the top of the fuel. It has been assessed that an automatic signal, suspected to be false, triggered the automatic fast depressurization by safety relief valves before the operators could open the safety valves in a more controlled manner [46]. The depressurization, together with the low water level in the pressure vessel, is estimated to have caused the remaining water in the reactor core to flash to steam, resulting in the loss of adequate core cooling. The subsequent series of events, leading to the loss of reactor core cooling, were similar to those at Unit 2.

The core started to overheat and the major steam discharge from the reactor pressure vessel to the containment suppression chamber increased the pressure to a level that caused the rupture disc in the vent line to burst, opening a release path to the environment [8]. Melting of the Unit 3 reactor core is estimated to have started about 43 hours after the tsunami. Large radioactive releases started about 47 hours after the tsunami [8].

Unit 4

Unit 4 was undergoing a scheduled inspection and was shut down before the accident. All fuel of Unit 4 was in the spent fuel pool at the time of the accident. Therefore, cooling of the Unit 4 reactor core was not necessary. Cooling of the spent fuel pool was not possible owing to the loss of electrical power, and as a result the pool temperature started to increase.

Spent fuel pools

In the first few days following the tsunami, the operators considered that there was sufficient water in the spent fuel pools and that overheating of the fuel was not an immediate issue. This view changed on 15 March, when the Unit 4 reactor building exploded. At the time, it was thought that the cause of the explosion was hydrogen, and the only possible source of hydrogen in Unit 4 was thought to be from overheated fuel in the spent fuel pool due to the loss of water cover. This immediately raised concerns about how much water remained in that pool, and efforts were made to determine the water level in the spent fuel pools.

On 16 March, visual inspections indicated that there was still water in the pool at Unit 4. However, concerns were raised about the status of Unit 3, which led to various mitigation efforts, including the airdrop of water from helicopters. Subsequent analysis and inspections revealed that the water level in the spent fuel pools of both Units 3 and 4 had not dropped to the level of the spent fuel. These inspections confirmed that the explosion in Unit 4 was caused by hydrogen, and that the source of the hydrogen was not the fuel in the Unit 4 spent fuel pool but the migration of hydrogen from Unit 3 to Unit 4 via a common ventilation system. However, the lack of knowledge about the actual conditions in the spent fuel pools during the accident, due to the loss of instrumentation, led to the effort to add water to the pool. A detailed description of the spent fuel pool events is given in Section 2.1.

Units 5 and 6

Units 5 and 6 were also affected by the tsunami, but their reactors were generating less residual heat, because they had been shut down for a considerable period prior to the accident. In addition, one of the emergency diesel generators at Unit 6 had survived the flooding and was operable. The operators therefore had more time to respond, and the cooling systems for both units were powered by the one remaining emergency diesel generator. This power supply maintained the cooling of the reactor cores and was eventually used to provide cooling to the spent fuel pools in Units 5 and 6, both of which were successfully cooled down to a safe condition [8].

Confinement of radioactive material and control of radioactive releases

As a result of the damage to the reactor cores in Units 1–3, large amounts of steam and hydrogen escaped the reactor pressure vessels. This, in turn, pressurized and heated the primary containment vessels. These vessels were breached and steam, hydrogen and other gases, together with radioactive material, were released into the reactor buildings and eventually to the environment.

The primary containment vessels of the reactors had not been designed to withstand the pressure that could be generated in a severe accident; because of this, venting systems had been installed in the 1990s [22, 23] to limit the pressure in the containment vessels in the event of an accident. There are indications that the primary containment vessels for Units 1–3 failed at various stages in the progression of the accident. This was the result of the pressure and temperature in the primary containment vessel rising to levels that were far in excess of their designed capability before venting could be implemented (see Section 2.1). The leakage of radioactive material from the reactor cores was partially mitigated by the suppression pools, which retained some of the radionuclides released from the reactor pressure vessels.

2.2.4. Assessment of beyond design basis accidents and accident management

Safety analyses conducted during the licensing process of the Fukushima Daiichi NPP, and during its operation, did not fully address the possibility of a complex sequence of events that could lead to severe reactor core damage. In particular, the safety analyses failed to identify the vulnerability of the plant to flooding and weaknesses in operating procedures and accident management guidelines. The probabilistic safety assessments did not address the possibility of internal flooding, and the assumptions regarding human performance for accident management were optimistic. Furthermore, the regulatory body had imposed only limited requirements for operators to consider the possibility of severe accidents.

The operators were not fully prepared for the multi-unit loss of power and the loss of cooling caused by the tsunami. Although TEPCO had developed severe accident management guidelines, they did not cover this unlikely combination of events. Operators had therefore not received appropriate training and had not taken part in relevant severe accident exercises, and the equipment available to them was not adequate in the degraded plant conditions.

In September 2012, the Nuclear Regulation Authority (NRA) was established. The NRA formulated new regulations for NPPs to protect the people and the environment, which came into force in 2013. These regulations strengthened countermeasures to prevent simultaneous loss of all safety functions due to common causes, including re-evaluation of the impact of external events such as earthquakes and tsunamis. New countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive materials were also introduced.

The IAEA safety standards in force at the time of the accident required an assessment to be undertaken to determine whether safety functions could be fulfilled for all normal operational modes,

accident conditions and beyond design basis accidents, including severe accidents. Important event sequences that could lead to a severe accident need to be identified using a combination of probabilistic methods, deterministic methods and sound engineering judgement [27]. In addition, specific deterministic beyond design basis accident analyses need to be performed to investigate credible accident scenarios that can be used to introduce improvements in accident management measures [41]. It is therefore necessary to determine whether safety functions can be fulfilled in beyond design basis accident conditions.

Box 2.7. Deterministic and probabilistic safety assessments [47, 48]

Safety analyses are analytical evaluations of physical phenomena occurring at NPPs. Deterministic safety analyses for an NPP predict the response to postulated initiating events. A specific set of rules and acceptance criteria is applied. Typically, these should focus on neutronic, thermohydraulic, radiological, thermomechanical and structural aspects, which are often analysed with different computational tools.

Best estimate deterministic safety analyses should be performed to confirm the strategies that have been developed to restore normal operational conditions at the plant following transients due to anticipated operational occurrences and design basis accidents. These strategies are reflected in the emergency operating procedures that define the actions that should be taken during such events. Deterministic safety analyses are required to provide the input that is necessary to specify the operator actions to be taken in response to some accidents, and the analyses should be an important element of the review of accident management strategies. In the development of the recovery strategies, to establish the available time period for the operator to take effective action, sensitivity calculations should be carried out on the timing of the necessary operator actions, and these calculations may be used to optimize the procedures.

Deterministic safety analyses should also be performed to assist the development of the strategy that an operator should follow if the emergency operating procedures fail to prevent a severe accident from occurring. The analyses should be used to identify what challenges can be expected during the progression of accidents and which phenomena will occur. They should be used to provide the basis for developing a set of guidelines for managing accidents and mitigating their consequences.

While deterministic analyses may be used to verify that acceptance criteria are met, probabilistic safety assessment (PSA) may be used to determine the probability of damage for each barrier. PSA may thus be a suitable tool for evaluation of the risk that arises from low frequency sequences that lead to barrier damage, whereas a deterministic analysis is adequate for events of higher frequency.

Deterministic safety analyses have an important part to play in the performance of a PSA because they provide information on whether the accident scenario will result in the failure of a fission product barrier. A PSA fault tree is a powerful tool that can be used to confirm assumptions that are commonly made in the deterministic calculation about the availability of systems.

The objectives of a PSA are to determine all significant contributing factors to the radiation risks arising from a facility or activity, and to evaluate the extent to which the overall design is well balanced and meets probabilistic safety criteria where these have been defined. In the area of reactor safety, PSA uses a comprehensive, structured approach to identify failure scenarios. It constitutes a conceptual and mathematical tool for deriving numerical estimates of risk. The probabilistic approach uses realistic assumptions whenever possible and provides a framework for addressing many of the uncertainties explicitly. Probabilistic approaches may provide insights into system performance reliability, interactions and weaknesses in the design, the application of defence in depth, and risks, that it may not be possible to derive from a deterministic analysis.

Improvements in the overall approach to safety analysis have permitted a better integration of deterministic and probabilistic approaches. With increasing quality of models and data, it is possible to develop more realistic deterministic analysis and to make use of probabilistic information in selecting accident scenarios. Increasing emphasis is being placed on specifying probabilistically how compliance with the deterministic safety criteria is to be demonstrated, for example, by specifying confidence intervals and how safety margins are specified.

Box 2.7. Deterministic and probabilistic safety assessments [47, 48] (cont.)

Several techniques can be used in performing a PSA. The usual approach is to use a combination of event trees and fault trees. The relative size (complexity) of the event trees and fault trees is largely a matter of preference of the analysis and also depends on the features of the software used.

The event trees outline the broad characteristics of the accident sequences that start from the initiating event and, depending on the success or failure of the mitigating safety and safety related systems, lead to a successful outcome or to damage to the core, or to one of the plant damage states (required for the Level 2 PSA). The fault trees are used to model the failure of the safety systems and the support systems to carry out their safety functions.

The fault trees should be developed to provide a logical failure model for the safety system failure states identified by the event tree analysis. The failure criterion that provides the top event of the fault tree for each safety system function should be the logical inverse of the accident sequence success criterion. The basic events modelled in the fault trees should be consistent with the available data on component failures. The fault tree models should be developed to the level of significant failure modes of individual components (pumps, valves, diesel generators, etc.) and individual human errors and should include all the basic events that could lead, either directly or in combination with other basic events, to the top event of the fault tree.

TEPCO started to perform probabilistic safety assessments, as well as some deterministic safety analyses of the more significant accident sequences, in the early 1990s. In line with the practice in IAEA Member States at that time, these probabilistic safety assessments were limited to events at single unit NPPs. Although the Fukushima Daiichi NPP was located in an area where tsunamis were possible, these analyses did not include common cause failures caused by flooding or extended loss of electrical power [8]. The probabilistic safety assessment studies for the Fukushima Daiichi NPP also did not consider internal flooding or fires, and the assumptions related to the operator's actions were optimistic.

A comprehensive probabilistic safety assessment, including internal flooding sequences, is needed to highlight the vulnerability to flooding of vital plant systems, such as emergency diesel generators and electrical switchgear. In 1991, a corroded pipe leaked water at a rate of 20 cubic metres per hour, which penetrated the room with the reactor's emergency power system through the door and cable penetrations at Unit 1 at the Fukushima Daiichi NPP. This event demonstrated the vulnerability to flooding with respect to the location of the emergency diesel generators and the electrical switchgear in the basement.

Accident management guidance had also been evaluated at the Fukushima Daiichi NPP through limited scope probabilistic safety assessment studies. For example, these assessments contained the use of the containment vent system through the application of a fault tree approach to simulate the equipment failures with a human error probability for manual operation. But there was no thorough assessment of the challenges in severe accident management, including the limited training and guidance provided to plant personnel. It was not recognized that assumptions about failure probability were overly optimistic and the studies did not lead to improvements in procedures and guidance [47] (see Box 2.8, on accident management).

The Fukushima Daiichi NPP had some weaknesses which were not fully evaluated by a probabilistic safety assessment, as recommended by the IAEA safety standards [47, 49]. Examples include the lack of protection for the emergency diesel generators, battery rooms and switchgear against flooding and the low likelihood of success of severe accident interventions, given the limited guidance, training and knowledge of plant personnel for severe accident management. Beyond design basis accidents were not sufficiently considered, which affected the capability to maintain cooling of the reactor core, the operators' ability to monitor important safety parameters and the management of the severe accident conditions (see Fig. 2.7).

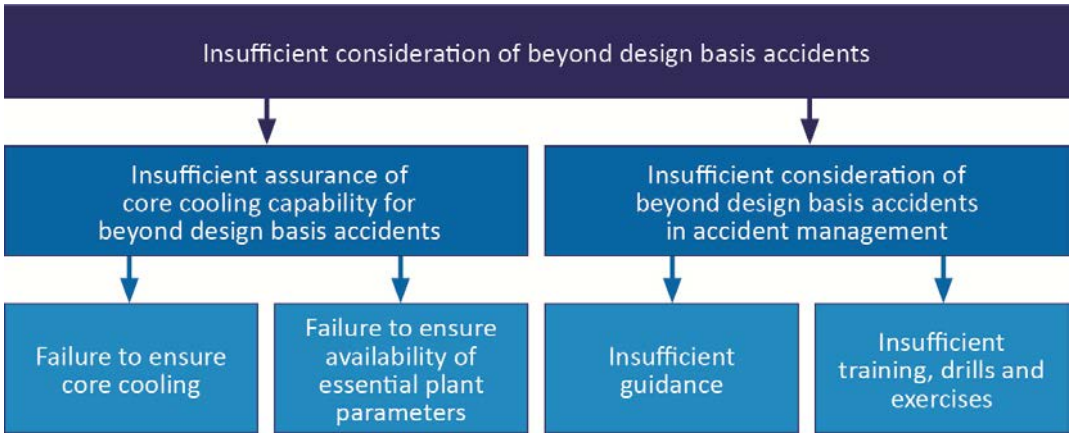


FIG. 2.7. Impact of the insufficient consideration of beyond design basis accidents affected the capability to maintain cooling of the reactor core, the operators' ability to monitor important safety parameters and the management of the severe accident conditions [27, 50].

Box 2.8. Accident management [41]

An accident management programme should be developed for all plants, irrespective of the total core damage frequency and fission product release frequency calculated for the plant. A structured top-down approach should be used to develop the accident management guidance. This approach should begin with the objectives and strategies, and result in procedures and guidelines, and should cover both the preventive and the mitigatory domains.

At the top level, the objectives of accident management are defined as follows: preventing significant core damage; terminating the progress of core damage once it has started; maintaining the integrity of the containment as long as possible; minimizing releases of radioactive material; achieving a long term stable state. To achieve these objectives, a number of strategies should be developed.

From the strategies, suitable and effective measures for accident management should be derived. Such measures include plant modifications, where these are deemed important for managing beyond design basis accidents and severe accidents, and personnel actions. These measures include repair of failed equipment. Appropriate guidance, in the form of procedures and guidelines, should be developed for the personnel responsible for executing the measures for accident management.

When developing guidance on accident management, consideration should be given to the full design capabilities of the plant, using both safety and non-safety systems, and including the possible use of some systems beyond their originally intended function and anticipated operating conditions, and possibly outside their design basis. The point at which the transition of responsibility and authority is to be made from the preventive to the mitigatory domain should be specified and should be based on properly defined and documented criteria.

For any change in the plant configuration, or if new results from research on physical phenomena become available, the implications for accident management guidance should be checked and, if necessary, a revision of the accident management guidance should be made.

The limited scope of the regulatory body's requirements for beyond design basis accidents contributed to the lack of proper consideration of relevant risks by plant operators. This was highlighted during an IAEA Integrated Regulatory Review Service (IRRS) mission in June 2007, which concluded that: "There are no legal regulations for the consideration of beyond the design basis [accidents], as Japanese plants are considered to be adequately safe as ensured by preventive measures" [51]. For example, the periodic safety review process in Japan did not require operating organizations to update their analyses to utilize the latest techniques [52].

The TEPCO accident management programme assumed that AC power would be promptly recovered at the Fukushima Daiichi NPP. TEPCO also assumed that other essential utilities, such as DC power and high pressure air, would be available at all times to provide power for instrumentation and to provide for the operation of valves. The programme and guidelines did not cover the possibility that a severe accident could affect several reactor units simultaneously or the possibility of difficulties in receiving support from outside the site because of serious disruption to the off-site infrastructure. This approach was in line with typical international practice at the time. The accident demonstrated that the operation of certain systems under beyond design basis conditions required exceptionally high skills on the part of the operators in order to maintain fundamental safety functions.

The accident management guidance in place at the Fukushima Daiichi NPP comprised a suite of documentation for use by the operators, including emergency operating procedures and severe accident management guidelines. Accident management guidelines were available for use by TEPCO technical support staff in the emergency response organization. Collectively, these documents covered the range of responses to design basis accidents and beyond design basis accidents, including severe accidents. The absence of electrical power and the lack of adequate information about the plant status made it difficult for the operators to effectively respond to the unfolding events. The accident management guidelines did not cover contingencies for the loss of instrumentation necessary to display the key parameters which allow operators to determine the status of the NPP. In addition, the guidelines did not provide recommendations for managing accidents when all safety related electrical distribution systems, and subsequently many of the dependent safety systems, were inoperable.

Personnel were not trained to perform accident management actions under conditions of prolonged station blackout or where information was limited or missing. Despite this, the operating staff performed their activities properly under the harsh conditions created by the accident. However, the inability to obtain fundamental information on the status of the plant and the need to improvise mitigation actions hampered the response. The absence of severe accident management requirements in the regulatory framework also contributed to the lack of preparation by TEPCO. The NSC published a guide on accident management in 1992 [23], and in the same year, the Ministry for International Trade and Industry (MITI) published a Roadmap of Accident Management. The Ministry also requested nuclear operating organizations to take actions to manage more severe accidents than those considered in the original design. However, this was not a mandatory requirement, and it resulted in limited voluntary actions by nuclear operating organizations. The IAEA IRRS mission to Japan in 2007 suggested the need for regulatory requirements for beyond design basis accidents, and suggested that NISA continue to develop a systematic approach to the consideration of such events, and also to the complementary use of probabilistic safety assessment and severe accident management [51]. The review mission's suggestions did not stimulate further efforts in this area.

2.2.5. Assessment of regulatory effectiveness

The regulation of nuclear safety in Japan at the time of the accident was performed by a number of organizations with different roles and responsibilities and complex inter-relationships. It was not fully clear which organizations had the responsibility and authority to issue binding instructions on how to respond to safety issues without delay.

The regulatory inspection programme was rigidly structured, which reduced the regulatory body's ability to verify safety at the proper times and to identify potential new safety issues.

The regulations, guidelines and procedures in place at the time of the accident were not fully in line with international practice in some key areas, most notably in relation to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture.

In the legal framework for nuclear safety applicable in Japan at the time of the accident, the Government had established main laws which were supplemented by subordinate laws and ministerial ordinances and statutes. The general structure of the legislative and regulatory framework at the time of the accident is illustrated in Figs 2.8 and 2.9. The regulatory structure in Japan at the time of the accident consisted of a number of Government departments and other organizations with responsibilities for nuclear safety. The structure had been revised twice, following the radiation incident aboard the nuclear powered ship *Mutsu* in 1974 and the criticality accident at JCO facility in Tokaimura in 1999, but some fundamental issues related to the clarity of roles and responsibilities had not been addressed [53, 54]. The IAEA IRRS mission in 2007 suggested the need to improve, refine and clarify a number of regulatory aspects [51], such as regulations regarding the treatment of beyond design basis accidents and clarification of the roles and responsibilities of NISA and the NSC within the Japanese regulatory system.

The Ministry of Economy, Trade and Industry (METI) was responsible for policy on the development and utilization of nuclear energy, as well as for the regulation of commercial nuclear installations. Within METI, the Agency for Natural Resources and Energy (ANRE) was responsible for overseeing the national energy supply, including promotion of nuclear energy. NISA was established in 2001 as a special agency attached to ANRE and given the responsibility as the nuclear safety regulatory body. The law required that, in case of conflict between safety and promotion, the Minister of METI should give priority to safety. METI established its National Strategic Plan based on this prioritization, and the IAEA IRRS mission in 2007 concluded that NISA was effectively independent of ANRE in its regulatory decision making. However, the mission also suggested that NISA's independence from METI be reflected more clearly in legislation.

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) also had regulatory responsibilities, including oversight of radiation protection and nuclear material safeguards at NPPs, research reactors and certain research and development facilities for nuclear power. The Ministry also supervised the National Institute of Radiological Sciences (NIRS) and the Japan Atomic Energy Agency (JAEA).

The NSC, located in the Cabinet Office and reporting to the Prime Minister, was an independent body with both advisory and supervisory roles in the framework of nuclear regulation. It developed and issued the nuclear safety related policy documents and regulatory guides that were used by NISA in its regulatory work. The NSC was empowered by law to require reports from NISA and supervised NISA's work. It also had its own staff to carry out independent reviews and assessments of NPP licence applications and to re-confirm the conclusions made by NISA. The IAEA IRRS mission in 2007 suggested that the role of NISA as the regulatory body in relation to the NSC was in need of clarification.

NISA was supported by the Japan Nuclear Energy Safety Organization (JNES), which was established in 2003 under a law passed in 2002 [51]. JNES's main functions consisted of conducting inspections at nuclear facilities, reviewing the periodic inspections of licensees, providing nuclear emergency preparedness support and coordinating safety related research projects. A comprehensive inspection programme is needed for a regulatory body to be able to independently identify plant safety issues. In Japan at the time of the accident, despite NISA's efforts [56], inspections were rigidly structured, with the type and frequency specified by law. In 2011, Japan's report to the Convention on Nuclear Safety stated that the operators' safety management activities were governed by the operational safety inspections that NISA had approved. NISA conducted quarterly inspections to check operators' compliance with the periodic safety reviews. Periodic inspections were also conducted by NISA and JNES at intervals not exceeding 13 months, focused on the operators' maintenance of structures, systems and components of the NPPs. They concentrated on safety significant structures, systems and components, for example, those belonging to the reactor shutdown system, the reactor coolant pressure boundary, the residual heat removal system and the containment

system. These regulatory procedures were in addition to the operators' own walkdown and maintenance management of nuclear installations, periodic safety assessments, and technical evaluations related to NPP ageing. NISA had limited ability to expand inspections beyond the legally defined scope, which restricted its ability to identify deficiencies and deviations and ensure that lessons were learned [51]. This approach limited the effectiveness of regulatory inspection to identify safety issues and to verify the safety of licensees' activities and their compliance with requirements.

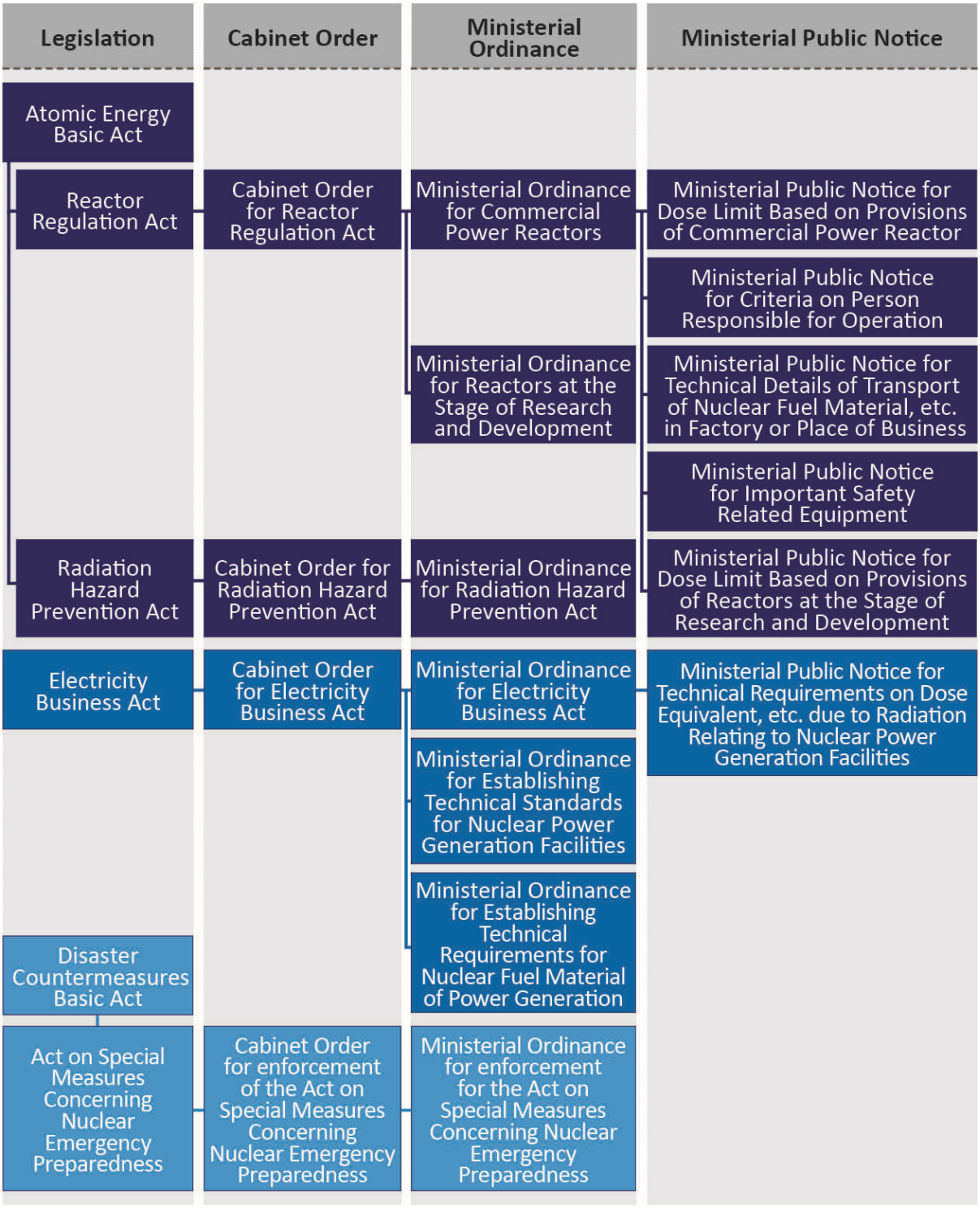


FIG. 2.8. The legislative and regulatory framework of nuclear installations safety in Japan at the time of the accident [55].

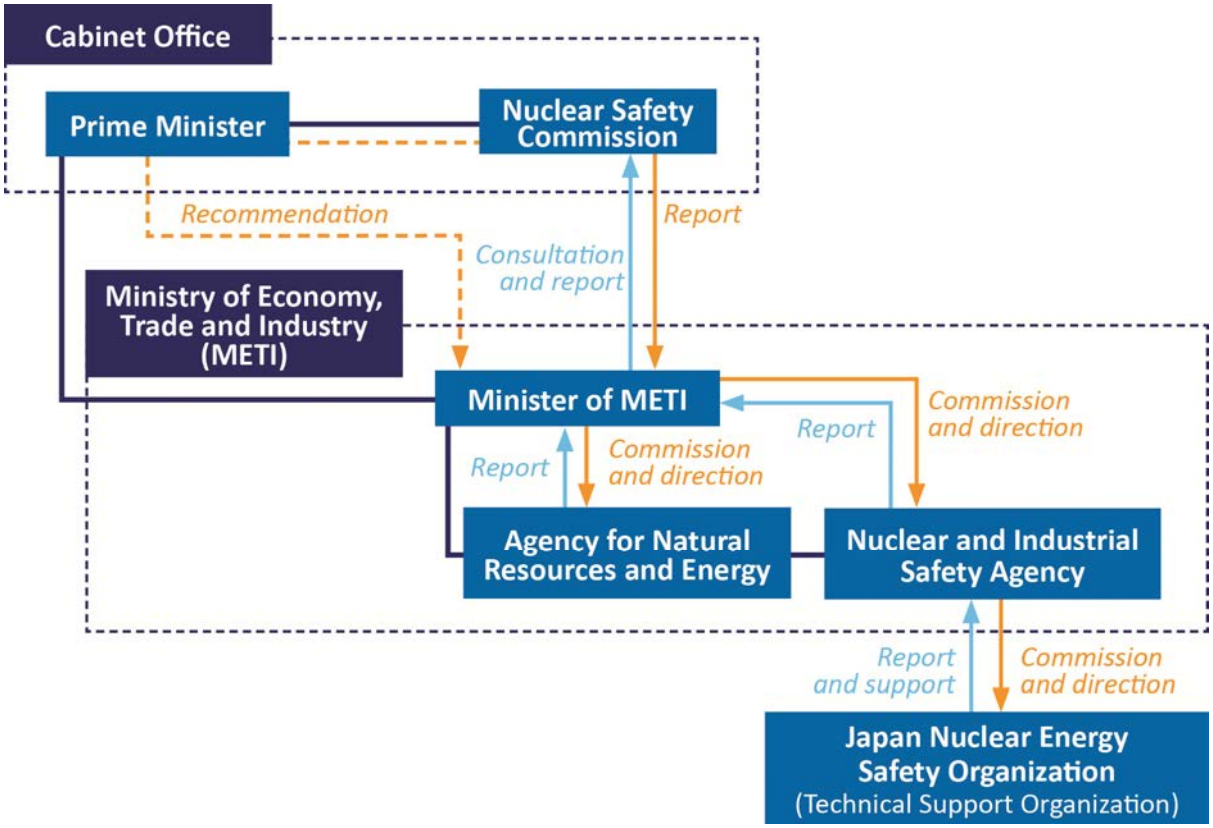


FIG. 2.9. Position of NISA in the Japanese Government.

A series of guidelines were issued by the NSC which were regarded, in practice, as requirements [34]. These guidelines were supplemented by consensus standards published by professional and academic societies. However, the regulations and guidelines in some key areas were not fully in line with international practice at the time of the accident. The most notable differences related to periodic safety reviews, re-evaluation of hazards, severe accident management and safety culture [52, 57, 58].

A periodic safety review provides a formal mechanism for re-examination by the licensees and the regulatory body of the design and external hazards in the light of new information and current standards and technology [52]. In Japan, periodic safety reviews at ten year intervals were required by regulations issued in 2003 [51], but these were of limited scope and not fully in line with international practice because they did not require a re-examination of external hazards [51, 52, 58].

The IAEA IRRS mission in 2007 suggested that NISA should be in a position to make a major contribution to the development of safety regulations. The mission also suggested that NISA needed the ability to modify its inspection programme in a flexible manner to optimize its effectiveness and focus and to be able to conduct safety inspections in locations and at times at its own discretion [51]. The IAEA IRRS mission also suggested that NISA foster frank and open relations with the nuclear industry and operating organizations in order to communicate regulatory concerns directly to the management level.

Establishment of the new regulatory authority

In September 2012, the Nuclear Regulation Authority (NRA) was established [59]. The NRA carried out a review of safety guidelines and regulatory requirements with the aim of formulating new regulations to protect people and the environment. In 2013, the new regulatory requirements for NPPs came into force. Based on the concept of defence in depth, importance was placed on the third and

fourth levels and the prevention of simultaneous loss of all safety functions due to common causes. Previous assumptions on the impact of earthquakes, tsunamis and other external events such as volcanic eruptions, tornadoes and forest fires were re-evaluated, and countermeasures for nuclear safety against these external events were considered. Countermeasures against internal fires and internal flooding and enhancements of the reliability of on-site and off-site power to deal with the possibility of station blackout were also considered.

In addition, countermeasures for severe accident response against core damage, containment vessel damage and a diffusion of radioactive materials, enhanced measures for water injection into spent fuel pools, countermeasures for airplane crashes, and the installation of an emergency response building were also required.

Examples of new regulatory requirements in the light of the accident at the Fukushima Daiichi NPP include: (1) reinforced requirements for seismic/tsunami resistance; (2) reinforced or newly introduced requirements for design basis; and (3) newly introduced requirements for measures against severe accidents [60].

The roles and responsibilities that had previously been assigned to different governmental organizations were integrated into the NRA. The NRA holds jurisdiction over some of the activities of the NIRS and the JAEA. The main nuclear safety technical support organization JNES was merged with the NRA on 1 March 2014.

The NRA has adopted a periodic safety review process aligned with IAEA safety standards that was enforced in December 2013. The system requires nuclear power reactor licensees to comprehensively evaluate the safety of reactors and to submit the results to the NRA within six months of the end of periodic inspection, showing the following:

— The compliance with regulatory requirements;
— Measures for improving safety on a voluntary basis;
— Assessment and review of safety margins for improvement and a probabilistic risk assessment;
— Comprehensive re-evaluation based on the above results and action plans for improving safety.

Japan requested the IAEA to carry out an IRRS mission towards the end of 2015, aimed at strengthening nuclear safety and enhancing the NRA's competence as an independent nuclear regulator through a continuous, transparent and open learning process.

2.2.6. Assessment of human and organizational factors

Before the accident, there was a basic assumption in Japan that the design of NPPs and the safety measures that had been put in place were sufficiently robust to withstand external events of low probability and high consequences.

Because of the basic assumption that NPPs in Japan were safe, there was a tendency for organizations and their staff not to challenge the level of safety. The reinforced basic assumption among the stakeholders about the robustness of the technical design of NPPs resulted in a situation where safety improvements were not introduced promptly.

The accident at the Fukushima Daiichi NPP showed that, in order to better identify plant vulnerabilities, it is necessary to take an integrated approach that takes account of the complex interactions between people, organizations and technology.

Prior to the accident, there was not sufficient consideration of low probability, high consequence external events which remained undetected. This was in part because of the basic assumption in

Japan, reinforced over many decades, that the robustness of the technical design of the nuclear plants would provide sufficient protection against postulated risks. Consequently, the events that led to the accident at the Fukushima Daiichi NPP were outside the boundaries of the basic assumptions of the operating organizations, the regulatory body and the Government. These basic assumptions influenced the decisions and actions of a wide range of stakeholders, not limited to those directly involved in the operation and regulation of NPPs.

Box 2.9. Safety culture

In INSAG-4, a publication of the International Nuclear Safety Group (INSAG), safety culture was defined as: "that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance" [61].

IAEA Safety Standard Series No. GS-G-3.5 [62] and Safety Reports Series No. 11 [63] make it clear that safety culture is itself a subset of the culture of the whole organization, with the latter comprising the mix of shared values, attitudes and patterns of behaviour that give the organization its particular character.

Organizations typically go through a number of phases in developing and strengthening safety culture. Safety Reports Series No. 11 identifies three stages:

(1) Safety is compliance driven and is based mainly on rules and regulations. At this stage, safety is seen as a technical issue, with compliance with externally imposed rules and regulations considered adequate for safety.

(2) Good safety performance becomes an organizational goal and is dealt with primarily in terms of safety targets or goals.

(3) Safety is seen as a continuing process of improvement to which everyone can contribute.

In reality, the three phases are not distinct, and any organization may have some parts that are ahead of others in the process of strengthening safety culture.

The basic assumptions influenced NISA not to exercise sufficient authority and, thus, NISA was not able to challenge other assumptions regarding nuclear safety. It was inhibited in the fulfilment of its oversight role by the lack of an appropriate regulatory framework and also by explicit legal constraints [6, 51]. For instance, the IAEA IRRS mission in 2007 found that NISA inspectors did not have unfettered access to licensees' utilities to perform inspections and were only allowed to conduct inspections during certain times. Due to the basic assumption that the robustness of the technical design would provide sufficient protection against postulated risks, NISA generally worked in a less integrative and more reactive manner, in some cases being focused on short term activities, and did not address more fundamental and long term issues such as the consideration and application of IAEA safety standards. In some cases, regulations were not updated or complex emergency drills were not carried out because of a concern that the public might get the impression that NPPs were not safe, in contrast to the basic assumption [5].

The same basic assumption that NPPs were safe also influenced TEPCO's actions, giving it confidence in the ability of the technical features of its plants to avoid severe nuclear accidents. This meant that TEPCO was not sufficiently prepared to mitigate the accident of March 2011 [6, 7, 65]. The risk of flooding triggering a nuclear accident was outside the basic assumption, so the latest international guidance on severe accident management was not always followed [66]. The basic assumption also excluded the possibility of a common cause failure which could lead to station blackout for multiple units.

The fact that relevant organizations and their staff did not challenge or re-examine the basic assumptions about nuclear safety illustrates a deficiency in safety culture. As identified in Box 2.9, the third stage of a safety culture programme identifies the need to have a continuing process of

improvement, which should include periodic reconsideration of the adequacy of nuclear safety. One means of challenging basic assumptions is to take a systemic approach to nuclear safety and to understand the complexity of the full range of interactions between human, organizational and technical factors. Not sufficiently addressing these interactions was one of the contributory factors to the accident, because the basic assumption remained undetected.

Box 2.10. Basic assumptions [64]

To understand safety culture in its entirety, the artefacts and behaviour, espoused values and basic assumptions that form the three levels of the concept of culture as it applies to safety must be identified. The application of the Three Level model to a specific organization would reflect the uniqueness of that organization and allow logical links to be made between the artefacts, espoused values and basic assumptions. Logical links will not be apparent in the illustrative examples shown below, as they are not derived from any particular organization.

Artefacts are the easiest to observe, but their meaning is the most difficult to interpret. Knowledge of espoused values will help with the meaning, but it is only when the basic assumptions are understood that the meaning of the components at the artefact level will become apparent.

Artefacts and behaviour: Architecture, greeting rituals, dress, forms of address — visible;

Espoused values: Strategies, goals, philosophies — can be elicited;

Basic assumptions: Human nature, basis on which people are respected — unconsciously held and usually tacit.

Basic assumptions lie at the deepest level of culture. They are fundamental beliefs that are so taken for granted that most people in a cultural group subscribe to them, but not in a conscious way. To understand any culture, it is necessary to unearth these basic assumptions that are operating. In the case of an organization, they will also reflect its history, and the values, beliefs and assumptions of the founders and key leaders who have made it successful. Basic assumptions are rarely discussed and confronted and are extremely difficult to change.

Box 2.11. Systemic approach to safety [67]

The systemic approach to safety addresses the whole system by considering the dynamic interactions within and among all relevant factors of the system — individual factors (e.g. knowledge, thoughts, decisions, actions), technical factors (e.g. technology, tools, equipment) and organizational factors (e.g. management system, organizational structure, governance, resources).

The systemic approach to safety works by addressing this complex system of interactions as a whole. For example, among the important factors to consider in these interactions at an NPP are those related to individuals, such as knowledge, decisions, thoughts, emotions and actions. The technical factors include the physical aspects of the NPP and the range of technical tools and equipment used for operation. The organizational factors include the management system, organizational structure, governance of the plant and human and financial resources. Taking into account the interaction between all the individual, technical and organizational factors reveals the complexity and non-linearity of the operations at an NPP. It is necessary to better examine the ways in which the weaknesses and strengths of all these factors influence one another in order proactively to reduce or eliminate risks.

The tendency of the majority of stakeholders not to challenge the adequacy of the existing safety features of the plant strengthened the assumption that the robustness of the plant's technical design and the existing safety measures would be sufficient to protect the plant. This led to necessary safety improvements not being made proactively and promptly [5–7].

The operators who directly responded in the early stages of the accident did so under extreme circumstances. The anxiety and stress associated with their actions were further exacerbated by the fact that they often did not have information about the safety of their families or the condition of their homes. Individuals at the site did not know how the accident would progress, which created significant uncertainty; despite this, they did all they could to protect people and the environment. The situation faced by the operators was unprecedented — managing a multiple unit accident during a national crisis with a heavily damaged infrastructure. This created an extremely adverse working environment from the physical and psychological perspectives.

The interaction of human, organizational and technical factors across all stakeholder organizations and between different levels inside each organization occurs within the broader scope of the safety culture of the organization, and in this way reflects the organization's safety culture. With a systemic approach to safety that analyses the human, organizational and technical factors, an organization can be better prepared for an unexpected event. Nuclear safety will also depend on people's attitudes and behaviour [67]. Human and organizational factors that lead to basic assumptions on safety not being challenged, may result in organizations and individuals taking decisions and performing actions that may inadvertently compromise nuclear safety. It is important to be mindful of such basic assumptions and work to understand their impact on nuclear safety.

2.3. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the nuclear safety considerations of the accident.

— **The assessment of natural hazards needs to be sufficiently conservative. The consideration of mainly historical data in the establishment of the design basis of NPPs is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.**
  Extreme natural events that have a very low probability of occurrence can result in significant consequences, and the prediction of extreme natural hazards remains difficult and controversial due to the existence of uncertainties. Additionally, such predictions may change during the life of an NPP as more information becomes available and methods of analysis improve. It is therefore necessary to use all relevant available data, both domestic and international, to ensure a reliable prediction of hazards, to define a reliable and realistic design basis against natural extreme events, and to design NPPs with sufficient safety margins.
— **The safety of NPPs needs to be re-evaluated on a periodic basis to consider advances in knowledge, and necessary corrective actions or compensatory measures need to be implemented promptly.**
  The periodic safety review programme at the Fukushima Daiichi NPP did not lead to safety upgrades based on regulatory requirements. TEPCO performed the re-evaluation on a voluntary basis considering advances in knowledge, including new information and data. When faced with a revised estimate of a hazard that exceeds previous predictions, it is important to ensure the safety of the installation by implementing interim corrective actions against the new hazard estimate while the accuracy of the revised value is being evaluated. If the accuracy of a new hazard estimate is confirmed, the operating organization and regulatory authority need to agree on a schedule and comprehensive action plan to promptly address the method of coping with such higher hazards to ensure plant safety.
— **The assessment of natural hazards needs to consider the potential for their occurrence in combination, either simultaneously or sequentially, and their combined effects on an NPP. The assessment of natural hazards also needs to consider their effects on multiple units at an NPP.**

The Fukushima Daiichi accident demonstrated the need to fully investigate the potential for a combination of natural hazards affecting multiple units at an NPP. The complex scenarios resulting from the occurrence of a combination of natural hazards need to be taken into account when considering accident mitigation measures and recovery actions.

— **Operating experience programmes need to include experience from both national and international sources. Safety improvements identified through operating experience programmes need to be implemented promptly. The use of operating experience needs to be evaluated periodically and independently.**
The operating experience evaluation programme at the Fukushima Daiichi NPP did not lead to design changes that took account of domestic or international experience involving flooding. The review of operating experience needs to be a standard part of plant oversight processes, with account taken of relevant sources such as the Incident Reporting System of the IAEA and the OECD Nuclear Energy Agency. Regulatory bodies need to perform independent reviews of national and international operating experience to confirm that operating organizations are taking concrete actions to improve safety.

— **The defence in depth concept remains valid, but implementation of the concept needs to be strengthened at all levels by adequate independence, redundancy, diversity and protection against internal and external hazards. There is a need to focus not only on accident prevention, but also on improving mitigation measures.**
The flooding resulting from the tsunami simultaneously challenged the first three protective levels of defence in depth, resulting in common cause failures of equipment and systems. Even when faced with this situation, operators were able to apply effective, albeit delayed, mitigation strategies. All layers of defence in depth associated with both prevention and mitigation of accidents should be strengthened by adequate independence, redundancy, diversity and protection so that they are not simultaneously challenged by an external or internal hazard and are not prone to common cause failure. The application of the defence in depth concept needs to be periodically re-examined over the lifetime of an NPP to ensure that any change in vulnerability to external events is understood and that appropriate changes to the design are made and implemented. There is a need for extreme external hazards to be addressed in periodic safety reviews, because such hazards can result in common cause failures that may simultaneously jeopardize several levels of defence in depth.

— **Instrumentation and control systems that are necessary during beyond design basis accidents need to remain operable in order to monitor essential plant safety parameters and to facilitate plant operations.**
The loss of instrumentation and control during the accident at the Fukushima Daiichi NPP left operators with little indication of actual plant conditions. The loss of instrumentation and control systems had a serious impact on efforts to prevent a severe accident or to mitigate its consequences. The extent and nature of the necessary instrumentation and control systems need to be defined with care, according to the characteristics of the design of the plant, including spent fuel pools. Systems need to be protected to ensure they are available when needed. This also demonstrated the need to improve strategies to allow for manual control of vital equipment.

— **Robust and reliable cooling systems that can function for both design basis and beyond design basis conditions need to be provided for the removal of residual heat.**
At the Fukushima Daiichi NPP, the operators were eventually, after some delay, able to deploy portable equipment to inject water into the reactors. Cooling systems based either on installed or portable equipment need to be qualified and tested to ensure that they function and can be deployed by operators when needed.

— **There is a need to ensure a reliable confinement function for beyond design basis accidents to prevent significant release of radioactive material to the environment.**
At the Fukushima Daiichi NPP, the failure of venting the containment, and the subsequent failure of the reactor building due to the hydrogen explosion, led to a significant release of radioactive material to the environment. The confinement function needs to be assessed to ensure that all

possible hazards are considered in the design of equipment intended to maintain the integrity of the confinement system.

— **Comprehensive probabilistic and deterministic safety analyses need to be performed to confirm the capability of a plant to withstand applicable beyond design basis accidents and to provide a high degree of confidence in the robustness of the plant design.**
Safety analyses can be used both to evaluate and to develop response strategies for beyond design basis accidents and may include the use of both deterministic and probabilistic methods. The probabilistic safety assessment studies conducted for the Fukushima Daiichi NPP were of limited scope and did not consider the possibility of flooding from internal or external sources. The limitations in these studies contributed to the limited scope of accident management procedures available to the operators.

— **Accident management provisions need to be comprehensive, well designed and up to date. They need to be derived on the basis of a comprehensive set of initiating events and plant conditions and also need to provide for accidents that affect several units at a multi-unit plant.**
The accident management procedures available to the operators at the Fukushima Daiichi NPP did not consider the possibility of a multi-unit accident, nor did they provide guidance for the complete loss of electrical power. Accident management provisions need to be based on a plant specific analysis performed by using a combination of deterministic and probabilistic methods. Accident management guidance and procedures need to consider the possibility of events taking place in several units simultaneously and in spent fuel pools. They also need to take into account the possibility of disrupted regional infrastructure, including serious deficiencies in communication, transport and utilities. Accident management provisions should also take into consideration the best available guidance from the international community and be periodically updated to account for new information.

— **Training, exercises and drills need to include postulated severe accident conditions to ensure that operators are as well prepared as possible. They need to include the simulated use of actual equipment that would be deployed in the management of a severe accident.**
Operators at the Fukushima Daiichi NPP had not been specifically trained on how to manually operate systems such as the Unit 1 isolation condenser and fire trucks as an alternative source for low pressure water injection. Special attention is needed in personnel training to perform actions under conditions of prolonged loss of all power, with limited information about the plant status and no information on important safety parameters. Staff training, exercises and drills need to realistically simulate the progression of severe accidents, including the simultaneous occurrence of accidents in several units at the same site. Training, exercises and drills need to involve not only on-site accident management personnel but all off-site responders at the operating organization, local, regional and national levels.

— **In order to ensure effective regulatory oversight of the safety of nuclear installations, it is essential that the regulatory body is independent and possesses legal authority, technical competence and a strong safety culture.**
NISA did not have sufficient authority to take necessary actions, including inspections at regulated facilities. It is essential that the regulatory body is able to make independent decisions on safety over the lifetime of installations. To ensure such independent decision making, the regulatory body must be competent and must possess sufficient human resources, adequate legal authority — including the right to suspend operation and/or to impose improvements in safety on operating organizations — and adequate financial resources. The regulatory body needs the authority to adapt its inspection programme in the light of new safety information. It must also be able to ensure that national regulatory requirements and corresponding guidelines for assessing the safety of nuclear installations are revised periodically in accordance with scientific and technical developments, operational experience, and international standards and practices.

— **In order to promote and strengthen safety culture, individuals and organizations need to continuously challenge or re-examine the prevailing assumptions about nuclear safety and the implications of decisions and actions that could affect nuclear safety.**

This can be achieved by individuals and organizations embracing a questioning attitude to identify the nature, boundaries and potential threats of their shared assumptions about nuclear safety. The institutionalization of a continuous dialogue within organizations, and among different organizations, on issues related to nuclear safety, and their significance and impact on decisions and actions, is essential. Periodic assessments of safety culture can help to foster reflection and dialogue on basic assumptions.

— **A systemic approach to safety needs to consider the interactions between human, organizational and technical factors. This approach needs to be taken through the entire life cycle of nuclear installations.**

The accident at the Fukushima Daiichi NPP showed that it is difficult to identify vulnerabilities in systems that involve complex interactions between people, organizations and technology because basic assumption regarding nuclear safety can remain undetected. A systemic approach that includes human, technological and organizational considerations is necessary to understand how the components of the overall system function and interact in both normal operation and accident conditions.

3. EMERGENCY PREPAREDNESS AND RESPONSE

This section describes the key events and response actions from the onset of the accident on 11 March 2011. It also considers the national emergency preparedness and response system in place in Japan prior to the accident and the international framework for emergency preparedness and response.

Key international requirements for preparedness to respond to a nuclear emergency which existed prior to the accident are summarized in Box 3.1.

Box 3.1. Key requirements for preparedness to respond to a nuclear emergency in the IAEA safety standards prior to the accident

The IAEA safety standards [68, 69] in force prior to the accident required the following:

(1) Utilizing an all-hazards approach in developing preparedness and response arrangements[63]; (2) developing an emergency classification system on the basis of observable conditions and measurable criteria (emergency action levels) and initiation of predetermined urgent protective actions for the public (in the predefined zones) promptly following the classification of the emergency by the operator; (3) establishing emergency zones for the full range of possible emergencies, including those of low probability; (4) establishing arrangements for the implementation of protective actions within the emergency zones and beyond, as required; (5) setting national criteria for decisions on public protective actions (evacuation, sheltering, iodine thyroid blocking, relocation, restriction of food and drinking water consumption and distribution, public monitoring and decontamination) in terms of doses and measurable quantities (operational intervention levels), taking account of a range of factors (such as financial and social aspects); (6) making arrangements for carrying out radiation monitoring and environmental sampling and assessment in order to identify new hazards promptly and to refine the strategy for response; (7) identifying, at the preparedness stage, special population groups within emergency zones (e.g. disabled persons, hospital patients) for whom specific arrangements need to be made; (8) establishing arrangements for emergency workers, including setting the dose criteria for different types of tasks, designating emergency workers and ensuring their protection, establishing guidance for managing, controlling and recording their doses, and providing specialized protective equipment, procedures and training; (9) planning for the transition from the emergency phase to long term recovery operations and resumption of normal social and economic activities, including clear allocation of responsibilities, sharing and transferring information, assessing consequences, establishing formal processes to decide on withdrawal of restrictions and other arrangements imposed during the emergency, setting relevant principles and criteria and consulting the public; (10) clearly assigning roles, responsibilities and authorities for emergency preparedness and response at all levels as part of emergency plans; (11) establishing organizational relationships and interfaces among operating and response organizations and preparing operational protocols to coordinate the emergency response at all levels; (12) developing and coordinating emergency plans and procedures at all levels on the basis of assessed hazards; (13) preparing for logistical support through provision of tools, instruments, supplies, equipment, communication systems, specific functional facilities and documentation, including planning for operability and usability of these items and facilities under postulated radiological, working and environmental conditions in the emergency response; (14) planning for and conducting of training, drills and exercises; and (15) establishing a quality assurance programme to ensure that all the supplies, equipment, communication systems, facilities and documentation, etc., are kept continuously up to date, available and functional for use in an emergency.

[63] 'Arrangements' — the integrated set of infrastructural elements necessary to provide the capability for performing a specified function or task required in response to a nuclear or radiological emergency. These elements may include authorities and responsibilities, organization, coordination, personnel, plans, procedures, facilities, equipment and training.

The types of protective actions in a nuclear emergency are summarized in Box 3.2.

Box 3.2. Types of protective actions in a nuclear emergency [48, 69]

'**Mitigatory actions'** are immediate actions to reduce the potential for conditions to develop that would result in exposure or a release of radioactive material requiring emergency actions on or off the site, or to mitigate plant conditions that could result in exposure or a release of radioactive material requiring emergency actions on or off the site.

'Urgent protective actions' are actions that must be taken promptly (normally within hours) in order to be effective. The most common urgent protective actions in a nuclear emergency are evacuation, sheltering, iodine thyroid blocking, restriction of the consumption of potentially contaminated food and decontamination of individuals.

'Early protective actions' are those actions that must be taken within days or weeks to be effective. They can be long lasting, even after the termination of the emergency. Unlike urgent protective actions, it is generally possible to base these actions on the results of monitoring that takes account of the specific nature of the release of radioactive material and its dispersion in the environment. Examples of early protective actions include relocation, restrictions on food and drinking water and controls on agriculture.

3.1. INITIAL RESPONSE IN JAPAN TO THE ACCIDENT

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at an NPP (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national Government would then assess and determine whether the situation was to be categorized as a 'nuclear emergency'[64]. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections.

Based on a report from the Fukushima Daiichi NPP, the national Government declared a nuclear emergency on the evening of 11 March and issued orders for protective actions for the public. The response at the national level was led by the Prime Minister and senior officials at the Prime Minister's Office in Tokyo.

The consequences of the earthquake and tsunami, and increased radiation levels, made the on-site response extremely difficult. The loss of AC and DC electrical power, the presence of a huge amount of rubble that hindered on-site response measures, aftershocks, alerts for further tsunamis and increased radiation levels meant that many mitigatory actions could not be carried out in a timely manner. The national Government was involved in decisions concerning mitigatory action on the site.

[64] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006, hereinafter referred to as the Nuclear Emergency Act.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi NPP was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions.

The primary legal basis for the national emergency preparedness and response system in Japan was set out in the Disaster Countermeasures Basic Act [70] and the Act on Special Measures Concerning Nuclear Emergency Preparedness [19] (Box 3.3).

Box 3.3. Key documents defining the national emergency preparedness and response system for a nuclear emergency in Japan at the time of the accident

<table>
<tr><td colspan="4">National legal basis</td></tr>
<tr><td colspan="2">Disaster Countermeasures Basic Act*</td><td colspan="2">Act on Special Measures Concerning Nuclear Emergency Preparedness</td></tr>
<tr><td colspan="4">National planning basis</td></tr>
<tr><td>Basic Disaster Management Plan*</td><td>Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness</td><td>Ordinance for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness</td><td>Regulatory Guide on Emergency Preparedness for Nuclear Facilities</td></tr>
<tr><td colspan="4">Operational plans and manuals</td></tr>
<tr><td>National</td><td colspan="2">Disaster Management Operation Plan*</td><td>Nuclear Emergency Response Manual</td></tr>
<tr><td>Prefectural/City/ Town/Village</td><td colspan="2">Prefectural/City/Town/Village Disaster Management Plans*</td><td>Prefectural/City/Town/ Village Nuclear Manuals</td></tr>
<tr><td>Operators</td><td colspan="2">Nuclear Operator Emergency Action Plans</td><td>Nuclear Operator Emergency Response Manuals</td></tr>
</table>

** These documents address various types of disasters, including nuclear emergencies*

3.1.1. Notification

Notification from the NPP to local and national governments was required under Article 10 of the Nuclear Emergency Act [19] when certain predefined 'specific events' occurred, such as failure of all AC power supplies for more than five minutes [55]. Under Article 15 of the Nuclear Emergency Act, a report of a 'nuclear emergency' would be sent when certain predefined criteria were met or exceeded, such as the loss of all capabilities to cool the reactor [21, 71].

It was assumed that a report of an event under Article 15 would follow a notification of an event under Article 10 [72]. Notification would trigger an assessment and judgement by the national Government as to whether the event was a 'nuclear emergency'. If this was judged to be the case, the Prime Minister would be briefed and presented with a draft declaration of a 'nuclear emergency'. The

Prime Minister would be responsible for deciding to declare a 'nuclear emergency' and issuing orders[65] and/or recommendations for protective actions to the public [73].

Key actions to be taken if an event fell under Article 10 and/or Article 15 of the Nuclear Emergency Act are summarized in Fig. 3.1 [19, 70, 73–75].

The tsunami wave that flooded the Fukushima Daiichi NPP arrived at 15:36 on 11 March 2011 [10]. Notification by the plant of a 'specific event' for Units 1 to 5 under Article 10 of the Nuclear Emergency Act [19] was sent to national and local governments at 15:42 on 11 March, followed at 16:45 by a report of an event at Units 1 and 2 classified as a 'nuclear emergency' under Article 15 of the Act [3, 8, 76, 77].

The type of the 'specific event' reported under Article 10 was a 'station blackout' for Units 1–5 [76]. The type of the event reported as a 'nuclear emergency' under Article 15 was initially the "inability of water injection of the emergency core cooling system" for Units 1 and 2 [77]. After receiving notification, the national Government assessed the situation and made a judgement that the situation was a 'nuclear emergency' [6].

The Prime Minister issued a declaration of a nuclear emergency at 19:03. This was more than two hours after having been notified by the Fukushima Daiichi NPP of an event at Units 1 and 2 classified as a 'nuclear emergency' under Article 15 of the Act, following lengthy discussions among off-site officials [3].

3.1.2. Mitigatory actions

An emergency response centre, headed by the Site Superintendent, was established at the Fukushima Daiichi NPP, in accordance with TEPCO's Disaster Response Manual, around 15 minutes after the earthquake [6, 8]. It was located in the seismically isolated building, which was fitted with special features including an autonomous electrical power supply and ventilation systems with filtration devices. This building had been constructed[66] as a result of lessons learned from the experience of the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and its use enabled mitigatory actions to continue at the site during the response to the accident [8].

The arrangements that existed prior to the accident envisaged that, in case of need, the on-site emergency response centre would send a request for support to TEPCO Headquarters, using TEPCO's capabilities or resources gathered from other nuclear operating organizations, through the Agreement on Cooperation between Japanese Nuclear Operators [8, 75].

Following a request from the Fukushima Daiichi NPP, additional staff and equipment from other Japanese NPPs (not operated by TEPCO) were mobilized to support the on-site emergency response. However, extensive damage caused to the transport infrastructure by the earthquake and tsunami, in addition to insufficient pre-planning, impaired the effectiveness of this support. For example, in cases where the request for equipment did not contain an adequate specification of what was required, it led to the procurement of equipment that was incompatible with existing plant equipment (due to mismatched fittings, connectors, etc.) [8].

---

[65] The Nuclear Emergency Act [19] and the Disaster Countermeasures Basic Act [70] use the terms 'instructions' and 'recommendations' for issuing protective actions. An 'instruction' is mandatory and the public is therefore required to adhere to it. A 'recommendation' is only a suggestion and therefore not mandatory. However, for the purposes of clarity, the term 'orders' is used in this report as an equivalent of 'instructions'.

[66] The construction started in March 2009 and the building was put into operation in July 2010.

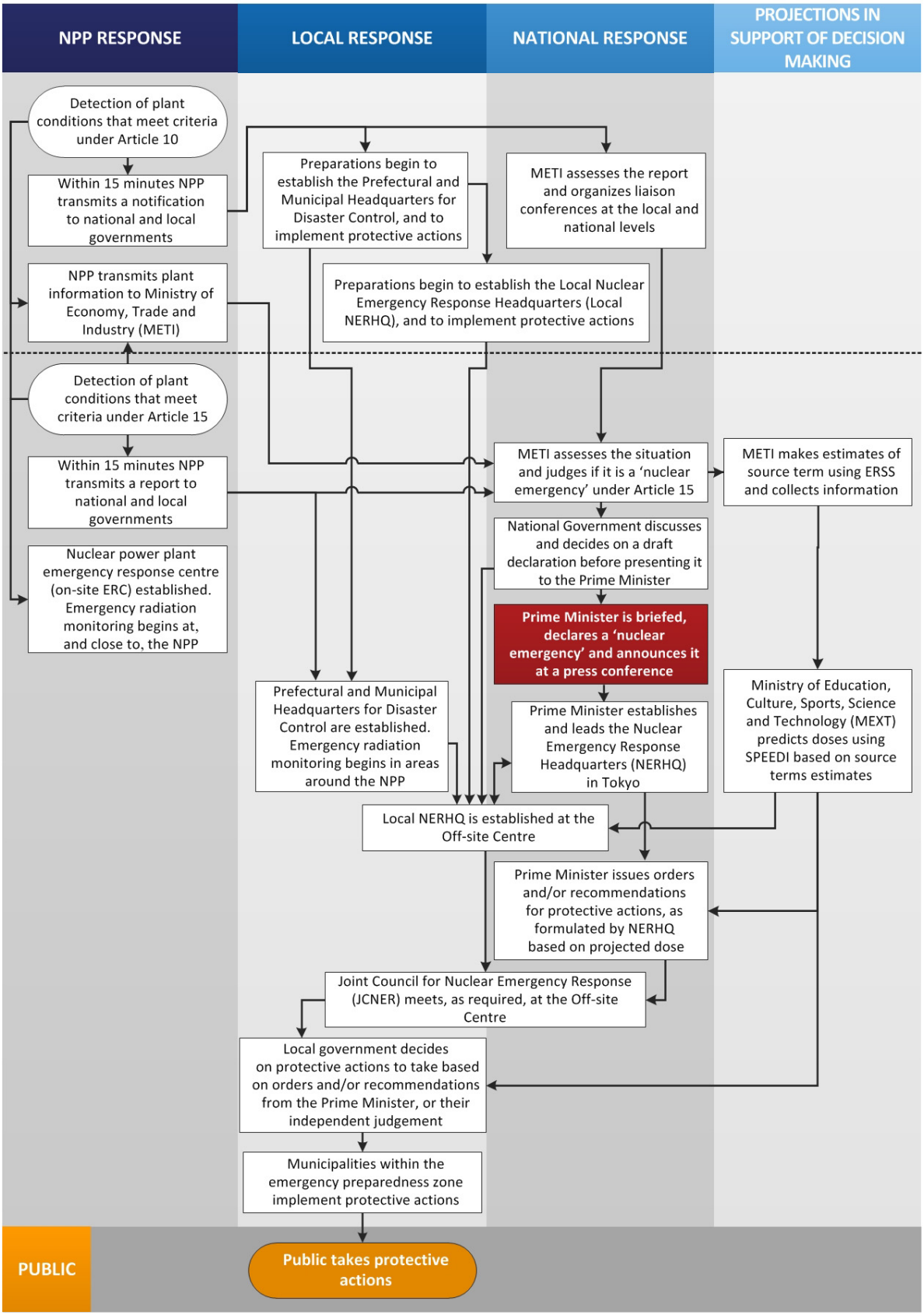


FIG. 3.1. Key actions if an event falls under Article 10 and/or Article 15 of the Nuclear Emergency Act, as planned prior to the accident (based on Refs [19, 70, 73–75]).

In response to the emergency, personnel from TEPCO, from contractors and from other Japanese NPPs (not operated by TEPCO) were dispatched to the site to assist with various tasks, including restoring power and monitoring instruments, injecting cooling water into reactors, removing rubble and monitoring radiation levels [8]. Personnel from national Government agencies and organizations — such as the Japan Self-Defense Force, police and firefighters — were also dispatched to the site. They helped with activities including operating the large equipment needed to pour or spray water onto the spent fuel pools in Units 1, 3 and 4, and providing helicopter surveillance of the spent fuel pools [3, 6, 8].

The earthquake and tsunami resulted in the loss of AC and DC electrical power and a huge amount of rubble. There were also aftershocks and alerts of possible further tsunamis. As a result of these factors, as well as increased radiation levels and the hydrogen explosions, and also due to the lack of detailed arrangements, the response was extremely difficult and many mitigatory actions could not be carried out in a timely manner [8]. Workers at the site carried out mitigatory actions under very difficult conditions; they worked longer hours and under far more tiring circumstances than would normally be expected [8].

The national Government was involved in decisions concerning mitigatory actions, such as the injection of sea water for fuel cooling [6, 7]. Roles, responsibilities and authorities in this regard had not been clearly assigned at the preparedness stage.

3.1.3. Management of the emergency

The national emergency preparedness and response system in place at the time of the accident envisaged that the core entities in managing the nuclear emergency would be the Nuclear Emergency Response Headquarters (NERHQ)[67] and its Secretariat[68], as well as the Local Nuclear Emergency Response Headquarters (Local NERHQ)[69]. The NERHQ would direct and coordinate the national response, which was to include preparing and issuing orders and/or recommendations on evacuation to the local government [19].

For a national response at the local level, the overall management of the response to a nuclear emergency was to be coordinated, as soon as possible, by the Local NERHQ at the Off-site Centre, located 5 km from the Fukushima Daiichi NPP. The Prefectural Nuclear Emergency Response Headquarters (Prefectural NERHQ) and the Joint Council for Nuclear Emergency Response (JCNER) were also planned to be located in the Off-site Centre [73, 74, 78].

For the prefectural response to a nuclear emergency, it was planned that the Prefectural NERHQ and the Fukushima Prefecture Headquarters for Disaster Control would coordinate activities at the prefectural level. The JCNER would coordinate between the national response at the local level and the prefectural response [19, 73, 74].

---

[67] The NERHQ was to be composed of those appointed by the Prime Minister from among the officials of the Cabinet Secretariat and designated administrative organs [19]. The Prime Minister was to serve as the Director General of the NERHQ, which was planned to be located in the Prime Minister's Office (see Fig. 3.2).

[68] The Secretariat was to be staffed by representatives of key organizations and headed by the Director General of the Nuclear and Industrial Safety Agency (NISA), which was part of the Ministry of Economy, Trade and Industry (METI). It was planned to be located in the METI/NISA emergency response centre in the METI building (see Fig. 3.2).

[69] The Local NERHQ was to be staffed with individuals from all relevant organizations, with the METI Senior Vice Minister as Director General. It was planned to be located at the Off-site Centre (see Fig. 3.2).

Separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. These arrangements did not envisage the need to respond to a nuclear emergency and a natural disaster occurring simultaneously [74, 78].

The locations of the core entities in the management of the response to a nuclear emergency as planned prior to the accident are shown in Fig. 3.2.

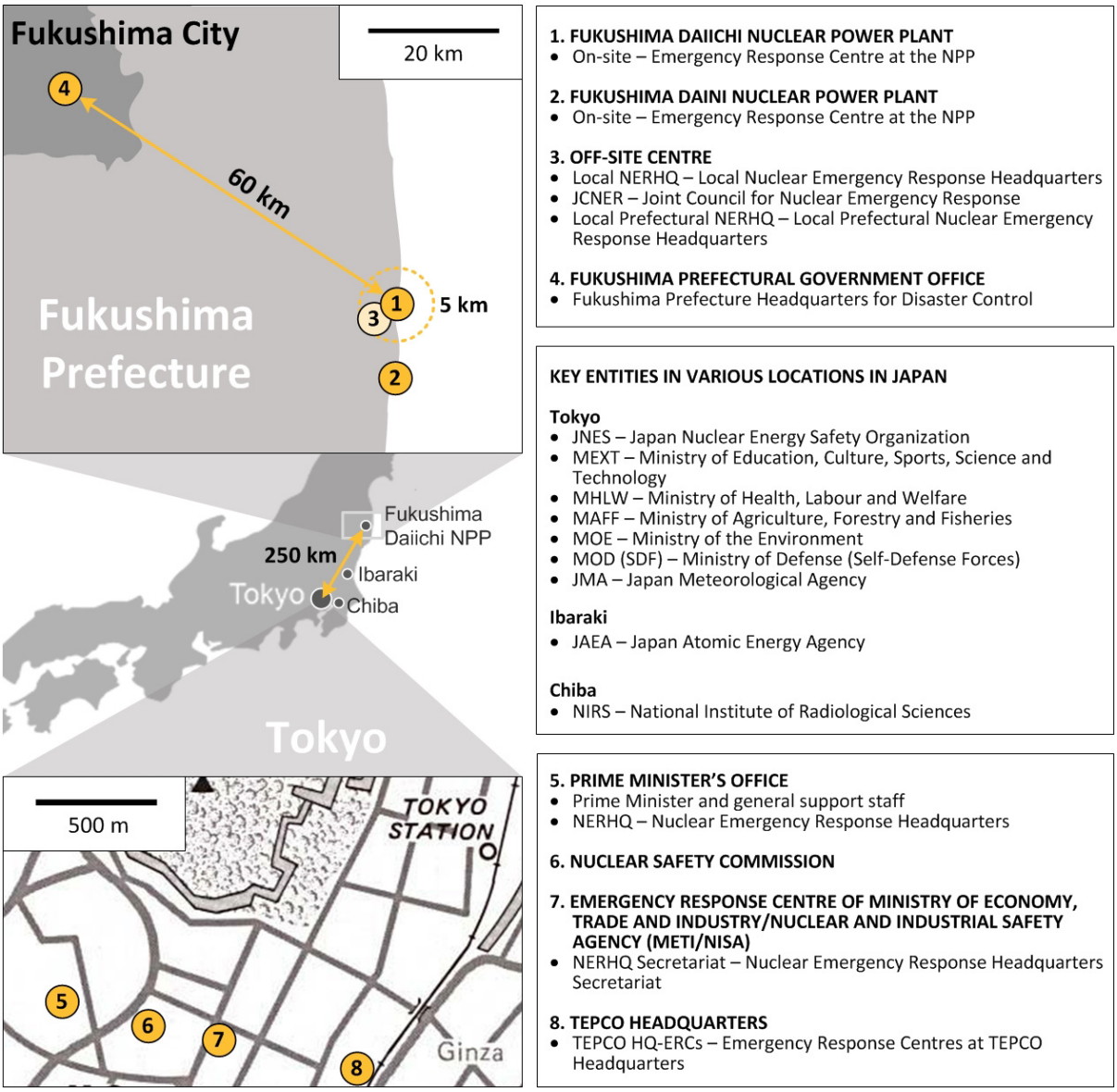


FIG. 3.2. Locations of the core entities involved in management of the response to a nuclear emergency[70].

At 14:50 on 11 March 2011, an Emergency Response Office for dealing with the earthquake was established in the Prime Minister's Office by the Deputy Chief Cabinet Secretary for Crisis Management. At 15:14, the national Government established the Emergency Disaster Response Headquarters in the Prime Minister's Office in Tokyo, with the Prime Minister as the Headquarters'

[70] Based on Refs [7, 8, 73, 74, 79–91].

Director General. At 16:36, the Deputy Chief Cabinet Secretary for Crisis Management established an Emergency Response Office for the nuclear accident at the Prime Minister's Office [6].

At 19:03 on 11 March 2011, the national Government established the Nuclear Emergency Response Headquarters, at the same time as the declaration of a nuclear emergency was issued [3].

As the accident evolved so fast, there was no time for detailed discussions during meetings of the NERHQ. The core group for the emergency response became the Prime Minister and senior officials, located at the Prime Minister's Office. The Prime Minister issued evacuation orders to local governments without the involvement of the Secretariat of the NERHQ [7].

The Government–TEPCO Integrated Response Office — an integrated headquarters of the operating organization and the Government response organization — was established on 15 March 2011 at TEPCO Headquarters in Tokyo [6] to ensure the timely sharing of information at the national level.

At the local level, the extensive damage caused by the earthquake and tsunami led to difficulties in initiating operations in the Off-site Centre [92]. As a result, the Local NERHQ and other entities, which were supposed to operate from the Off-site Centre (JCNER and Prefectural NERHQ), could not fulfil their roles. On 15 March 2011, it became necessary to evacuate the Off-site Centre, due to the worsening radiological conditions[71], and to relocate to the Fukushima Prefectural Public Hall, located approximately 60 km from the Fukushima Daiichi NPP [6, 92]. This facility did not have capabilities equivalent to those of the Off-site Centre, which led to difficulties, for example, in sharing information in real time among the relevant authorities.

For the prefectural response, a new 'nuclear squad'[72] was formed in the Fukushima Prefecture Headquarters for Disaster Control, as part of the structure set up to respond to the earthquake and tsunami, to coordinate activities at the prefectural level [7].

3.2. PROTECTING EMERGENCY WORKERS

At the time of the accident, the national legislation and guidance in Japan addressed measures to be taken for the protection of emergency workers[73], but only in general terms and not in sufficient detail.

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. However, there were no arrangements in place to integrate into the response those emergency workers who had not been designated prior to the accident.

---

[71] The Off-site Centre had not been designed to withstand the increasing radiation levels.

[72] A new nuclear squad was formed because the existing nine functional squads, as specified in the Fukushima Prefecture Disaster Management Plan [74], were engaged in response to the earthquake and tsunami [7].

[73] The IAEA uses the term 'emergency workers' to cover those with specified duties as a worker (any person who works, whether full time, part time or temporarily, for an employer and who has recognized rights and duties in relation to occupational radiation protection) in response to an emergency, including workers employed, both directly and indirectly, by registrants and licensees as well as personnel of responding organizations, such as police officers, firefighters, medical personnel, and drivers and crews of evacuation vehicles. In Japan, the term 'emergency preparedness personnel' is used to cover all those who perform emergency response activities in a nuclear emergency, such as "communication of public information and instructions to residents in the vicinity, guidance of residents in the vicinity for evacuation, traffic control, radiation monitoring, medical treatment provision, and actions to prevent a situation from developing into a disaster in a nuclear facility, and those who perform disaster recovery activities such as removal of radioactive contaminants" [93].

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. The dose limit for emergency workers undertaking specific tasks was temporarily increased to allow the necessary mitigatory actions to continue. Medical management of emergency workers was also severely affected and major efforts were required to meet the needs of on-site emergency workers.

Members of the public, referred to as 'helpers', volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.

3.2.1. Protection of personnel at the plant following the earthquake and tsunami

Following the tsunami alert, efforts were made to protect plant personnel (about 6000 people) from the expected impact of the tsunami. Tsunami alerts were broadcast using the on-site public address system, advising personnel to evacuate and to relocate to designated locations at higher levels. While in most cases these efforts were successful, not all personnel received the tsunami alert and evacuation orders [7, 8]. Two workers who were checking equipment after the earthquake on the underground floor of the Unit 4 turbine building were drowned in the flooding caused by the tsunami [8].

The protection of plant personnel from the effects of the tsunami was successful largely due to lessons learned from the experience at the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and efforts made afterwards in developing procedures for emergency exit [8].

From 11 to 14 March 2011, plant personnel not considered essential — including female workers and most of the employees of subcontractors — were evacuated from the site. On the morning of 15 March, an evacuation of additional plant personnel took place because of worsening conditions at the site. An estimated 50–70 staff remained at the site, while approximately 650 people were temporarily evacuated to the Fukushima Daini NPP using buses or private vehicles. They began to return to the Fukushima Daiichi NPP from noon on the same day [8].

3.2.2. Protective measures for emergency workers

The national legislation and guidance in Japan at the time of the accident addressed measures to be taken for the protection of emergency workers. However, the arrangements that were in place, such as the on-site plan, addressed these requirements only in a general way and not in sufficient detail. For example, the on-site plan covered the following areas: defining responsibilities; assigning generic duties in emergency preparedness and response; and listing an inventory of available instrumentation (e.g. survey meters and electronic dosimeters) [75].

Dose limits for emergency workers were set depending on their intended tasks, with an upper dose limit of 100 mSv for life saving actions and activities to prevent the development of catastrophic conditions, while efforts to minimize the exposure were required [93, 94].

During the accident, a range of impromptu measures were adopted to maintain an acceptable level of protection for on-site emergency workers under the extreme conditions. There was a lack of personal dosimeters, as most of those at the site had become inoperable after the tsunami. This made it necessary to take contingency measures to track the individual doses received by the on-site emergency workers [8]. For example, an instruction was issued to use a single electronic personal dosimeter per group of emergency workers expected to work in similar conditions. For emergency workers in the seismically isolated building, doses were measured and controlled by area dose rate

monitoring and by the amount of time spent by workers in the specific areas. This situation continued until the end of March 2011, by which time a sufficient number of dosimeters had been received from other NPPs [6, 8].

On 14 March 2011, the dose limit for emergency workers undertaking specific emergency work was temporarily increased to 250 mSv to allow the necessary activities to continue on-site and within a 30 km radius of the Fukushima Daiichi NPP [95]. A dose of 100 mSv remained the limit for emergency workers from the firefighting service for life-saving actions [6]. The temporary increase in the dose limit to 250 mSv was withdrawn on 1 November 2011 for on-site emergency workers who began working from this date onwards; on 16 December 2011 it was withdrawn for the majority of the remaining emergency workers; and on 30 April 2012 it was withdrawn for a small group of emergency workers with specialized knowledge and experience [96, 97].

Most on-site emergency workers received doses below 250 mSv [8]. There were six cases in which emergency workers incurred doses in excess of the dose criterion of 250 mSv, with the highest dose of 678 mSv (of which 590 mSv was due to internal contamination).

Internal contamination was attributed to the severe working conditions and the inadequate implementation of protective measures (e.g. improper use of respiratory protection, iodine thyroid blocking measures, actions that resulted in inadvertent ingestion of radionuclides), due primarily to the lack, or ineffectiveness, of training [5].

TEPCO also faced challenges in ensuring the well-being of on-site emergency workers, for example in providing adequate facilities and conditions (for resting, sleeping, eating, sanitation, etc.) [98–101].

During the response to the accident, people from the affected areas, as well as from all over Japan, including from a number of non-governmental organizations, referred to as ‘helpers’, volunteered to assist in activities such as the provision of food, water and necessities, and later in decontamination and monitoring activities. National authorities issued guidance on the type of activities helpers could carry out and on measures to be taken for their protection [102–104].

3.2.3. Designation of emergency workers

Many different types of emergency workers were needed to support the on-site and off-site emergency response. On-site emergency workers included NPP personnel, either directly employed by TEPCO or subcontracted, as well as personnel from the Japan Self-Defense Force, the firefighting services and police engaged in emergency work on the site [8]. Off-site emergency workers included personnel from different organizations and services (governmental and non-governmental). Their tasks included evacuation of the public and of special facilities, offering support to evacuees, providing medical care and carrying out monitoring and sampling [6, 97, 105, 106].

Not all of the emergency workers had been designated as such prior to the emergency (e.g. some TEPCO employees and employees of subcontractors), and arrangements were not in place to integrate them into the response after their designation as emergency workers. Additionally, many of those who had not been designated prior to the emergency had not been trained to work in conditions of a nuclear emergency. For example, they had not been trained in radiation protection aspects, informed of the potential health risks from radiation exposure, or trained in the use of respiratory protection or in dealing with patients potentially contaminated with radioactive material [107]. This resulted in some delay in implementation of mitigatory actions early in the response [6].

3.2.4. Medical management of emergency workers

Obtaining the necessary medical treatment for emergency workers with conventional injuries was difficult because several hospitals were closed as a result of the evacuation or sheltering, and some were not prepared to treat patients possibly contaminated with radioactive material [107, 108]. Until primary medical care was provided on the site, emergency workers with conventional injuries were transported to one of two local hospitals for treatment [108].

About 17 hours after the earthquake, the NIRS dispatched a Radiation Emergency Medical Assistance Team (REMAT), consisting initially of a physician, a nurse and a health physicist, to the Local NERHQ (in the Off-site Centre) to perform assessments of the contamination and decontamination for emergency workers [107].

Occupational health doctors began to provide primary care for on-site emergency workers at the emergency response centre in the seismically isolated building eight days after the beginning of the accident. Two triage centres were subsequently established, one on-site and the other in 'J-Village'[74] [3, 8, 108].

From 1 July 2011, an emergency care facility was established at the Fukushima Daiichi NPP. For this facility, medical staff trained to deal with radiation emergencies were recruited from all over Japan [8, 108].

3.3. PROTECTING THE PUBLIC

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). The arrangements did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no criteria for relocation.

Protective actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi NPP began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km of the plant to 3 km and then to 10 km. By the evening of 12 March it had been extended to 20 km. Similarly, the area in which people were ordered to shelter was extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20–30 km radius of the NPP, the public was ordered to shelter until 25 March, when the national Government

[74] J-Village is located about 20 km south of the Fukushima Daiichi NPP. Prior to the accident, it was a football training facility. After the accident, it was utilized as a general logistical support base, e.g. for preparing workers for assigned tasks, for their monitoring and decontamination, as necessary, after completion of the assigned tasks, for triage, etc. [3].

recommended voluntary evacuation. Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

On 22 April, the existing 20 km evacuation zone was established as a 'Restricted Area', with controlled re-entry. A 'Deliberate Evacuation Area' was also established beyond the 'Restricted Area' in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made regarding agricultural protective actions in the agricultural area and restrictions on the consumption and distribution of food and consumption of drinking water. In addition, a certification system for food and other products intended for export was established.

Several channels were used to keep the public informed and to respond to people's concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material.

3.3.1. Urgent protective actions and relocation

Prior to the accident, 10 km emergency planning zones, in which emergency preparedness was to be significantly enhanced, had been established around the Fukushima Daiichi and Fukushima Daini plant sites (Fig. 3.3). There were plans to implement protective actions within these zones [74].

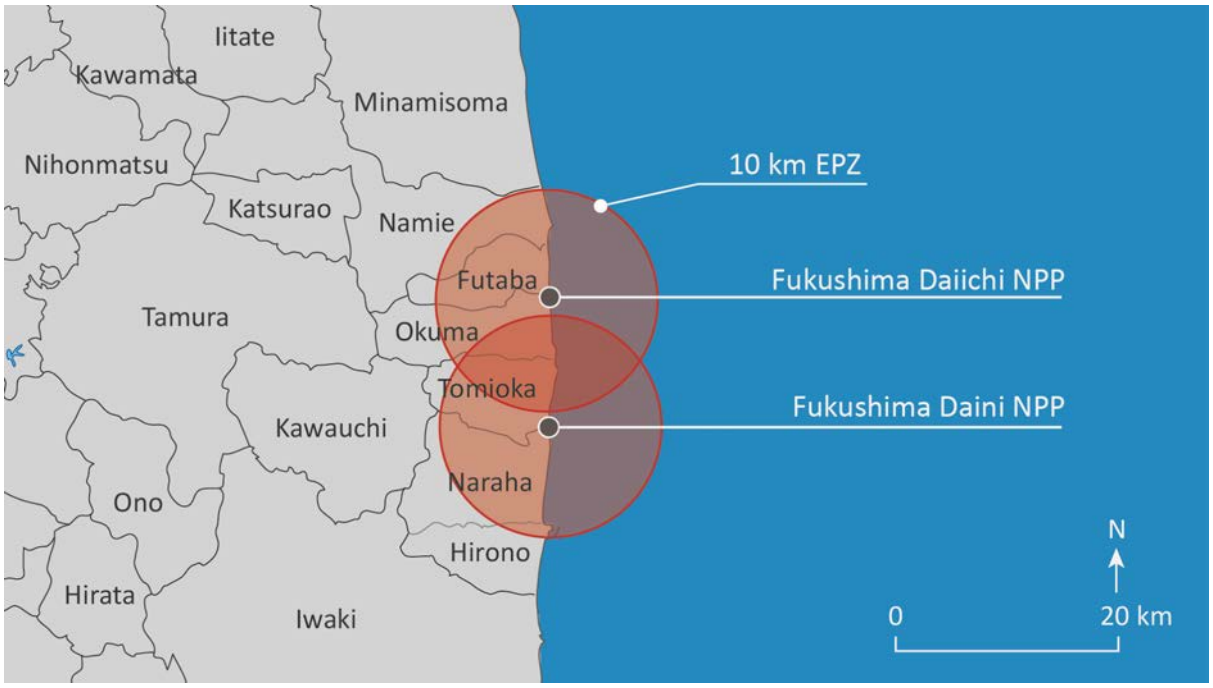


FIG. 3.3. Emergency planning zones (EPZs) for the Fukushima Daiichi and Fukushima Daini NPPs established prior to the accident (based on Ref. [74]).

The emergency response plans envisaged that decisions on protective actions would be based on dose projections performed at the time when a decision was necessary. Doses were to be projected by SPEEDI after the onset of the accident and to be compared with predetermined dose criteria to determine what protective actions were needed and where [73, 93]. This approach was not in line with IAEA safety standards, where the initial decisions on urgent protective actions for the public need to be based on plant conditions [68, 69].

Predetermined dose criteria were available for sheltering[75], evacuation[76] and iodine thyroid blocking[77] in terms of projected dose, but not in terms of measurable quantities. There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation[78] [93].

During the response to the accident, 'source term' estimates from the Emergency Response Support System (ERSS) could not be provided as an input to SPEEDI[79] owing to the loss of on-site power. Decisions on evacuation and sheltering were taken on the basis of plant conditions (i.e. loss of core cooling) rather than on dose projections as was planned [3, 7].

The decisions of the national and local governments on protective actions were not always coordinated, mainly as a result of the severe communication problems and partly due to the difficulties in activating the Off-site Centre [92]. At 20:50 on 11 March 2011, Fukushima Prefecture issued an evacuation order for residents within a radius of 2 km of the Fukushima Daiichi NPP on the basis of information received directly from TEPCO [3, 6, 7, 70].

At 21:23, the national Government issued an evacuation order for an area within a radius of 3 km of the plant, and sheltering for an area within a radius of 3–10 km. At 05:44 on 12 March 2011, the national Government issued an order for the evacuation of an area with a radius of 3–10 km, and at 18:25 it was extended to an area within a radius of 20 km of the plant[80] [3, 7].

The communication of evacuation orders to the public was arranged by using the local disaster management radio communication network, sound trucks, police cars and door-to-door visits. As a result of the plant conditions, difficulties in coordination and insufficient pre-planning, orders for evacuation and sheltering were modified several times within 24 hours, and eventually a zone with a radius of 20 km was ordered to evacuate, involving about 78 000 people [7].

---

[75] 'Sheltering' is the short term use of a structure for protection from an airborne plume and/or deposited radioactive material [48].

[76] 'Evacuation' is the rapid, temporary removal of people from an area to avoid or reduce short term radiation exposure in an emergency. Evacuation may be performed as a precautionary action based on plant conditions [48].

[77] 'Iodine thyroid blocking' is an urgent protective action to be taken in an emergency involving radioactive iodine. Iodine thyroid blocking involves the administration of a compound of stable iodine (usually potassium iodide) to prevent or reduce the uptake of radioactive isotopes of iodine by the thyroid gland [48].

[78] 'Relocation' is the non-urgent removal of people to avoid longer term exposure (e.g. within one year) from deposited radioactive material [48].

[79] Some projections of doses were performed using other assumptions; however, these projections were not used as a basis for deciding on urgent protective actions [4, 7].

[80] For the Fukushima Daini NPP, an evacuation order to citizens within a radius of 3 km and an order for sheltering within a 3–10 km radius of the plant was issued at 07:45 on 12 March 2011 [6]. Following the hydrogen explosion in Unit 1 of the Fukushima Daiichi NPP (at 15:36 on 12 March), a decision was made at 17:39 on 12 March to evacuate citizens from a 10 km radius around the Fukushima Daini NPP as a precaution in case of a similar hydrogen explosion at this plant [6]. As this 10 km evacuation zone was within the 20 km evacuation zone around the Fukushima Daiichi NPP, no further protective actions were needed in relation to the Fukushima Daini NPP.

There were difficulties in evacuation due to infrastructure damage and communication and transportation problems resulting from the earthquake and tsunami. Significant challenges were also encountered in evacuating patients from hospitals and nursing homes within the 20 km evacuation zone (e.g. providing appropriate transport and evacuation shelters with medical supplies). In spite of damaged roads and traffic jams, most residents not requiring medical support began to leave the evacuation area within a few hours after the orders for evacuation had been issued [7].

The order for the sheltering of residents living within a radius of 20–30 km area around the Fukushima Daiichi NPP was given on 15 March and remained in force until 25 March [3, 7]. This extended time of sheltering and the breakdown of the local infrastructure resulted in serious disruptions to people's lives [7]. On 25 March 2011, a recommendation for voluntary evacuation was issued by the national Government to residents within the 20–30 km zone [3, 7]. Many residents, however, had already voluntarily left the area.

Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, owing primarily to inadequate pre-planned arrangements. Some local governments distributed stable iodine tablets but did not advise taking them, while others distributed the tablets and advised the public to take them, and still others awaited instructions from the national Government [6].

Some residents returned to their homes in the evacuated areas to collect belongings before full access controls were established by the end of March 2011 [6]. On 22 April, the existing 20 km evacuation zone around the Fukushima Daiichi NPP was established as a 'Restricted Area', with controlled re-entry and conditions for temporary access, based on consultation with the local governments. In May 2011, short term temporary access was granted, with arrangements in place, including specific instructions and monitoring for contamination [6, 104, 109].

Monitoring of evacuees at the local level began on 12 March 2011. Decisions on the need for decontamination were based on operational criteria established prior to the accident. After several days, these criteria were increased to address existing conditions (e.g. low temperatures, insufficient water supplies) [5].

Environmental monitoring following the accident was performed in difficult and hazardous conditions and with limited equipment and staff. For example, the earthquake and tsunami disabled most of the existing local monitoring equipment. Monitoring within a radius of 20 km of the Fukushima Daiichi NPP began on 12 March and ended on 14 March, when evacuation within this area had been completed. In some locations beyond the 20 km evacuation zone, dose rates of the order of a few hundred microsieverts per hour (μSv/h) were measured from 15 March onward [3, 6].

On 11 April 2011, the national Government announced that the criterion of 20 mSv dose projected to be received within one year from the date of the accident would be used to determine areas beyond the 20 km evacuation zone from which people might need to be relocated[81] [3]. On 22 April 2011, a 'Deliberate Evacuation Area' was established beyond the 20 km evacuation zone to include areas where this projected dose criterion of 20 mSv might be exceeded. The national Government issued an order that relocation of people from this area should be implemented in approximately one month [3].

In addition to the 'Deliberate Evacuation Area', an 'Evacuation Prepared Area in Case of Emergency' was also established on 22 April 2011 (see Fig. 3.4). Residents of the 'Evacuation Prepared Area in Case of Emergency' were advised to shelter or evacuate by their own means in the event of possible

[81] Most of the official Japanese documents describing the response to the Fukushima Daiichi accident do not use the term 'relocation', but refer to the movement of people as 'evacuation'.

renewed concerns regarding the Fukushima Daiichi NPP. The designation of the 'Evacuation Prepared Area' was lifted on 30 September 2011 [6].

As a result of the monitoring conducted beyond the 'Restricted Area' (i.e. the 20 km evacuation zone) and the 'Deliberate Evacuation Area', specific locations were identified with projected doses to residents above 20 mSv within one year after the occurrence of the accident. On 16 June, the national Government announced a guideline which specified that these locations should be designated as 'Specific Spots Recommended for Evacuation'. Beginning on 30 June, the national Government began to designate these locations to be relocated [6, 7].

The areas and locations for which protective actions were ordered or recommended until 30 September 2011 are shown in Fig. 3.4.

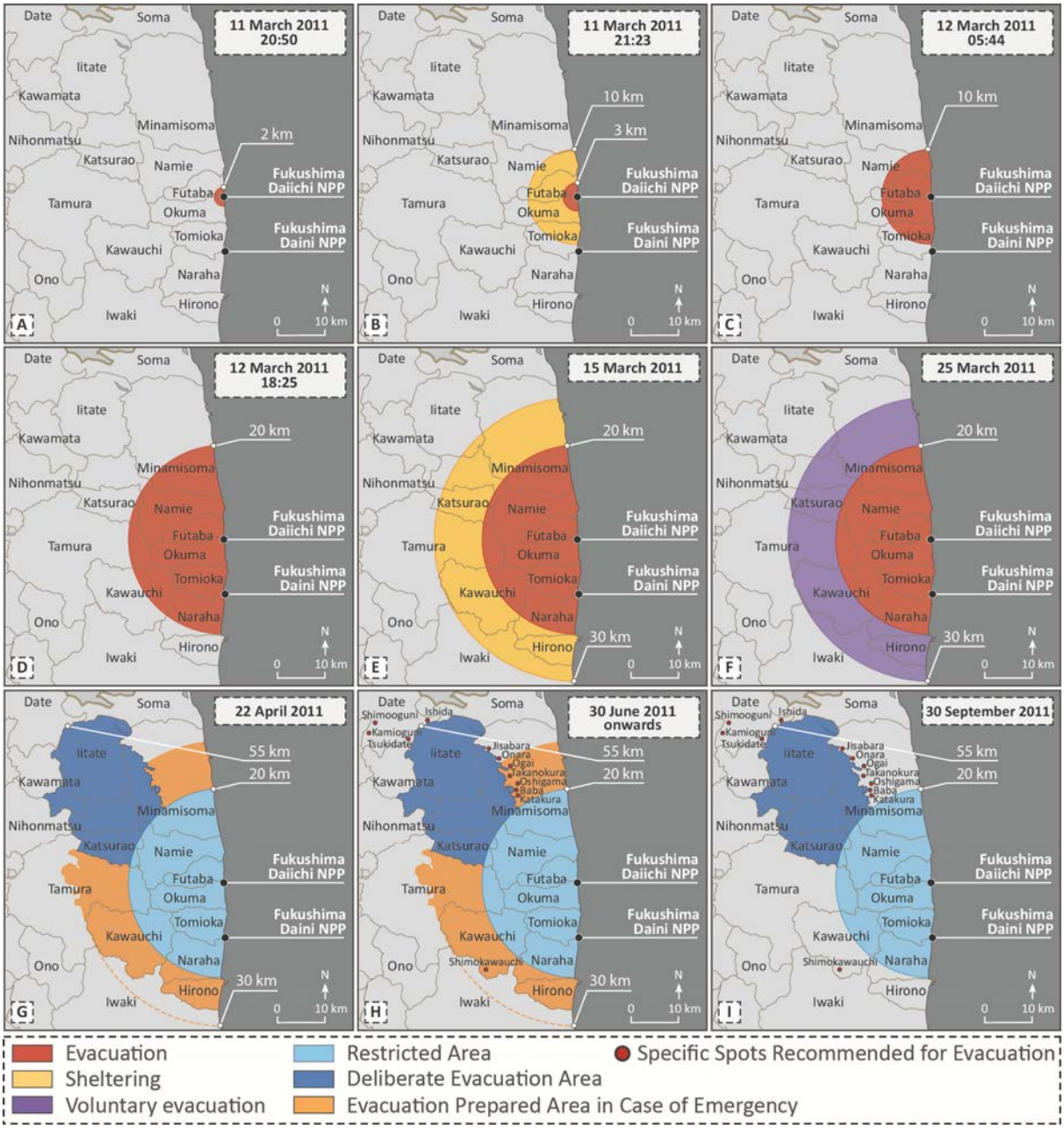


FIG. 3.4. Areas and locations where protective actions were ordered or recommended until 30 September 2011 (based on Refs [3, 6, 7, 104]).

Local government officials had also to decide at an early stage whether to reopen schools and under what conditions. Initially, on 19 April 2011, a dose criterion of 20 mSv/year was established for this purpose. On 27 May, in response to concerns on the part of the public, a notification was issued by the Government of Japan stating the objective to reduce the dose to 1 mSv/year in the near term [7].

3.3.2. Protective actions relating to food, drinking water and agriculture

The criteria of activity concentrations of specific radionuclides to be used in the case of a nuclear emergency for restrictions on food and drinking water produced in Japan had been developed before the accident [93]. However, these values had not been adopted for use in an emergency as specific regulatory limits[82] [6, 7]. On 17 March 2011, these criteria were established as provisional regulation values for radionuclide levels in food and drinking water under the Food Sanitation Act [110].

Following the detection of radioactive material in the environment, arrangements were made for controlling food and drinking water. These arrangements included: (1) radionuclide concentration levels of radioactive caesium and radioactive iodine in food and drinking water established as provisional regulation values under the Food Sanitation Act, above which food and drinking water were restricted; and (2) measurements of radionuclide concentrations in samples of food and drinking water. Within a few weeks, the levels of radioactive iodine (^{131}I) had decreased significantly owing to its short half-life (about 8 days), and the food restrictions in the medium to long term were based on concentrations of radioactive caesium only [110].

On 21 March 2011, the national Government began to issue restrictions on the distribution of specific food [111] that evolved with the changing situation. Food restrictions were formulated on the basis of the results of monitoring of food samples that determined which foods were exceeding the criteria and defined the geographical location(s) affected [112, 113].

A number of challenges with regard to protective actions related to food and drinks were encountered, including: (1) defining the criteria (activity concentrations of radionuclides) that could be used as the basis for food control; (2) determining which foods, in different geographical locations, were or could be affected with levels above these criteria; (3) dealing with the insufficient infrastructure and resources for sampling and analysis; and (4) addressing the concerns of some local governments about performing the sampling and analyses.

On 4 April 2011, a policy was established that enabled placement of food restrictions not only in areas defined by prefectural boundaries but also in smaller geographical areas (such as cities, towns and villages), as appropriate. The policy set out a process to establish or lift restrictions on different food products. Prefectures could apply for modifications to restrictions, on the condition that the food monitoring results were below provisional regulation values three consecutive times in weekly monitoring tests [7].

On 5 April 2011, based on measured concentrations of ^{131}I in fish samples, the provisional regulation values were added for activity concentrations of radioactive iodine in fishery products [114].

On 8 April 2011, a policy was issued on restrictions of rice cultivation in agricultural soil that had radioactive caesium levels in excess of established criteria [6].

[82] Criteria for food imported into Japan (370 Bq/kg of radioactive caesium — ^{134}Cs and ^{137}Cs) were established as regulatory limits following the accident at the Chernobyl NPP in the former Soviet Union in 1986 [7].

On 14 April 2011, radionuclide concentration levels of radioactive caesium and radioactive iodine in animal feed were established as provisional permissible values. Despite the restrictions on animal feed, some beef samples exceeded the provisional regulation values (in July 2011). A control regime was put in place to prevent such meat from being distributed to consumers [6].

On 1 April 2012, standard limits came into force which replaced the provisional regulation values. These limits specified activity concentrations for radionuclides in food and drinking water on the basis of an effective dose of 1 mSv/year (while the criterion of 5 mSv/year had been used as a basis for the provisional regulation values), and taking account of the contributions to dose of a range of radionuclides released during the accident. As a consequence, these values were much lower than the provisional regulation values that they replaced [115].

3.3.3. Public information

Arrangements for informing the public were in place prior to the accident. At the national level, arrangements existed that recognized the need for relevant response organizations to coordinate the provision of information to the public, including the content, timing and method of announcements [73]. The Fukushima Prefecture Disaster Management Plan also included arrangements for public information [74].

The regulatory body, NISA, released its initial message on the impact of the earthquake on nuclear facilities via 'Mobile NISA' at 15:16 on 11 March 2011, 30 minutes after the earthquake. The declaration of a nuclear emergency was issued by the Prime Minister at 19:03 and announced at a press conference at 19:45. This was followed by a Government press conference on evacuation orders at 21:52 [6, 7].

The national Government, NISA, local emergency response organizations, local governments and TEPCO held independent press conferences which continued until 25 April. The Chief Cabinet Secretary held regular press conferences twice a day and also on an ad hoc basis to provide information to the public on the accident and the views of the Government. More than 150 press releases were issued and 182 press conferences were held by NISA between 11 March and 31 May 2011 [3]. The results of environmental monitoring were presented at press conferences and press briefings by MEXT.

The Nuclear Safety Commission (NSC) held daily press conferences from 25 March to 24 April 2011, and eight press conferences were held by the NSC from 25 April to 19 May 2011 [3].

Joint press conferences between various organizations involved in the response were held from 25 April 2011 onward. This contributed to the consistency of the information that was provided [6]. The Local NERHQ published newsletters and distributed them to evacuation sites from April 2011 onward. Relevant information was also broadcast periodically via local radio stations [3].

Hotlines were established to answer inquiries from the public. For example, on 11 March 2011, NISA established a hotline to respond to queries relating to the evolution of the emergency and radiation safety, receiving approximately 15 000 calls between 17 March and 31 May 2011 [3]; on 13 March, a hotline of the NIRS was opened, with about 6500 calls answered by 11 April [116]; on 17 March 2011, MEXT and the JAEA opened a hotline, receiving a total of 17 500 calls by 18 May 2011 [3]. Fukushima Prefecture set up counselling services to address questions from residents about various aspects of radiation. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material [3].

From 12 March 2011 onward, the national Government posted information in English, Chinese and Korean on the web sites of the relevant ministries and agencies [117]. Information was provided to the

diplomatic corps in Tokyo through regular briefings, held by the national Government on a daily basis from 13 March to 18 May 2011, and three times a week from 19 May onward [6]. A notification channel via fax and email to the diplomatic corps was also established. The diplomatic missions of Japan provided information to their host States, which was posted on web sites in a total of 29 different languages [3].

Beginning on 13 March 2011, joint press conferences were held, mostly on a daily basis, for the foreign news media by relevant national ministries and government agencies [6].

Challenges encountered in providing information to the international community related principally to the demands on human resources for translating materials and responding to information requests by telephone [117].

International Nuclear and Radiological Event Scale (INES) ratings were reported by Japan following the Fukushima Daiichi accident. The INES rating was used separately for the different units at the same site. The rating was revised to a higher level several times within one month. Revisions of the INES rating to a higher level were a cause of significant concern to the public and the news media.

3.3.4. International trade

Many activities and measures were initiated that were aimed at: (1) reassuring the public, industries and States of the safety of Japanese products; (2) facilitating international trade in Japanese products and preventing delays in distribution; and (3) providing advice and guidance to businesses and industries, in particular in Fukushima Prefecture [98, 99, 118, 119].

Most importing States introduced control measures on Japanese goods; many increased existing import controls or requested a certificate from the Government of Japan; and some banned the import of Japanese goods or those from certain regions of Japan (mostly agricultural products) for a period of time. In June 2011, Japan established a certification system for food products intended for export, which helped to reassure the public and other interested parties that controls were in place. This system was extended in September 2011 to cover shipping containers and some industrial products intended for export [120].

3.3.5. Waste management in the emergency phase

Arrangements for the management of radioactive waste established in Japan prior to the accident covered waste generated in facilities such as NPPs, but it did not include radioactive waste that had been generated in public areas [121]. Detailed strategies, guidelines and instructions for radioactive waste management were developed after the accident.

The ‘Near-Term Policy to Ensure the Safety for Treating and Disposing Contaminated Waste around the Site of the Fukushima Dai-ichi Nuclear Power Plants’ was issued by the NSC on 3 June 2011 [122]. This document provided dosimetric criteria for: recycled materials; protection of workers treating the materials; protection of members of the public in the vicinity of treatment facilities; and protection of members of the public in the vicinity of a disposal site. The NSC proposed that materials affected by the accident — i.e. debris, sludge from the water and sewage treatments, incinerated ash, trees, plants and soil resulting from decontamination activities — would be disposed of under proper management and that some materials may be considered for reuse. Products manufactured from these reused materials would be checked for contamination and managed appropriately before being released onto the market. Appropriate protective measures would ensure that radiation exposures on the part of workers and the public were kept as low as reasonably achievable [122].

The 'Basic Policy for Emergency Response on Decontamination Work' [123] was established by the NERHQ on 26 August 2011 as an interim policy until the 'Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011' was fully in force. The Act was enacted on 26 August 2011, promulgated on 30 August 2011 — with portions of the Act entering into force the same day — and entered fully into force in January 2012 [124]. It outlined the management of the contaminated areas and included the assignment of responsibilities to the national and local governments, the operator and the public. It facilitated the transition from an emergency exposure situation to an existing exposure situation. It also formalized the long term management of environmental monitoring, decontamination measures and the designation, treatment, storage and disposal of soil and waste contaminated by radioactive material.

3.4. TRANSITION FROM THE EMERGENCY PHASE TO THE RECOVERY PHASE AND ANALYSES OF THE RESPONSE

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection (ICRP).

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), and two investigation committees created by the Government and the Parliament, respectively.[83]

After the accident, national emergency preparedness and response arrangements in Japan were, in many cases, revised to take account of the findings of these analyses and of relevant IAEA safety standards in the area of emergency preparedness and response.

3.4.1. Transition from the emergency phase to the recovery phase

In developing arrangements for the transition from the emergency phase to the recovery phase after the accident, the Japanese authorities decided to apply the latest recommendations of the ICRP [127–129]. The specific policies, guidelines and criteria, as well as overall arrangements for the transition from the emergency phase to the recovery phase, were developed after the accident [130]. This process included adjusting the protective actions and arrangements made early in the emergency response and taking account of the information available on the conditions in the affected areas (obtained primarily through comprehensive monitoring) [131, 132]. It also included consideration of the necessary longer term recovery operations.

These actions and arrangements primarily addressed the immediate needs arising during the transition process. The provisions for the protection of workers were gradually modified, depending on the work being undertaken [6, 96].

[83] Reports from academia and from the private sector were also issued (e.g. from the Atomic Energy Society of Japan and the Rebuild Japan Initiative Foundation) [125, 126].

On 17 April 2011, TEPCO issued a 'roadmap', outlining the steps towards recovery on the site (basic policy, targets and immediate actions in the areas of cooling, mitigation of consequences, and monitoring and decontamination) [24].

On 17 May 2011, METI issued a 'Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers' [130]. This listed nine groups of actions divided into steps scheduled to be implemented over different periods connected to TEPCO's roadmap. Step 1 had a target of mid-July, step 2 a target of around three to six months after achieving step 1, and step 3 for the mid-term period. This roadmap was intended to facilitate communication and preparations for the transition to long term recovery operations and the resumption of normal social and economic activity. It allocated responsibilities and specified other organizational aspects of the transition process and the objectives and conditions for termination of the emergency phase.

3.4.2. Analyses of the response

Analyses of the accident and the emergency response were undertaken by various bodies in order to identify lessons and to enhance, among other areas, emergency preparedness and response arrangements in Japan. A number of improvements in these arrangements were identified as a result.

For example, the report of the Government of Japan to the IAEA Ministerial Conference in June 2011 [3] presented lessons in the following areas important for emergency preparedness and response: (1) combined natural disaster and nuclear emergency; (2) environmental monitoring; (3) allocation of roles between central and local organizations; (4) communication in an emergency; (5) response to assistance from other States and communication with the international community; (6) modelling of the release of radioactive materials; and (7) criteria for evacuation and radiation protection guidelines in nuclear emergencies.[84]

The Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, created by the Government, found that there was a need for Japan to take into account lessons from the international community and to include international standards, such as those developed by the IAEA, in its national guidelines [5].

TEPCO's Fukushima Nuclear Accident Analysis Report [8] highlighted issues that were identified during the response to the emergency that included: emergency response organization; communication of information; transportation of materials and equipment; and radiation protection.

The report of the Fukushima Nuclear Accident Independent Investigation Commission established by the National Diet of Japan contained a recommendation for, among other things, reform of the national emergency preparedness and response system, including clarification of the roles and responsibilities of the Government, local government and operators in an emergency [7].

On the basis of these analyses and lessons identified, corrective actions were taken to strengthen emergency preparedness and response arrangements [133, 134]. A Nuclear Emergency Preparedness Commission was established within the Cabinet to ensure that nuclear emergency response policies would be implemented and promoted by the Government [134]. The NRA developed Nuclear

[84] An additional report was submitted to the IAEA in September 2011 [4]. It provided information on further developments and progress in addressing the lessons that had been identified in the first report issued in June 2011.

Emergency Response Guidelines[85] [136], also taking into account the IAEA safety standards in the area of emergency preparedness and response.

3.5. RESPONSE WITHIN THE INTERNATIONAL FRAMEWORK FOR EMERGENCY PREPAREDNESS AND RESPONSE

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements.[86]

At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the interagency response.

The international response to the accident involved many States and a number of international organizations.

The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point. The IAEA also sent expert missions to Japan and coordinated the inter-agency response.

Different States[87] either took or recommended different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.

Relevant organizations participating in the Inter-Agency Committee on Radiological and Nuclear Emergencies regularly exchanged information. Joint press releases were also issued.

The IAEA, through its emergency arrangements, liaised directly with NISA, which was the official contact point in Japan [143]. Japan provided information in accordance with Article 3 of the Early Notification Convention.

The IAEA Secretariat shared information on the emergency as it developed and kept States, relevant international organizations and the public informed [143].

---

[85] The Nuclear Emergency Response Guidelines were based on the interim report on the revision of the Regulatory Guide for Emergency Preparedness of Nuclear Facilities [93], which was issued in 2012 [135].

[86] The primary international legal instruments are the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. The international safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 [69] and No. GS-G-2.1 [68]. Safety Series No. 115 [137] also included elements related to emergency preparedness and response. The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET) and Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

[87] The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment.

The IAEA's role at the time did not include providing a prognosis of the potential evolution of an accident or an assessment of the possible consequences. Its role in responding to an emergency at an NPP was expanded through the adoption of the IAEA Action Plan on Nuclear Safety [144]. This requested the Agency to provide Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information during a nuclear emergency on its potential consequences, including analysis of the available information, and prognoses of possible scenarios based on evidence, scientific knowledge and the capabilities of Member States.

Box 3.4. International framework for emergency preparedness and response for a nuclear or radiological emergency at the time of the accident

The primary responsibility for emergency preparedness and response for a nuclear or radiological emergency rests with the State, as does the primary responsibility for the protection of human life, health, property and the environment. The State is responsible for ensuring that emergency preparedness and response arrangements are in place at the national, regional, local and operating organization/facility levels. Where appropriate, the State is also responsible for ensuring the coordination of national arrangements for emergency preparedness and response with the relevant international arrangements to which the State has acceded or is otherwise a party (e.g. through bilateral and/or multinational agreements).

The international framework at the time of the accident comprised international legal instruments, IAEA safety standards and operational arrangements.

The Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, hereinafter referred to as the Early Notification Convention and the Assistance Convention, assign specific response functions and responsibilities to the IAEA and to the Parties. Various international organizations — by virtue of their statutory functions or of related legal instruments — have functions and responsibilities that encompass aspects of emergency preparedness and response [138, 139].

The IAEA safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 (co-sponsored by seven international organizations) and IAEA Safety Standards Series No. GS-G-2.1 (co-sponsored by six international organizations) [68, 69]. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (IAEA Safety Series No. 115) also included parts that were related to emergency preparedness and response [137].

International operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET) and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) [140–142].

ENATOM facilitated the implementation of those articles of the Early Notification Convention and the Assistance Convention that were operational in nature, such as the provisions for notification and information exchange and the communication protocols for Contact Points identified under the Early Notification Convention and the Assistance Convention (through messages via faxes, telephone lines, emails and a secure and protected web site that could be responded to around the clock). These measures were the subject of regular exercises of various levels of complexity called convention exercises (ConvEx).

RANET was established to facilitate the provision of international assistance upon request and in compliance with the Assistance Convention. This system forms an operational mechanism to provide assistance in different technical areas, with the help of national capabilities registered in the network.

JPLAN describes a common understanding of how each organization acts during a response and in making preparedness arrangements for a nuclear or radiological emergency. It provides a mechanism for coordination, and clarifies the roles and capabilities of the participating international organizations. It is maintained by the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), for which the IAEA provides the Secretariat. At the time of the accident, IACRNE comprised 15 international intergovernmental organizations.

Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The visit to Japan from 17 to 19 March 2011 by the IAEA Director General, and the subsequent deployment of liaison officers to Tokyo, improved communication between the IAEA and the contact point [143].

Some States issued advice or a specific instruction for the protection of their nationals in Japan. Some advised their nationals in Japan to follow the orders and recommendations issued by the Japanese authorities in response to the emergency, while some States issued advice that differed from that provided by the Japanese authorities and other States [145]. Differences in the recommendations among States were due to various factors, including a lack of information on the evolving situation. These differences were generally not well explained to the public and occasionally caused confusion and concern.

The IAEA sent expert missions to Japan and coordinated the provision of Member State offers of assistance to Japan. The Assistance Convention was not invoked and RANET[88] was not utilized. States provided assistance to Japan directly. This support helped the Government of Japan to manage the nuclear emergency, which, together with the effects of the earthquake and tsunami, challenged the national response capability. One of the difficulties in accepting international assistance in the early stages of the national response was the absence of national arrangements for receiving such assistance [5, 143].

In accordance with its responsibilities, the IAEA Secretariat promptly activated the JPLAN and initiated coordination of the inter-agency response. Members of IACRNE exchanged information, focusing in particular on reaching a common understanding of the aftermath of the accident and coordinating efforts to keep the public informed. Regular video teleconferences were held until July 2011. Joint press releases were also issued.

As part of the bilateral agreements between the secretariats, the Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO) and World Meteorological Organization (WMO) sent liaison officers to the IAEA to ensure effective coordination of the international response.

3.6. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of emergency preparedness and the response to the accident. The response to the accident highlighted lessons from past emergencies and confirmed the importance of being adequately prepared for an emergency response.

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**
Consideration needs to be given to the possibility of a severe nuclear accident, irrespective of the cause, possibly involving more than one unit at a site and occurring simultaneously with a natural disaster, which could result in disruption at the site and of the local infrastructure. Systems,

[88] The IAEA Secretariat, together with Member States registered in RANET, continues to enhance this network on the basis of experience from the Fukushima Daiichi accident.

communications and monitoring equipment for providing essential information for both on-site and off-site responses need to be able to function under such circumstances.

Facilities where the response will be managed (e.g. on-site and off-site emergency response centres) need to be selected or designed to be operational under a full range of emergency conditions (radiological, working and environmental conditions), and need to be suitably located and/or protected so as to ensure their operability and habitability under such conditions.

— **The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.**

Arrangements are needed that integrate the response to a nuclear emergency with the response to natural disasters and human-made disasters (e.g. earthquakes, floods and fires).

The on-site response needs to be managed by personnel located at the site who have knowledge of the plant and of the situation. The on-site and off-site responses need to be coordinated based on pre-planned arrangements.

— **Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, be given adequate training, and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency, and helpers who volunteer to assist in the emergency response.**

The practical arrangements for the protection of emergency workers need to be addressed in a consistent manner and in adequate detail in relevant plans and procedures. Account needs to be taken of those who may not have been designated as emergency workers at the preparedness stage. Dose criteria for emergency workers need to be set in advance and applied in a consistent manner for the assigned emergency duties. Arrangements for ensuring the well-being of emergency workers (including contact with their families) need to be in place.

In addition, arrangements need to be pre-planned for members of the public (referred to as 'helpers') who volunteer to assist in response actions to be integrated into the emergency response organization and to be afforded an adequate level of radiation protection.

— **Arrangements need to be in place to allow decisions to be made on the implementation of predetermined urgent protective actions for the public, based on predefined plant conditions.**

These arrangements are necessary because decision support systems, including those using computer models, may not be able to predict the size and timing of a radioactive release (the 'source term'), the movements of plumes, deposition levels or resulting doses sufficiently quickly or accurately in an emergency to be able to provide the sole basis for deciding on initial urgent protective actions.

At the preparedness stage, there is a need to develop an emergency classification system based on observable conditions and measurable criteria (emergency action levels). This system enables the declaration of an emergency shortly after the detection of conditions at a plant that indicate actual or projected damage to the fuel and initiation of predetermined, urgent protective actions for the public (in the predefined zones) promptly following classification of the emergency by the operator. This emergency classification system needs to cover a full range of abnormal plant conditions.

— **Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.**

At the preparedness stage, there is a need to establish arrangements to, among other things: (1) define emergency planning zones and areas; (2) establish dose and operational criteria (levels of measurable quantities) for taking urgent protective actions and other response actions, including dealing with special population groups within emergency zones (e.g. patients in hospitals); (3) enable urgent protective actions to be taken before or shortly after a release of radioactive

material; (4) enable prompt establishment of access controls in areas where urgent protective actions are in place; (5) extend protective actions beyond the established emergency planning zones and areas if necessary; (6) establish dose and operational criteria for taking early protective actions and other response actions (e.g. relocation and food restrictions) that are justified and optimized, taking into account a range of factors such as radiological and non-radiological consequences, including economic, social and psychological consequences; and (7) establish arrangements for revision of operational criteria for taking early protective actions on the basis of the prevailing conditions.

— **Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.**

These arrangements need to be developed with a clear understanding of the full range of possible health hazards presented in a nuclear emergency and of the potential radiological and non-radiological consequences of any protective actions.

Protective actions need to be taken in a timely and safe manner, taking into account possible unfavourable conditions (e.g. severe weather or damage to infrastructure). Preparations in advance are necessary to ensure the safe evacuation of special facilities, such as hospitals and nursing homes; continuing care or supervision must be provided for those who need it.

— **Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.**

Public concerns need to be effectively addressed in a nuclear emergency. This includes the means to relate measurable quantities (e.g. dose rates) and projected radiation doses to radiological health hazards in a manner that allows decision makers (and the public) to make informed decisions concerning protective actions. Addressing public concerns contributes to mitigating both the radiological and the non-radiological consequences of the emergency.

International concerns could be addressed, in part, by means of certification systems to demonstrate that tradable goods meet international standards and to reassure importing States and the public.

— **Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and for transition to the recovery phase.**

At the preparedness stage, there is a need to plan for the transition from the emergency phase to the long term recovery phase and for resumption of normal social and economic activities. The arrangements need to: (1) establish formal processes to decide on the termination of protective actions and other response actions; (2) clearly allocate responsibilities; (3) establish criteria for the termination of protective actions and other response actions; and (4) provide a strategy and process for consulting the public.

— **Timely analysis of an emergency and the response to it, drawing lessons and identifying possible improvements, enhances emergency arrangements.**

Such an analysis needs to include a review of all relevant arrangements, including national laws and regulations, allocation of authorities and responsibilities, emergency response plans and procedures, facilities, equipment, training and exercises. Analysis provides a basis for revision of the arrangements, as necessary. The adequacy of revised emergency arrangements needs to be demonstrated through exercises.

— **The implementation of international arrangements for notification and assistance needs to be strengthened.**

Awareness of international arrangements for notification and assistance in a nuclear or radiological emergency, as well as existing operational mechanisms, needs to be increased, including mechanisms and procedures for notification and information exchange, for requesting and providing international assistance, etc. There is a need for enhanced training and exercises on the operational aspects of the Early Notification Convention and the Assistance Convention.

Participation in existing mechanisms for the provision of international assistance under the Assistance Convention needs to be an integral part of national emergency preparedness efforts. Arrangements need to be in place at the preparedness stage for requesting and receiving assistance (on the basis of bilateral agreements or under the Assistance Convention) in a nuclear or radiological emergency.

Lists of officially designated contact points, as required under the Early Notification Convention and the Assistance Convention, need to be continuously updated and prepared for immediate requests for information from the IAEA.

Application of the IAEA safety standards on emergency preparedness and response at the national level would improve preparedness and response, facilitate communication in an emergency and contribute to the harmonization of national criteria for protective actions and other response actions.

— **There is a need to improve consultation and sharing of information among States on protective actions and other response actions.**

Consultation and sharing of information on protective actions and other response actions among States in an emergency helps to ensure that actions are taken consistently. In addition, a clear and understandable explanation of the technical basis for decisions on protective actions and other response action is crucial in order to increase public understanding and acceptance at both the national and international levels.

4. RADIOLOGICAL CONSEQUENCES

Section 4 considers the radiological consequences of the accident at the Fukushima Daiichi NPP for people and the environment. The radiological consequences of the accident have been addressed by a number of international organizations and bodies. WHO issued a preliminary estimation of radiation doses [146] and subsequently assessed the risk attributed to the accident [147]. More recently, UNSCEAR estimated radiation levels and effects [148]. Radiation protection lessons have been compiled by the ICRP [149, 150]. Other international organizations, notably FAO and WMO, have also provided relevant information. Some of these international activities are described in Box 4.1.

Box 4.1. International activities related to the radiological consequences of the accident at the Fukushima Daiichi NPP

In addition to the IAEA, other international bodies have been active in addressing the radiological consequences of the accident at the Fukushima Daiichi NPP:

— The World Health Organization (WHO), a specialized agency of the United Nations concerned with public health, issued a preliminary estimate of the radiation doses incurred due to the accident [146] and, subsequently, a health risk assessment [147].
— The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which reports to the United Nations General Assembly, reported its estimates of the levels and effects of radiation exposure attributable to the accident, including a considerable amount of data on environmental radioactivity and radiation doses [148].
— The International Commission on Radiological Protection (ICRP), a non-governmental international body of experts that issues widely used recommendations on radiological protection, issued a review of radiological protection issues during and after the accident, aimed at improving the international system of radiological protection [149, 150].
— The Food and Agriculture Organization of the United Nations (FAO), a specialized agency of the United Nations involved in agriculture, forestry and fisheries practices for ensuring good nutrition and food security for all, worked in partnership with the IAEA, through the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), in preparing for and responding to nuclear or radiological emergencies affecting food, agriculture, forestry and fisheries, and compiled a significant database on radionuclide concentrations in food due to the accident [151].
— The World Meteorological Organization (WMO), a specialized agency of the United Nations for meteorology, operational hydrology and related geophysical sciences, issued an evaluation of meteorological analyses for the radionuclide dispersion and deposition from the accident [152].
— The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) reported on the nuclear safety response and lessons learned from the accident [153].
— These and other organizations such as the United Nations Environment Programme (UNEP), the International Labour Organization (ILO), the Pan American Health Organization (PAHO), and the European Commission (EC) co-sponsor international safety standards that are issued under the aegis of the IAEA. WHO establishes Guidelines for Drinking-water Quality to be used in existing exposure situations, which contains parameters for radioactivity in drinking water [154]. The FAO and WHO Codex Alimentarius Commission establishes the Codex Alimentarius, a collection of internationally harmonized food standards to protect the health of consumers and to ensure fair practices in the international food trade, which contain standards on the presence of radionuclides in food [155].

Official bodies in many States, including Japan, carried out numerous evaluations of the radiological consequences of the accident at the Fukushima Daiichi NPP (e.g. Ref. [5]). National professional radiation protection organizations, both in Japan and elsewhere, identified important lessons for radiation protection (e.g. Ref. [156]). Fukushima Prefecture launched the Fukushima Health Management Survey [157] in June 2011 [158]. This survey, which is described in Box 4.2, was discussed at the International Expert Symposium in Fukushima [159, 160].

Box 4.2. The Fukushima Health Management Survey

The Fukushima Health Management Survey is a general examination and investigation of the health situation of people in Fukushima Prefecture [157]. It is based on a series of questionnaires and has the following objectives: "(1) to assess residents' radiation dose, and (2) to monitor residents' health conditions, which result in disease prevention, early detection and early medical treatment, thereby (3) to maintain and promote their future health" [161].

Following the response, effective doses due to external exposures incurred in the four months following the nuclear accident were estimated by the National Institute of Radiological Sciences (NIRS) on the basis of recorded movements of respondents, in combination with an understanding of the relevant radiation levels. In addition, there were detailed surveys that included: (1) thyroid ultrasound examinations, covering roughly 370 000 residents aged 0 to 18 years at the time of the nuclear accident (the initial screening was performed within the first three years after the accident, followed by complete thyroid examinations from 2014 onwards, and regular monitoring of the residents thereafter); (2) a comprehensive health check aimed at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases, having as a main target 210 000 former residents of evacuation zones whose lifestyle changed drastically after the accident (additional tests such as differential leukocyte counts, are being performed apart from the routine tests included in general medical check-ups at the workplace or by the local government); (3) a Mental Health and Lifestyle Survey aimed at providing adequate care, mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress; and (4) a pregnancy and birth survey aimed at providing appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, as well as to their children. (This survey is being updated every year to take account of new data, particularly on pregnancy and births [162].)

The Fukushima Medical University received a mandate to conduct the health survey from Fukushima Prefecture and launched the Radiation Medical Science Center for the Fukushima Health Management Survey to conduct the basic survey of external dose estimates and four detailed surveys. The survey and its results are assessed periodically by the Prefectural Oversight Committee Meeting for the Fukushima Health Management Survey.

This section builds on these international and national data, evaluations and estimates by making use of new information, in particular information provided by the Japanese authorities to the IAEA for this report. It should be noted that the estimates in various international and national reports have been performed at different times and with different levels of information. Thus, while some direct comparisons can be made between the various results, differences between the data, methodology and dates of the studies make any detailed comparison difficult.

Quantities and units

Specialized international quantities[89] and units[90] [163, 164] were used for monitoring and reporting radiological data of the accident. The fundamental international radiation protection quantities and units which are used in this report are briefly described in Box 4.3.

[89] The term 'quantity' is used in this report in its scientific sense of being a measurable property, in this case of phenomena such as radioactivity or radiation.

[90] The unit of a quantity is a definite amount of such a quantity, which is used as a standard for measurement.

Box 4.3. The fundamental radiation protection quantities and units used in this report

The quantity used to describe radioactivity is termed *activity* and its unit of measurement is called *becquerel* (Bq). One becquerel represents an extremely small level of activity. For example, the human body contains around 5000 Bq of naturally radioactive potassium-40 (for a person weighing 70 kg, with 140 g of potassium in the body). Therefore, in order to measure the large releases of radionuclides from the accident, a suitable prefix, such as peta (P) is used in this report: 1 petabecquerel (PBq) equals 10^{15} Bq.

The release of radioactive material led to the exposure of people to ionizing radiation, through both *external exposure*, when the activity was outside the body, and *internal exposure*, when the radionuclides were incorporated into the body (e.g. by ingestion or inhalation or through the skin). The quantity describing the mean radiation exposure incurred by organs and tissues is termed *absorbed dose* and its unit of measurement is joule per kilogram called *gray* (Gy), often expressed as thousandths of a Gy, or *milligrays* (mGy).

For radiation protection purposes, the absorbed dose has to be weighted because different types of radiation have varying levels of effectiveness in causing harm, and different organs and tissues have different sensitivities to radiation exposure. The quantity resulting from the application of *radiation weighting factors* to the absorbed dose in organs and tissues is called *equivalent dose*, and its unit is termed *sievert* (Sv), usually expressed as thousandths of a Sv, or *millisieverts* (mSv). In the report, thousandths of mSv, or *microsieverts* (μSv), are also used. The quantity resulting from the application of *tissue weighting factors* is called *effective dose* and is also measured in mSv. While there is some variation between individuals in the effect of a given exposure to radiation, for radiation protection purposes doses are estimated as though delivered to a defined ideal reference individual, as it is not feasible to take into account individual differences.

The *absorbed dose* and the *equivalent dose* are used for doses incurred by tissues and organs. Given the type of radiation involved, in all radiation exposures from the accident (except insignificant exposures to neutrons) the reported absorbed doses were numerically equal to the corresponding equivalent doses and vice versa. The *effective dose* is used for assessing the whole body implications. An internal exposure will continue as long as any of the inhaled or ingested radioactive substances remain in the body. The *committed dose* caused by this continuing exposure is calculated as that dose which is expected over the exposed person's lifetime.

The following estimates of effective doses commonly incurred are provided as a reference [165]:

— Global natural background radiation delivers an annual average effective dose of 2.4 mSv, with a typical range of 1–13 mSv, and with sizeable population groups incurring up to 10–20 mSv, and in extreme cases up to around 100 mSv.
— The globally averaged annual effective dose due to medical radiodiagnosis is 0.6 mSv, and a single computed tomography examination can deliver an effective dose of around 10 mSv. (It should be noted that medical exposure is usually localized to part of the body, i.e. it is not uniformly distributed in the body.)

Other quantities used in practice are derived from the fundamental radiation protection quantities. Box 4.4 describes some of these derived quantities and a number of related issues. The many quantities and units were not easily understandable by the public in the aftermath of the accident. The ICRP, in its assessment of radiological protection issues arising during and after the accident, concluded that international action should be taken in the future to ensure that "any confusion on protection quantities and units be resolved" [149].

Box 4.4. Measurement quantities and operational terms

The protection quantities *equivalent dose* and *effective dose* are not directly measurable. Therefore, instruments for measuring external exposure, either incurred by persons or present in the environment (or in the ambience), are calibrated against operational quantities called *personal dose equivalent* and *ambient dose equivalent*, respectively. These are *proxies* of the protection quantities, i.e. a measured quantity used to infer the value of the quantity of interest, and they are also measured in mSv. These operational quantities were used for monitoring in the aftermath of the accident and are used in the report when referring to monitored values.

Depending on the type of exposure situation, particular terms are used to facilitate the explanation of the concept of exposure control, as follows:

— In *planned exposure situations*[1], the *additional dose* expected to be added by a planned operation is used. For these situations, the relevant individual dose restrictions are known as *dose limits*. Dose limits are values of the additional effective doses or the additional equivalent doses to individuals expected from a planned exposure situation that are not to be exceeded; they are applicable to the additional individual doses from external exposure in a given period of time plus the additional individual dose commitment from intakes of radionuclides in that time period.
— In *emergency exposure situations*[2], three concepts of dose are used: (1) the *projected dose* (the dose that would be expected to be received if no protective actions were taken); (2) the *avertable dose* (the dose that could be averted if a protective action was taken); and (3) the *residual dose* (the dose expected to be incurred in the *existing exposure situations*[3] remaining after protective actions have been terminated). *Reference levels* are applied to residual doses as guidance levels for optimizing protection. These represent the level of dose "above which it is judged to be inappropriate to plan to allow exposure to occur and below which optimization of protection should be implemented" [129].

There are also quantities derived from *activity*, such as quantities related to the presence of radioactivity in the environment expressing, for instance, the activity on land or in products of public consumption. Relevant derived quantities are the *deposition density*, which expresses the *activity per unit area,* usually expressed in Bq/m^2; the *specific activity*, which expresses the *activity per unit mass* or *weight,* usually expressed in Bq/kg; and the *activity concentration*, which expresses the *activity per unit volume,* usually expressed in Bq/L. These quantities are usually referred to as *contamination*. This term is formally defined in international standards as: (1) the *presence* of radionuclides on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable; or (2) the *process* giving rise to their presence in such places, in both cases with no indication of the magnitude of the hazard involved. However, the term *contamination* carries a connotation of impurity or danger that is not intended in its formal denotation as presence or process.

---

[1] *Planned exposure situations* arise from the planned operation of radiation sources (e.g. the normal operation of the Fukushima Daiichi NPP) or from planned operations that result in exposure from sources. Since provisions for protection and safety can be made in advance, exposures can be restricted from the outset. In planned exposure situations, a certain level of exposure is expected to occur.

[2] *Emergency exposure situations* include situations of exposure that arise as a result of an accident and require prompt action in order to avoid or reduce adverse consequences.

[3] *Existing exposure situations* are situations of exposure that already exist when a decision on the need for control needs to be taken and include exposure due to residual radioactive material arising from a nuclear or radiological emergency after an emergency exposure situation has been declared to be ended.

Uncertainties

The estimates of the radiological consequences of the accident are subject to a number of uncertainties, which are often expressed as the range of likely values of the relevant quantities. Some of these uncertainties have been accounted for after a statistical analysis of the variables involved, for example in the estimates of personal radiation dose due to external exposure, but not all uncertainties have been resolved. While the risks from radiation exposure are better understood than risks from

exposure to other agents, it is important that relevant uncertainties are addressed and communicated properly [166, 167].

Statistical analyses

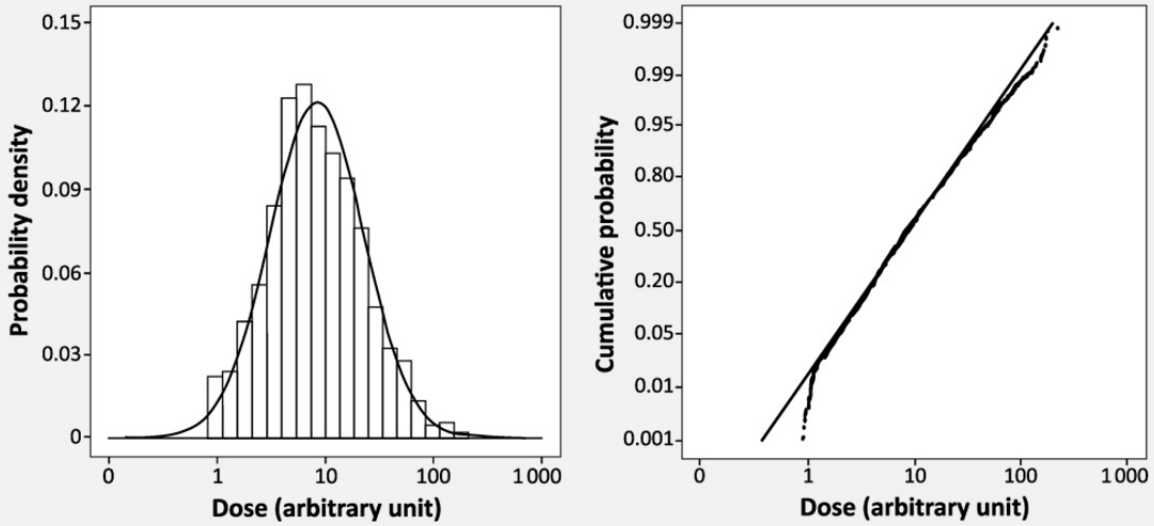
In order to deal with uncertainties, statistical analyses of some relevant variable data have been performed. The variables include specific activity in food and, in particular, personal radiation doses. The analyses of radiation doses covered estimates based on the use of questionnaires and ambient and environmental radiation data, and those based on personal monitoring through personal dosimeters and whole body counting of incorporated radioactivity. The basis for the statistical analyses is summarized in Box 4.5, which describes probability distributions of data, in particular the *log-normal probability distribution* that was specifically used in the analyses. There are many circumstances in which multiple measurement data, including measurements of environmental quantities, are expected to be statistically distributed following an approximate log-normal probability distribution. A large amount of information is available on the statistical distribution of doses incurred by exposed populations, which shows approximate log-normal distributions. Relevant evidence came from UNSCEAR occupational dose estimates [168] and also from the analysis of public doses from the accident at the Chernobyl NPP in 1986 [169]. However, a number of issues have been presented in the analyses of the data submitted following log-normal distributions, and some of them are summarized in Box 4.6.

Box 4.5. Statistical analysis of estimated and measured data

Some relevant data used in this report — notably data on personal doses and also on activity in food — were analysed statistically. The values of the variable quantity (e.g. the values of activity or dose) were classified according to their frequency distribution. For this, the whole range of data was *binned*, namely grouped together in *bins,* or a series of small interval ranges of numerical values, into which the data were sorted for analysis. The data in each bin were displayed adjacent one to another in a *histogram* that is a diagram consisting of rectangles representing the bins, whose positions represent the values of the quantity and whose dimension represents the number of data in every bin. The histogram was then normalized, multiplying the values of the rectangles by a factor that makes the total area of the rectangles equal to 1. When sufficient data are available and the intervals become very small, the histogram tends towards a smooth curve termed a *probability density function* that describes the relative likelihood for the quantity (e.g. the activity in food or the dose incurred by people) to have a given value.

While the most common distribution is the *normal* (or Gaussian) distribution, represented by a bell shaped probability density function that is symmetric with respect to the maximum probability, the most relevant distribution for the purpose of the report is the *logarithmic-normal* or *log-normal* distribution. The log-normal distribution is a probability distribution of a quantity, such as the activity or the dose, whose logarithm is normally distributed. Thus, the log-normal probability density function is symmetrical with respect to the maximum only when displayed as a function of the logarithm of the quantity (e.g. the logarithm of the activity or the logarithm of the dose) rather than as a function of the quantity. An example of such a log-normal probability distribution, showing an idealized histogram and its probability density function, is illustrated on the left hand side of the figure below.

Box 4.5. Statistical analysis of estimated and measured data (cont.)



The probability density function can be *integrated*, meaning that the values of the bins in the normalized histogram can be summed, from the lower to the higher values of the quantity. This summation, as a function of the quantity, is termed a *cumulative probability function* and describes the likelihood that a quantity with a given probability distribution will be found to have a value less than or equal to the value.

The *log-normal cumulative probability function* could be plotted as a straight line in a coordinate plane of abscissas representing the quantity (e.g. the dose) calibrated logarithmically versus ordinates representing the cumulative probability calibrated as a *normal* function. An example of such representation is shown on the right hand side of the figure above, where the integral of the actual experimental data of the bins in the left-hand figure is plotted vis-à-vis the straight line.

Box 4.6. Issues with log-normal distribution of the data

While the binning of data sets usually results in a relatively smooth distribution of the bin levels, for some data sets of the submitted information this was not the case. For these data sets the bin distributions look distorted, usually due to the accumulation of a large amount of data in a particular bin. For instance, in some data sets all the values near the detection limit were accumulated in one (initial) bin without discrimination, while higher values were properly discriminated. In the statistical analyses the decision was made to distribute this misleadingly accumulated data according to a probability density distribution derived from the actual data (using its relevant statistical values, such as mean and standard deviation) and, on this basis building up a conjectural, randomly created, distribution including a larger number of bins. The result is a conceptual histogram which is tailored to the statistical values of the real data and to which a smooth probability density curve can be fit. This probability density function, which describes how the distribution should ideally look like if the data have been sufficiently detailed and discriminated, is presented together with the cumulative probability function in the relevant figures of the report. In one of the figures the actual distribution of bins is also presented for comparison.

Box 4.6. Issues with log-normal distribution of the data (cont.)

While exact adherence to the log-normal distribution may not be observable across the full range of data, explanations of the deviations, in particular deviations from the straight line in the cumulative probability, can usually be elaborated and they form an important part of the analysis. A cause of deviation is uncertainty originating both in the measurements themselves and in the statistical nature of the sampling process. A particular problem in the analyses of incurred doses, which is typical of accidental situations, was the likely inhomogeneous nature of the cohorts of exposed people. Other causes included constrained distribution in the data; for instance, at high doses, there might be higher than expected cumulative probability (i.e. fewer people than expected are incurring high dose) with the most likely explanation that dose restrictions have been applied successfully. If they are higher than expected in the low dose range (i.e. more people than expected are incurring low doses), a plausible explanation is that a dose equal to the detection limit has been (misleadingly) assigned to all people with doses below these levels; conversely, if they are lower than expected it might mean that a zero dose has been assigned (again misleadingly) to everybody with doses below the detection level. Sometimes deviations from the straight line became ostensible due to the high level of inconsistency in the local data; for example, when two different population groups were mixed, such as evacuees with residents that remained in the area, there may be evidence of the change in the slope of the cumulative probability distribution, with each sector reflecting the doses received in each area. Sometimes there were protracted collections of information that distorted the data, e.g. due to radioactive decay over time. Deviations from linearity in a log-normal cumulative probability plot may be used to make plausible inferences about the underlying data.

4.1. RADIOACTIVITY IN THE ENVIRONMENT

The accident resulted in the release of radionuclides to the environment. Assessments of the releases have been performed by many organizations using different models. Most of the atmospheric releases were blown eastward by the prevailing winds, depositing onto and dispersing within the North Pacific Ocean. Uncertainties in estimations of the amount and composition of the radioactive substances were difficult to resolve for reasons that included the lack of monitored data on the deposition of the atmospheric releases on the ocean.

Changes in the wind direction meant that a relatively small part of the atmospheric releases were deposited on land, mostly in a north-westerly direction from the Fukushima Daiichi NPP. The presence and activity of radionuclides deposited in the terrestrial environment were monitored and characterized. The measured activity of radionuclides decreases over time due to physical decay, environmental transport processes and cleanup activities.

In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi NPP directly into the sea at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.

Radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs were released and found in drinking water, food and some non-edible items. Restrictions to prevent the consumption of these products were established by the Japanese authorities in response to the accident.

4.1.1. Releases

Many assessments of the releases of radionuclides from the accident at the Fukushima Daiichi NPP have been performed using established mathematical models and methods and associated computer codes (see Refs [170–177]).

In the early phase of the accident, the noble gases ^{85}Kr and ^{133}Xe, with half-lives of 10.76 years and 5.25 days, respectively, contributed to external exposure from the plume of the atmospheric releases. The short lived ^{131}I, with a half-life of 8.02 days, contributed to the equivalent doses to the thyroid gland if ingested or inhaled. The longer lived ^{134}Cs and ^{137}Cs, with half-lives of 2.06 years and 30.17 years, respectively, contributed to both equivalent doses and effective doses through external and internal exposure. While ^{131}I decays relatively quickly, it can give rise to relatively high equivalent doses to the thyroid gland. In some areas, ^{137}Cs may continue to be present in the environment, and without remediation it could remain a contributor to effective doses to individuals.

Radionuclides of strontium, ruthenium and some actinides (e.g. plutonium) were also released in varying amounts. As indicated in Section 2.1, neutrons were detected near the main gate of the plant (which is around 1 km away from Units 1–3), between 05:30 and 10:50 on 13 March. It is estimated that the neutrons came from the spontaneous nuclear fission of radionuclides that could have been released as a result of damage to the reactor core. Such a phenomenon was predictable, and the presence of these radionuclides at relatively low levels has been reported.

Releases to the atmosphere

Noble gases were a significant part of the early releases from the Fukushima Daiichi NPP; around 6000–12 000 PBq of ^{133}Xe are estimated to have been released (or 500–15 000 PBq, if early estimates are included in the evaluation). The mean total activity of ^{131}I released was around 100–400 PBq, and that of ^{137}Cs was around 7–20 PBq (or 90–700 PBq and 7–50 PBq, if early estimates are included). The releases from the accident are estimated to be approximately one tenth of the releases from the accident in 1986 at the Chernobyl NPP [169, 178, 179]. Most of the releases were dispersed over the North Pacific Ocean; as a result, the amount and isotopic composition of material released (the 'source term') could not be reconfirmed by environmental measurements of the radionuclide deposits [177].

Releases into the sea

Most of the atmospheric releases dispersed over the North Pacific Ocean fell on the oceanic surface layer. There were direct releases and also discharges into the sea at the site, with the primary source of highly radioactive water from a trench at the Fukushima Daiichi NPP. The peak radioactive releases were observed at the beginning of April 2011. The direct releases and discharges of ^{131}I into the sea were estimated to be 10–20 PBq. The direct releases and discharges of ^{137}Cs were estimated by most analyses to be in the range of 1–6 PBq, but some assessments reported estimates of 2.3–26.9 PBq [175].

4.1.2. Dispersion

Many theoretical models have been used to estimate the dispersion patterns. Extensive measurements of activity concentration of ^{131}I, ^{134}Cs and ^{137}Cs in the environment, including in air, soil, sea water, sediments and biota, were performed and have also been used for estimating the dispersion of the releases.

Atmospheric dispersion

The transport of the atmospheric radioactive releases was directed mainly to the east and north of Japan, following the prevailing wind direction, and then around the globe. Figure 4.1 presents an example of the many atmospheric transport models that were used to estimate the atmospheric transport of the various radionuclides and their deposition patterns, which describe the results of modelling the global dispersion of ^{137}Cs [180]. The figure illustrates activity concentration in air by using the original code of colours of the reference, where small changes in the degree of the colour

correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity concentration in the atmosphere decreased noticeably with distance from the Fukushima Daiichi NPP.

Highly sensitive radiation monitoring networks detected extremely low levels of radioactivity attributable to the accident as far away as Europe and North America. However, the effects of these releases on the level of global environmental background radioactivity were negligible.

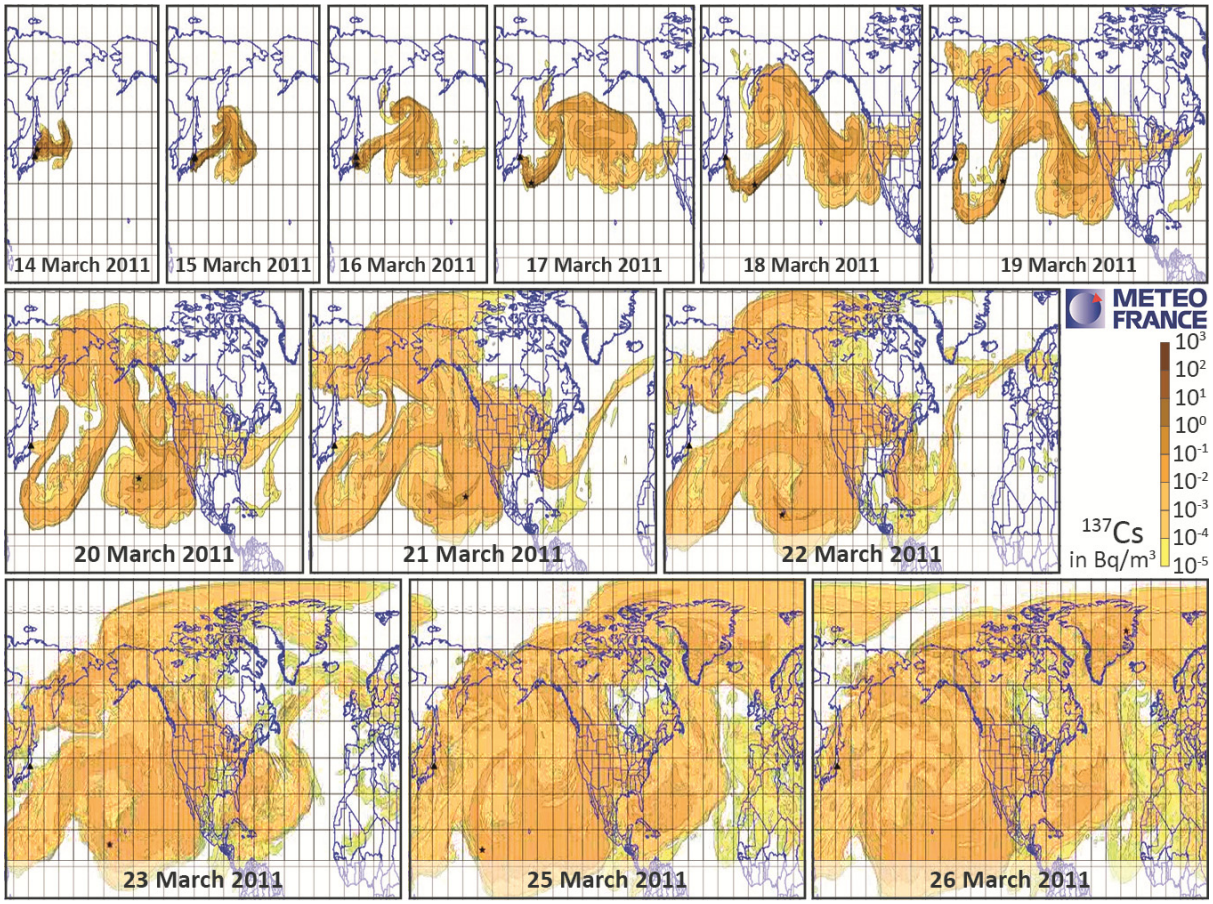


FIG. 4.1. Results from one of the global models of the atmospheric dispersion of ^{137}Cs, presented in its original code of colours (see Ref. [180] for details) (Illustration courtesy of Meteo-France).

Oceanic dispersion of direct releases and discharges into the sea at the site

Most of the released and discharged radionuclides that entered into the sea at the site moved eastward with the Kuroshio current[91], were transported over large distances via the North Pacific Ocean gyre[92] and became highly diluted in the sea water [181]. Radioactivity spread over large oceanic distances

[91] The Kuroshio current is a northward flowing ocean current on the western side of the North Pacific Ocean that flows past the Fukushima Daiichi NPP.

[92] The North Pacific Ocean gyre is one of the five major oceanic gyres, covering most of the North Pacific Ocean; it has a clockwise circular pattern and is formed by the North Pacific Ocean current to the north, the California current to the east, the north equatorial current to the south, and the Kuroshio current to the west.

and was detected in extremely small amounts far away from the accident, sometimes via pathways through oceanic biota, such as blue-fin tuna fish [182].

While the precise movement of radionuclides in the ocean is difficult to assess by measurements alone, a number of oceanic transport models were used to assess their dispersion patterns. Figure 4.2 illustrates examples of these models describing the dispersion of ^{137}Cs in the North Pacific Ocean. The figure uses the original code of colours employed in each particular reference. As in the case of atmospheric dispersion, small changes in the degree or tone of the colours correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity in the ocean decreased noticeably with distance from the Fukushima Daiichi NPP. All models show that the activity of ^{137}Cs in the ocean was very low.

(a)

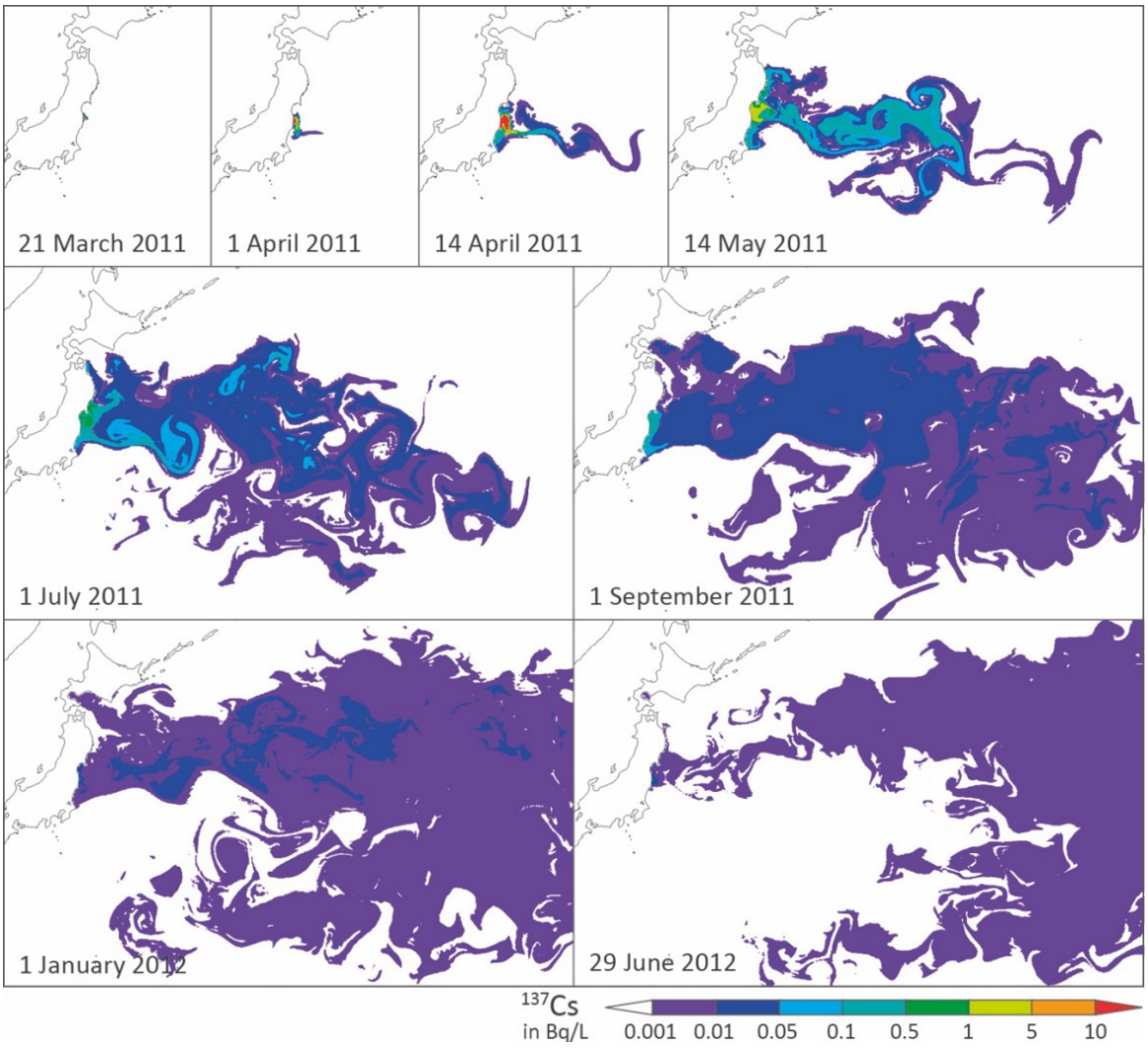
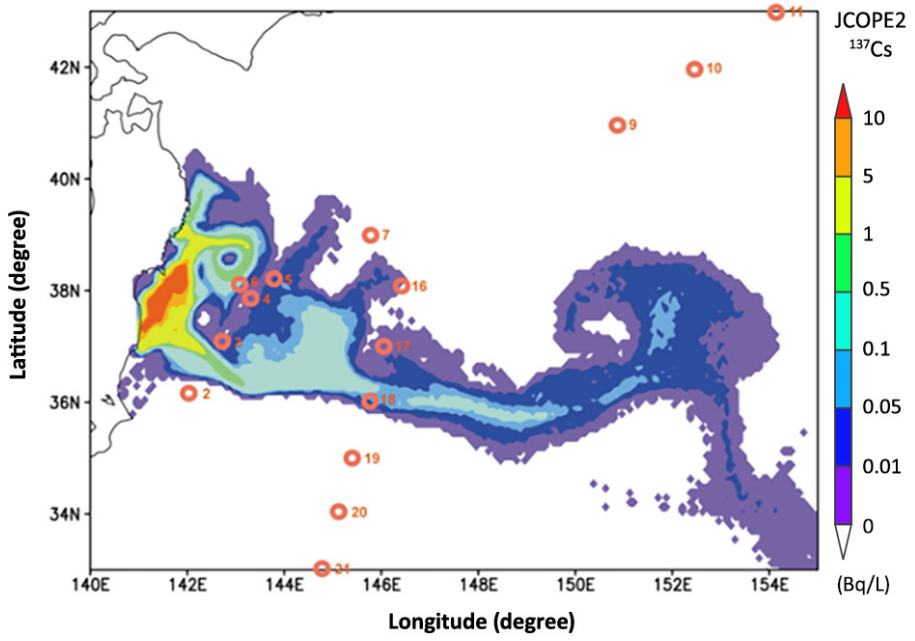


FIG. 4.2. Various oceanic models have been used to estimate the activity concentration of ^{137}Cs in sea water (the code of colours and the units used are those employed in the references): (a) an example of modelling contaminated waters from 21 March 2011 to 29 June 2012 [183, 184].

(b)



(c)

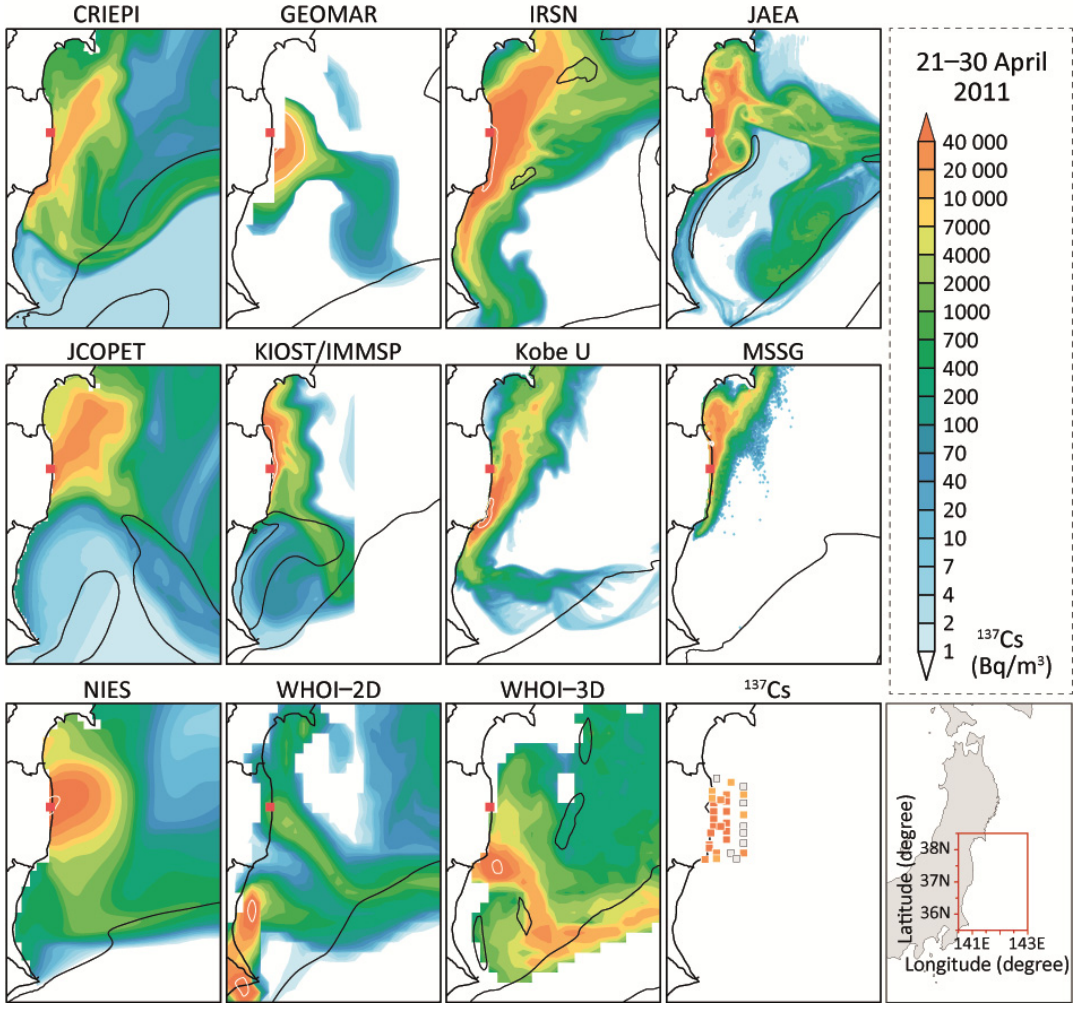


FIG. 4.2. (cont.) Various oceanic models have been used to estimate the activity concentration of ^{137}Cs in sea water (the code of colours and the units used are those employed in the references): (b) simulated horizontal distribution of ^{137}Cs in surface waters between 14 and 26 April 2011 [185]; (c) horizontal distribution of the ^{137}Cs concentrations averaged over a ten day period from 21 to 30 April 2011, with the name of the models indicated above each panel [175].

4.1.3. Deposition

The activity deposited on the Earth's surface is quantified as deposition density and measured in terms of activity per unit area, usually expressed in Bq/m^2. When the deposition is terrestrial, it is usually referred to as ground 'contamination'.

Oceanic deposition

The deposition of ^{137}Cs onto the ocean was studied using different models (see Fig. 4.3).

It is difficult to produce an accurate estimate of the amount of ^{137}Cs released to the atmosphere which was deposited on the ocean surface [186]. As a reference, the global pre-accident deposition of ^{137}Cs as of 1970 is estimated at 290 ± 30 PBq and the typical (background) level of ^{137}Cs in the North Pacific Ocean was approximately 69 PBq [187, 188].

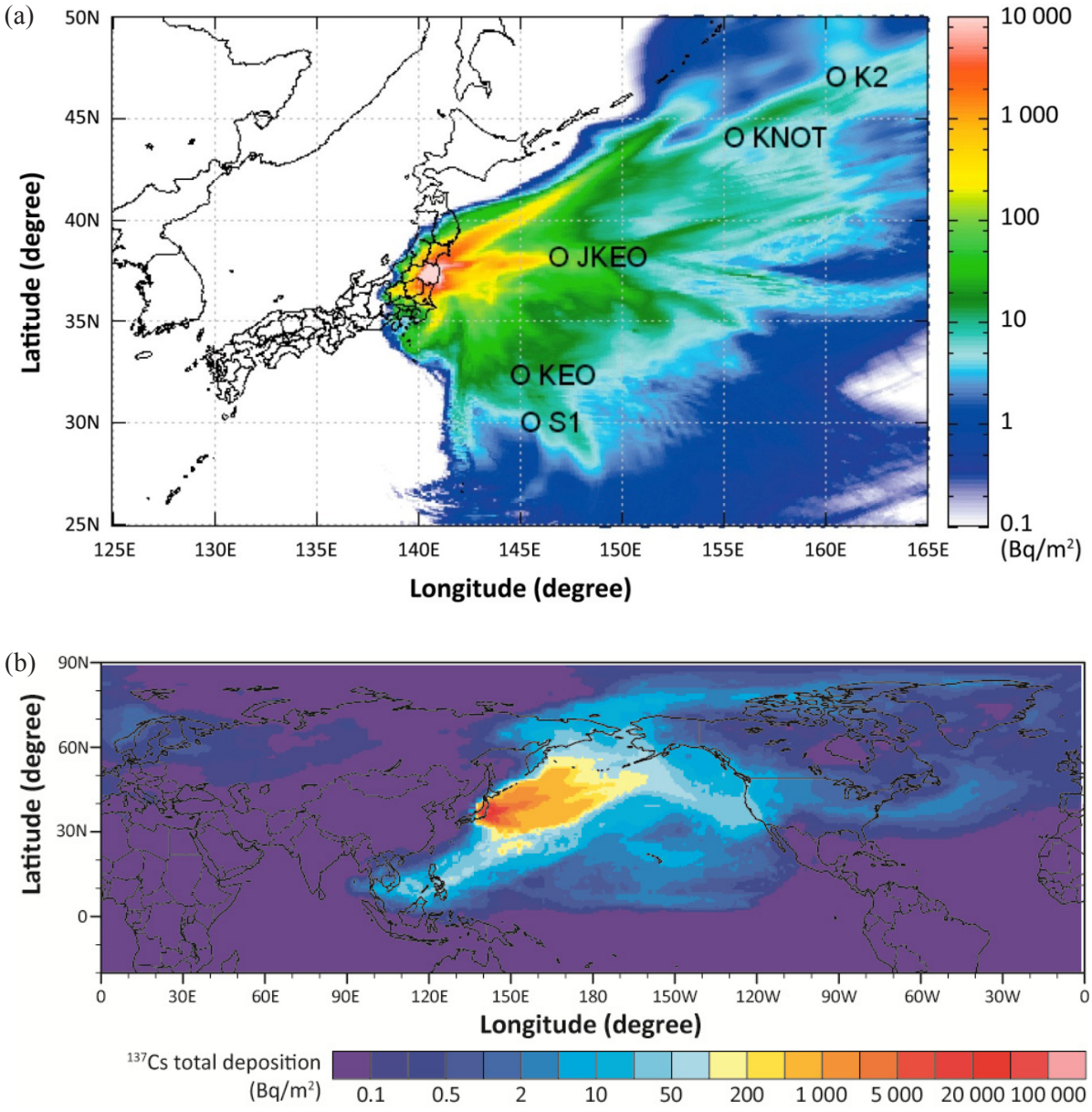


FIG. 4.3. Various models have been used to estimate the oceanic deposition density of ^{137}Cs (the units used are Bq/m^2). (a) Modelling the cumulative aeolian input through 1 April 2011 [185]; and (b) an example of the ensemble averaged ^{137}Cs deposition (11–31 March 2011) [175].

Terrestrial deposition

While most atmospheric releases were dispersed eastward, the releases that took place on 12, 14 and 15 March were blown over land, and relevant radionuclides, notably ^{131}I, ^{134}Cs and ^{137}Cs were deposited on the ground. The deposition patterns varied greatly, being influenced strongly by rain, snowfall and other local or regional conditions, such as topography and land use. Another factor that influenced the pattern of deposition in the terrestrial environment was the different physical and chemical characteristics of iodine and caesium.

The largest long lived deposits of ^{137}Cs were found to the north-west of the Fukushima Daiichi NPP, where the total deposition of ^{137}Cs on the land surface of Japan was estimated to have been around 2–3 PBq [188]. The deposition density decreases with time through physical and environmental decay. Caesium can move relatively easily through the environment owing to the solubility of its compounds. Weathering effects, such as wind and rain, and other environmental effects can reduce the presence of caesium in the environment. All these effects reduce the presence of ^{137}Cs in a time shorter than its half-life. In many affected areas, the presence of ^{137}Cs has been further reduced by cleanup and other remediation efforts.

Figure 4.4 presents detailed maps of the aerially measured ambient dose equivalent to the north-west of the site of the accident and its variation with time (see also Fig. 4.2 (c)).

The presence of ^{137}Cs from the accident in the terrestrial environment can result in protracted exposures of individuals, in addition to the exposures they normally incur from natural background levels of radiation. There is a global background level of deposition density of ^{137}Cs, attributable mainly to fallout from past nuclear testing. The background global levels were estimated by UNSCEAR to have been as high as approximately 4000 Bq/m^2, during the mid-1960s, at latitude 40^o–50^o in the Northern Hemisphere; the lowest global values at that time were estimated to have been around a few hundred Bq/m^2 at latitude 60^o–70^o in the southern hemisphere [190]. A number of studies analysed the influence of local conditions and concluded that the accumulated background deposition could have been around, or even higher than, 10 000 Bq/m^2 (e.g. see Ref. [187]). The global deposition levels have decayed since the 1960s. For 2000, the highest value was estimated by UNSCEAR to be around 2000 Bq/m^2 [190].

In areas north-west of the Fukushima Daiichi NPP, significantly higher levels of ^{137}Cs deposition density were measured. Presented by order of magnitude, the levels at the most affected areas were of the order of 10 000 000 Bq/m^2 and many areas had levels of around 1 000 000 Bq/m^2. The distribution of deposits for the whole affected area of Fukushima Prefecture is inhomogeneous, and the levels immediately outside the most affected areas in Fukushima Prefecture were around 10 000 Bq/m^2. While some other regions of Japan show elevated deposition levels, the levels attributable to the accident in most of Japan were generally lower than around 1000 Bq/m^2 [191, 192].

The highest levels of deposited ^{131}I exceeded 3 000 000 Bq/m^2 immediately after the accident but, owing to the short half-life of ^{131}I, the levels decreased rapidly and are no longer measurable.

4.1.4. Consumer products

In the affected areas, radionuclides, such as ^{131}I, ^{134}Cs and ^{137}Cs, were found in some consumer products and other items in daily use by individuals and households, such as food, drinking water and some non-edible products.

Restrictions were established after the accident, on 21 March, by the Japanese authorities to prevent the consumption of drinking water and food containing radionuclides at levels that were higher than provisional regulation values (see Section 3).

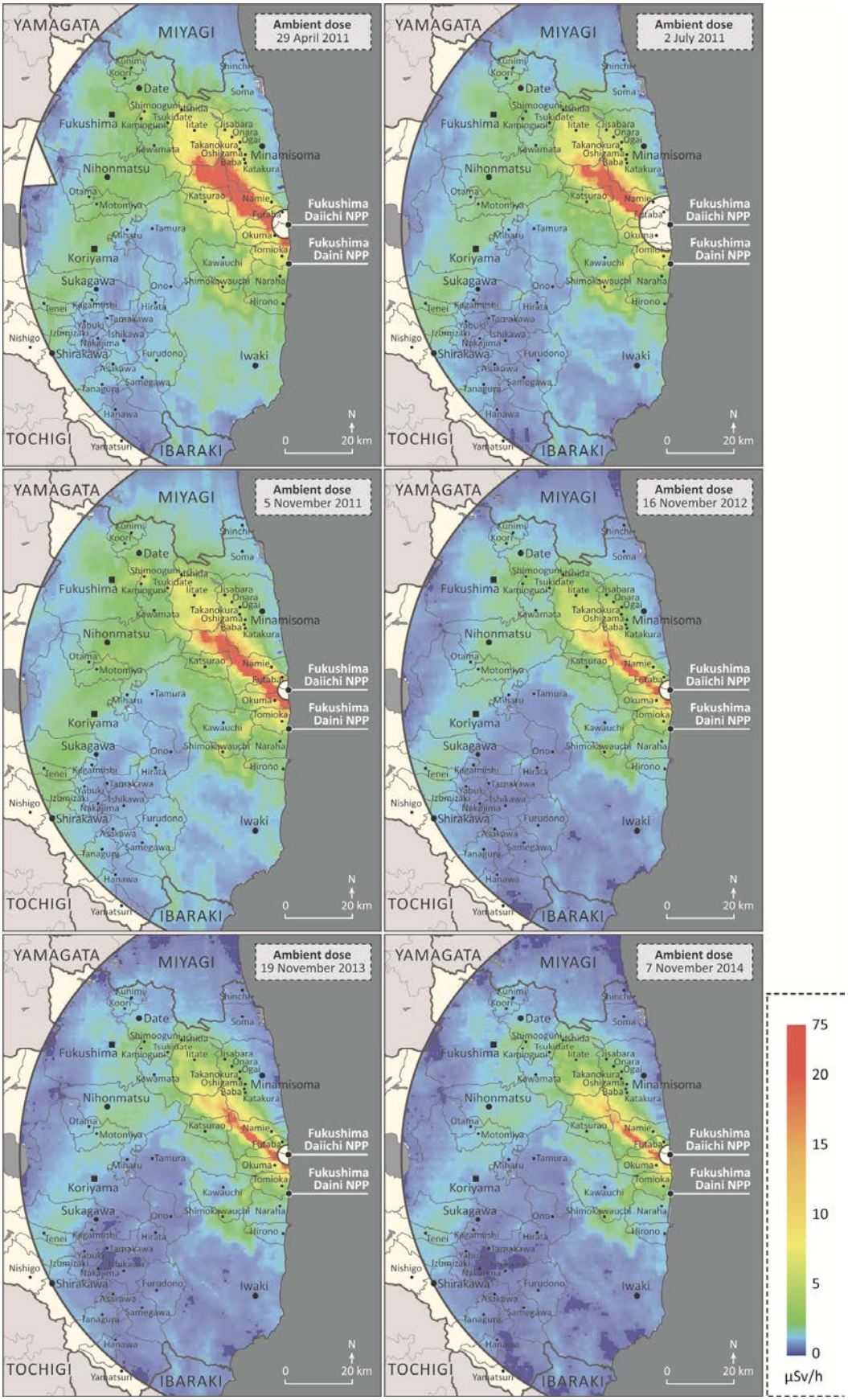
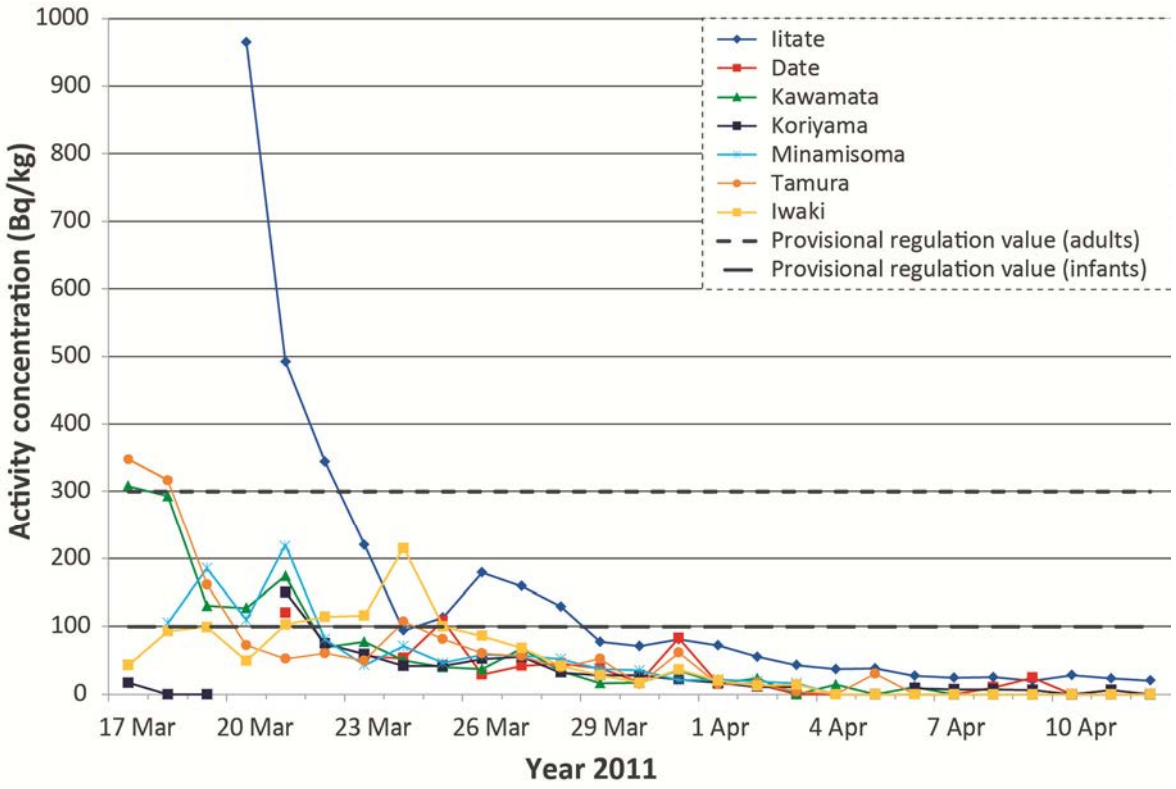


FIG. 4.4. Measured aerial ambient dose equivalent rate (in μSv/h) resulting from deposits from the releases that spread in areas to the north-west of the plant [189].

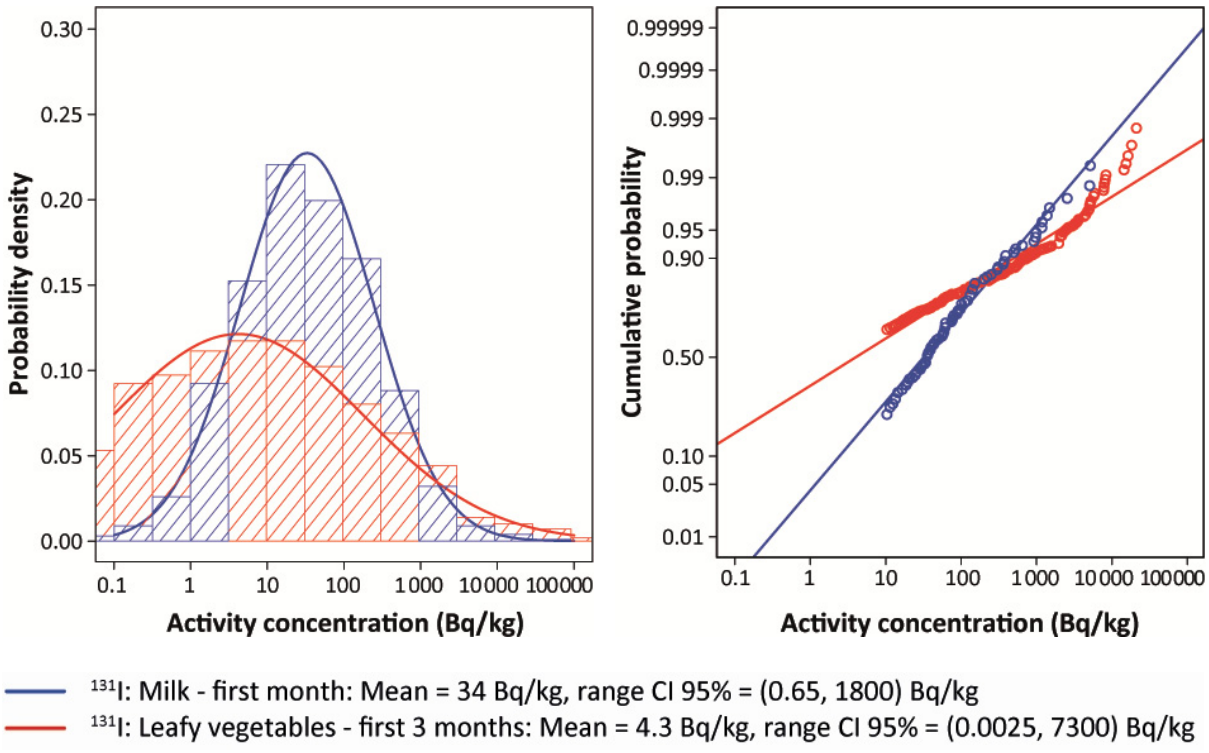
WHO guidance values for permissible levels of radionuclides in drinking water are intended for normal circumstances (see Box 4.1). After April 2012, all drinking water in Japan was below the WHO guidance values [193].

With rare exceptions, the levels of radionuclides in food available on the market did not exceed those established in the Codex Alimentarius, which are applicable to international trade (see Box 4.1). There were cases where higher levels of radionuclides were found in uncultivated foods, such as wild boar meat, wild mushrooms and wild plants, including ferns [194]. Eating uncultivated food is uncommon in Japan. Wild plants are mostly eaten for a limited period in the spring by a limited number of people. Direct sales of wild mushrooms and plants by farmers are very rare. Cultivated mushrooms are available in the market if the levels of activity concentration are under the regulated values.

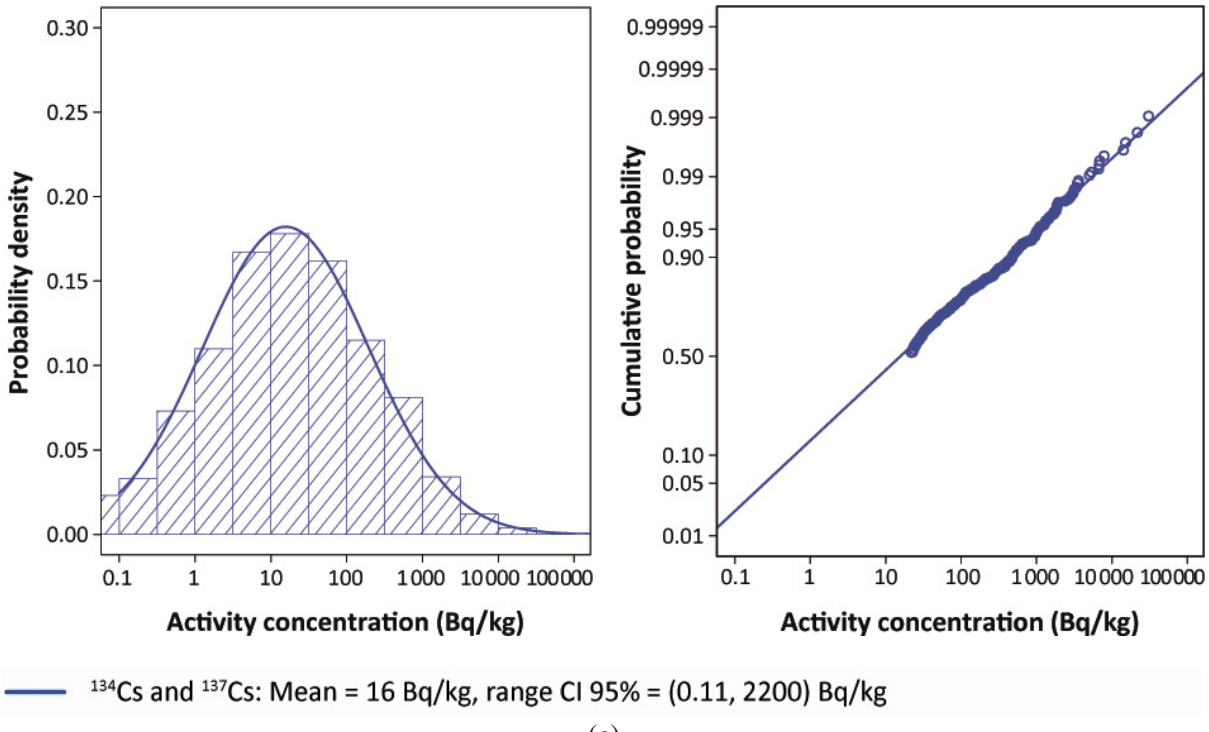
Some examples of activity concentration in drinking water and specific activity in food are presented in Fig. 4.5. The time evolution activity concentration of ^{131}I measured in drinking water supplies is illustrated for various locations in Fukushima Prefecture compared with the levels established in the provisional regulations issued by the Japanese authorities [195]. The log-normal probability density and cumulative probability distributions were assessed for the ^{131}I specific activity in milk during the first month after the accident and in leafy vegetables in the first three months after the accident. For ^{134}Cs and ^{137}Cs specific activity in mushrooms (including mainly cultivated mushrooms in the open air), they were assessed during the 12 months after the accident. These assessments, which are based on the statistical analysis of data collected by FAO [151], illustrate a likelihood of around 90% that values were below the Codex Alimentarius level of 1000 Bq/kg (the level established by the Japanese authorities was originally 500 Bq/kg and was then reduced to 100 Bq/kg [193]). This conservative approach created difficulties for producers and consumers.



(a)



(b)



(c)

FIG. 4.5. Some examples of radioactivity in drinking water and food. (a) Time evolution activity concentration of ^{131}I measured in drinking water supplies in various locations of Fukushima Prefecture [195]. (b) Log-normal probability distribution of ^{131}I activity concentration in milk in the first month after the accident and in leafy vegetables in the first three months after the accident. (c) Log-normal probability distribution of ^{134}Cs and ^{137}Cs activity concentration in mushrooms during the 12 months after the accident [151]. (Figures 4.5(b) and 4.5(c) present the normalized idealized probability density distribution (see Box 4.6) and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used in the activity concentration in food.)

4.2. PROTECTING PEOPLE AGAINST RADIATION EXPOSURE

Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations[93]. The application of some of the protective measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.

There were some differences between the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.

People were exposed to radiation attributable to the accident through a number of different routes, known as exposure pathways. These are discussed in Box 4.7. Radiation doses incurred by people were estimated by modelling and/or environmental and personal measurements through the various exposure pathways. These estimates and measurements were then used for restricting exposure and ensuring the protection of people.

4.2.1 Restriction of public exposure

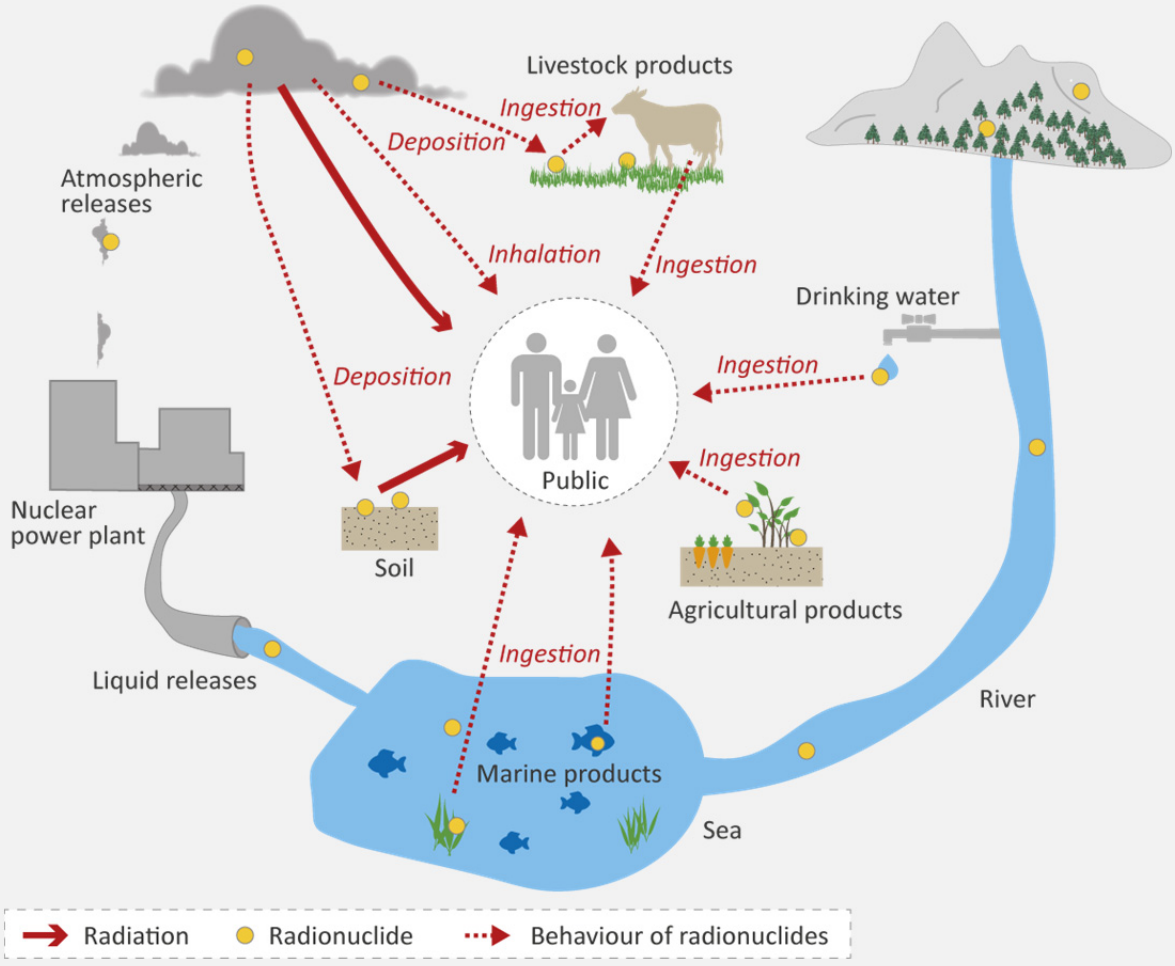
The version of the Basic Safety Standards (BSS) applicable at the time of the accident had been issued in 1996 [137] and was based on the ICRP recommendations issued in 1990 [196]. It included requirements on intervention levels in the case of accidents, considering expected projected doses and potential reductions of avertable doses. At the time of the accident, the 1996 BSS were being revised to reflect the ICRP recommendations that had been issued in 2007 [129] (see Box 4.8). These recommendations contained a different approach to dealing with emergencies, particularly reviewing the concept of intervention levels, which had been designed as criteria for individual protective actions, and introducing the concept of reference levels that were intended to be used for deciding protection strategies (on the understanding that generic criteria would be introduced in safety standards for dealing with individual protective actions).

The 2007 ICRP recommendations provided a framework for reference levels, with examples for all exposure situations, including emergency situations. As an example for the highest planned residual dose from a radiological emergency, they recommended reference levels that could be greater than 20 mSv, either acute or annual, but not more than 100 mSv. They also recommended that consideration should be given to reducing doses, increasing efforts should be made to reduce doses as they approach 100 mSv, individuals should receive information on radiation risk and on measures to reduce doses, and assessment of individual doses should be undertaken. The Japanese regulatory body, NISA, chose to apply the lower reference level of 20 mSv/year as a reference level for public protection.

[93] International recommendations on radiation protection are issued by the ICRP. These recommendations are taken into account in the establishment of international safety standards, including radiation protection standards (the International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources (the Basic Safety Standards, or BSS)), which were developed and established by several international organizations and issued under the aegis of the IAEA. The BSS are used worldwide in the development of national regulations for the protection of people and the environment from the potential detrimental effects of exposure to ionizing radiation. The 2007 ICRP recommendations provided a revised framework for radiation protection. These included introducing reference levels for protection strategies. At the time of the accident, the BSS were being revised, inter alia, to take account of these recommendations.

Box 4.7. Exposure pathways

Exposure pathways are courses, sequences of changes, or events which constitute the progression by which radioactive substances move through the environment and eventually make people vulnerable to incurring radiation doses. They are characterized by many aspects, including the process for the substances to reach the environment, the media in which the substances move from the source, the point of exposure where people are affected by radiation, the exposure routes describing how people are exposed to external radiation and how the radioactive substances may enter the body (e.g. by eating, drinking, via the skin) and the population that could be potentially exposed. The figure below gives a simplified description of the exposure pathways from the accident at the Fukushima Daiichi NPP.



Protection of children

The protection of children was a special concern for parents in areas affected by the accident. For protection purposes, the current ICRP recommendations use a detriment-adjusted risk coefficient for the whole population, including children, that is higher (by about 30%) than that for an adult population. This difference is reflected in the international radiation protection recommendations and standards.

Impact of radiation protection measures and actions taken to protect the public

Proper infrastructure for public facilities is essential for supporting measures to limit public exposure in the aftermath of a nuclear or radiological emergency [199]. The consequences of the earthquake, tsunami and accident had to be dealt with in a situation in which local infrastructure had collapsed.

Due to the earthquake and the tsunami, many public facilities, homes and businesses were destroyed or damaged; access to telephones and the Internet, supplies of electricity, gas, and drinking water, public transport, and the distribution of food, gasoline and heating oil were all severely disrupted. The outside temperature was low, it was raining and snowing, and heating was inadequate. This meant that many residents could not stay in the shelters for long periods without warm clothes and overcoats.

These difficult conditions affected the implementation of the protective measures required to protect people against radiation exposure. For example, people who were sheltered could not be decontaminated through washing because in most shelters water was rationed and reserved for drinking.

Box 4.8. Revising the Basic Safety Standards in effect at the time of the accident: Reference levels

The international safety standards for radiation protection in effect at the time of the accident were the 1996 International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, or 1996 BSS [137]. These standards required that the additional effective dose that individuals may receive from planned and regulated practices be limited to 1 mSv in a year (in special circumstances, an effective dose of up to 5 mSv could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year). The 1996 BSS underlined that these dose limits were not relevant for decisions on whether and how to undertake an intervention in case of accidents, when consideration had to be given to projected doses and potential reductions of avertable doses and eventual residual doses. The requirements of the 1996 BSS relating specifically to emergencies provided generic intervention levels at which intervention was expected to be undertaken in an emergency, such as sheltering, evacuation and thyroid blocking, and generic action levels for food.

In addition, the IAEA had, in 2002, issued safety standards with specific requirements on preparedness and response for a nuclear or radiological emergency [69], including dose criteria for the implementation of protective actions, such as sheltering, evacuation and iodine thyroid blocking. These standards established requirements for an adequate level of preparedness and response for a nuclear or radiological emergency with the aim of minimizing the consequences of an emergency if it were to occur (see Section 3 for more information).

At the time of the accident, the 1996 BSS were being reviewed, partly in the light of new general ICRP recommendations that had been issued in 2007 [129]. Just before the accident, the ICRP had issued specific recommendations on the application of its new recommendations for the protection of people in emergency exposure situations [127] and those living in long term contaminated areas after a nuclear accident or a radiation emergency [197].

The 2007 ICRP recommendations revised the approach to dealing with emergency exposure situations, including the concept of reference level to be used for protecting strategies. The recommended reference level was an effective dose (either acute or annual) that could be greater than 20 mSv but not higher than 100 mSv. This was to be used for generic criteria for dealing with individual protective actions in unusual, and often extreme, situations where actions taken to reduce exposures would be disruptive, with the understanding that an effective dose rising towards 100 mSv will almost always justify protective action. For stages in post-accident rehabilitation, the reference level could be greater than 1 mSv, but not more than 20 mSv. The new recommendations further emphasized that the chosen value for a reference level would depend upon the prevailing circumstances of the exposure under consideration.

The new approach was introduced in the revised BSS, issued in 2014 as IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [198].

Some protective actions were very difficult for the authorities and extremely demanding for the affected individuals and communities [200, 201]. Sheltering and evacuation were particularly disruptive for around 160 000 people who were isolated from their communities and had access to only limited supplies to meet their daily needs (Fig. 4.6(a)). People were eventually relocated, but their normal living conditions were seriously affected (Fig. 4.6(b)). Employment and participation in

community activities were limited. Their prospects were uncertain and planning for the future was very difficult.



(a) (b)

FIG. 4.6. The initial evacuation led to crowded conditions in shelters. (a) A senior TEPCO executive apologizes to evacuees at an evacuation centre on 22 March 2011 (photograph courtesy of Koichi Nakamura/AP Images/picturedesk.com); (b) the normal living conditions of the people who were relocated were greatly affected (photograph courtesy of Dr Yujiro Kuroda/Fukushima Medical University).

People who had already suffered the consequences of the earthquake and tsunami were also subject to additional physical and psychological stress caused by their sheltering, evacuation and relocation. Restrictions on products for public consumption were important and necessary, but caused economic and reputational or social damage to local producers.

4.2.2 Restriction of occupational exposure, including exposure of emergency workers

Japan is a Party to the Radiation Protection Convention, 1960 (No. 115), adopted under the aegis of the ILO [164]. The Japanese regulations for occupational exposures were consistent with international recommendations and standards on occupational protection. These regulations established a dose limit for occupational exposure as an effective dose of 20 mSv per year, averaged over five years, and 50 mSv in any single year [137]. For emergency workers, "worker[s] who may be exposed in excess of occupational *dose limits* while performing actions to mitigate the consequences of an *emergency* for human health and *safety*, quality of life, property and the environment" [48], a limiting effective dose criterion of 100 mSv was in place. This criterion had to be temporarily increased by the Japanese authorities to a dose limit of 250 mSv for the emergency workers who were within 30 km of the Fukushima Daiichi NPP until 16 December 2011 (see Section 3.2).

The dose limit for occupational exposure in 'special circumstances', established by the international standards at the time of the accident (1996 BSS), was 100 mSv [137]. The upper level of the internationally recommended reference levels by the ICRP was also 100 mSv [129], although the recommendations indicate that, in exceptional situations, informed volunteer workers may receive doses above this level to save lives, prevent severe radiation induced health effects or prevent the development of catastrophic conditions. In setting the value of 250 mSv, the Japanese authorities took account of previous recommendations by the ICRP [196, 202] and the requirements in the IAEA safety standards, which suggested a guidance value of 500 mSv for persons engaged in emergency activities or in emergency operations aimed at preventing further worsening of a nuclear accident. The revised dose limit for emergency workers was implemented in the exemption ordinance of the Ministry of Health, Labour and Welfare (MHLW) three days after the declaration of the emergency by the authorities (14 March 2011). The exemption ordinance was abolished on 16 December 2011 [203].

4.3. RADIATION EXPOSURE

In the short term, the most significant contributors to the exposure of the public were: (1) external exposure from radionuclides in the plume and deposited on the ground; and (2) internal exposure of the thyroid gland, due to the intake of ^{131}I, and internal exposure of other organs and tissues, mainly due to the intake of ^{134}Cs and ^{137}Cs. In the long term, the most important contributor to the exposure of the public will be external radiation from the deposited ^{137}Cs.

The early assessments of radiation doses used environmental monitoring and dose estimation models, resulting in some overestimations. For the estimates in this report, personal monitoring data provided by the local authorities were also included to provide more robust information on the actual individual doses incurred and their distribution. These estimates indicate that the effective doses incurred by members of the public were low and generally comparable with the range of effective doses incurred due to global levels of natural background radiation.

In the aftermath of a nuclear accident involving releases of ^{131}I and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of ^{131}I was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.

By December 2011, around 23 000 emergency workers had been involved in the emergency operations. The effective doses incurred by most of them were below the occupational dose limits in Japan. Of this number, 174 exceeded the original criterion for emergency workers and 6 emergency workers exceeded the temporarily revised effective dose criterion in an emergency established by the Japanese authority. Some shortcomings occurred in the implementation of occupational radiation protection requirements, including during the early monitoring and recording of radiation doses of emergency workers, in the availability and use of some protective equipment and in associated training.

The dose estimates in this report used as a basis international dose estimates by WHO and UNSCEAR, which are summarized in Box 4.9. This report also benefited from the availability of additional data, particularly from the Fukushima Health Management Survey and data on direct measurements of dose to people and radiation in the environment. These data were provided by experts, institutions, the local authorities and the Government of Japan, as well as by TEPCO, and were subjected to a statistical analysis.

The various estimates differed because they were carried out at different times and with different methodologies. While WHO estimates were generally higher than those of UNSCEAR, this was primarily because they were early dose projections based on very limited data following the accident. The dose estimates for members of the public by WHO and UNSCEAR were constrained by limited availability of direct radiation measurements of individual doses incurred by people and were mainly made using dose assessment models based on environmental conditions. Although the differences make a detailed comparison difficult, the estimates in this report and those of WHO and UNSCEAR are largely consistent in showing that doses generally fell below reference levels established in international recommendations and standards.

Box 4.9. Dose estimates by WHO in 2012 [146] and UNSCEAR in 2014 [148]

In 2012, the World Health Organization (WHO) issued an early evaluation of radiation exposure from the accident, which gave an initial estimate of radiation doses to characteristic members of the public using modelling techniques applied to information made publicly available by government institutions and collected up to September 2011. At that time, the data necessary for a full evaluation were either not available or not sufficient. A number of cautious assumptions were used that may have resulted in some doses being overestimated. For example, cautious assumptions were used to minimize the possibility of underestimating eventual health risks regarding protective actions and the consumption of food. Nevertheless, the evaluation showed that the total effective dose typically received by individual members of the public in two locations of relatively high exposure in Fukushima Prefecture during the first year after the accident was within an effective dose band of 10–50 mSv. In these most affected locations, external exposure was the major contributor to the effective dose. In the rest of Fukushima Prefecture, the effective dose was estimated to be within an effective dose band of 1–10 mSv. Effective doses in most of Japan were estimated to be within an effective dose band of 0.1–1 mSv, while in the rest of the world, all the effective doses were below 0.01 mSv and usually far below this level.

In 2014, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) issued a report on the accident that included assessed doses to workers and members of the public. Estimates of external effective doses to members of the public were based on the information available on ^{137}Cs deposition density in different areas as a function of time, and the estimated location and movement patterns of the population. UNSCEAR estimates indicated that, in the evacuated areas with the highest average estimates, the effective dose received by adults before and during the evacuation was, on average, less than 10 mSv, and about half of that level for those evacuated early. Adults living in Fukushima City were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated effective doses for one year old infants were about twice as high.

Those living in other areas within Fukushima Prefecture and in neighbouring prefectures were estimated to have received comparable or lower effective doses; even lower effective doses were estimated to have been received elsewhere in Japan. Lifetime effective doses attributable to the accident that, on average, could be received by those continuing to live in Fukushima Prefecture have been estimated by UNSCEAR to be just over 10 mSv. Radiation exposures in neighbouring States and the rest of the world resulting from the accident were far below those received in Japan; the effective doses were less than 0.01 mSv. However, UNSCEAR emphasized that there was considerable variation among individuals around this value, depending on their location and what food they consumed.

Note: As indicated in Box 4.3, the global natural background doses reported by UNSCEAR are an annual average dose of 2.4 mSv (which implies a total accumulated lifetime dose of around 170 mSv), with a typical range of 1–13 mSv, while sizeable population groups receive natural background doses of 10–20 mSv.

4.3.1 Public exposures

External exposure

The initial approach to estimating the effective doses incurred by members of the public due to external exposure was mainly based on data from environmental measurements of ambient dose equivalent rates and on calculations and surveys of location and personal behaviour. The data used encompassed extensive measurements of ambient dose equivalent, including the use of car-borne instrumentation.

The NIRS estimated the effective doses due to external exposures incurred by respondents to the Fukushima Health Management Survey questionnaires in the four months following the nuclear accident [204]. The estimations were based on the declared movements of people and the relevant radiation levels in the local environments.

A number of estimates of the individual effective doses due to external exposure in the first four months have been published [205–208]. For example, in the Soso area[94] (which includes the 'evacuation zone' and 'Deliberate Evacuation Area'), these doses were below 5 mSv for 98.7% of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and Deliberate Evacuation Area, the doses were below 3 mSv for 99.4% of the residents surveyed [208].

A statistical analysis was undertaken in this report of individual effective doses due to external radiation in various municipalities of Fukushima Prefecture that had been estimated by the NIRS using the Fukushima Health Management Survey data for the period 11 March–11 July 2011 (the effective dose due to external exposure to natural background radiation was excluded). The results of this analysis are presented in Fig. 4.7 for municipalities located in the area within the 20 km radius and for municipalities outside this area. This figure illustrates that external doses in the first four months were, on average, lower among the populations in the 20 km zone than those from locations outside this area, as a consequence of the early evacuation of this zone. The results within the 20 km zone tend to show wider distributions than those for locations outside the zone. This is due to the evacuation of members of the same community to different locations and often further movements leading to differences in the doses received. This complicated pattern was modelled by the NIRS using 18 evacuation scenarios.

There are uncertainties associated with the use of interviews with residents, environmental measurements and dose estimation models for assessing public doses. Personal radiation monitoring of members of the public is therefore vital for a reliable reconstruction of radiation doses.

The more important corroboration of individual doses from external radiation was provided by the data on individual monitoring using personal dosimeters. When personal monitoring data became available, they allowed comparison between the two different approaches, using assumptions about people's habits and models, to estimate the effective dose incurred versus monitoring the actual personal dose equivalent incurred[95].

The results indicated that the doses actually incurred, as measured by personal monitors, were generally lower than the estimated doses from questionnaires and modelling. An example of this comparison, which was carried out by a local government, is presented in Fig. 4.8. It shows that modelled doses are usually overestimations compared with actually incurred doses (this was also observed during the dose assessments in the aftermath of the Chernobyl accident [169]).

The large amount of information provided by Japan to the IAEA included data on personal dose equivalents and results from whole body counting measurements.

This information had been recorded at different times, over different periods, using different measurement techniques, and measurements were carried out in many, but not all, affected areas. What these data have in common is the fact that all personal dose equivalents are low (the committed effective doses estimated from whole body counting were negligible, see below), resulting in effective dose levels that are comparable with typical background effective dose levels.

[94] An area in the eastern part of Fukushima Prefecture, comprising Soma City, Minamisoma City, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Katsurao Village, Namie Town, Shinti Town and Iitate Village, many of which were within the designated 'evacuation zone' or 'Deliberate Evacuation Area'.

[95] The quantity used for personal monitoring, the personal dose equivalent, is a proxy of the quantity effective dose.

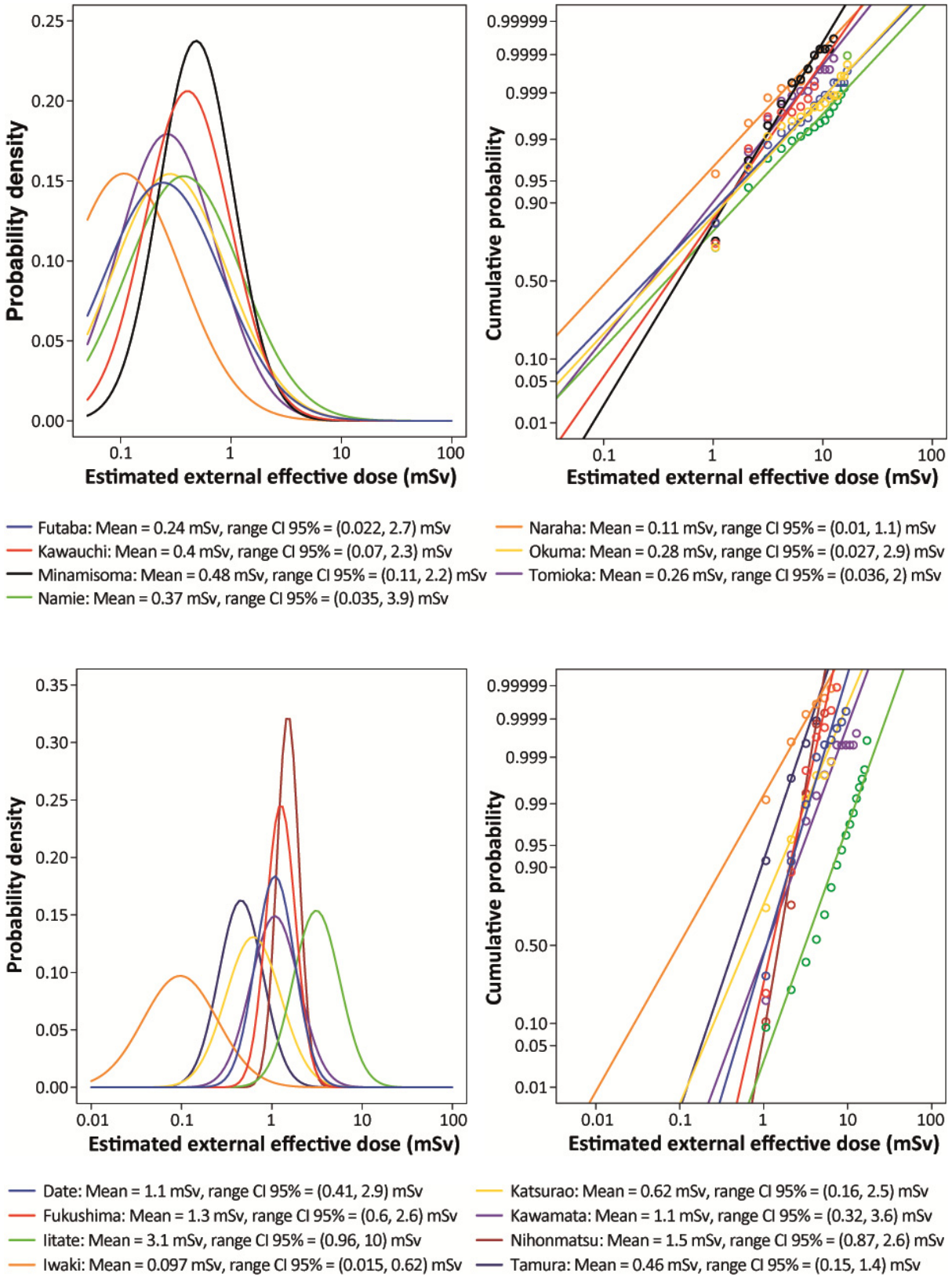


FIG. 4.7. Log-normal normalized idealized probability density and cumulative probability distributions of the estimated external effective doses in various cities, towns and villages of Fukushima Prefecture for the four months following the accident on the basis of Fukushima Health Management Survey data. The upper part of the figure presents the analysis for places located in the area within the 20 km radius (see Section 3) and the lower part of the figure for places outside this area. The legend under the plots indicates the mean doses and the 95% confidence interval for these places. In the original data, all doses below 1 mSv were accumulated in the 1 mSv bin.

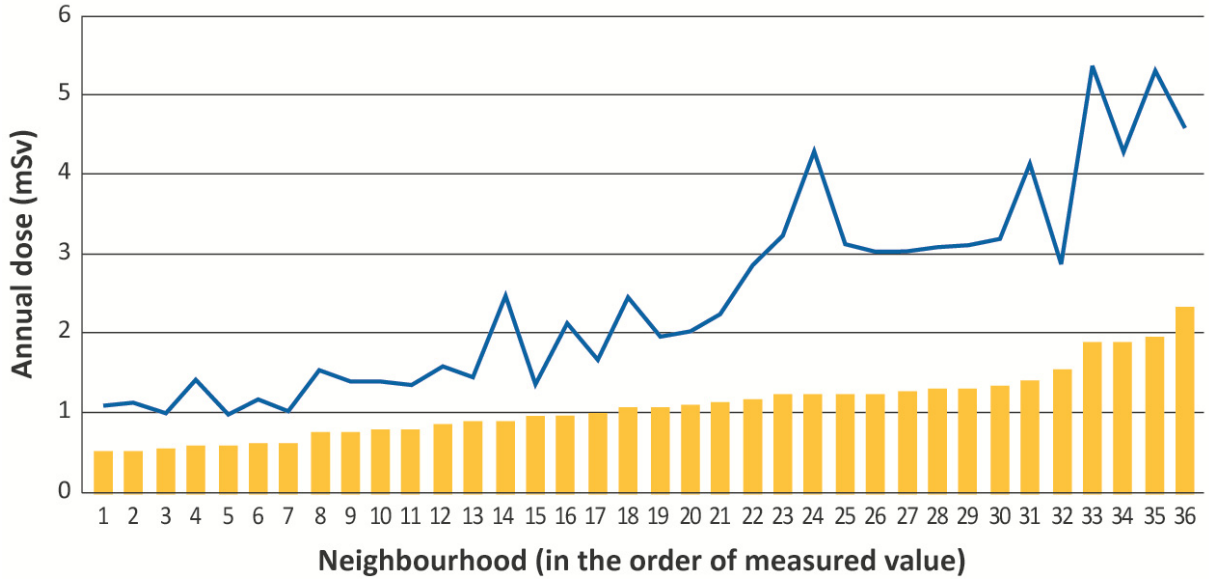


FIG. 4.8. Comparison of external individual dose estimates with measurements for a representative affected city between July 2012 and June 2013. The effective doses are assessed by estimation (line), assuming indoor occupancy and shielding for 16 h, outdoors for 8 h, and by personal monitoring (bar) of personal dose equivalent, in various neighbourhoods of the city (numerated) [209].

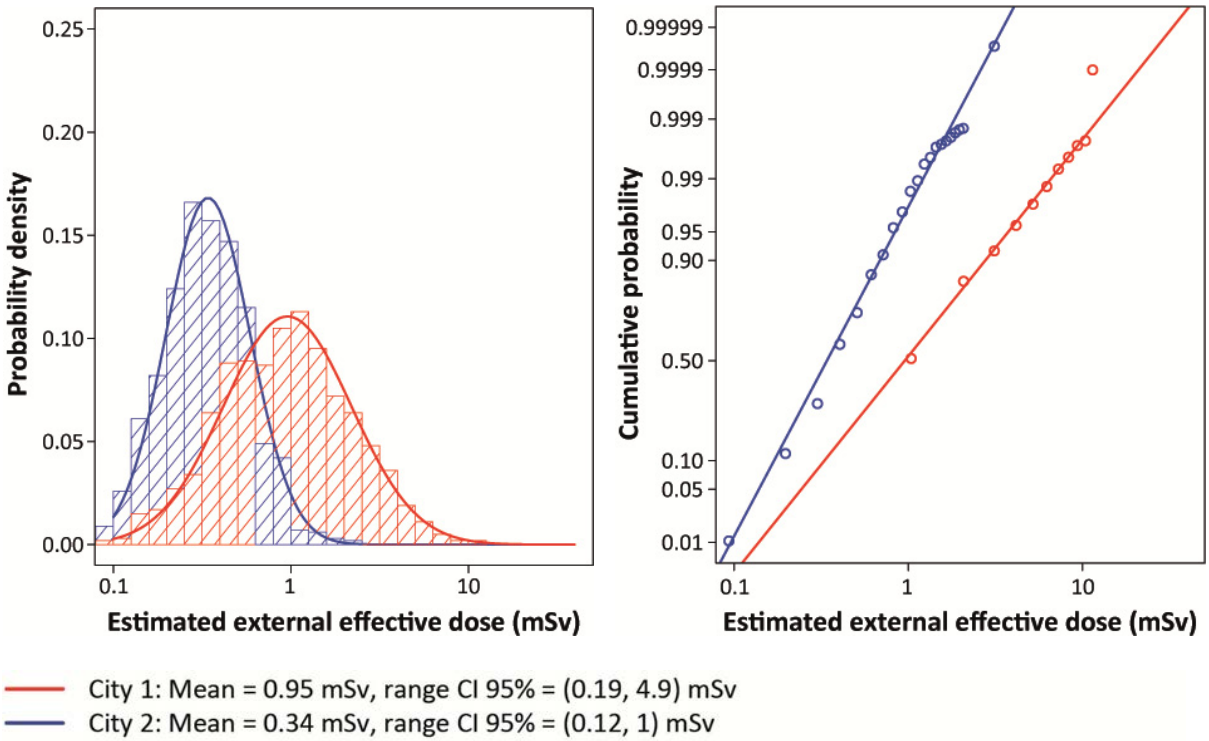


FIG. 4.9. Probability distribution of monitored personal dose equivalents of members of the public during 2011 provided by the Government of Japan for two municipalities in the affected area for which annualized data were available. For city 1 the normalized idealized probability density distribution is illustrated in red; for city 2 the normalized idealized probability density is illustrated in blue; for both cities the cumulative probability distribution is illustrated (see Box 4.6). The distribution shows that personal dose equivalents are low, with averages below 1 mSv per year, providing 95% confidence that individuals who incurred effective doses in those municipalities sustained doses below 5 mSv.

Figure 4.9 illustrates this analysis for two municipalities in the affected areas for which annualized information was available. The analysis reconfirmed that the annual personal dose equivalents are low, with average effective doses below 1 mSv per year, providing 95% confidence that people incurred effective doses below 5 mSv.

Internal exposure

Measurements of intake of radionuclides using whole body counting were made by the NIRS, the JAEA and other organizations in Japan.

After the accident, monitoring was carried out on more than 200 000 residents in various locations within Fukushima Prefecture. The levels were generally lower than the very low detection limits of the whole body counters, indicating little or no intake of radionuclides into the body. As a result, it was neither possible nor necessary to undertake detailed statistical analysis of these data.

Where it was possible to convert measured intakes to effective dose, making assumptions about the timing and nature of the intake, the vast majority of estimates of the committed effective dose were less than 1 mSv [210]. The estimated effective dose commitment from whole body counting measurements of ^{134}Cs and ^{137}Cs was reported to be lower than around 1 mSv in 99% of the residents [206].

Many whole body counting measurements were carried out several months after the accident [211, 212] and are therefore often only applicable to ^{134}Cs and ^{137}Cs, due to the short half-life of ^{131}I. Given the importance of intakes of ^{131}I through both inhalation and ingestion in the first month following the accident, this made judgements on internal exposure difficult. However, it was possible to detect ^{131}I in measurements of evacuees and short term visitors to Fukushima Prefecture carried out at Nagasaki University [213]. The highest estimated thyroid absorbed dose was 20 mGy (i.e. a thyroid equivalent dose of 20 mSv), with a corresponding effective dose of around 1 mSv.

The internal doses incurred in the initial period were dependent on whether people ate locally produced food or food from elsewhere, or drank tap water, during the first few days, before restrictions were fully put in place. Market basket surveys suggested that exposures from the consumption of milk, food and water were very low, as locally produced milk and food products were not distributed to shelters and only bottled water was used for drinking and preparing baby formula.

Exposure from the consumption of vegetables was low as very few, if any, locally produced vegetables grown outdoors were being eaten; it was early spring, before the growing season. Effectively, the only locally produced vegetables consumed were those grown in greenhouses, which were not contaminated.

Doses to the thyroid gland in children

In the aftermath of a nuclear accident involving substantial releases of ^{131}I, doses to the thyroid gland in children are an important public health concern. The main potential pathway for thyroid doses in children is usually the intake of milk containing ^{131}I.

However, the typical intake of ^{131}I via cow's milk was very low following the accident, owing to a number of factors. Dairy practices in Japan, such as generally sheltering cattle, prevented the ingestion of ^{131}I by dairy cows. The intake of ^{131}I via milk was also limited by the relatively low contribution of milk to the diet of infants and by the strict restrictions on the consumption of milk imposed by the authorities following the accident. While there were alternative ^{131}I ingestion pathways such as the consumption of leafy vegetables and drinking water, especially in the very early

period following the release, the prompt restrictions on drinking water and food limited the intake via these pathways.

As a result of these factors, the intake of ^{131}I by children is likely to have been low and mainly attributable to inhalation. However, there were uncertainties associated with the estimates of ^{131}I intakes and thyroid equivalent doses in children in the first few days following the accident.

Thyroid equivalent doses to children were estimated by monitoring levels of external radiation from ^{131}I activity in the gland. These levels were measured on the skin, near the thyroid, of children from areas where thyroid doses were predicted to be high. A limited number of these direct measurements were reported for the weeks following the accident. The results of one study, in which 1080 measurements were made on children aged 1–15 years in Iwaki City, Kawamata Town and Iitate Village in the period 26–30 March 2011, are summarized in Fig. 4.10 [214].

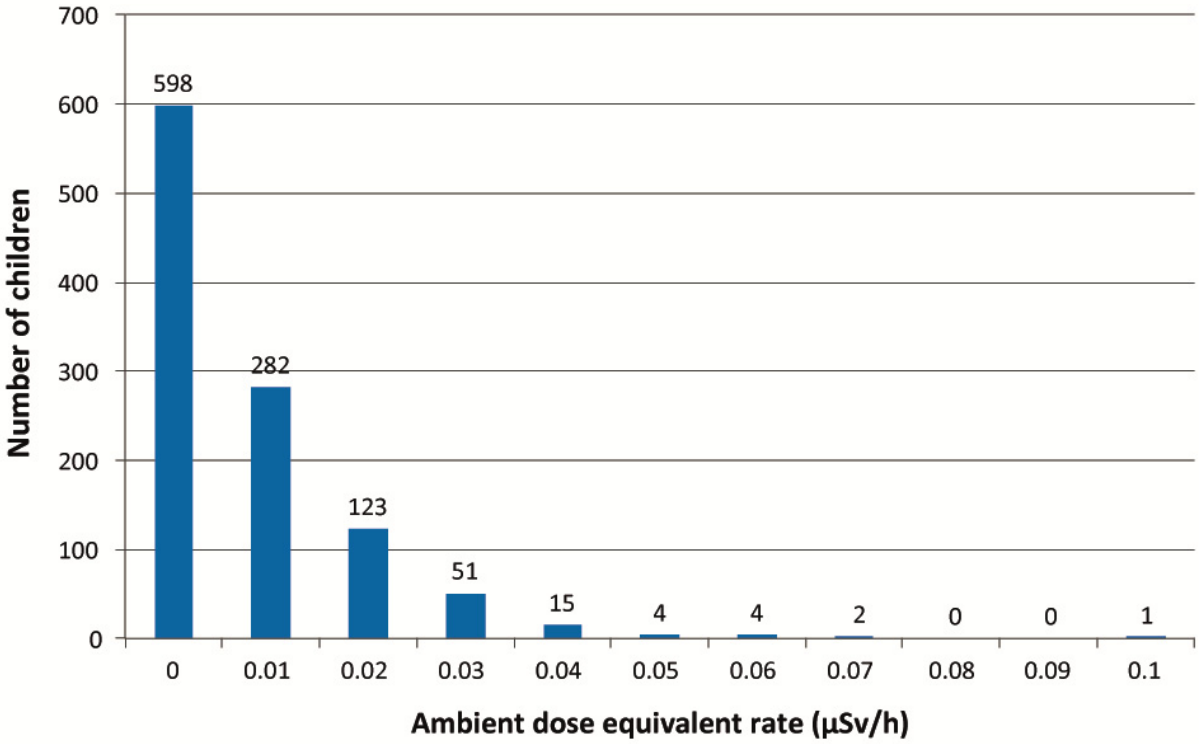


FIG. 4.10. Distribution of net value of measured dose rate in thyroid gland estimated by subtracting the background value from the reading value [214], i.e. the net ambient dose equivalent rates at the thyroid gland, in 1080 children aged 0–15 years. For 99% of the children tested, the ambient dose equivalent rate measured near the thyroid was 0.000 04 mSv per hour or less, corresponding to a thyroid equivalent dose of approximately 20 mSv or less.

The highest ambient dose equivalent rate measured near the thyroid of one year old children was 0.0001 mSv per hour, which would be consistent with an absorbed dose to the thyroid of approximately 50 mGy (a thyroid equivalent dose of 50 mSv). It was reported that thyroid equivalent doses, determined in March 2011 using an NaI (Tl) scintillation survey meter in children in the evacuation zone and 'Deliberate Evacuation Area', were lower than around 10 mSv in 95.7% of children (with a maximum of 43 mSv) [214]. It is likely that all doses were lower than the generic optimized intervention value for iodine prophylaxis of 100 mGy of avertable committed absorbed dose to the thyroid due to radioiodine established in the 1996 BSS [137]. They were also lower than the projected dose of 50 mSv in the first seven days for iodine thyroid blocking established in the revised BSS [198] as generic criteria for protective actions and other response actions in emergency

exposure situations to reduce the risk of stochastic effects. In comparison, the absorbed doses by thyroid of children following the Chernobyl accident ranged up to several thousand mGy [169, 178], nearly 100 to 1000 times higher.

4.3.2 Occupational exposures

Following the accident, on-site emergency workers were immediately subjected to extremely harsh working conditions and very high radiation levels as they sought to stabilize the reactors. In the period from March 2011 to March 2012, 174 of the approximately 23 000 workers on the site exceeded the original effective dose criterion in an emergency of 100 mSv, six of whom exceeded the (temporarily revised) effective dose criterion in an emergency of 250 mSv. No workers exceeded an effective dose of 100 mSv in subsequent years. One worker[96] exceeded the occupational annual effective dose limit of 50 mSv in the period from April 2012 to March 2013 [203]. Figure 4.11 presents the comparison of effective doses incurred by emergency workers at the Fukushima Daiichi NPP between March 2011 and October 2014.

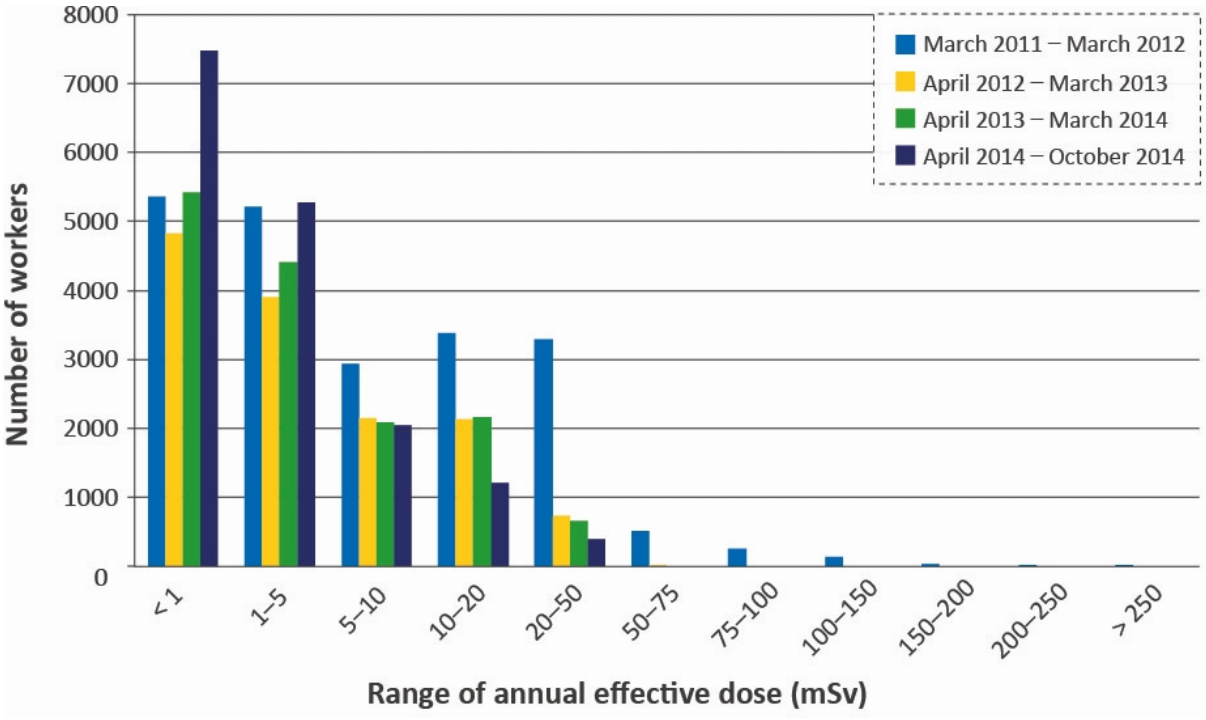


FIG. 4.11. Comparison of effective dose for emergency workers at the Fukushima Daiichi NPP between March 2011 and October 2014 (TEPCO employees and contractors). High effective doses occurred over the year following the accident. By 2012, effective doses to workers were low, and were comparable with those incurred in normal operations [215].

[96] This worker was categorized as having been subjected to the emergency dose limit of 100 mSv instead of the occupational dose limit of 50 mSv per year.

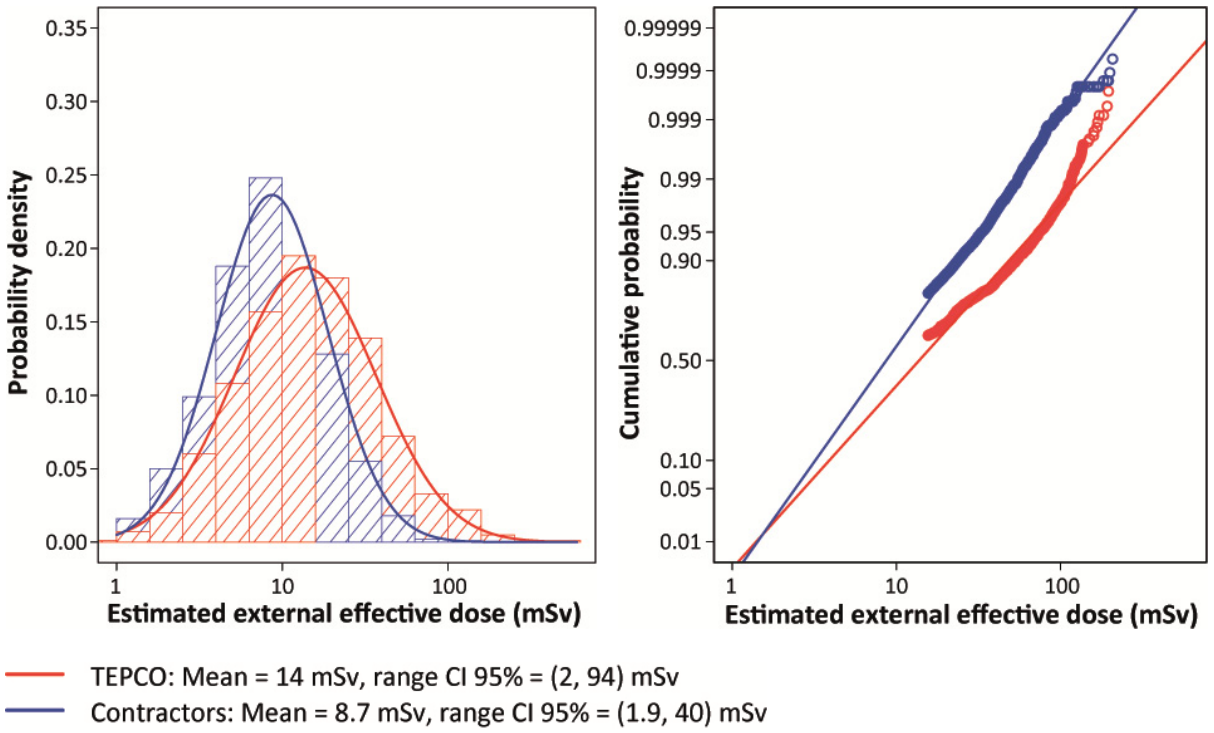


FIG. 4.12. Normalized idealized probability density distribution and cumulative probability distribution (see Box 4.6) of personal dose equivalent monitored for workers from TEPCO and contracted workers for 2011. Doses for TEPCO workers were generally higher than those of contract workers because TEPCO employees were working in higher dose areas [215].

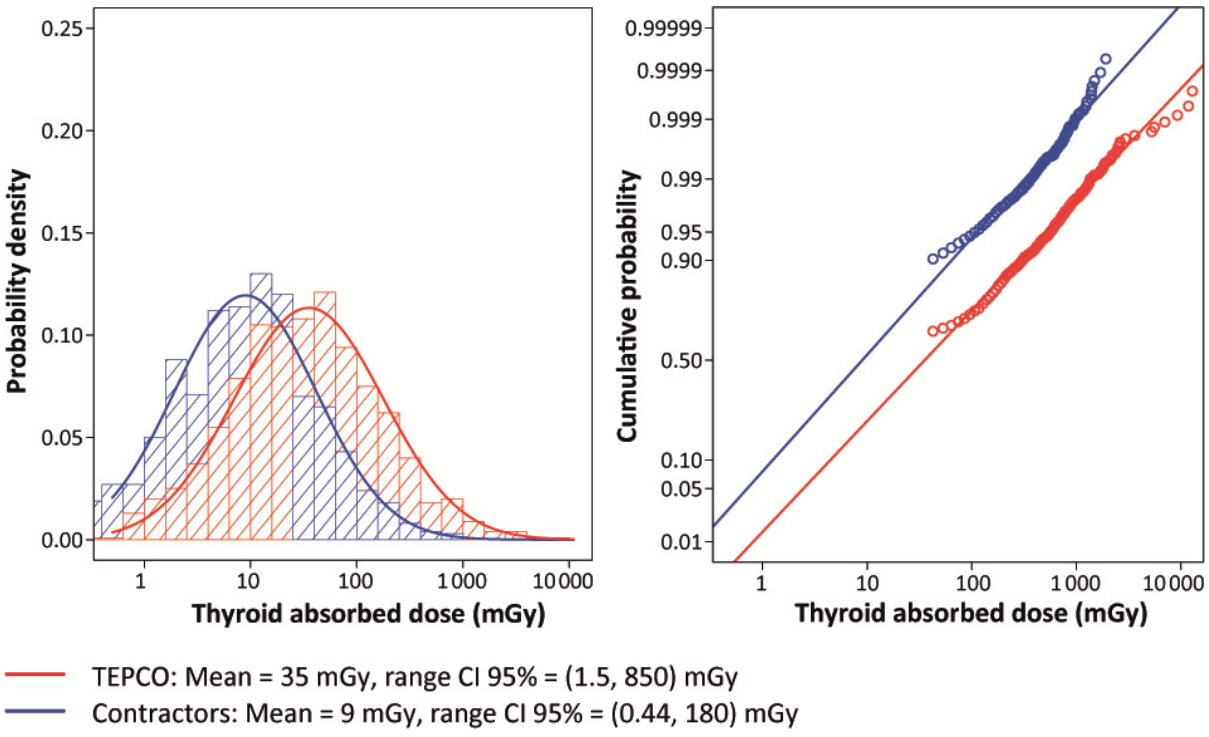
The personal dose equivalent values for both TEPCO workers and contract workers were submitted by TEPCO and were statistically analysed. The results are presented in Fig. 4.12.

In the early phase, the main contributor to effective doses, in particular to the doses incurred by the six on-site emergency workers who exceeded the temporarily revised dose criterion for emergency workers, was internal exposure from the intake of radionuclides. This was caused by challenges associated with harsh emergency working conditions, improper use of respirators and insufficient training.

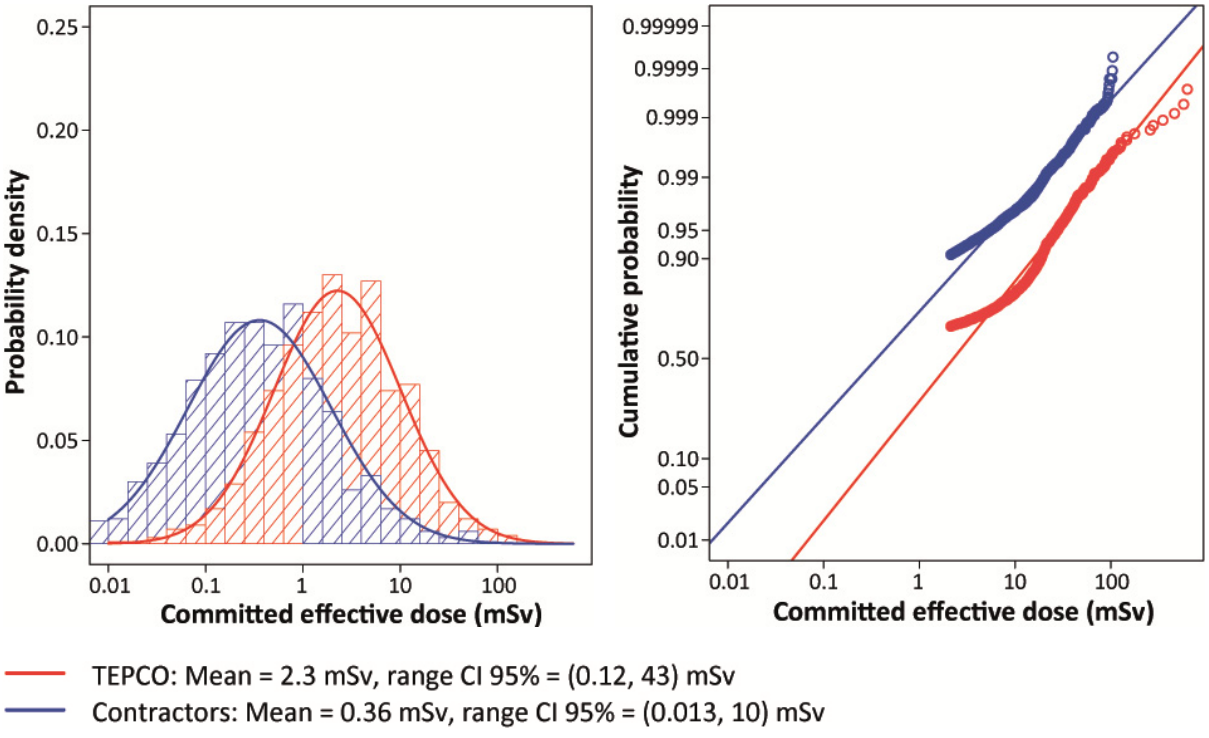
The internal doses were mostly thyroid equivalent doses from inhaled ^{131}I. Although the majority of workers at the Fukushima Daiichi NPP received thyroid equivalent doses below 100 mSv, 1757 workers received thyroid equivalent doses above this level, with 17 workers receiving thyroid equivalent doses above 2000 mSv and two receiving thyroid equivalent doses in excess of 12 000 mSv [216].

There are several uncertainties associated with the estimates of the workers' radiation doses due to internal exposure, particularly with thyroid equivalent doses. For instance, the scenario that was assumed for the incorporation of radionuclides into the body (e.g. the timing) is crucial for internal dose estimation. There was also some time lag in undertaking thyroid measurements due to the emergency operations and general post-accident conditions. The MHLW conducted a re-evaluation of the committed effective dose of emergency workers. The Ministry has promoted the standardization of methodologies of cautious assessments of internal dose in order to avoid underestimates of doses as much as reasonably achievable [217].

The statistical analysis of the distribution of the reported thyroid absorbed doses and of the estimated committed effective doses due to internal exposure is presented in Fig. 4.13.



(a)



(b)

FIG. 4.13. Normalized idealized probability density distribution and cumulative probability distribution of internal doses (see Box 4.6). (a) Thyroid absorbed dose; and (b) the consequent committed effective dose. The higher than expected distribution in the lower doses may imply that doses equivalent to the detection level were assigned to all people for whom radioactivity was undetectable [215].

The occupational exposures of workers on-site are consistent with the findings of UNSCEAR. Re-assessments of doses to TEPCO workers and contractors, which became available after the publication of the UNSCEAR report, were used in the statistical analysis of doses in this report, reducing the uncertainties. Some uncertainties remain about doses from short lived radionuclides, the influence of high background radiation in early whole body counting measurements, delays in thyroid measurements and the sufficiency of the bioassay information. Organizations in Japan are working to further reduce the uncertainties in the occupational dose assessment, specifically in the internal exposure assessments (e.g. Ref. [218]).

Firefighters, police officers and Japan Self-Defense Force personnel were also involved in a range of on-site emergency activities (see Section 3). No members of this group received effective doses in excess of 100 mSv, and the majority received effective doses of less than 10 mSv. Of over 8000 personnel who worked off the site for whom dosimetric information was available, five received effective doses in excess of 10 mSv but less than 20 mSv. The maximum effective dose recorded for police officers working off-site was around 5 mSv.

Personnel from other countries helped in the emergency. Available data show that, among those from the United States of America who assisted or performed environmental monitoring in the Fukushima area, the maximum effective dose received was 0.12 mSv for US military personnel and 0.068 mSv for US Department of Energy staff [219], all below regulatory limits. Among IAEA staff members who participated in environmental monitoring and provided advice on protection and safety, the mean effective dose was around 0.5 mSv, while one staff member received an effective dose of around 2.5 mSv from external exposure.

4.4. HEALTH EFFECTS

No early radiation induced health effects were observed among workers or members of the public that could be attributed to the accident.

The latency time for late radiation health effects can be decades, and therefore it is not possible to discount the potential occurrence of such effects among an exposed population by observations a few years after exposure. However, given the low levels of doses reported among members of the public, the conclusions of this report are in agreement with those of UNSCEAR to the United Nations General Assembly. UNSCEAR found that "no discernible increased incidence of radiation-related health effects are expected among exposed members of the public and their descendants" (which was reported within the context of the health implications related to "levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami") [148]. Among the group of workers who received effective doses of 100 mSv or more, UNSCEAR concluded that "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence" [148].

The Fukushima Health Management Survey was implemented to monitor the health of the affected population of Fukushima Prefecture. This survey is aimed at the early detection and treatment of diseases, as well as prevention of lifestyle related diseases. At the time of writing, an intensive screening of children's thyroid glands is taking place as part of the survey. Highly sensitive equipment is being used, which has detected asymptomatic thyroid abnormalities among a significant number of surveyed children (which would not have been detectable by clinical means). The abnormalities identified in the survey are unlikely to be associated with radiation exposure from the accident and most probably denote the natural occurrence of thyroid abnormalities in children of this age. The incidence of thyroid cancer in children is the most likely health effect

after an accident involving significant releases of radioiodine. Because the reported thyroid doses attributable to the accident were generally low, an increase in childhood thyroid cancer attributable to the accident is unlikely. However, uncertainties remained concerning the thyroid equivalent doses incurred by children immediately after the accident.

Prenatal radiation effects have not been observed and are not expected to occur, given that the reported doses are well below the threshold at which these effects may take place. Unwanted terminations of pregnancy attributable to the radiological situation have not been reported. Concerning the possibility of parents' exposures resulting in hereditary effects in their descendants, UNSCEAR concluded that, in general, "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure" [167].

Some psychological conditions were reported among the population affected by the nuclear accident. Since a number of these people had suffered the combined impacts of a major earthquake and a devastating tsunami as well as the accident, it is difficult to assess to what extent these effects could be attributed to the nuclear accident alone. The Fukushima Health Management Survey's Mental Health and Lifestyle Survey shows associated psychological problems in some vulnerable groups of the affected population, such as increases in anxiety and post-traumatic stress disorders. UNSCEAR estimated that "The most important health effect [from the accident] is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation" [148].

A comprehensive health check of the affected population is being carried out under the Fukushima Health Management Survey, described in Box 4.2. The programme aims at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases. Additional tests, such as differential leukocyte counts, are being performed in addition to routine general medical check-ups at the workplace or by the local government [220].

4.4.1 Early radiation induced health effects

Radiation exposure can induce health effects caused by the killing of cells. The severity of these effects increases with dose, and they can range from skin injuries to the collapse of vital tissues. Most of these effects occur early after a dose is incurred above the threshold levels that are known for each potential effect. The available information indicates that no individual received a dose at or above these threshold levels to cause acute radiation effects as a result of the accident. Two workers were exposed on their legs from contaminated water from the turbine hall. The skin equivalent doses of these workers were reported to be lower than the estimated threshold for deterministic effects[97] [81] and the applicable international limits[98] [222].

---

[97] ICRP estimates for the exposure of the skin are that an early response, such as early transient erythema, is seen a few hours after doses of >2000 mGy, when the exposed area is relatively large. The ICRP also estimates that the approximate threshold doses are as follows: early transient erythema 2000 mGy, main erythema reaction 6000 mGy, temporary epilation 3000 mGy, permanent epilation 7000 mGy, dry desquamation 14 000 mGy, moist desquamation 18 000 mGy, secondary ulceration 24 000 mGy, late erythema 15 000 mGy, ischaemic dermal necrosis 18 000 mGy, dermal atrophy (first phase) 10 000 mGy, telangiectasia 10 000 mGy and dermal necrosis (late phase) >15 000 mGy [221].

[98] The recommended occupational dose limit for skin in planned exposure situations is an equivalent dose of 500 mSv/year, averaged over 1 cm^2 area of skin regardless of the area exposed (see table 6 in Ref. [129] and schedule III in Ref. [198]). The generic criterion established for acute doses to the skin, for which protective actions and other response actions are expected to be undertaken under any circumstances to avoid or to minimize severe deterministic effects, is 10 000 mGy incurred in a 100 cm^2 dermis (skin structures at a depth of 40 mg/cm^2 (or 0.4 mm) below the surface) (see table IV.1 in Ref. [198]).

UNSCEAR already observed that: "No radiation related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident" [223].

4.4.2 Potential late radiation induced health effects

Under the severe circumstances and conditions of the accident, of the approximately 23 000 workers involved in emergency operations, the number exceeding a dose of 100 mSv was 174. UNSCEAR concluded that among this group "an increased risk of cancer would be expected in the future. However, any increased incidence of cancer in this group is expected to be indiscernible because of the difficulty of confirming such a small incidence against the normal statistical fluctuations in cancer incidence" [223].

With reference to potential late effects among members of the public, international estimates were published before this report (see Box 4.1). WHO issued a hypothetical estimate[99] of additional lifetime risks over baseline rates for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers for the population in the locations with the highest dose rates, which was based on WHO preliminary dose estimates[100] [146, 147].

UNSCEAR, following its updated dose estimate, reported that:

> "The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants" [223].

Before reporting on the accident, UNSCEAR had informed the United Nations General Assembly that "increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation" [167]. The information available indicates that members of the public incurred annual doses that were not higher than annual doses due to typical background levels of radiation. This indicates that no discernible increased incidence of radiation related health effects is expected among exposed members of the public or their descendants, in agreement with UNSCEAR estimates.

This estimate is also generally applicable to the special case of adult thyroid cancer. In adult life, this risk is very much lower than that from radiation exposure in childhood (see the discussion of thyroid effects in children below). Given the reported radiation equivalent doses to the thyroid, it is unlikely that there would be a discernible increase in thyroid cancers among the adult population.

---

[99] Given the limited information available at the time, the assessment contained a number of conservative assumptions. WHO indicated that "all efforts were made to avoid any underestimation of doses" and that "some possible dose overestimation may have occurred" [146].

[100] WHO's health risk assessment estimated that "in the two most affected locations of Fukushima Prefecture, the preliminary estimated radiation effective doses for the first year ranged from 12 to 25 mSv" and that, on the basis of these estimates, "in the highest dose location, the estimated additional lifetime risks for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk as methodological options were consciously chosen to avoid underestimation of risks. For leukaemia, the lifetime risks are predicted to increase by up to around 7% over baseline cancer rates in males exposed as infants; for breast cancer, the estimated lifetime risks increase by up to around 6% over baseline rates in females exposed as infants; for all solid cancers, the estimated lifetime risks increase by up to around 4% over baseline rates in females exposed as infants; and for thyroid cancer, the estimated lifetime risk increases by up to around 70% over baseline rates in females exposed as infants. These percentages represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers" [147].

For the few workers who received high thyroid equivalent doses (see Section 4.3.2), an increased risk of developing thyroid disorders could be inferred. These thyroid equivalent dose levels can reduce the function of the gland to such an extent that hypothyroidism ensues. Hyperthyroidism is not expected because the reported thyroid equivalent doses are below the level of around 15 000 mSv, above which such effects could occur. Effects for low and medium thyroid equivalent doses, typical of the range of doses received by the emergency workers, are difficult to quantify, and the potential for and magnitude of effects remains unclear.

4.4.3 Radiation effects in children

The potential for radiation effects in children is an issue of special concern. International recommendations and standards for radiation protection take account of children in an exposed population. For radiation protection purposes, they postulate a potential nominal radiation risk for an entire population, i.e. a population including children[101], that is about 30% higher than the postulated risk for an adult population (such nominal risks have been estimated on the basis of epidemiological studies of populations exposed to high radiation doses) [129, 224].

Thyroid effects in children

For thyroid cancer, children are more radiosensitive than adults. For a given intake of radioiodines, the dose to the thyroid for infants is eight or nine times as large as that for adults. A substantial environmental presence of ^{131}I can result in thyroid cancer in children. The normal incidence of some types of thyroid cancer in children is low and the sensitivity of children's thyroid glands to radiation is high. Owing to this higher sensitivity, in the aftermath of the accident it was important to undertake follow-up screening in order to detect early any potential increase in the incidence of this type of cancer [225].

The results of three years of thyroid ultrasound examinations performed under the Fukushima Health Management Survey were reported [226]. The screening covered roughly 370 000 children aged 0–18 years at the time of the accident. This initial screening was followed by complete thyroid examinations from 2014 onwards, and the residents will be monitored regularly in subsequent years.

The examinations use highly sensitive ultrasound sonography equipment for screening the thyroid gland. The screening has detected asymptomatic[102] thyroid abnormalities — nodules, cysts and cancers — that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [227]. The latency time for radiation induced thyroid cancer is longer than the four years that have elapsed since the accident, at the time of writing. In many cases, thyroid cancers were found in children in their late teenage years, but no cases were found in the most vulnerable group of children, who were aged under five years on 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the initial screening conducted in 2011–2013 [228]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident.

On the basis of the data made available on indirect measurements of external dose equivalent due to activity in the thyroid (see Fig. 4.10), thyroid equivalent doses in children appear to have been low.

[101] The term 'children' includes those exposed as infants, children and adolescents.

[102] Asymptomatic effects are those that produce no symptoms, i.e. nothing that indicates a condition of disease, in particular nothing apparent to the children, to their parents or even to doctors.

For the levels of doses reported, increases in thyroid cancer in children would not be attributable to radiation exposure.

4.4.4 Prenatal radiation induced health effects

A 'prenatal (or 'antenatal') effect of exposure' is the term used to refer to effects of radiation on the embryo and foetus. At absorbed doses under 100 mGy, lethal effects of irradiation in the pre-implantation period of embryonic development are considered to be very infrequent, and there is an absorbed dose threshold of around 100 mGy for the induction of other effects [229–231]. Absorbed doses to the embryo and foetus that could be attributable to the accident were much lower than the threshold absorbed dose for the occurrence of these effects.

The pregnancy survey carried out as part of the Fukushima Health Management Survey (see Box 4.2) helped the provision of appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, and to their children. This survey is being updated every year to take account of new data, particularly on pregnancy and births [162]. The aim was to collect data that might improve obstetrical and prenatal care and to support women who were pregnant or gave birth in Fukushima Prefecture following the accident. On the basis of the survey results, there were no significant adverse outcomes, and the incidences of stillbirth, pre-term birth, low birth weight and congenital abnormalities were found to be similar to those elsewhere in Japan [232].

UNSCEAR reported to the United Nations General Assembly that "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure" [167]. Therefore, the findings in this report indicate that no heritable effects will be attributable to the accident.

Following accidents involving significant potential for radiation exposure, some pregnant women seek medical advice on whether or not their pregnancy should be terminated. In the case of the Fukushima Daiichi accident, a study by the Obstetrics and Gynaecology Department of the Fukushima Medical University reported that no such elective terminations had been carried out in the aftermath of the accident [232, 233].

4.4.5 Psychological consequences

Although not directly attributable to radiation exposure, psychological consequences were considered in this report. UNSCEAR reported that:

> "The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported." [148]

A number of studies on psychological conditions following the Fukushima Daiichi accident have been performed. These studies focused largely on pregnant women and mothers of infants, rescue and cleanup workers, and evacuees. Some psychological consequences have been detected in the affected population [234–244][103]. According to these studies, communication and dissemination of accurate

[103] Psychological consequences have been detected in other traumatic situations and may include depression, post-traumatic stress responses, chronic anxiety, sleep disturbance, severe headaches and increased smoking and use of alcohol, as well as dysfunctional behaviour such as intense anger, despair, extreme anxiety about health, and feelings of stigmatization and discrimination. As demonstrated after previous accidents, such as the Chernobyl accident, the majority of people affected are generally resilient to psychological conditions, but exceptions have been reported in a number of studies [169, 245–247].

information to the public at an early stage and during the development of the accident contributed to the alleviation of undesired psychological reactions [150].

The largest study is the Mental Health and Lifestyle Survey, conducted as part of the Fukushima Health Management Survey [248], which aims at providing adequate care mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress. The questionnaires contained standard measures of symptoms of post-traumatic stress disorder and psychological distress (anxiety) as well as questions about concerns regarding radiation exposure and adversity resulting from the earthquake and tsunami (e.g. loss of family or relatives, damage to houses, loss of employment, decrease in income, movement within or outside Fukushima Prefecture).

The results of the Mental Health and Lifestyle Survey were published [236]. They confirmed that the affected population experienced considerable distress and symptoms of post-traumatic stress disorder. The survey indicated that "sociodemographic data showed that many evacuee households were separated after the disaster and had to move several times", suggesting this was a cause of psychological conditions.

Two other methods were used to assess the mental health status of adult evacuees [249, 250] and an additional survey was performed to assess alcoholism [251]. These surveys indicated that mental health symptoms were substantially worse than would be expected from surveys of the general population [237]. Children's mental health status was assessed using another questionnaire approach [252, 253], which suggested some psychological difficulties among the surveyed children, but with relative improvements year by year.

Studies were also performed on the affected workers. A study comparing workers at the Fukushima Daiichi and Fukushima Daini NPPs in April–June 2011 found significantly more symptoms of general psychological distress and post-traumatic stress responses among Fukushima Daiichi workers (see Fig. 4.14). In both groups of workers, there were also statistically significant associations between experiencing discrimination and slurs and symptoms of both these conditions.

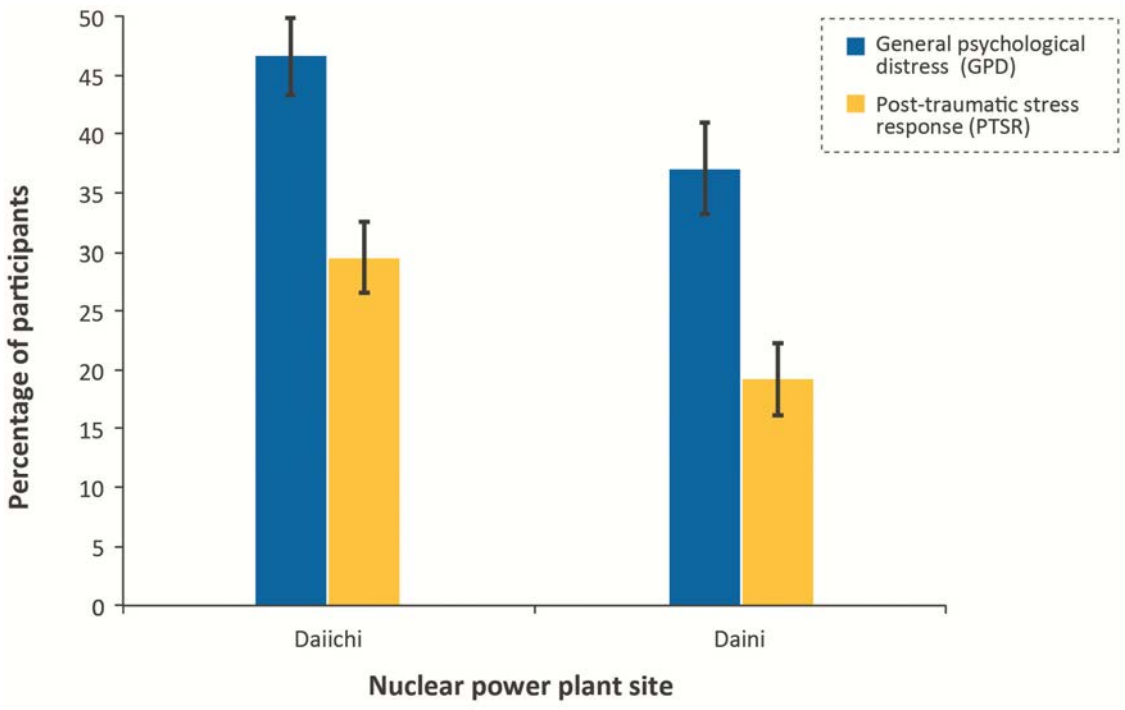


FIG. 4.14. Percentage of workers at the Fukushima Daiichi and Fukushima Daini NPPs reporting psychological distress, April 2011 [242].

4.5. RADIOLOGICAL CONSEQUENCES FOR NON-HUMAN BIOTA

No observations of direct radiation induced effects in plants and animals have been reported, although limited observational studies were conducted in the period immediately after the accident. There are limitations in the available methodologies for assessing radiological consequences, but, based on previous experience and the levels of radionuclides present in the environment, it is unlikely that there would be any major radiological consequences for biota populations or ecosystems as a consequence of the accident.

Protection of the environment[104] includes "the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services. The term also includes the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media, for example soil, water and air; and natural processes, such as carbon, nitrogen and water cycles" [198]. The earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu [254, 255].[105]

The immediate priority following the accident was the protection of people rather than species in the environment, for which exposures are not easy to control. Although residents within a 20 km radius of the plant were evacuated in order to reduce their radiation exposures, the exposure of non-human organisms inhabiting these areas was unavoidable. The approaches used in this report to assess the potential radiological impact of the accident on non-human organisms were those recommended by the ICRP [224, 257]. The estimated exposures were then compared with information on the impact of such exposures on different types of plants and animals as published in the literature (see Refs [258, 259]).

The overall uncertainties associated with the types of models applied in this assessment are large, particularly where assumptions about environmental transfers are involved [260]. These assessment methodologies tend to be based on simple assumptions, and uncertainties are usually taken into account by the use of conservative assumptions. The benchmarks used to relate calculated doses to radiation effects are primarily related to chronic rather than acute exposures and to a limited range of individual organisms rather than populations or ecosystems. The current methodologies do not take account of interactions between components of ecosystems or the combined impact of radiation and other environmental stressors. There is a need for improvements in both the assessment methodologies and in the understanding of radiation induced effects to ecosystems.

The estimated absorbed doses were highest for plants during the first weeks after the accident, but remained below levels at which acute effects would be anticipated. The relevant reference levels were exceeded for some terrestrial reference organisms (such as pine, grass, deer and rats) in the early phase following the accident. However, no overall impact on the populations of these organisms or the ecosystems has been observed.

Earlier publications by UNSCEAR [261, 262] reported that minor damage could occur in conifers at doses below 1.2 Gy, while more serious damage, leading to death, could occur at doses in the range of 10–20 Gy. From the assessed doses it is possible to infer that any direct lethal effects are unlikely on wild grass, as it is more radioresistant. For the terrestrial animals, the estimated dose rates in the early phase indicated that there is a low probability of reproductive disturbances.

---

[104] In this report, the term 'environment' refers to the "conditions under which people, animals and plants live or develop and which sustain all life and development; especially such conditions as affected by human activities" [198].

[105] Other reports of the effect of the tsunami on the ecosystems can be found in Ref. [256].

Although dose rates exceeded some reference values in the early phases of the accident, no impact on animal and plant populations and ecosystems is expected. Long term effects are also not expected, as the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected and dose rates declined relatively rapidly after the accident.

4.6. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the radiological consequences of the accident.

— **In case of an accidental release of radioactive substances to the environment, the prompt quantification and characterization of the amount and composition of the release is needed. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**
The quantification and characterization of the source term of the accident at the Fukushima Daiichi NPP proved to be difficult. Prompt monitoring of the environment provides confirmation of the levels of radionuclides and establishes the initial basis for protecting people. The results can be used to inform the public and to develop strategies for response and recovery activities. It is also important to continue environmental monitoring to verify that there are no further significant releases of radionuclides and to provide information to decision makers and other stakeholders on the possible redistribution of radionuclides in the environment over time.

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**
There is a recognized need for simple explanations of a number of radiation protection issues, including:
  - Differences between the concepts of dose limits and reference levels and the associated rationale;
  - Criteria for the justification of protective measures and actions aimed at averting radiation doses in the long term, in particular when they involve significant disruptions to normal life;
  - Specific situations relating to the radiation protection of workers in an emergency.

The principles of radiation protection are based not solely on science, but also on value judgements based on ethical principles. In some circumstances, protective measures and actions involve protracted social disruption. Under these circumstances, the potential benefit from avoiding radiation doses must outweigh the individual and social detriment caused by the protective measures and actions themselves. It is important to explain to stakeholders the justification for long-standing radiation protection measures and actions.

— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**
The Japanese authorities established measures for controlling the presence of radioactive substances in consumer products, which were generally more stringent than the available international guidance. The current international system for controlling radioactivity in consumer products is governed by distinct guidance, for example the Codex Alimentarius for food (including bottled water) in international trade, IAEA safety standards for food and drinking water for use in an emergency, WHO guidelines for drinking water in existing exposure situations and

IAEA safety standards for non-edible products for exemption purposes. There is a need for consistency in the international standards for acceptable levels of radioactivity in products for public consumption in order to facilitate their application by regulatory bodies and their understanding by the public. National standards need to be in line with international standards, where this is feasible. Moreover, there is a need for criteria for dealing with the protracted presence of radionuclides on land.

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**

The early estimation of doses was based on environmental measures and modelling, resulting in some conservative assumptions on doses incurred and projected.

Personal monitoring of ^{131}I in the thyroids of children needs to be undertaken as soon as possible following radioiodine releases to the environment, owing to the short half-life of this radionuclide. Personal monitoring of external radiation and the internal presence of the longer lived radionuclides (e.g. ^{137}Cs) needs to be undertaken as soon as feasible and to continue over time, as appropriate.

In the absence of personal radiation measurements, modelling of environmental and ambient data may be needed to estimate the radiation doses incurred by individuals. In these cases, the uncertainties associated with the assumptions used in the models need to be clearly explained, particularly if the results are being used to inform decision making on protective measures and actions or to estimate the potential for radiation induced health effects.

— **While dairy products were not the main pathway for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**

The estimates of thyroid doses to children following the accident were low. This was the result of a combination of factors, including the time of year (before the growing season), agricultural practices in Japan, low consumption of cow's milk by infants and the controls on milk consumption that were immediately introduced. These factors contributed to the low level of intake of ^{131}I.

— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**

Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated by emergency workers are the most valuable approach to obtaining information for estimating radiation risks and potential health effects and to optimizing protection. There is a need to monitor and register occupational radiation doses through a robust system of personal dosimeters and measurements. Monitoring of ^{131}I in the thyroid needs to be undertaken as soon as possible.

Immediately following the Fukushima Daiichi accident, the provision of personal protective equipment for restricting the exposure of workers and monitoring was difficult.

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation if levels of exposure are similar to the global average background levels of radiation.**

In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable with typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident.

An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**
The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought" [149].**
Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of their importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, to alleviate their concerns and support their own protection initiatives.**
Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives.

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism, and of the use of natural resources.**
It may be difficult to substantially reduce doses to non-human biota because of the impracticability of introducing countermeasures. Impact assessments for plants and animals in the aftermath of accidents such as that at the Fukushima Daiichi NPP require consideration of numerous potential stressors — radiation exposure being one of many. Consideration also needs to be given to the potential for the buildup and accumulation of long lived radionuclides in the environment and how this might affect plants and animals over multiple generations.

5. POST-ACCIDENT RECOVERY

Immediately following the accident at the Fukushima Daiichi NPP, priority was given to stabilizing conditions at the plant and protecting the public through actions that included sheltering and evacuation of residents in the affected areas and restrictions on food[106] and drinking water. As work progressed and conditions at the site were stabilized, greater emphasis was placed on recovery from the accident, including the revitalization of the community and infrastructure.

This section considers progress in post-accident recovery up until March 2015 as well as plans for the future. It considers, primarily, the existing exposure situation that followed the emergency phase.

5.1. OFF-SITE REMEDIATION OF AREAS AFFECTED BY THE ACCIDENT

The long term goal of post-accident recovery[107] is to re-establish an acceptable basis for a fully functioning society in the affected areas. Consideration needs to be given to remediation[108] of the areas affected by the accident in order to reduce radiation doses, consistent with adopted reference levels. In preparing for the return of evacuees, factors such as the restoration of infrastructure and the viability and sustainable economic activity of the community need to be considered.

Prior to the Fukushima Daiichi accident, policies and strategies for post-accident remediation were not in place in Japan, and it became necessary to develop them in the period after the accident. The remediation policy was enacted by the Government of Japan in August 2011.[109] It assigned responsibilities to the national and local governments, the operator and the public, and created the necessary institutional arrangements for the implementation of a coordinated work programme.

A remediation strategy was developed and implementation began. The strategy specifies that priority areas for remediation are residential areas, including buildings and gardens, farmland, roads and infrastructure, with emphasis on the reduction of external exposures.

External dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure. The remediation strategy is therefore focused on decontamination activities to reduce the levels of radiocaesium present in priority areas, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land.

Following the accident, the authorities in Japan adopted a 'reference level' as a target level of dose for the overall remediation strategy. This level was consistent with the lower end of the range specified in international guidance. The application of a low reference level has the effect of increasing the quantity of contaminated materials generated in remediation activities, and thereby

---

[106] Including restrictions on the distribution and sale of food, the use of agricultural land and the collection of wild food products (see Section 3.3).

[107] Post-accident recovery includes: remediation of areas affected by the accident; the stabilization of damaged on-site facilities and preparations for decommissioning; the management of contaminated material and radioactive waste arising from these activities; and community revitalization and stakeholder engagement.

[108] Remediation is defined as any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

[109] Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110, 2011.

increasing the costs and the demands on limited resources. The experience obtained in Japan could be used in developing practical guidance on the application of international safety standards in post-accident recovery situations.

Two categories of contaminated areas were defined on the basis of additional annual doses estimated in the autumn of 2011. The national Government was assigned responsibility for formulating and implementing remediation plans in the first area (the 'Special Decontamination Area') — within a radius of 20 km of the Fukushima Daiichi site and in areas where additional annual doses arising from contamination on the ground were projected to exceed 20 mSv in the first year after the accident. The municipalities were given responsibility for implementing remediation activities in the other area (the 'Intensive Contamination Survey Area'), where the additional annual doses were projected to exceed 1 mSv but to remain below 20 mSv. Specific dose reduction goals were set, including a long term goal of achieving an additional annual dose of 1 mSv or less.

5.1.1. Establishment of a legal and regulatory framework for remediation

Following the accident, a policy on recovery and remediation was established by the Government of Japan through the enactment of the 'Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011', in August 2011 [124]. The Act includes provisions for prioritization of sites to be remediated, allocation of funds to carry out the remediation work and involvement of stakeholders in the overall process.

The first steps in developing a remediation programme are the definition of appropriate reference levels and the establishment of a remediation strategy to achieve the required reduction in the radiation exposure of members of the public. International guidance recommends that a reference level be selected from the range of additional dose of 1–20 mSv/year, depending on the prevailing circumstances (Box 5.1) [129, 198, 263].[110]

It is important in setting reference levels within this range that they are not too high, which could jeopardize the required safety objective, or too low, which could result in a less than optimal use of limited resources. In the initial stages of remediation in Japan in 2011, the Government of Japan set reference levels that were intentionally low [264, 265], and a long term goal for residents, following remediation, of an additional dose of no more than 1 mSv/year was adopted [266]. This is the lowest value in the range given in international guidance (Box 5.1).

The high level of conservatism in the approach used to estimate doses to people was illustrated by an assessment by UNSCEAR [148]. The estimated doses are based on the activity per unit area of ^{134}Cs and ^{137}Cs, taking into account the decline of activity due to decay, the loss of activity due to weathering from surfaces and the shielding factor typical for wooden houses. Calculations undertaken for the purpose of this report, using the same methodology used by UNSCEAR [148, 267], indicated that the average additional radiation doses in 2012 in large parts of the Intensive Contamination Survey Area (see Section 5.1.2) would have been well below 1 mSv/year.

[110] A pre-publication version of the interim edition of the International Basic Safety Standards was available at the time of the accident [263]. IAEA Safety Standards Series No. GSR Part 3 [198] was subsequently published in 2014.

Box 5.1. Reference level for remediation

The 'reference level' is the target dose for the overall remediation strategy, but it is not a dose limit. International guidance [129, 263] recommends reference levels in the range of 1–20 mSv/year for additional exposure of a member of the public in 'existing exposure situations', depending on the prevailing circumstances.

Reference levels are established by the Government, the regulatory body or another relevant authority, according to the arrangements in the national regulatory framework. Reference levels in post-accident situations are used to identify optimal strategies for remediation. These strategies will ensure that remediation is performed through the efficient use of available human, technical and financial resources to achieve the best outcomes in the protection of the affected communities.

Specific actions applied to reduce environmental contamination and radiation doses to people are generally guided by derived 'remediation action levels'. Usually, these are specified in terms of easily measurable quantities, such as ambient gamma dose rates (μSv/h) or deposited activity per unit area (Bq/m^2), and derived from the reference levels by using models and assumptions about people's living habits and about the behaviour of radionuclides in the environment.

5.1.2. Remediation strategy adopted

The remediation strategy was influenced by the fact that internal doses following the accident were largely avoided by implementing restrictions on food and drinking water. As a consequence, the remediation actions described here were primarily concerned with decontamination efforts to reduce the levels of external doses.

The Government of Japan's remediation strategy set an approach to the rapid reduction of radiation dose, prioritizing remediation in residential areas, on farmland and in forest areas adjacent to residential or agricultural areas [124, 266]. To facilitate this, in August 2011, it classified the land to be remediated as follows:

— **Special Decontamination Area** (Fig. 5.1, right). This area overlaps the former 'Restricted Area', i.e. the evacuation zone within a 20 km radius of the Fukushima Daiichi NPP, and the former 'Deliberate Evacuation Area', which were situated beyond the 20 km radius from the plant where the additional annual dose for individuals could exceed 20 mSv in the first year after the accident. Within the Special Decontamination Area, the national Government has the responsibility of formulating and implementing remediation plans.
— **Intensive Contamination Survey Area** (Fig. 5.1, right). This area includes those municipalities where the additional radiation dose in the first year was estimated to be between 1 and 20 mSv for individuals in some parts of the municipality[111]. Municipalities conduct monitoring surveys to identify areas requiring decontamination and carry out remediation activities in these areas, with the national Government providing financial and technical support.

In 2012 and 2013, the areas in which evacuation orders had been issued were further subdivided into the following three categories on the basis of the estimated annual total dose to people inhabiting the area, if any (Fig. 5.1, left) [268, 269]:

— **Area 1 (green).** Areas where evacuation orders were ready to be lifted. The estimated annual dose was expected to be 20 mSv or less.

[111] An ambient dose rate of 0.23 μSv/h was used as the radiological criterion for this area. This dose rate corresponds to a conservatively estimated additional effective dose of 1 mSv in one year.

— **Area 2 (orange).** Areas in which residents were still not permitted to live. The estimated annual dose was expected to exceed 20 mSv.
— **Area 3 (red).** Areas to which it was anticipated that residents would not be able to return for a long time. The estimated annual dose was over 50 mSv, and the average annual dose over the period of six years after the accident was expected to be more than 20 mSv.

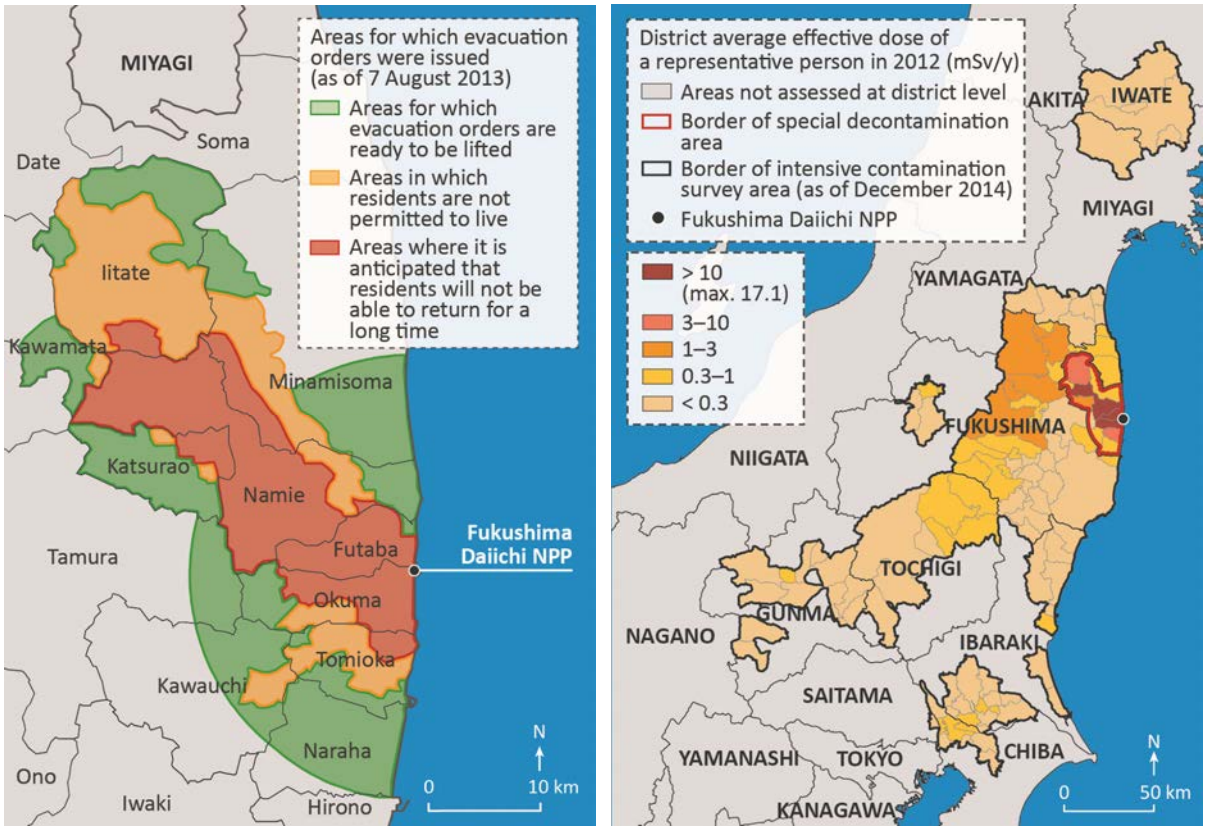


FIG. 5.1. The map on the left shows the subdivision of the evacuation zone as of 7 August 2013 [270]. The map on the right shows the designation of the 'Special Decontamination Area' and the 'Intensive Contamination Survey Area' as of December 2014 and indicates the estimated additional radiation doses of representative persons in 2012.

5.1.3. Progress in remediation

A number of pilot projects were undertaken in 2011. The JAEA initially performed a series of small scale studies at two sites outside the evacuated zones to assess the effectiveness of decontamination in achieving reductions in dose rate for various types of surfaces (e.g. streets, roofs, walls and lawns) [271]. Later studies considered the feasibility of decontamination of larger areas in the evacuated zones, assessed the effectiveness of these measures in reducing ambient gamma dose rates and explored the implications for worker safety and waste management.

These pilot studies played an important role in planning and implementing remediation strategies. They provided information on the effectiveness and applicability of decontamination techniques and helped to establish procedures for the radiation protection of workers [272].

Commonly implemented remediation measures following the Fukushima Daiichi accident are listed in Table 5.1. Topsoil removal, which generates a large amount of waste, was widely used in the first years of remediation.

TABLE 5.1. COMMONLY IMPLEMENTED REMEDIATION MEASURES

Target	Remediation measures
Houses and buildings	Removal of deposits from the roof, deck and gutters Wiping roofs and walls Vacuum sanding High pressure washing
Schoolyards, gardens and parks	Topsoil removal Weed/grass/pasture removal
Roads	Removal of deposits in ditches High pressure washing
Gardens and trees	Mowing Removal of fallen leaves Removal of topsoil High pressure washing Paring tree surfaces
Farmlands	Tillage reversal Topsoil removal Soil treatment (e.g. enhanced application of fertilizer) Soil hardening and removal Weed/grass/pasture removal
Animal production	Control of radiocaesium levels in animal feed
Forests and woodland	Removal of fallen leaves and lower twigs Pruning

Remediation strategies were later implemented in both the Intensive Contamination Survey Area and the Special Decontamination Area, and significant progress was made. By the end of March 2015, decontamination in most parts of the Intensive Contamination Survey Area outside Fukushima Prefecture was almost complete (in about 80% of the municipalities). In the Intensive Contamination Survey Area within Fukushima Prefecture, around 90% of the public facilities, 60% of residential houses and 50% of roads had been decontaminated [273].

Within the Special Decontamination Area, decontamination plans had been completed in four municipalities in March 2015 (Tamura City, Kawauchi Village, Naraha Town and Okuma Town). Decontamination of residential areas had also been completed in two more municipalities (Katsurao Village and Kawamata Town) and had almost been completed in Iitate Village [273]. Most decontamination plans in both decontamination areas 1 and 2 within Fukushima Prefecture were due to be completed before the end of March 2016, although some were due to continue into 2017 (Fig. 5.2).

Investigations performed in residential areas of Tamura and Naraha municipalities showed that ambient gamma dose rates had been reduced by an average of 36% and 46%, respectively. Gamma dose rates (see Box 5.1) were determined by measuring ambient dose rates at a distance of 1 m from the decontaminated surfaces, both before and after remediation actions. Average dose rate reductions in the two municipalities following remedial actions in farmlands, forests and roads were between 21% and 44% [273].

The data indicate that the reduction of ambient gamma dose rates is more significant in areas with higher initial dose rates. After remediation, the gamma dose rates continue to decline owing to the natural processes of weathering and radioactive decay.

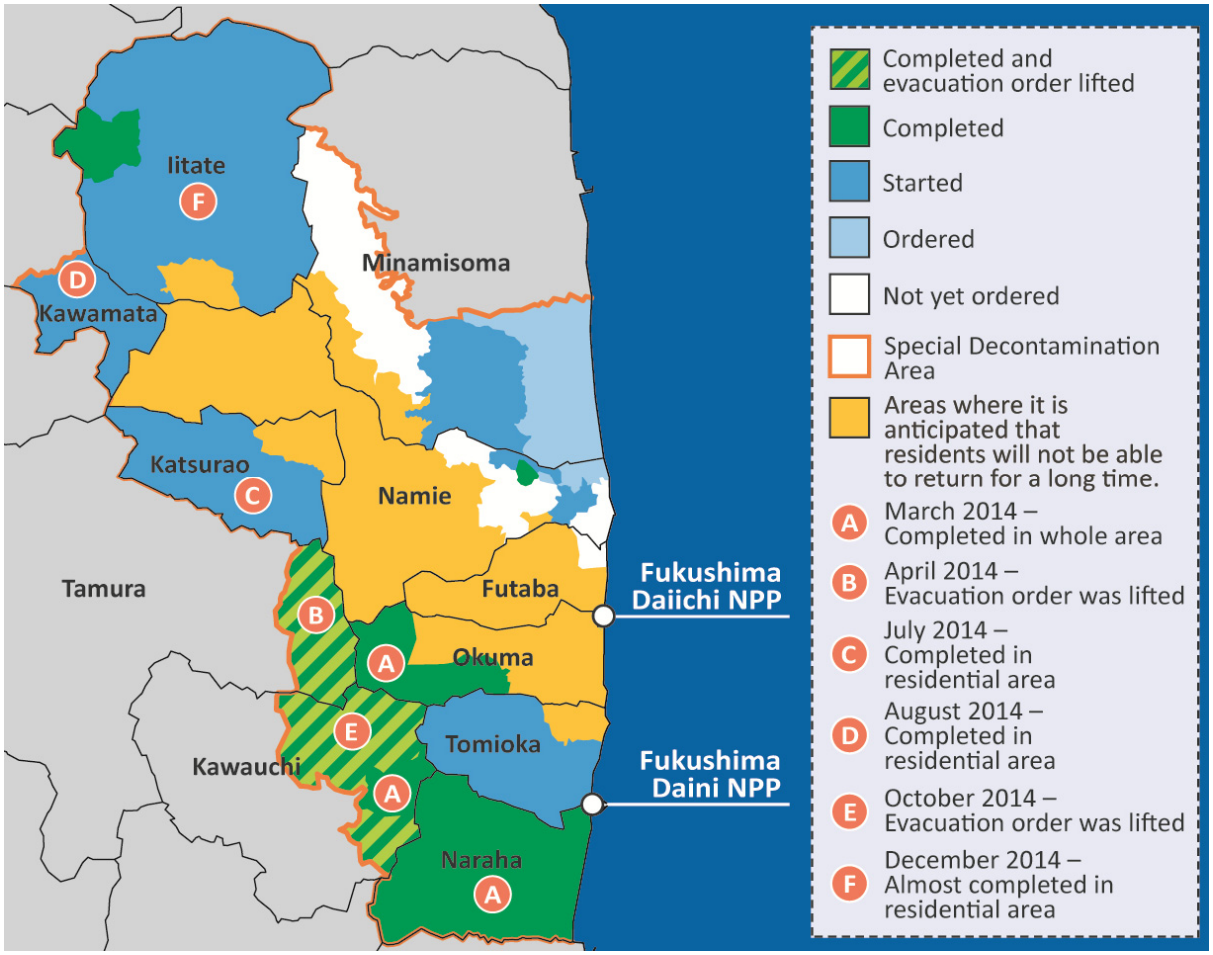


FIG. 5.2. Progress of remediation in the Special Decontamination Area up to December 2014 [273].

Examples of remediation are shown in Fig. 5.3.

Unit costs for decontamination in the Special Decontamination Areas directly controlled by the national Government ranged from around 1100 yen/m^2 (forests) to approximately 5500 yen/m^2 (parks) [274].

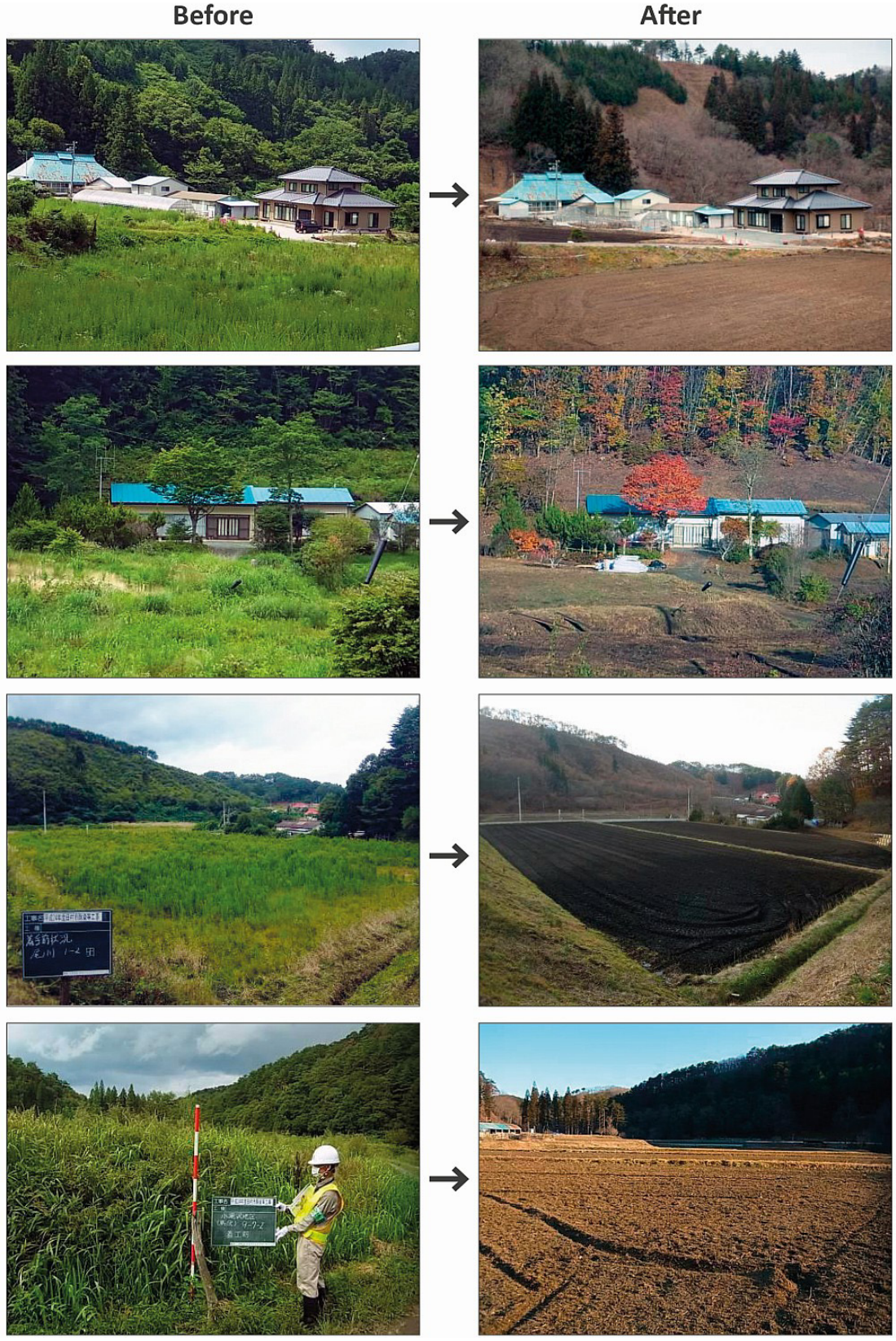


FIG. 5.3. Landscapes before and after remediation in Tamura City (photographs courtesy of Ministry of the Environment, Japan).

5.2. ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING

A comprehensive, high level strategic plan for stabilization and decommissioning of the damaged NPP was developed jointly by TEPCO and the relevant Japanese Government agencies. The plan was first issued in December 2011 and subsequently revised to reflect the experience gained and an improved understanding of the conditions of the damaged NPP, as well as the magnitude of the future challenges. The strategic plan addresses the complex nature of on-site work and includes: the approach to ensure safety; measures towards decommissioning; systems and environments to facilitate the work; and research and development requirements.

At the time of writing, safety functions had been re-established and structures, systems and components were in place to reliably maintain stable conditions. However, there was a continuing need for control of ingress of groundwater to the damaged and contaminated reactor buildings. The resulting contaminated water was being treated to remove radionuclides to the extent possible and stored in more than 800 tanks. More sustainable solutions are needed, considering all options, including the possible resumption of controlled discharge into the sea. Final decision making will require engaging relevant stakeholders and consideration of socioeconomic conditions in the consultation process, as well as implementation of a comprehensive monitoring programme.

Plans for the management of spent fuel and fuel debris were developed and removal of fuel from spent fuel pools began.[112] A conceptual model of future activities for removing fuel debris was also developed, which takes account of the many preliminary steps required, including visual confirmation of the configuration and composition of the debris. The high radiation dose levels in the damaged reactors meant that no such confirmation had been possible at the time of writing.

Japanese authorities have estimated that the timescale for completing decommissioning activities is likely to be in the range of 30–40 years. Decisions regarding the final conditions of the plant and site will be the subject of further analysis and discussions.

Box 5.2. Stabilization and post-accident decommissioning

The term ‘decommissioning’ refers to the administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility.

In practical terms, decommissioning is the progressive removal of the facility’s structures, systems and components. Under normal circumstances, decommissioning of an NPP is a planned activity that is initiated after the decision has been taken to end operations. Post-accident decommissioning presents a different set of challenges: the condition of the facilities and the status of the fuel and the plant equipment need to be first determined and a path forward decided. This may require development of new technologies and methodologies.

If reactor shutdown is the consequence of an accident, the facility needs to be brought to a safe configuration (stabilization) before an approved final decommissioning plan is put into effect. Stabilization comprises actions required to ensure that the plant structures (such as the buildings that house the damaged reactors), systems (such as electrical supply systems) and components (such as pumps or motors) are put in a stable condition and can operate for as long as may be required.

[112] Removal of fuel from the Unit 4 spent fuel pool was completed in December 2014.

5.2.1. Strategic plan

Following the emergency phase, TEPCO and the relevant government agencies established a strategic plan — the 'Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4' — for stabilization and decommissioning activities [275]. The plan was first issued in December 2011 and subsequently revised to take account of the greater experience and improved understanding of the on-site conditions [276].[113] It is a comprehensive, high level strategic plan for those supervising the recovery. Decommissioning is projected to be completed on a timescale of 30–40 years, according to Japanese authorities' estimates.

The plan describes the strategic approach for areas of work concerning:

— **The approach to ensuring safety**, which includes strategic objectives for reducing risks and optimizing the removal of fuel and fuel debris.
— **Mid-term and long term measures towards decommissioning**, which include plans for the removal of fuel and fuel debris from each reactor unit. These plans are sufficiently flexible to address the possible range of conditions that may be revealed as more information is gained in the processes of removing fuel and fuel debris.
— **Systems and environment to facilitate work**, for which TEPCO established an organization for the centralized monitoring of the health and radiation exposure of workers. Efforts to improve radiation protection of workers continued, and plans were put in place for managing and ensuring the availability of a trained workforce throughout the decommissioning process.
— **Research and development**, which is necessary, as much of the work to be accomplished at the Fukushima Daiichi NPP is the first of its kind, requiring equipment and technology that has yet to be developed or used on a large scale. The International Research Institute for Nuclear Decommissioning was established to develop technologies for nuclear decommissioning, promote cooperation with international and domestic organizations on nuclear decommissioning, and develop human resources for research and development.

5.2.2. Preparations for decommissioning

Shortly after its establishment [278], the NRA developed a new regulatory framework for the regulation of so-called disaster experienced facilities, which need special measures to prevent further accidents and to ensure nuclear security. On 7 November 2012, the NRA designated the Fukushima Daiichi NPP as 'Specified Reactor Facilities', which are facilities where a nuclear accident has occurred and special regulations commensurate with the prevailing conditions at the facility are stipulated.

This designation allowed the NRA to require TEPCO to develop a plan to implement the actions outlined in the strategic plan [275]. TEPCO's Implementation Plan was submitted in December 2012 [279] and was subsequently approved. TEPCO is responsible for carrying out the actions specified in the Implementation Plan. The execution of these actions is reviewed by the NRA.

Additionally, the NRA developed a regulatory requirement for managing the additional effective dose at the site boundary in February 2014 and identified actions in 'Measures for Mid-term Risk Reduction at TEPCO's Fukushima Daiichi NPS' in February 2015 [280].

---

[113] It is anticipated that there will be further revisions to the Roadmap as plans are adapted in response to changing conditions and new information. The third revision of the Roadmap was issued during the final preparation of this report (June 2015). This modified the schedule for and the approach to fuel and debris removal and refined approaches to risk reduction, communication with local stakeholders, reduction in workers' exposures, and management of research and development [277].

TEPCO established stable conditions at the site to maintain protection and safety and allow progress towards decommissioning [275]. Important support functions, such as normal and backup electrical supplies, were re-established and upgraded. Fundamental safety functions were also re-established. Arrangements to ensure the long term reliability of stable conditions include:

— Monitoring plant conditions;
— Cooling the fuel and fuel debris;
— Maintaining nuclear subcriticality;
— Controlling levels of hydrogen;
— Ensuring structural stability of the reactor buildings;
— Controlling water ingress to the reactor buildings and preventing leakage to the environment;
— Ensuring essential electrical power supplies;
— Ensuring the fulfilment of fundamental safety functions over the long term.

Important safety functions were re-established and upgraded, for example, by installing multiple backup features and replacing and/or upgrading mobile and temporary systems to augment permanent ones. The situation on the site remains complex, and careful monitoring and control is required to ensure continued stable conditions.

5.2.3. Management of contaminated water

Water that enters damaged reactor buildings becomes contaminated and poses a particularly challenging problem due to the large volumes involved. At the time of writing, water continued to enter the reactor buildings at the Fukushima Daiichi NPP in two ways: water injection into the reactor cores for cooling purposes and ingress of groundwater. Characterizing and managing this water continued to be necessary (Fig. 5.4).

Before the accident, groundwater flowing from the mountainside to the rear of the Fukushima Daiichi NPP was pumped at a rate of approximately 850 m^3/d from sub-drains located around the buildings of Units 1–4 to control the groundwater level. As a consequence of the accident, the sub-drains and pumps that previously suppressed building buoyancy and prevented groundwater from entering the buildings ceased operation [281].

After the accident, approximately 400 m^3/d of uncontaminated groundwater flowed into the buildings. Approximately 400 m^3/d of water is circulated through the Unit 1–3 reactors for cooling. The groundwater that enters the buildings is mixed with the circulating water used for cooling the reactors, leading to a total volume of approximately 800 m^3/d of contaminated water that has to be managed. Approximately 400 m^3/d of this water is re-injected into the reactors for cooling the fuel and fuel debris, and the remaining 400 m^3/d is stored in the contaminated water storage tanks [276].

The water is treated to remove radionuclides, with the exception of tritium, which cannot be removed [282]. The treated water was stored on the site in 826 tanks (as of 12 February 2015) [283].

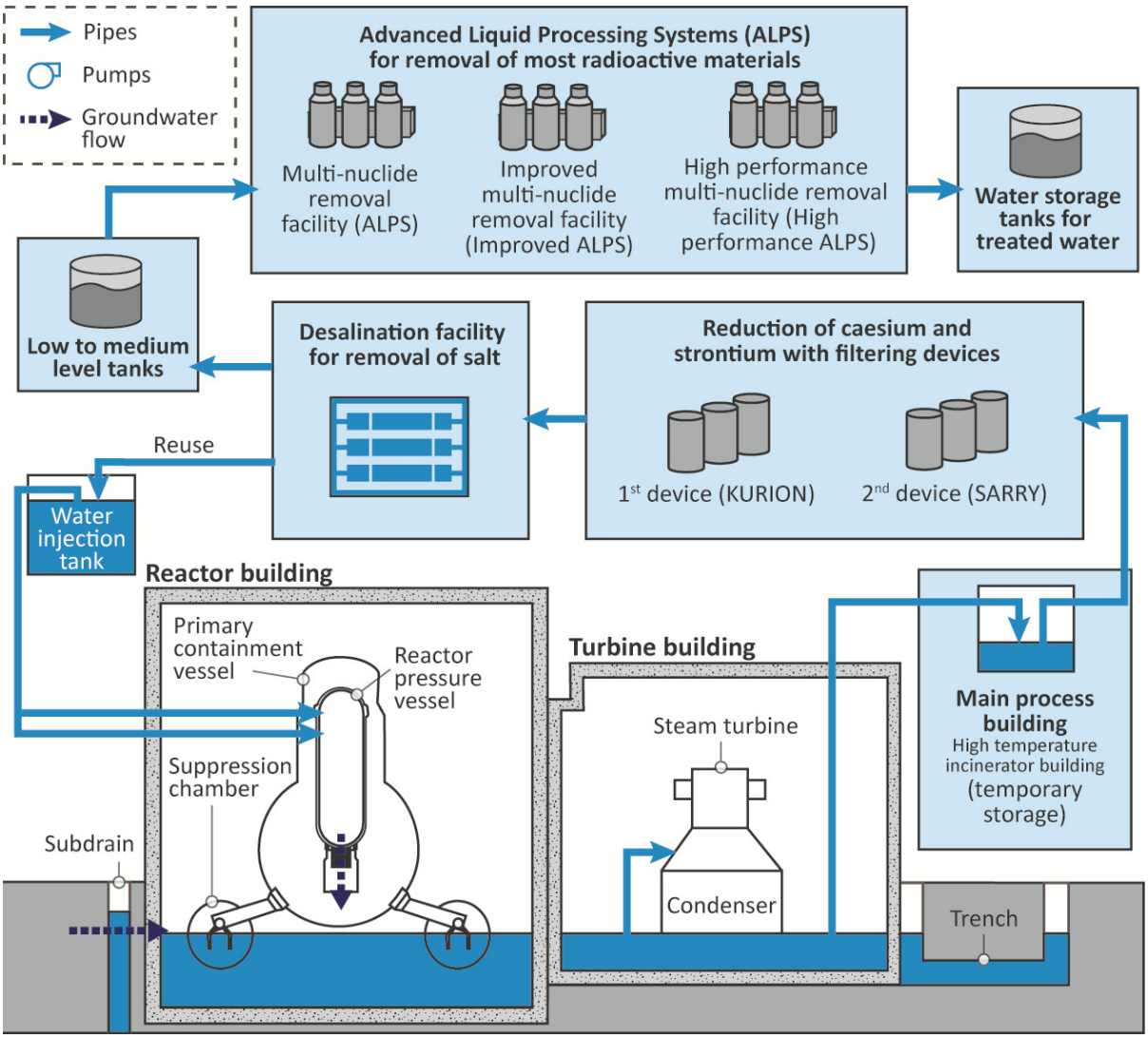


FIG. 5.4. Management of contaminated water on the site [284].

Various water management techniques have been deployed, or were being planned, including the improvement and installation of additional treatment systems and storage tanks, the restoration of the sub-drain system and the installation of seaside impermeable walls. Uncontaminated groundwater from uphill of the damaged facilities is being bypassed around the facilities and into the ocean (Fig. 5.5) [285]. In addition, a cryogenic 'frozen' wall on the mountain side of the reactor buildings was under construction to prevent further water ingress. A cryogenic wall on the sea side of the reactor buildings was also planned.

With the approval of the NRA and the acceptance of the relevant stakeholders, including Fukushima Prefecture and the fishing industry, TEPCO began discharging the bypassed uncontaminated groundwater directly into the sea in May 2014 [285]. This measure reduced the volume of water requiring treatment.

The large quantities of contaminated water on the site present a variety of risks. Owing to malfunctions of tanks, pipes and valves, or during heavy rainfall, leaks of radioactively contaminated water from components were observed. In some cases, the leaks led to releases of radionuclides into the sea. The identification of such leaks triggered more intensive monitoring, both on the site as well as in the marine environment [287]. Although measures were being implemented to stop or reduce the

leakage, more sustainable solutions are needed, considering all options, including the possible resumption of controlled discharges into the sea. As a result of the IAEA Review Missions [288, 289], TEPCO was advised to perform an assessment of the potential radiological impact of the release of water containing tritium and any other residual radionuclides into the sea. It was also recognized that final decision making would require engaging all stakeholders, including TEPCO, the NRA, the national Government, the Fukushima Prefecture government, local communities and others, and that there was a need to consider socioeconomic conditions in the consultation process and to implement a comprehensive monitoring programme to ensure that there was no detrimental impact on human health and the environment [288, 289]. In this context, further guidance on the application of international guidance for discharges in post-accident situations would be beneficial.

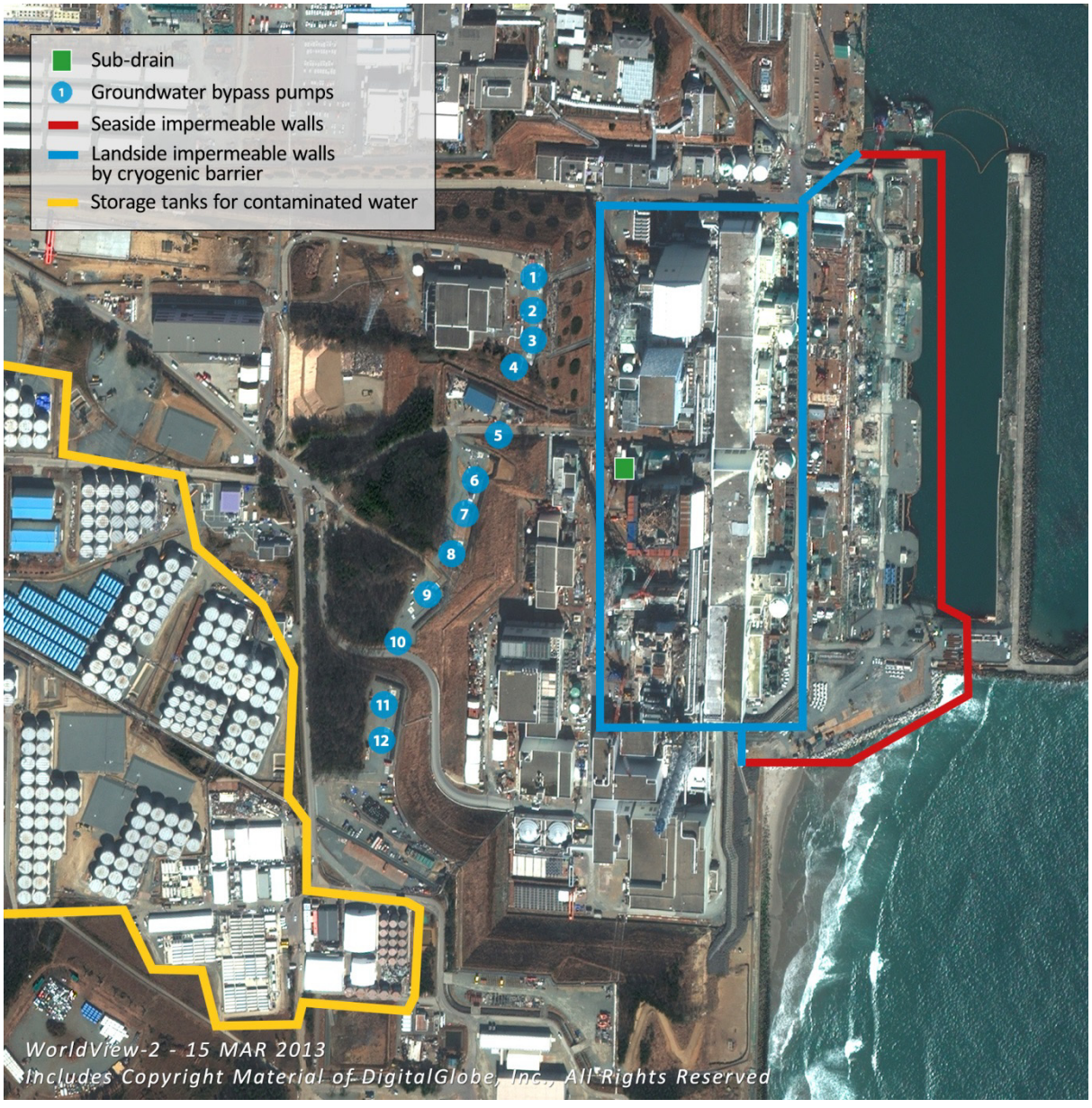


FIG. 5.5. Illustration of water management efforts. Storage tanks for contaminated water are shown on the left [286].

5.2.4. Removal of spent fuel and fuel debris

The preparation for decommissioning the accident damaged facilities includes the removal of spent fuel and new fuel assemblies from storage pools inside the damaged reactor buildings. TEPCO began removing the fuel in the storage pool inside the Unit 4 reactor building to the common fuel pool in November 2013. The operation was completed in December 2014 [290].

It will require several years to remove the spent fuel and new fuel assemblies from the storage pools in Units 1–3. A more accurate estimate of the time needed is dependent on the progress in removing the debris resulting from the explosions, preparing the upper structure of Units 1–3 for access, providing supports for equipment and structures for removal, and other measures. The spent fuel will be placed in a common pool for temporary storage.

Removal and management of debris from the melted fuel in the reactor core is a much more complex challenge. Visual confirmation of the configuration and the composition of the damaged fuel ('fuel debris') resulting from the accident has not been possible due to the high radiation dose levels in the damaged reactors. Available analyses indicate that most of the fuel in Unit 1 melted and that some penetrated the bottom of the reactor pressure vessel to the primary containment vessel, whereas in Units 2 and 3, fuel also melted, but a greater proportion remained within the reactor pressure vessels [9].

At the time of writing, the Government of Japan was sponsoring conceptual studies on ways of gaining access to and removing fuel debris [276, 291]. A conceptual model for future activities for removing fuel debris has been developed, which takes account of the many preliminary steps required, including:

(1) **Reduction of radiation levels in the reactor buildings**. Access by workers to the spaces inside the reactor buildings is difficult because of high dose rates and rubble and contaminated dust that have been scattered inside them. Decontamination, in many instances with remotely operated equipment, will be needed to make access possible.
(2) **Repair of the primary containment vessels containing water**. An investigation will be conducted and the required equipment will be developed to stop water leakage from the containment vessels, after which the water levels will be monitored and maintained as needed for subsequent operations.
(3) **Characterization of the conditions inside the primary containment vessels**. Removal of the fuel debris requires determining the exact locations of the pieces of fuel debris. Equipment to investigate the conditions inside the containment vessels will be developed and the necessary information, such as the locations, distributions and shapes of the pieces of fuel debris, will be obtained.
(4) **Characterization of the conditions inside the reactor pressure vessels**. This includes the distribution of fuel debris, levels of radioactivity and the physical configuration of the damaged pressure vessels.
(5) **Development of technologies for the removal of fuel debris**. The preconditions for removal of fuel debris will be identified, leading to the development of technologies and equipment to open the reactors, remove structural impediments inside the reactor pressure vessels and remove fuel debris.
(6) **Water management.** Beyond cooling and boron control, careful water management will be necessary as the approach to the removal of fuel debris progresses. For example, additional means will be needed for removal of particulate material that becomes suspended in water as a result of the removal operations.
(7) **Packaging, transfer and storage of fuel debris**. As debris is removed from the reactor pressure vessels and the primary containment vessels, it will need to be placed in shielded containers. The

containers will need to be removed from the reactor buildings and placed in interim storage on the Fukushima Daiichi site until a final decision on their disposition has been taken.

(8) **Prevention of nuclear criticality of fuel debris**. Evaluations will be conducted and monitoring techniques put in place to preclude any possibility of nuclear criticality within the debris.

(9) **Accounting for, and control of, nuclear material in the fuel debris**. Accountability is required for fissionable material, in conformity with the safeguards agreement between Japan and the IAEA and with Japanese domestic law. Because the standard methods cannot be applied to the fuel debris, accountability measures will be established before the fuel debris is removed from the reactors.

Fuel debris will be removed while submerged in water to provide shielding and to minimize radioactive releases to the air. The high levels of radiation and contamination, and the unknown distribution and properties of the fuel debris, mean that much of the work will need to be conducted by use of remotely operated equipment. Strategies for removal of fuel debris will need to be adjusted as data become available regarding the conditions of the fuel and fuel debris, as will plans to design, engineer and build appropriate equipment.

5.2.5. Decommissioning end state for the site

Under normal (non-accident) circumstances, the end state of an NPP is defined and described in the licence application and subsequent supporting documents. Two strategies for achieving a plant end state are generally available: immediate dismantling and deferred dismantling, which is sometimes referred to as safe storage. Under exceptional circumstances, for example following a nuclear accident, entombment may also be considered [292].

A nuclear accident may invalidate prior decommissioning planning owing, for example, to the need to stabilize structures, systems and components before the new decommissioning plan can be developed. Decommissioning plans, removal of the fuel debris and options for the final end state of the site depend on the nature of the accident and will include consideration of the status of: nuclear residues, particles and radioactive materials remaining within the facilities; spent fuel and fuel debris in storage; and solid radioactive waste and processed water in storage [293]. The interests of stakeholders, obtained, for example, through an appropriate public consultation process, will also influence the planning and execution of the decommissioning.

It is currently not possible to predict the end state of the Fukushima Daiichi NPP [291]. It may be noted that none of the three plants elsewhere in the world that experienced the most severe fuel damage in previous accidents has yet achieved the final end state for complete decommissioning [293] (Box 5.3).

Box 5.3. Status of decommissioning of damaged nuclear facilities

The three facilities elsewhere that have experienced the most severe fuel damage in previous accidents are Windscale (United Kingdom), Three Mile Island (United States of America) and Chernobyl (former Soviet Union). Their status at the time of writing was as follows:

The Windscale pile, damaged in an accident in 1957, was in a care and maintenance condition, with a plan to place it in safe storage in the next few years and with final decommissioning planned to occur around 2050.

The unit damaged at the Three Mile Island NPP in 1979 was in a safe storage mode, with a plan for complete dismantlement and site remediation within the next 20 years.

Chernobyl Unit 4, severely damaged in the accident in 1986, was in the process of being placed in a condition of safe storage, with final decommissioning projected for around 2050.

A final decision on the end state to be achieved at the Fukushima Daiichi site will need to consider many factors, including the future use of the land, possible radiation doses to the decommissioning workers, the waste that would be generated and options for the waste conditioning and disposal.

5.3. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE

Stabilization of a damaged NPP and the on-site decontamination and remediation efforts in the surrounding areas result in large quantities of contaminated material and of radioactive waste. On the site, large amounts of contaminated solid and liquid material, as well as radioactive waste, have been generated following various recovery activities.[114] The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

Following the Fukushima Daiichi accident, there were difficulties in establishing locations to store the large amounts of contaminated material arising from off-site remediation activities. Several hundred temporary storage facilities had been established in local communities. Efforts to establish an interim storage facility were continuing.

5.3.1. Managing the waste

A large amount of waste (known as 'disaster waste') was generated by the earthquake and tsunami, some of which was contaminated (predominantly by ^{134}Cs and ^{137}Cs) as a result of releases from the Fukushima Daiichi NPP. On-site stabilization activities have increased the inventory of contaminated material and of solid and liquid radioactive waste necessitating management, while off-site remediation activities have increased the amount of contaminated material.

Box 5.4. Radioactive waste

Radioactive waste is material for which no further use is foreseen that contains radionuclides with a content or concentration above a specified level. Disposal is the internationally recognized end point for the management of radioactive waste. However, storage of some radioactive waste for periods of tens of years is often necessary while disposal facilities are being developed. Certain types of radioactive waste (low level radioactive waste) can be disposed of in 'near surface' waste disposal facilities.

The management (i.e. pretreatment, treatment, conditioning, transport, storage and future disposal) of large amounts of waste with differing physical, chemical and radiological properties presents a challenge. Equipment, activities and facilities have had to be developed and/or modified under circumstances made more difficult by the loss of infrastructure caused by the earthquake and tsunami and by high radiation levels. Amendments to legislation and to the national approach to waste management were also necessary [124, 266, 278, 294].

5.3.2. Off-site activities

Off-site remediation was initiated with the objective of reducing external exposures. The remedial actions included the removal of topsoil and vegetation and the decontamination of public and residential areas. The size of the area requiring remediation was influenced by the radiological criteria

[114] The distinction between contaminated material and radioactive waste depends upon the radionuclides and the activity concentrations associated with the materials.

and action levels adopted, which also had implications for the amount of contaminated material requiring management.

In general, a low reference level results in the generation of a larger amount of contaminated material. It is estimated that the stockpile of soil and other contaminated material generated from remediation activities after the accident will be approximately 16–22 million m^3 after the reduction in volume by incineration of plants and trees [273].

The stages of the waste management process used in Fukushima Prefecture are illustrated in Fig. 5.6. The management of waste generated in the remediation activities involves its collection in temporary storage facilities near the locations for decontamination. Many hundreds of temporary storage facilities have been constructed. After temporary storage, this waste will be transported into the interim storage facility. Some of the material has contamination at levels that are sufficiently low to allow the use of existing infrastructure for the disposal of municipal solid waste (e.g. municipal incinerator facilities and waste landfills). However, the process of obtaining the agreement of municipalities to use conventional incinerators to reduce the volume of off-site contaminated material has proved to be difficult.

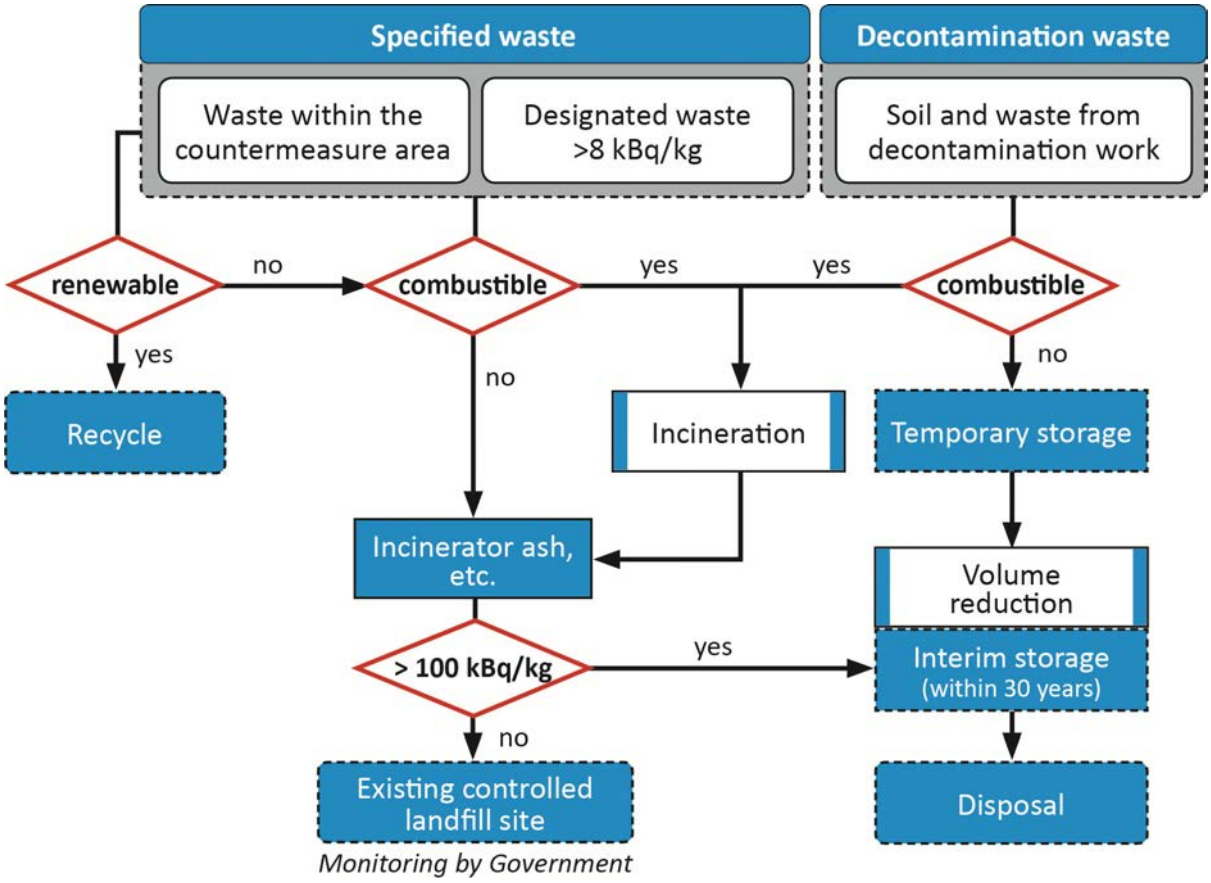


FIG. 5.6. Flow chart for the management of specified waste and decontamination waste in Fukushima Prefecture [295].

There were delays in site selection for temporary and interim storage facilities. Obtaining the agreement of the local population has been a contributing factor in the siting delays. However, following discussions of national and local government officials with local residents and landowners, the plan to construct an interim storage facility was accepted in Okuma Town in December 2014 and in Futaba Town in January 2015. In January 2015, the Ministry of the Environment (MOE) confirmed plans and arrangements for pilot-scale transport of contaminated soil to the interim storage facility from March 2015 [273]; for testing purposes, these transports started on 13 March 2015.

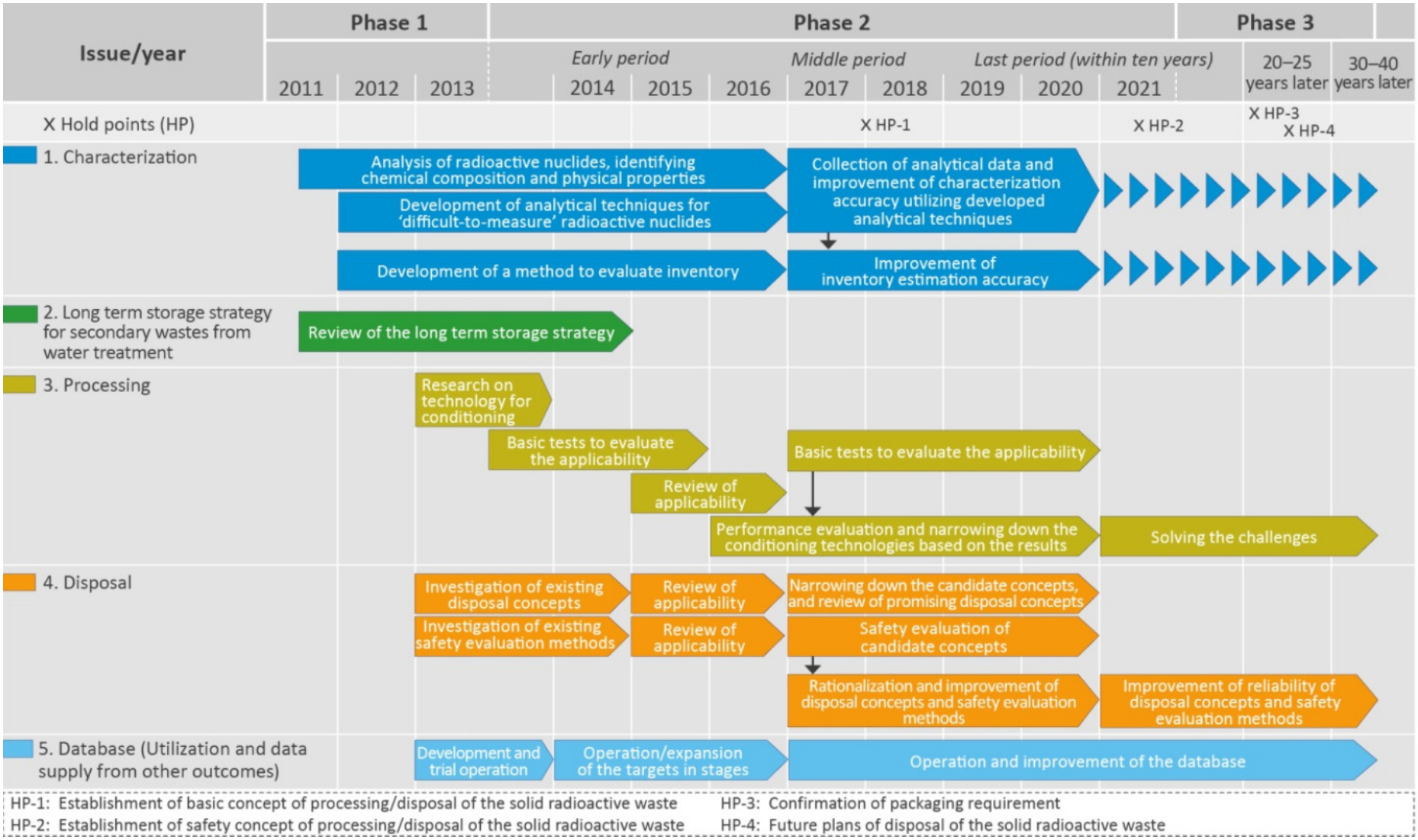


FIG. 5.7. Part of the strategy for on-site waste management [291].

5.3.3. On-site activities

At the Fukushima Daiichi NPP, large amounts of contaminated solid and liquid material as well as radioactive waste have been generated following various recovery activities. For example, as of 30 November 2014, 131 900 m^3 of debris and 79 700 m^3 of trees were being stored on the site [296, 297]. The generation of these large amounts of contaminated material and radioactive waste has required the establishment of effective strategies for waste management. In particular, there has been a need to develop facilities for treatment and storage of many hundreds of thousands of cubic metres of contaminated and treated water as well as for solid waste resulting from the treatment processes and the clearing of large areas of land. Part of the strategy for on-site waste management, including the facilities for water treatment and storage, is illustrated in Fig. 5.7.

There is a continuing need for storage capacities for various types of solid and liquid waste streams (Fig. 5.8). Consequently, volume reduction has become an important component in the management of on-site waste, for example through waste avoidance, installation of incinerators, and reuse and recycling of materials. Additional waste is expected from the decommissioning of the NPP [298]. The types and amounts of waste will depend on the approach adopted.



FIG. 5.8. Aerial view of the on-site area showing the water storage tanks [301].

There have been efforts to move radioactive waste away from the site boundary in order to limit dose rates at the boundary to less than 1 mSv/year. These activities have no impact on public exposure as there is no public presence at the site boundary [299].

The management of waste on the site poses many complex challenges, requiring further research and development. As new capabilities are obtained, a strategy for final disposal of on-site waste will need to be considered, involving decisions for both the near term and the long term [300].

5.4. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have had significant consequences for the way of life of the affected population. Evacuation and relocation measures and restrictions on food involved hardships for the people affected. The revitalization and reconstruction projects introduced in Fukushima Prefecture were developed from an understanding of the socioeconomic consequences of the accident. These projects address issues such as reconstruction of infrastructure, community revitalization and support and compensation.

Communication with the public on recovery activities is essential to build trust. To communicate effectively, it is necessary for experts to understand the information needs of the affected population and to provide understandable information through relevant means. Communication improved in the aftermath of the accident, and the affected population became increasingly involved in decision making and remediation measures.

The accident and the protective actions introduced in both the emergency phase and the recovery phase impacted the way of life of populations in the areas affected. By 30 January 2015, the number of evacuees was around 119 000, compared with a peak of around 164 000 in June 2012. The hardships associated with evacuation, relocation and restrictions on food are substantial [268, 269].

The earthquake, the tsunami and the accident resulted in the destruction, degradation or disuse of infrastructure (including schools, hospitals and commercial enterprises), had an impact on business and trade, and brought about demographic changes through the evacuation of large numbers of people. It was reported that young families were more likely to remain evacuated, and the elderly were more likely to return to their homes [302]. Recovery and revitalization plans at the national and local levels recognize the importance of physical and socioeconomic reconstruction and address issues such as reconstruction of infrastructure, community support and compensation [269].

The particular challenges for people living in temporary accommodation include a range of issues of general physical and mental well-being that are associated with high levels of unemployment and the difficulties associated with provisional accommodation [239]. The total number of evacuees living in temporary accommodation as a result of the earthquake, tsunami and nuclear accident is not known precisely but, by June 2013, 16 800 temporary housing units had been constructed and nearly 24 000 families were living in accommodation rented by the prefectural government [269]. In addition, there were plans to build 2586 units of permanent public housing by 2015 for people affected by the earthquake and tsunami. For those evacuated in the response to the accident, 4890 units of permanent public housing were planned [283].

5.4.1. Socioeconomic consequences

Evacuation resulted in the loss of farms and businesses. Fishing ceased within 30 km of the site (reduced to 20 km at the end of September 2011). Agricultural and other commercial activities have ceased in an area of about 700 km^2 outside the Special Decontamination Area [269, 303, 304].

Socioeconomic consequences in the agricultural sector and other enterprises were also seen outside the Special Decontamination Area and the Intensive Contamination Survey Area. In addition to the loss of employment and of livelihoods for those affected, restrictions on food, export losses involving food and consumer goods, the costs of monitoring to demonstrate compliance with radiological criteria and the payment of compensation to people affected have also had an effect. Indirect socioeconomic consequences include those arising from the loss of consumer confidence, not only in food products, but also in commodities from and businesses in the affected areas [269, 303, 305].

The combination of earthquake, tsunami and nuclear accident had a direct effect on the Japanese economy. Exports fell by 2.4% in April 2011 compared with the level in April 2010. At the same time, imports increased, especially those of fuels, chemicals and food, resulting in a deficit in the trade balance in April and May 2011 [303]. Imports of fossil fuel remained at a higher level at the time of writing [306].

Although at the time of the accident Japan was not party to any of the conventions on civil liability for nuclear damage (it joined the Convention on Supplementary Compensation for Nuclear Damage (CSC) on 15 January 2015), legislation enacted in 1961 was consistent with the basic principles of nuclear liability as embodied in those conventions. Under this legislation, TEPCO was exclusively liable for nuclear damage caused by the Fukushima Daiichi accident [307]. Its liability was unlimited in amount. Following the accident, TEPCO was not granted exemption from liability by the Government and Parliament on the assumption that the exemption clause related to a grave natural disaster, as specified in the Act on Compensation for Nuclear Damage, was inapplicable in this case. Various means to allow TEPCO to meet its obligations towards the victims of the accident have been implemented, including provisional compensation payments as an emergency measure, the provision of financial support to TEPCO by the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF), and NDF becoming the controlling shareholder of TEPCO. Moreover, the creation of the Dispute Reconciliation Committee for Nuclear Damage Compensation and the issuance of legally non-binding guidelines provided a mechanism for prompt out of court settlements of compensation for nuclear damage.

The established compensation policy applies to those ordered to evacuate and also covers impacts on livelihood and way of life, loss of profits due to restrictions and loss of trust by consumers, and infrastructure changes for people remaining in the area. In addition, there are specific provisions for parents with young families and for pregnant women [308].

According to guidelines established in December 2011, people subject to evacuation received compensation of the order of 100 000 yen per person and per month. Additional compensation of about 900 000 yen per person will be paid to those returning to live in the areas affected within a year after the lifting of the evacuation order [309].

5.4.2. Revitalization

A number of initiatives to stimulate the revitalization of Fukushima Prefecture have been implemented with government and local support. These include the reconstruction of infrastructure, housing and transport. Some actions focus on regaining consumers' trust in products, while also promoting local pride and tourism. Recognizing that the availability of work and employment is also a driving factor for the return of residents (or for the settlement of new populations), other initiatives focus on rebuilding businesses as well as creating new commercial opportunities.

Revitalization initiatives and reconstruction activities linked to recovery range from those at the national Government level to initiatives by non-governmental organizations and local communities. The Government of Japan established a Reconstruction Agency; Fukushima Prefecture has initiated various activities including the establishment of the Centre for Environmental Creation [234, 269];

and the Fukushima Revitalization Headquarters was set up by TEPCO in 2013. All projects aim to combine radiation protection actions with broader societal aspects, such as the revitalization of infrastructure and public engagement and — in the case of the Revitalization Headquarters — compensation [310].

The actions vary across the prefecture, often depending on the engagement of local leaders and the different challenges within the region. Examples of successful revitalization initiatives include cooperation between peach growers and distributors and the food industry to restore public trust in food produced in Fukushima Prefecture [269, 311].

5.4.3. Engagement of and communication with stakeholders

Engagement of stakeholders has increased and strategies for consultation and involvement have improved as remediation and recovery actions have progressed. The response to the accident has provided a number of examples that show the benefits of involving affected populations in activities for recovery, from consultation and dialogue to remediation actions (so-called self-help actions).

Open and effective communication with the public is an essential part of revitalization. An information hub for the area on decontamination (Decontamination Information Plaza) was opened in Fukushima City in January 2012 as a joint project of Fukushima Prefecture and the MOE [312].

Other communication activities at the local level include dialogues between experts and the public and specific advice for self-help actions. These activities have helped to restore communication with Fukushima residents and to rebuild trust.

A flow chart of the implementation process for remediation and associated interactions with stakeholders is shown in Fig. 5.9. All steps in the development of plans and their implementation included stakeholder participation and consultation. In the case of remediation of privately owned land, agreement is required from the landowners before any remediation activities can be started.

In a nuclear accident, the media, in both traditional and new forms, play an important role in communicating with the public. The Fukushima Daiichi accident was characterized by a high level of media coverage, through the Internet, social media and, in the initial phase, continuous television and radio broadcasts. The coverage of the accident lasted for several months, focusing mainly on problems linked to the accident site, but also on the protective actions taken by Japanese authorities. Social media intensified reporting on the event, as well as disseminating the views of individuals and non-governmental organizations. A considerable amount of information was available, of varying quality and levels of credibility [310].

Radiation safety experts needed to learn what kind of information the public was requesting and to provide it in an understandable manner. Critical questions asked by the affected communities and by the media focused on what levels of radiation are ‘safe’ [314].

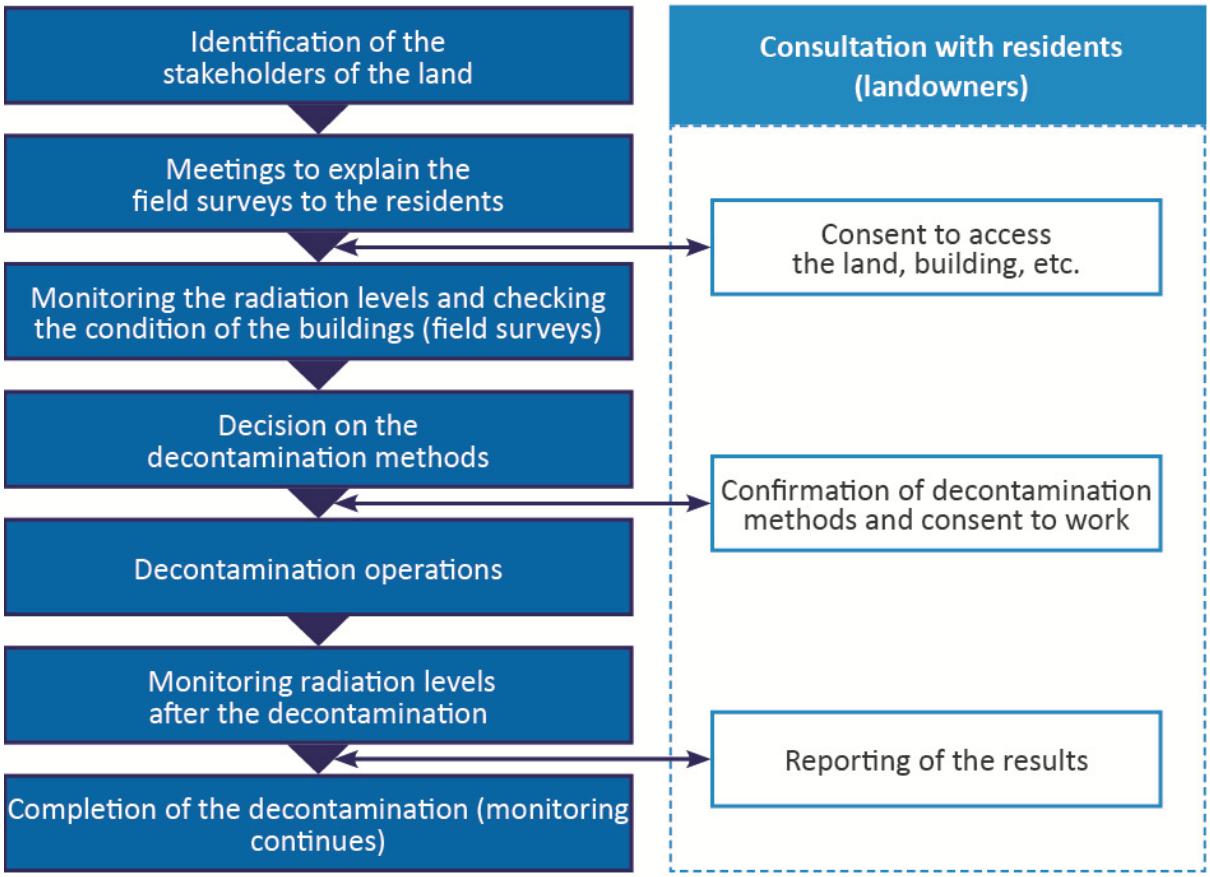


FIG. 5.9. Flow chart of the process for remediation and for consultation with residents [313].

5.5. OBSERVATIONS AND LESSONS

A number of observations and lessons have been compiled as a result of the assessment of the post-accident activities.

— **Pre-accident planning for post-accident recovery is necessary to improve decision making under pressure in the immediate post-accident situation. National strategies and measures for post-accident recovery need to be prepared in advance in order to enable an effective and appropriate overall recovery programme to be put in place in case of a nuclear accident. These strategies and measures need to include the establishment of a legal and regulatory framework; generic remediation strategies and criteria for residual radiation doses and contamination levels; a plan for stabilization and decommissioning of damaged nuclear facilities; and a generic strategy for managing large quantities of contaminated material and radioactive waste.**

These strategies and measures need to include:

- The establishment of a legal and regulatory framework that specifies the roles and responsibilities of the various institutions to be involved. This framework needs to address off-site remediation, on-site stabilization and preparations for decommissioning, management of contaminated material and radioactive waste, and community revitalization and stakeholder engagement.
- Generic remediation strategies and criteria (reference and derived action levels) for residual radiation doses and contamination levels.
- A plan for the stabilization of conditions on the site of a damaged nuclear facility and preparations for its decommissioning.

- Development of a generic strategy for managing large quantities of contaminated material and radioactive waste, supported by generic safety assessments for storage and disposal facilities.
- Sufficient flexibility to ensure that the management of post-accident conditions can be adapted in response to changing conditions and acquired information and experience.

— **Remediation strategies need to take account of the effectiveness and feasibility of individual measures and the amount of contaminated material that will be generated in the remediation process.**

Having established reference levels for residual radiation doses and contamination levels, it is essential to control carefully the amount of contaminated material generated by implementing the remediation strategy in order to minimize the amount of waste to be managed. The absence of preparations for recovery from a nuclear accident in Japan meant that, initially, large volumes of potentially contaminated material were generated. As time elapsed and planning developed, remediation actions were optimized, leading to improved control of the amount of waste to be managed.

Pilot projects were useful in determining both the effectiveness of particular remediation techniques and the amount of waste generated by particular techniques. Pilot projects also contributed to establishing procedures for the radiation protection of workers.

— **As part of the remediation strategy, the implementation of rigorous testing of and controls on food is necessary to prevent or minimize ingestion doses.**

The systematic implementation of rigorous testing of and controls on food after the accident demonstrated that ingestion doses can be kept at low levels.

To establish confidence in locally produced food, local monitoring stations were set up to allow people in affected areas to bring food to be measured. This control of ingestion doses simplified the recovery by allowing remediation to focus on techniques that reduce external doses.

— **Further international guidance is needed on the practical application of safety standards for radiation protection in post-accident recovery situations.**

Further practical guidance is needed on the application of the IAEA safety standards in existing exposure situations. The reference levels adopted for the early post-accident years need to be periodically reviewed and modified, as appropriate, in response to the changing radiological conditions. The guidance needs to include a methodology for the selection of case and site specific reference levels, in terms of dose and derived quantities, as well as mechanisms to integrate technical and scientific advice with other socially relevant factors to establish a coherent, transparent and collectively accepted decision making process.

— **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.**

Preparations for the decommissioning of a facility damaged in an accident would first involve stabilization to ensure that structures, systems and components are in place to reliably maintain stable conditions for the long term until their functions are no longer needed. Post-accident preparations for decommissioning take decades. Arrangements are necessary to maintain the necessary expertise and workforce throughout this entire period.

Decision making on interim decommissioning stages and on the final conditions of the site and the damaged reactors needs to include a dialogue with stakeholders. Decision making on decommissioning depends on the conditions of the damaged reactors, fuel and debris, which cannot be determined in the period immediately following an accident. Factors to be considered in decision making include: dose levels for workers in decommissioning; the volumes and types of waste generated; and the efforts necessary for waste treatment. In the early stage of cleanup activities, it is unrealistic to predict the final conditions of the plant site, but expectations and plans for the land need to be considered in the decision making process.

— **Retrieving damaged fuel and characterizing and removing fuel debris require solutions that are specific to the accident, and special methods and tools may need to be developed.**

A reactor accident involving damage to nuclear fuel results in particular conditions in the reactor that are unique to the accident. The removal and management of damaged fuel elements and of

debris from melted fuel are complex tasks. The debris needs to be characterized, removed, packaged and placed in storage until disposal is implemented, under difficult conditions, associated largely with high radiation levels.

— **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**

A waste management strategy is needed for the implementation of pre-disposal management (e.g. handling, treatment, conditioning and storage) of accident-generated contaminated material and radioactive waste. It also needs to identify appropriate routes for the disposal of materials. Waste management strategies may involve the use of existing processing, storage and disposal facilities, such as incinerators or leachate controlled landfills. However, other approaches may be necessary, depending on the volumes and characteristics of the waste involved. The development of such strategies could be supported by the development of a generic safety case.

Strategies for the post-accident management of large volumes of contaminated water are also necessary, including consideration of its controlled discharge to the environment. Although there is international guidance for discharges during the normal operation of nuclear facilities, further guidance on its application in post-accident situations is needed.

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**

Nuclear accidents and the protective and remedial actions introduced in both the emergency phase and the post-accident recovery phase, with the objective of reducing doses, have far-reaching consequences on the way of life of the affected population. Engagement of stakeholders at various stages of remediation and recovery is essential.

— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**

Governments need to provide a realistic description of a recovery programme to the public that is consistent, clear and timely. A variety of information channels, including social media, need to be used to reach all interested groups.

Perceptions of radiation risks and answers to questions about ‘safe’ radiation levels have many dimensions, including scientific, societal and ethical. These answers need to be clearly communicated to relevant communities through educational programmes — ideally before an accident has occurred.

It is important that the affected population receive support for local recovery efforts. Support for self-help actions related to remediation and for rebuilding businesses can increase involvement in the recovery programme, and build the trust of the affected population.

6. THE IAEA RESPONSE TO THE ACCIDENT

This section provides an overview of key IAEA activities following the Fukushima Daiichi accident, both in the immediate phase and in the longer term. These include initial activities, IAEA missions to Japan, the Ministerial Conferences on Nuclear Safety and the IAEA Action Plan.

The IAEA is the depositary for the Convention on Nuclear Safety, and its role is to provide the Secretariat for the meetings by convening, preparing and servicing these meetings, as well as transmitting relevant information to the Contracting Parties. The activities related to the meetings of the Contracting Parties to the Convention on Nuclear Safety following the Fukushima Daiichi accident are also presented in this section.

6.1. IAEA ACTIVITIES

6.1.1. Initial activities

The responsibility for responding to a nuclear or radiological emergency and for the protection of workers, the public and the environment, rests with the operating organization at the level of the facility concerned, and with the affected State at the local, regional and national levels.

The IAEA has a central role in the international framework[115] for emergency preparedness and response. This role includes: (1) notification and official information exchange through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance upon request; and (4) coordination of the inter-agency response.[116]

The IAEA discharges this role through its Incident and Emergency System (IES). This system includes a 24-hour contact point and an operational focal point, the Incident and Emergency Centre (IEC).

At 06:42 UTC[117] on 11 March 2011, the IAEA activated the IES following a notification from the IAEA's International Seismic Safety Centre. This notification indicated the occurrence of an earthquake, the potential for damage at four NPPs[118] on the north-eastern coast of Japan and the risk of a tsunami [143]. At 07:21 UTC, the IAEA established initial communication with the official contact point designated by Japan under the Early Notification Convention and the Assistance Convention.

---

[115] The international emergency preparedness and response framework at the time of the accident consisted of: (a) international legal instruments and agreements, in particular the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention); (b) IAEA safety standards and technical guidance in the area of emergency preparedness and response; and (c) international operational arrangements and tools, in particular the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET), and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

[116] The primary coordinating body for nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). This body was established following the Chernobyl accident in 1986 and currently includes 18 international organizations. One of the primary roles of IACRNE is the development and maintenance of the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN 2010 at the time of the accident).

[117] Universal Time Coordinated (UTC) is nine hours behind Japan Standard Time.

[118] Fukushima Daiichi and Fukushima Daini of the Tokyo Electric Power Company (TEPCO), Onagawa (Tohoku Power Company) and Tokai (Japan Atomic Power Company).

In the initial days of the accident, it became evident that the reactors and the fuel in the spent fuel pools at the Fukushima Daiichi NPP could be at risk of severe damage. Consequently, the IAEA established teams to evaluate key nuclear and radiological safety issues. The IAEA Laboratories[119] reviewed environmental data provided by the Japanese authorities on monitoring of the marine environment and received terrestrial environment samples for independent analysis.

The IAEA Director General visited Tokyo from 17 to 19 March for high level consultations, to express the solidarity of the international community and its full support to Japan in dealing with the consequences of the earthquake, tsunami and nuclear accident, and to convey offers of assistance from more than a dozen countries. The Director General also discussed the possibility of the IAEA providing or coordinating specific types of assistance, such as expert missions and fact finding missions, and emphasized the importance of transparency and the timely provision of official information by Japan.

On 28 March, at a special briefing on the accident for IAEA Member States, the Director General announced that a high level IAEA Conference on Nuclear Safety would take place in Vienna before the summer. He stated that it was "vitally important that we learn the right lessons from what happened on 11 March and afterwards, in order to strengthen nuclear safety throughout the world" [315].

Between 18 March and 18 April, at the request of Japan, the IAEA sent four radiological monitoring teams to Japan to help validate the results of the more extensive measurements taken by the Japanese authorities. The teams undertook measurements at a number of locations inside and outside the 20 km evacuation zone around the Fukushima Daiichi NPP and in the vicinity of Tokyo. A senior IAEA official was sent to Japan to coordinate the relevant IAEA activities and to transmit offers of assistance from Member States to the Japanese authorities. IAEA liaison officers were sent to Tokyo to facilitate and improve communication with Japan's regulatory body, which at that time was NISA.

A joint Food Safety Assessment Team from the IAEA and FAO visited Japan from 26 to 31 March. The team provided advice and assistance to the authorities at the national and local levels on technical issues relating to food safety and agricultural countermeasures. Advice was provided on sampling and analytical strategies and interpretation of monitoring data to ensure that reliable, continuous updates could be provided on the extent of food contamination in the affected areas. These data were used for the development of mitigation and remediation strategies by the Japanese authorities.

An IAEA team of experts on boiling water reactors was sent to Japan on 3 April, concluding its work on 12 April. The team toured both the Fukushima Daiichi and Fukushima Daini sites, meeting plant personnel in order to better understand the accident, the mitigation actions taken up to that time and the basis of the major decisions that had been made. They also held meetings with staff of several government offices and had detailed technical discussions with TEPCO and NISA in Tokyo.

The first statement by the IAEA on the accident was made public less than three hours after the earthquake on 11 March. Five additional statements were published later that day, conveying information received from Japan. More than 120 updates were published up to 22 April 2011. The IAEA held 16 news conferences between 14 March and 2 June 2011, in addition to those held during the Director General's visit to Japan. The IAEA's public information activities also included responding to thousands of telephone calls and providing detailed technical responses to hundreds of queries from the media.

[119] The IAEA Laboratories, located in Seibersdorf, Austria, and in Monaco, specialize in evaluating terrestrial and marine environmental samples, respectively.

The IAEA posted daily briefings for Member States and the public on its public web site. These briefings covered: the status of Units 1–6 at the Fukushima Daiichi NPP; radiation monitoring data for radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs; the results of radiation monitoring of food and information on restrictions on the distribution and consumption of food and drinking water; and data on monitoring of the marine environment. The IAEA also provided briefings on the accident to the Permanent Missions of IAEA Member States in Vienna.

6.1.2. IAEA missions to Japan

Based upon an agreement with the Government of Japan, an International Fact Finding Expert Mission was undertaken by experts from the IAEA and Member States from 24 May to 2 June 2011. The mission gathered information for a preliminary assessment of the accident at the Fukushima Daiichi NPP and on events at other sites (Fukushima Daini and Tokai Daini). In addition, generic safety issues associated with natural events were identified that needed further exploration or assessment on the basis of the IAEA safety standards.

The scope of the mission included: external events of natural origin; plant safety assessment and the application of defence in depth; plant response after an earthquake and tsunami; management of a severe accident; management of spent fuel in a severely degraded facility; emergency preparedness and response; and radiological consequences. The mission findings [34] included 15 conclusions and 16 lessons, which were reported to the IAEA Ministerial Conference on Nuclear Safety in June 2011.

Other IAEA missions to Japan are summarized in Table 6.1.

Following the recommendation of the second decommissioning mission, projects were started to enhance transparency and to provide independent assessments of monitoring of the marine environment by Japan. Proficiency tests were conducted at the IAEA Environment Laboratories in Monaco to monitor the performance and analytical capabilities of participating laboratories. The results of the marine monitoring programme are regularly updated on the IAEA's web site.

6.1.3. IAEA Ministerial Conference on Nuclear Safety

In June 2011, a Ministerial Conference on Nuclear Safety was convened by the Director General at IAEA Headquarters with the objective of strengthening nuclear safety by drawing on the lessons from the accident. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a preliminary assessment of the accident. The conference also considered actions for safety improvements, issues regarding emergency preparedness and response, and implications for the global nuclear safety framework.

The outcome was a Ministerial Declaration on Nuclear Safety [320], which outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken. The key measures were: to strengthen the IAEA safety standards; to systematically review the safety of all NPPs, including by expanding the IAEA's programme of expert peer reviews; to enhance the effectiveness of national nuclear regulatory bodies and ensure their independence; to strengthen the global emergency preparedness and response system; and to expand the IAEA's role in receiving and disseminating information. The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety in consultation with Member States.

TABLE 6.1. IAEA MISSIONS TO JAPAN

Date	Mission	Objectives
7–15 Oct. 2011	International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [316]	Assist Japan's plans to remediate large areas contaminated by the accident. Review Japan's ongoing remediation strategies, plans and activities, including contamination mapping. Share findings with the international community to disseminate lessons from the accident.
23–31 Jan. 2012	IAEA Mission to Review NISA's Approach to Comprehensive Assessments for Safety of Existing Power Reactor Facilities [317]	Review (at the request of the Japanese Government) NISA's Comprehensive Assessments for the Safety of Existing Power Reactor Facilities, and the results of the licensee's assessments.
30 Jul.–11 Aug. 2012	IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japanese Earthquake and Tsunami [318]	Examine the performance of structures, systems and components following the earthquake and tsunami.
15–22 Apr. 2013	International Peer Review of the Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (first mission) [319]	Review the 'Decommissioning Roadmap'; challenges; condition of the reactors; management of waste; protection of employees; and structural integrity of reactor buildings and other structures.
14–21 Oct. 2013	Follow-up International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP [265]	Evaluate the progress of ongoing remediation work in Japan and provide advice on addressing remediation challenges.
6–12 Nov. 2013	Expert visit on marine monitoring	Observe seawater sampling and data analysis in Fukushima (7 and 8 Nov. 2013) and meet the relevant Japanese authorities in Tokyo to collect information on marine monitoring conducted by Japan under its Sea Area Monitoring Plan.
25 Nov.– 4 Dec. 2013	International Peer Review of the Mid-and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (second mission) [288]	Review the updated 'Decommissioning Roadmap'; removal of spent fuel from storage pools; management of contaminated water; waste management; and marine monitoring.
10–16 Sept. and 4–14 Nov. 2014	Expert mission on marine monitoring confidence building and data quality assurance	Focus on availability of marine monitoring results.
8–15 Feb. 2015	International Peer Review of the Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 (third mission) [289]	Review implementation of the Decommissioning Roadmap'; management of contaminated water; groundwater ingress; removal of spent fuel and fuel debris; and institutional and organisational issues.

6.1.4. The IAEA Action Plan on Nuclear Safety

The draft IAEA Action Plan on Nuclear Safety was approved by the Board of Governors in September 2011. The Action Plan was then presented at the regular session of the 2011 IAEA General Conference, where it was unanimously endorsed by Member States [144]. The General Conference subsequently called upon the IAEA Secretariat and Member States to implement the actions as an overarching priority in a comprehensive and coordinated manner [321].

Activities under the Action Plan started immediately after its adoption. The full and effective implementation of the activities in this plan required joint efforts and full commitment by the IAEA Secretariat, Member States and other stakeholders.

Since the adoption of the Action Plan, significant progress has been made in several key areas, such as: assessments of the safety vulnerabilities of NPPs; strengthening of the IAEA's peer review services; review and revision, as necessary, of the relevant IAEA safety standards; improvements in emergency preparedness and response capabilities; capacity building; and enhancing communication and information sharing with Member States, international organizations and the public. Regular progress reports were presented to the IAEA Board of Governors and the IAEA General Conference [322–324].

In the resolution adopting the Action Plan, the IAEA's role in responding to a nuclear emergency was expanded to include providing Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information on its potential consequences. This is to include an analysis of available information and a prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

A number of international experts meetings (IEMs) were organized in different areas of safety to analyse the technical aspects and to learn the lessons from the Fukushima Daiichi accident. Reports on these key safety areas, including the results of the IEMs, were published by the IAEA (see Table 6.2).

Additional reports were prepared in 2013 on the following subjects:

— Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on a series of technical meetings held in 2012–2013 [327].
— Strengthening Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on the results of the International Conference on Effective Nuclear Regulatory Systems, Ottawa, Canada, 2013 [328].

6.1.5. Cooperation with Fukushima Prefecture

A memorandum of cooperation between the IAEA and Fukushima Prefecture was signed in December 2012 [329]. On the basis of this memorandum, practical arrangements on cooperation in the areas of radiation monitoring and remediation [330], human health [331], and emergency preparedness and response [332] were signed, with Fukushima Prefecture, the Fukushima Medical University and the Ministry of Foreign Affairs of Japan, respectively.

An IAEA Response and Assistance Network (RANET) Capacity Building Centre was designated in Fukushima City in May 2013. The centre is used for a range of IAEA activities aimed at enhancing capacity for emergency preparedness and response, both in Japan and worldwide. A number of training workshops were held at the centre dealing with monitoring during a nuclear and radiological emergency, notification, reporting and requesting assistance, and emergency preparedness and response.

TABLE 6.2. INTERNATIONAL EXPERTS MEETINGS (IEMs)

Date	Title	Focus
19–22 Mar. 2012	IEM 1: Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [42]	Analyse technical aspects; understand root causes; share lessons from the accident.
18–20 Jun. 2012	IEM 2: Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency [314]	Identify and analyse lessons from the accident and discuss best practices for improving the dissemination of information.
4–7 Sep. 2012	IEM 3: Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [325]	Share lessons; exchange information and identify issues to be further investigated on: seismic and tsunami hazard assessment; special flooding issues; uncertainties associated with hazard assessments; approaches to establishing design values; addressing beyond design basis events; safety against earthquakes and tsunamis.
28 Jan.–1 Feb. 2013	IEM 4: Decommissioning and Remediation after a Nuclear Accident [293]	Examine short term and long term issues for decommissioning of accident damaged facilities; management of radioactive waste arising from a nuclear accident; and remediation of the off-site environment.
21–24 May 2013	IEM 5: Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [67]	Explore ways to improve nuclear safety culture across a range of key institutions, including operating organizations and regulatory bodies.
17–21 Feb. 2014	IEM 6: Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding [326]	Focus on radiation protection issues highlighted by the Fukushima Daiichi accident and how these could be addressed at both the national and international levels.
17–20 Mar. 2014	IEM 7: Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Gather and share knowledge and experience gained in the light of the Fukushima Daiichi accident concerning severe accident management; identify lessons and best practices.
16–20 Feb. 2015	IEM 8: Strengthening Research and Development Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Facilitate the exchange of information arising from new R&D activities undertaken by IAEA Member States, as well as by the OECD Nuclear Energy Agency (OECD/NEA) and other international organizations dealing with severe accidents at NPPs, including those affecting spent fuel pools; further strengthen international collaboration among Member States and international organizations.
20–24 Apr. 2015	IEM 9: Assessment and Prognosis in Response to a Nuclear or Radiological Emergency	Facilitate the exchange of timely, clear, factually correct information during a nuclear or radiological emergency and its potential consequences, including analysis of available information and prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

6.1.6. Fukushima Ministerial Conference on Nuclear Safety

In December 2012, the Government of Japan organized a Ministerial Conference in Fukushima Prefecture, co-sponsored by the IAEA, with the principal objective of contributing to strengthening nuclear safety worldwide [333]. The conference provided an opportunity to share with the international community further knowledge and lessons learned from the accident and to discuss the progress of international efforts aimed at strengthening nuclear safety, including progress in the implementation of the Action Plan.

Discussions included: levels of radiation at Fukushima Daiichi; post-accident challenges for decommissioning and remediation; and the status of damage and recovery in the areas around the plant. The conference highlighted the importance of taking actions on the basis of scientific and factual information in the event of a nuclear or radiological emergency, and of enhancing international cooperation.

6.2. MEETINGS OF THE CONTRACTING PARTIES TO THE CONVENTION ON NUCLEAR SAFETY

Box 6.1. The Convention on Nuclear Safety

The Convention on Nuclear Safety was adopted in Vienna on 17 June 1994 [334]. It is the first legally binding international treaty to address the safety of nuclear installations (land based civil NPPs) and aims: to achieve and maintain a high level of nuclear safety worldwide; to establish and maintain effective defences against potential radiological hazards to protect individuals, society and the environment; and to prevent accidents with radiological consequences and to mitigate such consequences should they occur. The Convention entered into force on 24 October 1996. As of March 2015, there were 77 Contracting Parties.

The obligations of the Contracting Parties are based to a large extent on the principles now contained in the IAEA Fundamental Safety Principles (SF-1) [335]. These obligations cover, in particular: the siting, design, construction and operation of nuclear installations; the establishment and maintenance of a legislative and regulatory framework; the establishment of a regulatory body with adequate authority, competence, and financial and human resources; the availability of adequate financial and human resources to support the safety of nuclear installations; the assessment and verification of safety; quality assurance; and emergency preparedness.

Contracting Parties are required to submit a report on the measures they have taken to implement each of the obligations of the Convention. These reports are reviewed during review meetings of the Contracting Parties held every three years under the auspices of the IAEA.

6.2.1. Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety

At the Fifth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, held from 4 to 14 April 2011, the Parties adopted a statement in which they, inter alia, reaffirmed their commitment to the objectives of the Convention. The Contracting Parties agreed to hold an extraordinary meeting to review and discuss initial analyses of the accident and the effectiveness of the Convention.

The Extraordinary Meeting was convened at IAEA Headquarters in Vienna from 27 to 31 August 2012. The Contracting Parties discussed: external events; design issues; severe accident management and recovery (on-site); national organizations; emergency preparedness and response; post-accident management (off-site); and international cooperation.

The Contracting Parties also agreed by consensus on a number of concrete actions to enhance the effectiveness of the peer review process. The three underlying guidance documents[120] of the Convention were amended in order to enhance the transparency of the review process, encourage Contracting Parties to refer to the IAEA safety standards in their National Reports, and reinforce efforts for continuous improvement by performing periodic reassessments of safety through periodic safety reviews or alternative methods.

[120] The Rules of Procedure and Financial Rules [336], the Guidelines regarding the Review Process [337] and the Guidelines regarding the National Reports [338].

A Working Group on Effectiveness and Transparency was established to report to the Sixth Review Meeting of the Contracting Parties on further actions to strengthen the Convention on Nuclear Safety and on proposals to amend it, where necessary. The Contracting Parties also considered a list of action oriented objectives for strengthening nuclear safety, which was attached to the Summary Report of the Extraordinary Meeting [339].

6.2.2. Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety was held from 24 March to 4 April 2014. During a special session of the meeting, Contracting Parties reported on the actions carried out in light of the Fukushima Daiichi accident. It was noted that, while nuclear safety and arrangements for emergency preparedness and response had improved, more remained to be done. National safety frameworks were being further enhanced, with steps taken to establish the effective independence of regulatory bodies and to update regulations. International cooperation had also increased, with greater participation in peer reviews and exchange of information [340].

Contracting Parties to the Convention on Nuclear Safety reported on the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; enhancement of power systems to improve reliability; re-evaluation of site-specific external natural hazards and multi-unit events; improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and improvement of severe accident management provisions and guidelines.

The Contracting Parties also adopted proposals to further amend the underlying guidance documents of the Convention and made recommendations for action by the IAEA Secretariat, the Contracting Parties and other organizations.

Finally, the Contracting Parties decided by vote to convene a Diplomatic Conference within one year to consider a proposal by Switzerland to amend Article 18 of the Convention, on the design and construction of both new and existing NPPs.

6.2.3. Diplomatic Conference and the Vienna Declaration on Nuclear Safety

The Diplomatic Conference was convened by the Director General at IAEA Headquarters on 9 February 2015 and was attended by 71 Contracting Parties. The Parties unanimously adopted the Vienna Declaration on Nuclear Safety. This Declaration included the following principles for the implementation of the third objective of the Convention, which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur:

> "1. New nuclear power plants are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.
>
> 2. Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime in order to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.
>
> 3. National requirements and regulations for addressing this objective throughout the lifetime of nuclear power plants are to take into account the relevant IAEA safety standards and, as

appropriate, other good practices as identified *inter alia* in the Review Meetings of the CNS [Convention on Nuclear Safety]" [341].

The Vienna Declaration took into account the significant number of efforts and initiatives at the international, national and regional levels that had taken place since the accident at the Fukushima Daiichi NPP to enhance nuclear safety worldwide.

REFERENCES

[1] NATIONAL POLICE AGENCY, Damage Situation and Police Countermeasures Associated with the 2011Tohoku District–off the Pacific Ocean Earthquake (2015), https://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3

[3] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO's Fukushima Nuclear Power Stations (2011), http://www.iaea.org/newscenter/focus/fukushima/japan-report

[4] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: The Accident at TEPCO's Fukushima Nuclear Power Stations, Second Report (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html

[5] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Final Report, Cabinet Secretariat of the Government of Japan (2012), http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html

[6] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Interim Report, Cabinet Secretariat of the Government of Japan (2011), http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html

[7] NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission, National Diet of Japan, Tokyo (2012).

[8] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report, TEPCO, Tokyo (2012).

[9] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression, TEPCO, Tokyo (2013).

[10] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident, Progress Rep. No. 2, TEPCO, Tokyo (2014).

[11] NUCLEAR REGULATION AUTHORITY, Analysis of the TEPCO Fukushima Daiichi NPS Accident, Interim Rep. (2014), https://www.iaea.org/sites/default/files/anaylysis_nra1014.pdf

[12] JAPAN METEOROLOGICAL AGENCY, Information on the 2011 off the Pacific Coast of Tohoku Earthquake (2015), http://www.jma.go.jp/jma/en/2011_Earthquake/Information_on_2011_Earthquake.html

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Power Reactor Information System (PRIS) (2015), http://www.iaea.org/pris/

[14] JAPAN METEOROLOGICAL AGENCY, Tsunami Information (Estimated Tsunami Arrival Time and Height) (2011), http://www.jma.go.jp/en/tsunami/info_04_20110311145026.html

[15] COASTAL ENGINEERING COMMITTEE OF JAPAN SOCIETY OF CIVIL ENGINEERS, The 2011 off the Pacific Coast of Tohoku Earthquake Tsunami Information (2013), http://www.coastal.jp/tsunami2011/index.php?Field%20survey%20results

[16] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Fukushima Daiichi Unit 1 Establishment Permit, NISA (1966) (in Japanese).

[17] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Dry Storage Cask Leak Test Results Reported to METI (2013) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/20130530_03.html
[18] TOKYO ELECTRIC POWER COMPANY, Operation Manuals of TEPCO Fukushima Daiichi NPP in Case of Accident (2011) (in Japanese), http://www.nsr.go.jp/archive/nisa/earthquake/manual/manual_index.html
[19] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006 (Japan), http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf
[20] TOKYO ELECTRIC POWER COMPANY, Building diagrams for 1F ground level and cross section of Unit 4 and the common spent fuel pool, official communication (2014).
[21] Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 195 of April 5, 2000 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/H12/H12SE195.html
[22] NUCLEAR SAFETY COMMISSION, Accident Management: Measures against Severe Accidents at Light Water Nuclear Power Reactor Facilities (1992) (in Japanese), http://www.mext.go.jp/b_menu/hakusho/nc/t19920528001/t19920528001.html
[23] NUCLEAR SAFETY COMMISSION, Accident Management for Severe Accidents at Light Water Power Reactor Installations, NSCRG: L-AM-II.01, NSC, Tokyo (1997).
[24] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (2011), http://www.meti.go.jp/english/speeches/pdf/20110417_a.pdf
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1, IAEA, Vienna (2000). (This publication is superseded by SSR-2/1 (2012)).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, Safety Series No. 50-SG-S1, IAEA, Vienna (1979). (This publication is superseded by SSG-9 (2010)).
[29] Nuclear Reactor Establishment Change Permit Application, Nuclear Industry Report to the Government No. 5–11 (1993).
[30] SAKAI, T., TOKYO ELECTRIC POWER COMPANY, "Past tsunami assessments and tsunami on 11 March 2011", paper presented at 5th Meeting of Working Group 2, Vienna, 2014.
[31] JAPAN SOCIETY OF CIVIL ENGINEERS, Tsunami Assessment Method for Nuclear Power Plants in Japan (2002) (in Japanese), http://committees.jsce.or.jp/ceofnp/node/5
[32] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities, NSC, Tokyo (2006).
[33] HEADQUARTERS FOR EARTHQUAKE RESEARCH PROMOTION, On the Long-term Evaluation of Seismic Activity off Eastern Japan between the Sanriku Coast and the Boso Peninsula (2002) (in Japanese), http://www.jishin.go.jp/main/chousa/kaikou_pdf/sanriku_boso.pdf
[34] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Fact Finding Expert Mission of the Fukushima Dai-ichi NPP Accident Following the Great East Japan Earthquake and Tsunami (2011), http://www-pub.iaea.org/MTCD/meetings/PDFplus/2011/cn200/documentation/cn200_Final-Fukushima-Mission_Report.pdf
[35] GOVERNMENT OF INDIA, Actions Taken for Indian NPPs Subsequent to Fukushima Nuclear Accident. National Report to the Convention on Nuclear Safety (2012), http://www.aerb.gov.in/AERBPortal/pages/English/t/documents/CNS2012.pdf
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Extreme External Events in the Design and Assessment of Nuclear Power Plants, IAEA-TECDOC-1341, IAEA, Vienna (2003).

[37] INTERNATIONAL ATOMIC ENERGY AGENCY, International Reporting System for Operating Experience (2014) (unpublished).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Follow-up IAEA Mission in Relation to the Findings and Lessons Learned from the 16 July 2007 Earthquake at Kashiwazaki-Kariwa NPP, IAEA, Vienna (2009).
[39] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Defence in Depth in Nuclear Safety, INSAG-10, IAEA, Vienna (1996).
[40] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Basic Safety Principles for Nuclear Power Plants: 75-INSAG-3 Rev. 1, INSAG-12, IAEA, Vienna (1999).
[41] INTERNATIONAL ATOMIC ENERGY AGENCY, Severe Accident Management Programmes for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.15, IAEA, Vienna (2009).
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).
[43] INTERNATIONAL ATOMIC ENERGY AGENCY, Topical Issues in Nuclear Installation Safety: Defence in Depth — Advances and Challenges for Nuclear Installation Safety, IAEA-TECDOC-CD-1749, IAEA, Vienna (2014).
[44] SANDIA NATIONAL LABORATORIES, Fukushima Daiichi Accident Study (Status as of April 2012) SAND2012-6173, SNL, Albuquerque, NM (2012).
[45] ELECTRIC POWER RESEARCH INSTITUTE, Fukushima Technical Evaluation, Phase 1 — MAAP5 Analysis, EPRI, Palo Alto (2013).
[46] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident. Progress Rep. No. 2 (2014), http://www.tepco.co.jp/en/press/corp-com/release/betu14_e/images/140806e0101.pdf
[47] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-3, IAEA, Vienna (2010).
[48] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection: 2007 Edition, IAEA, Vienna (2007).
[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, IAEA, Vienna (2010).
[50] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Operation, IAEA Safety Standards Series No. NS-R-2, IAEA, Vienna (2000). (This publication is superseded by SSR-2/2 (2011)).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Regulatory Review Service (IRRS) to Japan, IAEA-NSNI-IRRS-2007/01, IAEA, Vienna (2007).
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.10, IAEA, Vienna (2003). (This publication is superseded by SSG-25 (2013)).
[53] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from the JCO Nuclear Criticality Accident in Japan in 1999 (2009), http://www-ns.iaea.org/downloads/iec/tokaimura-report.pdf
[54] SHIROYAMA, H., "Regulatory failures of nuclear safety in Japan — the case of Fukushima accident", paper presented at Earth System Governance Tokyo Conf.: Complex Architectures, Multiple Agents, Tokyo (2013), http://tokyo2013.earthsystemgovernance.org/wp-content/uploads/2013/01/0202-SHIROYAMA_Hideaki-.pdf
[55] GOVERNMENT OF JAPAN, Convention on Nuclear Safety National Report of Japan for the Fifth Review Meeting (2010), http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/conventions/2011.pdf
[56] KATO, S., "Recent development in safety regulation of nuclear fuel cycle activities", Proc. Int. Conf. on Topical Issues in Nuclear Safety, Vienna, 2001, IAEA, Vienna (2002).
[57] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1, IAEA, Vienna (2010).

[58] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants: Experience of Member States, IAEA-TECDOC-1643, IAEA, Vienna (2010).
[59] NUCLEAR REGULATION AUTHORITY, FY2012 Annual Report, NRA, Tokyo (2012).
[60] NUCLEAR REGULATION AUTHORITY, Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors (2013), http://www.nsr.go.jp/data/000067212.pdf
[61] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Safety Culture, Safety Series No. 75-INSAG-4, IAEA, Vienna (1991).
[62] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).
[63] INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Safety Culture in Nuclear Activities: Practical Suggestions to Assist Progress, Safety Reports Series No. 11, IAEA, Vienna (1998).
[64] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Culture in Nuclear Installations, IAEA-TECDOC-1329, IAEA, Vienna (2002).
[65] INSTITUTE OF NUCLEAR POWER OPERATIONS, Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005 Addendum, INPO, Atlanta (2012).
[66] NUCLEAR REGULATORY COMMISSION, A Comparison of US and Japanese Regulatory Requirements in Effect at the Time of the Fukushima Accident, NRC, Washington, DC (2013).
[67] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2014).
[68] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007).
[69] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).
[70] Disaster Countermeasures Basic Act, Act No. 223 of 15 November 1961, as last amended in 1997 (Japan), http://www.adrc.asia/documents/law/DisasterCountermeasuresBasicAct.pdf
[71] Ordinance for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 2 of April 5, 2000 (Japan) (in Japanese), http://law.e-gov.go.jp/haishi/H12F03103016002.html
[72] NUCLEAR REGULATION AUTHORITY, Comment received on Section 3.1 on Technical Volume 3, official communication (23 July 2014).
[73] GOVERNMENT OF JAPAN, Nuclear Emergency Response Manual, Government of Japan (2010) (in Japanese).
[74] FUKUSHIMA PREFECTURE, Fukushima Prefecture Disaster Management Plan (2009) (in Japanese).
[75] TOKYO ELECTRIC POWER COMPANY, Nuclear Operator Emergency Action Plan for the Fukushima Dai-ichi Nuclear Power Station, TEPCO, Tokyo (2010).
[76] TOKYO ELECTRIC POWER COMPANY, Specific Event Report, Fax No. 0042 (11 March 2011).
[77] TOKYO ELECTRIC POWER COMPANY, Report from Nuclear Power Plant Management of TEPCO to Minister of Economy, Trade and Industry, Fax No. 1560 (11 March 2011).
[78] GOVERNMENT OF JAPAN, CENTRAL DISASTER MANAGEMENT COUNCIL, The Basic Disaster Management Plan, Government of Japan, Tokyo (2008).
[79] GOVERNMENT OF JAPAN, Official web site of the Prime Minister of Japan and His Cabinet (2015), http://japan.kantei.go.jp/index.html
[80] NUCLEAR REGULATION AUTHORITY, About NISA (2015), http://www.nsr.go.jp/archive/nisa/english/aboutnisa/contact.html

[81] TOKYO ELECTRIC POWER COMPANY, TEPCO at a Glance (2015), http://www.tepco.co.jp/en/corpinfo/overview/p-glance-e.html
[82] NUCLEAR REGULATION AUTHORITY, About the Nuclear Safety Commission (2015), http://www.nsr.go.jp/archive/nsc/NSCenglish/aboutus/overview/overview.htm
[83] NUCLEAR REGULATION AUTHORITY, About JNES (2015), http://www.nsr.go.jp/archive/jnes/english/index.html
[84] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Home page of the Ministry of Education, Culture, Sports, Science and Technology (2015), http://www.mext.go.jp/english/
[85] MINISTRY OF HEALTH, LABOUR AND WELFARE, Home page of the Ministry of Health, Labour and Welfare (2015), http://www.mhlw.go.jp/english/
[86] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Home page of the Ministry of Agriculture, Forestry and Fisheries (2015), http://www.maff.go.jp/e/
[87] MINISTRY OF THE ENVIRONMENT, Home page of the Ministry of Environment (2015), http://www.env.go.jp/en/
[88] MINISTRY OF DEFENSE, Home page of the Ministry of Defense of Japan (2015), http://www.mod.go.jp/e/index.html
[89] JAPAN METEOROLOGICAL AGENCY, Home page of the Japan Meteorological Agency (2015), http://www.jma.go.jp/jma/indexe.html
[90] JAPAN ATOMIC ENERGY AGENCY, Home page of the Japan Atomic Energy Agency (2015), http://www.jaea.go.jp/english/index.html
[91] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Home page of National Institute of Radiological Sciences (2015), http://www.nirs.go.jp/ENG/index.shtml
[92] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Initial Operations in the Local Nuclear Emergency Response Headquarters (2013), https://www.nsr.go.jp/archive/jnes/content/000124530.pdf
[93] NUCLEAR SAFETY COMMISSION, Regulatory Guide: Emergency Preparedness for Nuclear Facilities, NSC, Tokyo (1980).
[94] Ordinance on Prevention of Ionizing Radiation Hazards, Ordinance of the Ministry of Labour No. 41 of September 30, 1972, as last amended by Ordinance No. 172 of July 16, 2001 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/S47/S47F04101000041.html
[95] MINISTRY OF HEALTH, LABOUR AND WELFARE, Enforcement of the Ministerial Ordinance on Exemption of the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011 (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/ri_0315_07.html
[96] MINISTRY OF HEALTH, LABOUR AND WELFARE, Consultation with and Recommendation from the Labor Policy Council on “the Outline of the Draft Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011” (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111121.html
[97] MINISTRY OF HEALTH, LABOUR AND WELFARE, Response and Action Taken by the MHLW of Japan on Radiation Protection for Workers Involved in the TEPCO Fukushima Daiichi NPP Accident, MHLW, Tokyo (2013).
[98] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the “Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011). http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_assistance_03.pdf
[99] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the “Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident” (2011). http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110617roadmap_assistance_report.pdf
[100] TOKYO ELECTRIC POWER COMPANY, Status of Improvement on Working Environment of workers in Fukushima Daiichi Nuclear Power Station (Attachment 2: About Cool Vest) (2011), http://www.tepco.co.jp/en/press/corp-com/release/11061013-e.html

[101] TOKYO ELECTRIC POWER COMPANY, Progress Status of Cooling (Reactors) (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110517e5.pdf
[102] MINISTRY OF HEALTH, LABOUR AND WELFARE, Occupational Safety and Health Department Notification (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/ri_0909_01.html
[103] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_120615_a03.pdf
[104] NUCLEAR REGULATION AUTHORITY, WG3 question 4, 1st submission, official communication (2013).
[105] GOVERNMENT OF JAPAN, WG3 question 5, 6th submission, official communication (2014).
[106] WATANABE, Y., "Relief activities conducted by the Japanese Red Cross Society after the Fukushima Daiichi Nuclear Power Plant Accident and the challenges for the future", IAEA Report on Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2015).
[107] TOMINAGA, T., HACHIYA, M., AKASHI, M., Lessons learned from response to the accident at the TEPCO Fukushima Daiichi Nuclear Power Plant: from the viewpoint of radiation emergency medicine and combined disaster, Radiat. Emergency Med. **1** 1–2 (2012) 56–61.
[108] TANIGAWA, K., HASEGAWA, A., "Medical perspective", Radiation Disaster Medicine (TANIGAWA, K., CHHEM, R. K., Eds), Springer, Heidelberg (2014).
[109] NUCLEAR REGULATION AUTHORITY, WG3 question 7, 1st submission, official communication (2013).
[110] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Food Contaminated by Radioactivity (2011), http://www.mhlw.go.jp/english/topics/foodsafety/dl/food-110317.pdf
[111] MINISTRY OF HEALTH, LABOUR AND WELFARE, Issuance of Instruction to Restrict Distribution of Foods Concerned, in Relation to the Accident at Fukushima Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110321.pdf
[112] MINISTRY OF HEALTH, LABOUR AND WELFARE, Restriction of Distribution and/or Consumption of Foods Concerned in Fukushima and Ibaraki Prefectures (2011), http://www.mhlw.go.jp/stf/houdou/2r98520000015wun-att/2r98520000015xym.pdf
[113] MINISTRY OF HEALTH, LABOUR AND WELFARE, Monitoring of Radioactive Contaminants for Agricultural and Livestock Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110323.pdf
[114] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Provisional Regulation Values for Radioactive Iodine in Fishery Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110405.pdf
[115] MINISTRY OF HEALTH, LABOUR AND WELFARE, New Standard Limits for Radionuclides in Foods (2012), http://www.mhlw.go.jp/english/topics/2011eq/dl/new_standard.pdf
[116] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Telephone Consultations on Radiation Exposure: Report on Tabulated Results from the Year Following the TEPCO Fukushima Daiichi Nuclear Disaster (2014), http://www.nirs.go.jp/publication/irregular/pdf/nirs_m_265en.pdf
[117] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Issues in Public Communications Activities and Future Efforts Related to the Accident at the TEPCO's Fukushima Dai-ichi Nuclear Power Station, NISA, Tokyo (2012) (in Japanese).
[118] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110817_assistance_02.pdf
[119] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110920_assistance_02.pdf

[120] JAPAN EXTERNAL TRADE ORGANIZATION, Great East Japan Earthquake Influence on International Business (2014) (in Japanese), www.jetro.go.jp/world/shinsai/20110318_11.html
[121] GOVERNMENT OF JAPAN, National Report of Japan to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (2011), http://www.nsr.go.jp/english/cooperation/conventions/data/jc_4th.pdf
[122] NUCLEAR SAFETY COMMISSION, Near-term Policy to Ensure the Safety in Treating and Disposing Contaminated Waste around the Site of Fukushima Dai-ichi Nuclear Power Plants, NSC, Tokyo (2011).
[123] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Basic Policy for Emergency Response on Decontamination Work (2011), http://www.kantei.go.jp/jp/singi/genshiryoku/dai19/19_03_gensai.pdf
[124] MINISTRY OF THE ENVIRONMENT, Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110 as of 2011 (Japan).
[125] ATOMIC ENERGY SOCIETY OF JAPAN, Final Report of the AESJ Investigation Committee (Announcement) (2014), http://www.aesj.or.jp/en/announcement/finalreport20141119.pdf
[126] INDEPENDENT INVESTIGATION COMMISSION ON THE FUKUSHIMA NUCLEAR ACCIDENT, The Fukushima Daiichi Nuclear Power Station Disaster: Investigating the Myth and Reality, Routledge, London and New York (2014).
[127] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations, Publication 109, Pergamon Press, Oxford and New York (2009).
[128] NUCLEAR SAFETY COMMISSION, Basic Policy of the Nuclear Safety Commission of Japan on Radiation Protection for Termination of Evacuation and Reconstruction (2011), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110719suggest_4.pdf
[129] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Elsevier, Oxford (2007).
[130] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110517roadmap_assistance.pdf
[131] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0613.pdf
[132] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Lifting the Evacuation-Prepared Area in Case of Emergency Designation (2011), http://www.reconstruction.go.jp/topics/41gennshiryoku.pdf
[133] NUCLEAR EMERGENCY PREPAREDNESS COMMISSION, Nuclear Emergency Response Manual (2012) (in Japanese), http://www.kantei.go.jp/jp/singi/genshiryoku_bousai/pdf/taisaku_manual.pdf
[134] NUCLEAR REGULATION AUTHORITY, National Report to the 6th Review Meeting of the Convention on Nuclear Safety (2013), http://www.nsr.go.jp/english/cooperation/conventions/data/cns_6th.pdf
[135] NUCLEAR SAFETY COMMISSION, Interim Report for Reviewing “Regulatory Guide: Emergency Preparedness for Nuclear Facilities” (2012) (in Japanese), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20120322review_3.pdf
[136] NUCLEAR REGULATION AUTHORITY, Nuclear Emergency Response Guidelines (2012) (in Japanese), http://www.nsr.go.jp/activity/bousai/data/130905_saitaishishin.pdf

[137] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996). (This publication is superseded by GSR Part 3 (2014)).
[138] Convention on Early Notification of a Nuclear Accident, INFCIRC/335, IAEA, Vienna (1986).
[139] Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, INFCIRC/336, IAEA, Vienna (1986).
[140] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Radiation Emergency Management Plan of the International Organizations, EPR-JPLAN, IAEA, Vienna (2010).
[141] INTERNATIONAL ATOMIC ENERGY AGENCY, Emergency Notification and Assistance Technical Operations Manual, EPR-ENATOM (2007), IAEA, Vienna (2007).
[142] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Response and Assistance Network (2010), http://www-ns.iaea.org/downloads/iec/info-brochures/13-27031-ranet.pdf
[143] IAEA Activities in Response to the Fukushima Accident, GOV/INF/2011/8, IAEA, Vienna (2011).
[144] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Action Plan on Nuclear Safety (2011), http://www.iaea.org/sites/default/files/actionplanns.pdf
[145] OECD NUCLEAR ENERGY AGENCY, Patterns in Governmental Decisions and Recommendations (GDR) Information Exchange during the Fukushima NPP Accident, NEA/CRPPH(2012)3, OECD, Paris (2012).
[146] WORLD HEALTH ORGANIZATION, Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, WHO, Geneva (2012).
[147] WORLD HEALTH ORGANIZATION, Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation, WHO, Geneva (2013).
[148] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).
[149] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).
[150] GONZÁLEZ, A.J., AKASHI, M., BOICE, J.D., Jr., CHINO, M., HOMMA, T., ISHIGURE, N., KAI, M., KUSUMI, S., LEE, J.-K., MENZEL, H.-G., NIWA, O., SAKAI, K., WEISS, W., YAMASHITA, S., YONEKURA, Y., Radiological protection issues arising during and after the Fukushima nuclear reactor accident, J. Radiol. Prot. **33** 3 (2013) 497–571.
[151] UNITED NATIONS, FAO/IAEA Food Database, UNSCEAR 2013 Report, Attachment C-8 of Annex A:, Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).
[152] WORLD METEOROLOGICAL ORGANIZATION, Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daiichi Nuclear Power Plant Accident, WMO, Geneva (2013).
[153] OECD NUCLEAR ENERGY AGENCY, The Fukushima Daiichi Nuclear Power Plant Accident, OECD, Paris (2013).
[154] WORLD HEALTH ORGANIZATION, Guidelines for Drinking-water Quality, 3rd edn, WHO, Geneva (2008).
[155] General Standard for Contaminants and Toxins in Food and Feed of 1995, as last amended 2013, Codex Alimentarius Commission, http://www.fao.org/fileadmin/user_upload/agns/pdf/CXS_193e.pdf
[156] JAPAN HEALTH PHYSICS SOCIETY, Issues Associated with Radiation Protection after Fukushima Daiichi Nuclear Power Plant Disaster: Responses of and Recommendations from Japan Health Physics Society, JHPS (2012).

[157] YASUMURA, S., "Overview of Fukushima Health Management Survey", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima (2014), http://www.fmu.ac.jp/radiationhealth/symposium201409/media/5_S2_Yasumura_FINAL(0909).pdf
[158] FUKUSHIMA PREFECTURE, Agenda, 3rd Meeting of the Oversight Committee for the Fukushima Health Management Survey (2011) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/6497.pdf
[159] SASAKAWA, Y., International Expert Symposium in Fukushima, September 2011, J. Radiol. Prot. **32** 1 (2012) E7–E8.
[160] Conclusions and recommendations of the International Expert Symposium in Fukushima: Radiation and Health Risks, J. Radiol. Prot. **31** 4 (2011) 381–384.
[161] FUKUSHIMA PREFECTURE, Terms of Reference of the Committee for the Fukushima Health Management Survey (2011) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/65128.pdf
[162] FUKUSHIMA MEDICAL UNIVERSITY, Basic Survey (Radiation Dose Estimates), 19th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey, Fukushima, Japan, (2015), http://www.fmu.ac.jp/radiationhealth/results/media/19-1_Basic_Survey.pdf
[163] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Radiation Quantities and Units, ICRU Rep. 33, Bethesda, MD (1980).
[164] INTERNATIONAL LABOUR ORGANIZATION, Convention Concerning the Protection of Workers against Ionising Radiations, No. 115, ILO, Geneva (1960).
[165] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. I, Annexes A and B, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2010).
[166] NATIONAL COUNCIL ON RADIATION PROTECTION MEASUREMENTS, Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection, NCRP Rep. No. 126, NCRP, Bethesda, MA (1997).
[167] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/67/46, UN, New York (2012).
[168] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 1977 Report, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1977).
[169] INTERNATIONAL ATOMIC ENERGY AGENCY, The International Chernobyl Project: Technical Report, IAEA, Vienna (1991).
[170] ESLINGER, P.W., et al., Source term estimation of radioxenon released from the Fukushima Dai-ichi nuclear reactors using measured air concentrations and atmospheric transport modeling, J. Environ. Radioact. **127** (2014) 127–132.
[171] STOHL, A., et al., Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: Determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. **12** 5 (2012) 2313–2343.
[172] BOWYER, T. W., et al., Elevated radioxenon detected remotely following the Fukushima Nuclear accident, J. Environ. Radioact. **102** 7 (2011) 681–687.
[173] SCHÖPPNER, M., et al., Estimation of the time-dependent radioactive source-term from the Fukushima nuclear power plant accident using atmospheric transport modelling, J. Environ. Radioact. **114** (2012) 10–14.
[174] TERADA, H., KATATA, G., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioact. **112** (2012) 141–154.
[175] SCIENCE COUNCIL OF JAPAN, A Review of the Model Comparison of Transportation and Deposition of Radioactive Materials Released to the Environment as a Result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant Accident (2014), http://www.jpgu.org/scj/report/20140902scj_report_e.pdf
[176] CHINO, M., et al., Preliminary estimation of release amounts of ^{131}I and ^{137}Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere, J. Nucl. Sci. Technol. **48** 7 (2011) 1129–1134.

[177] BUESSELER, K., AOYAMA, M., FUKASAWA, M., Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Technol. **45** 23 (2011) 9931–9935.
[178] EUROPEAN COMMISSION, INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, One Decade after Chernobyl: Summing up the Consequences of the Accident, IAEA, Vienna (1996).
[179] Chernobyl: Looking Back to Go Forward (Proc. Int. Conf Vienna, 2005), IAEA, Vienna (2005).
[180] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Accident de la Centrale de Fukushima Daiichi: Modélisation de la Dispersion des Rejets Radioactifs dans l'Atmosphère à l'Échelle Mondiale (2011),
http://www.irsn.fr/FR/popup/Pages/irsn-meteo-france_30mars.aspx
[181] Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plant on the Ocean (Proc. Fukushima Ocean Impacts Symp. Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).
[182] MADIGAN, D.J., BAUMANN, Z., FISHER, N.S., Pacific bluefin tuna transport Fukushima-derived radionuclides from Japan to California, Proceedings of the National Academy of Sciences **109** 24 (2012) 9483-9486.
[183] MASUMOTO, Y., "Ocean models: How far/fast does Fukushima contamination travel?", Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp.Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).
[184] MASUMOTO, Y., et al., Oceanic dispersion simulations of ^{137}Cs released from the Fukushima Daiichi nuclear power plant, Elements **8** 3 (2012) 207–212.
[185] HONDA, M.C., AONO, T., AOYAMA, M., Dispersion of artificial caesium-134 and -137 in the Western North Pacific one month after the Fukushima accident, Geochem. J. **46** 6 (2012) e1–9.
[186] RYPINA, I.I., et al., Short-term dispersal of Fukushima-derived radionuclides off Japan: modeling efforts and model-data intercomparison, Biogeosciences **10** 1 (2013) 4973–4990.
[187] AOYAMA, M., HIROSE, K., IGARASHI, Y., Re-construction and updating our understanding on the global weapons tests ^{137}Cs fallout, J. Environ. Monitor. **8** 4 (2006) 431–438.
[188] BUESSELER, K., AOYAMA, M., "Fukushima results", Exploring the impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp. Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).
[189] NUCLEAR REGULATION AUTHORITY, Radiation Monitoring Information. Monitoring Information of Environmental Radioactivity Level, NRA (2015) (in Japanese),
http://radioactivity.nsr.go.jp/ja/list/191/list-1.html
[190] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2000 Report, Vol. I, Sources, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).
[191] NUCLEAR REGULATION AUTHORITY, Reading of Radioactivity Level in Fallout by Prefecture (2011-2015),
http://radioactivity.nsr.go.jp/en/list/194/list-1.html
[192] NUCLEAR REGULATION AUTHORITY, Airborne Monitoring,
http://radioactivity.nsr.go.jp/en/list/278/list-1.html
[193] MINISTRY OF HEALTH, LABOUR AND WELFARE, Notice No. 0315 Article 1 of the Department of Food Safety (2012),
http://www.mhlw.go.jp/english/topics/2011eq/dl/food-120821_1.pdf
[194] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: Project NSRW 9/13 Assistance in the Use of Radiation Monitoring Data to Develop Maps to be Made Available to the Public, Fukushima Prefecture, 16–19 December 2013 (unpublished).
[195] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Survey Results of Radioactive Materials in Tap Water, MHLW, Tokyo (2011).
[196] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford and New York (1991).
[197] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency, Publication 111, Elsevier, Oxford (2009).

[198] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
[199] AKASHI, M., TOMINAGA, T., HACHIYA, M., TATSUZAKI, H., "Medical management of the consequences of the Fukushima nuclear plant incident", Medical Basis for Radiation Accident Preparedness (Proc. 5th Int. REAC/TS Symp. Oak Ridge, 2013), Oak Ridge, TN (2013).
[200] YASUMURA, S., GOTO, A., YAMAZAKI, S., REICH, M.R., Excess mortality among relocated institutionalized elderly after the Fukushima nuclear disaster, Public Health **127** 2 (2013) 186–188.
[201] NOMURA, S., et al., Mortality risk amongst nursing home residents evacuated after the Fukushima Nuclear accident: A retrospective cohort study, PLoS ONE **8** 3 (2013) e60192.
[202] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Principles for Intervention for Protection of the Public in a Radiological Emergency, Publication 63, Pergamon Press, Oxford and New York (1993).
[203] MINISTRY OF HEALTH, LABOUR AND WELFARE, Publication and Enforcement of "the Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011" (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111216.html
[204] AKAHANE, K., et al., NIRS external dose estimation system for Fukushima residents after the Fukushima Dai-ichi NPP accident, Sci. Rep. **3** (2013) 1670.
[205] ISHIKAWA, T., "The basic survey: Estimation of external doses to residents in Fukushima Prefecture", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/6_S2_Ishikawa.pdf
[206] NAGATAKI, S., TAKAMURA, N., KAMIYA, K., AKASHI, M., Measurements of individual radiation doses in residents living around the Fukushima nuclear power plant, Radiat. Res. **180** 5 (2013) 439–447.
[207] FUKUSHIMA MEDICAL UNIVERSITY, "Response rates to the basic survey by district. Data as of 31 December 2014" (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015), https://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey_Appendix.pdf
[208] FUKUSHIMA MEDICAL UNIVERSITY, "Basic survey (radiation dose estimates)" (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015) (2015), http://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey.pdf
[209] DATE CITY, Newsletter on Recovery and Revival in Date City No. 8: Analyses on Measurement of Annual Dose from External Exposure (2013) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/10035.pdf
[210] TSUBOKURA, M., et al., Absence of internal radiation contamination by radioactive cesium among children affected by the Fukushima Daiichi nuclear power plant disaster, Health Phys **108** 1 (2015) 39–43.
[211] HAYANO, R.S., et al., Whole-body counter survey results 4 months after the Fukushima Dai-ichi NPP accident in Minamisoma City, Fukushima, J. Radiol. Prot. **34** 4 (2014) 787.
[212] HAYANO, R. S., et al., Internal radiocesium contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP accident as measured by extensive whole-body-counter surveys, Proc. Jpn Acad. Ser. B Phys. Biol. Sci. **89** 4 (2013) 157–163.
[213] MATSUDA, N., et al., Assessment of internal exposure doses in Fukushima by a whole body counter within one month after the nuclear power plant accident, J. Radiat. Res. **179** 6 (2013) 663–668.
[214] KIM, E., et al., "Screening survey on thyroid exposure for children after the Fukushima Daiichi nuclear power station accident", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.) (KURIHARA, O., AKAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 59–66.
[215] TOKYO ELECTRIC POWER COMPANY, Updated worker doses, official communication (2015).

[216] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Exposure Dose of Workers at the Fukushima Daiichi Nuclear Power Station. Attachment: Distribution of Thyroid Equivalent Doses (2015), http://www.tepco.co.jp/en/press/corp-com/release/2015/1248073_6844.html
[217] MINISTRY OF HEALTH, LABOUR AND WELFARE, Re-evaluation Results of Committed Doses for Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_130705_a02.pdf
[218] YASUI, S., Governmental re-evaluation of the committed effective dose received by emergency workers at the TEPCO Fukushima Daiichi NPP accident, J. Occupat. Environ. Hyg. **12** 5 (2015) D60–D70.
[219] DEFENSE THREAT REDUCTION AGENCY, Radiation Dose Assessments for Shore-based Individuals in Operation Tomodachi, DTRA-TR-12-001, DTRA, Fort Belvoir, VA (2012).
[220] HASHIMOTO, S., et al., "First two-year result of the comprehensive health check as one facet of the Fukushima Health Management Survey" paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/7_S2_Hashimoto_FINAL(0909).pdf
[221] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP Statement on Tissue Reactions/Early and Late Effects of Radiation in Normal Tissues and Organs: Threshold Doses for Tissue Reactions in a Radiation Protection Context, Publication 118, Elsevier, Oxford (2012).
[222] TOKYO ELECTRIC POWER COMPANY, Result of the Investigation on Exposure to Radiation of Workers from Cooperative Companies at Unit 3 in Fukushima Daiichi Nuclear Power Station (2011), http://www.tepco.co.jp/en/press/corp-com/release/11032503-e.html
[223] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/68/46, UN, New York (2013).
[224] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Low-dose Extrapolation of Radiation-related Cancer Risk, Publication 99, Elsevier, Oxford (2005).
[225] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/63/46, UN, New York (2008).
[226] SUZUKI, S., et al., "Three-Year Results and Future Scope of the Fukushima Thyroid Ultrasound Examination after the Fukushima NPP Accident", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima (2014), http://www.fmu.ac.jp/radiationhealth/symposium201409/media/9_S2_Suzuki_FINAL(0909).pdf
[227] HAYASHIDA, N., et al., Thyroid ultrasound findings in a follow-up survey of children from three Japanese Prefectures: Aomori, Yamanashi, and Nagasaki, Sci. Rep. **5** (2015).
[228] FUKUSHIMA PREFECTURE, Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey (2015), http://www.fmu.ac.jp/radiationhealth/results/20150212_Thyroid_Ultrasound_Examination.html
[229] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Pregnancy and Medical Radiation, Publication 84, Pergamon Press, Oxford and New York (2000).
[230] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Doses to the Embryo and Foetus from Intakes of Radionuclides by the Mother, Publication 88, Pergamon Press, Oxford and New York (2001).
[231] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Biological Effects after Prenatal Irradiation (Embryo and Foetus), Publication 90, Pergamon Press, Oxford and New York (2003).
[232] NOMURA, Y., "Pregnancy and birth survey (by the Radiation Medical Science Center for the Fukushima Health Management Survey)", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/10_S2_Nomura_FINAL(0909).pdf
[233] NOMURA, Y., FUJIMORI, K., Survey of pregnant women in Fukushima Prefecture and future issues, Fukushima J. Med. Sci. **60** 2 (2014) 213.
[234] YASUMURA, S., et al., Study protocol for the Fukushima Health Management Survey, J. Epidemiol. **22** 5 (2012) 375–383.
[235] KAWAKAMI, N., Mental Health of Residents Living in Shelters, Japanese Association of Epidemiology, Tokyo (2014).

[236] YABE, H., et al., Psychological distress after the Great East Japan Earthquake and Fukushima Daiichi nuclear power plant accident: results of a Mental Health and Lifestyle Survey through the Fukushima Health Management Survey in FY2011 and FY2012, Fukushima J. Med. Sci. **60** 1 (2014) 57–67.
[237] KAWAKAMI, N., TSUCHIYA, M., UMEDA, M., KOENEN, K.C., KESSLER, R.C., Trauma and posttraumatic stress disorder in Japan: results from the World Mental Health Japan Survey, J. Psychiatr. Res. **53** (2014) 157–165.
[238] IWADARE, Y., et al., Posttraumatic symptoms in elementary and junior high school children after the 2011 Japan earthquake and tsunami: Symptom severity and recovery vary by age and sex, J. Pediatrics **164** 4 (2014) 917–921.
[239] BROMET, E.J., Emotional consequences of nuclear power plant disasters, Health Phys. **106** 2 (2014) 206–210.
[240] GOTO, A., et al., Maternal confidence of Fukushima mothers before and after the nuclear power plant disaster in Northeast Japan: analyses of municipal health records, J. Commun. Healthcare **7** 2 (2014) 106–116.
[241] BROMET, E. J., et al., Cross-national epidemiology of DSM-IV major depressive episode, BMC Med. **9** 1 (2011) 90.
[242] SHIGEMURA, J., TANIGAWA, T., SAITO, I., NOMURA, S., Psychological distress in workers at the Fukushima nuclear power plants, JAMA **308** 7 (2012) 667–669.
[243] SHIGEMURA, J., et al., Associations between disaster exposures, peritraumatic distress, and posttraumatic stress responses in Fukushima nuclear plant workers following the 2011 nuclear accident: the Fukushima NEWS project study, PLoS One **9** 2 (2014) e87516.
[244] MATSUOKA, Y., et al., Concern over radiation exposure and psychological distress among rescue workers following the Great East Japan Earthquake, BMC Public Health **12** (2012) 249.
[245] BROMET, E.J., Mental health consequences of the Chernobyl disaster, J Radiol Prot **32** 1 (2012) N71–75.
[246] BROMET, E.J., HAVENAAR, J. M., Psychological and perceived health effects of the Chernobyl disaster: A 20-year review, Health Phys **93** 5 (2007) 516–521.
[247] BROMET, E.J., HAVENAAR, J. M., GUEY, L. T., A 25 year retrospective review of the psychological consequences of the Chernobyl accident, Clin. Oncol. **23** 4 (2011) 297–305.
[248] MAEDA, M., et al., "Psychological effects on people in Fukushima: Results of a mental health and lifestyle survey", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/8_S2_Maeda_FINAL(0909).pdf
[249] KESSLER, R.C., et al., Screening for serious mental illness in the general population, Arch. Gen. Psychiat. **60** 2 (2003) 184–189.
[250] BLANCHARD, E.B., JONES-ALEXANDER, J., BUCKLEY, T.C., FORNERIS, C.A., Psychometric properties of the PTSD checklist (PCL), Behav. Res. Ther. **34** 8 (1996) 669–673.
[251] EWING, J.A., Detecting alcoholism. The CAGE questionnaire, JAMA **252** 14 (1984) 1905–1907.
[252] GOODMAN, R., Psychometric properties of the strengths and difficulties questionnaire, J. Am. Acad. Child Adolesc. Psychiatry **40** 11 (2001) 1337–1345.
[253] MATSUISHI, T., et al., Scale properties of the Japanese version of the strengths and difficulties questionnaire (SDQ): A study of infant and school children in community samples, Brain Dev. **30** 6 (2008) 410–415.
[254] OGURI, K., et al., Hadal disturbance in the Japan Trench induced by the 2011 Tohoku–Oki earthquake, Sci. Rep. **3** (2013).
[255] BIODIVERSITY CENTER OF JAPAN, Official web site about the effect of the earthquake and the tsunami (in Japanese), http://www.shiokaze.biodic.go.jp
[256] NAKAJIMA, H., KOARAI, M., Assessment of tsunami flood situation from the Great East Japan Earthquake, Bull. Geosp. Inf. Auth. Jpn. **59** (2011) 55–66.
[257] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, A Framework for Assessing the Impact of Ionising Radiation on Non-human Species, Publication 91, Pergamon Press, Oxford and New York (2003).

[258] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Environment Under Different Exposure Situations, Publication 124, Pergamon Press, Oxford and New York (2014).
[259] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: Transfer Parameters for Reference Animals and Plants, Publication 114, Elsevier, Oxford (2009).
[260] LINKOV, I., BURMISTROV, D., Model uncertainty and choices made by modelers: Lessons learned from the International Atomic Energy Agency model intercomparisons, Risk Anal. **23** 6 (2003) 1297–1308.
[261] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. II, Scientific Annexes C, D and E, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2011).
[262] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 1996 Report, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1996).
[263] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (Interim Edition), IAEA Safety Standards Series No. GSR Part 3 (Interim), IAEA, Vienna (2011). (This publication is superseded by GSR Part 3 (2014)).
[264] INTERNATIONAL ATOMIC ENERGY AGENCY, Summary Report of the Preliminary Findings of the IAEA Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP (2011),
https://www.iaea.org/sites/default/files/preliminaryfindings2011.pdf
[265] INTERNATIONAL ATOMIC ENERGY AGENCY, The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site of the Fukushima Daiichi Nuclear Power Plant (2013),
https://www.iaea.org/sites/default/files/final_report230114.pdf
[266] MINISTRY OF THE ENVIRONMENT, Basic Principles of the Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged from the Nuclear Power Station Accident Associated with the Tohoku District—Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 (2011),
http://josen.env.go.jp/en/framework/pdf/basic_principles.pdf
[267] GOLIKOV, V., et al., Evaluation of conversion coefficients from measurable to risk quantities for external exposure over contaminated soil by use of physical human phantoms, Radiat. Environ. Biophys **46** 4 (2007) 375–382.
[268] CABINET OFFICE, "Designating and rearranging the areas of evacuation", paper presented at Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.
[269] FUKUSHIMA PREFECTURE, Steps for Revitalization in Fukushima (2014),
http://www.pref.fukushima.lg.jp.e.od.hp.transer.com/sec/11015b/fukkoukeikaku1081.html
[270] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Areas to which Evacuation Orders have been Issued (2013),
http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20130807_01.pdf
[271] JAPAN ATOMIC ENERGY AGENCY, Use of Knowledge and Experience Gained from the Fukushima Daiichi Nuclear Power Station Accident to Establish the Technical Basis for Strategic Off-Site Response (2015),
http://jolissrch-inter.tokai-sc.jaea.go.jp/search/servlet/search?5049878
[272] JAPAN ATOMIC ENERGY AGENCY, Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Station: Overview, Analysis and Lessons Learned, Part 1: A Report on the "Decontamination Pilot Project", JAEA-Review 2014-051, JAEA, Tokyo (2015).
[273] MINISTRY OF THE ENVIRONMENT, Progress on Off-site Clean-up Efforts in Japan (2015),
http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf?150113
[274] MINISTRY OF THE ENVIRONMENT, Unit prices for decontamination in the SDAs directly controlled by the national government, official communication (2015).
[275] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1-4, TEPCO (2011),
http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/111221_02.pdf

[276] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Revised Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1-4 (2013), http://josen.env.go.jp/en/documents/pdf/workshop_july_17-18_2013_02.pdf
[277] INTER-MINISTERIAL COUNCIL FOR CONTAMINATED WATER AND DECOMMISSIONING ISSUES, Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station (2015).
[278] Act for Establishment of the Nuclear Regulation Authority, Act No. 47, 27 June, 2012, as amended by Act No. 82 of 2013 (Japan), https://www.nsr.go.jp/data/000067231.pdf
[279] TOKYO ELECTRIC POWER COMPANY, Implementation Plan of the Measures to be taken at Fukushima Daiichi Nuclear Power Station Designated as a Specified Reactor Facility (Outline) (2012), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_12120701-e.pdf
[280] NUCLEAR REGULATION AUTHORITY, Measures for Mid-Term Risk Reduction at TEPCO's Fukushima Daiichi NPS (2015), http://www.nsr.go.jp/data/000098679.pdf
[281] CONTAMINATED WATER TREATMENT MEASURES COMMITTEE, Measures for the Prevention of Groundwater Inflow, TEPCO (2012).
[282] GOVERNMENT OF JAPAN, TOKYO ELECTRIC POWER COMPANY, Progress Status and Future Challenges of Mid-to-Long-Term Roadmap towards the Decommissioning of Units 1–4 of TEPCO Fukushima Daiichi Nuclear Power Plant (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m121203-e.pdf
[283] TOKYO ELECTRIC POWER COMPANY, Comments received on Section 5, official communication (2 March 2015).
[284] TOKYO ELECTRIC POWER COMPANY, Contaminated Water Treatment (2015), http://www.tepco.co.jp/en/decommision/planaction/alps/index-e.html
[285] TOKYO ELECTRIC POWER COMPANY, Fukushima Daiichi NPS Prompt Report 2014: Bypass of Clean Groundwater to Ocean Starts (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1236566_5892.html
[286] TOKYO ELECTRIC POWER COMPANY, "Measures to stop or reduce ingress of groundwater into reactor and turbine buildings", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[287] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Fact Sheet: Overview of Contaminated Water Issue at TEPCO's Fukushima Daiichi Nuclear Power Station, Agency for Natural Resources and Energy (2013), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20130822_01.pdf
[288] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission) (2014), http://www.meti.go.jp/press/2013/02/20140213003/20140213003-2.pdf
[289] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Third Mission) (2015), https://www.iaea.org/sites/default/files/missionreport170215.pdf
[290] TOKYO ELECTRIC POWER COMPANY, Fuel Removal of the Unit 4 Spent Fuel Pool of the Fukushima Daiichi NPP Completed (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/handouts/2014/images/handouts_141222_04-j.pdf
[291] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (2013), http://www.meti.go.jp/english/press/2013/pdf/0627_01.pdf
[292] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities Using Radioactive Material, IAEA Safety Standards Series No. WS-R-5, IAEA, Vienna (2006). (This publication is superseded by GSR Part 6 (2014)).
[293] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013).

[294] OECD NUCLEAR ENERGY AGENCY, Nucl. Law Bull. **90** 2 (2012).
[295] GOVERNMENT OF JAPAN, Flow chart of specified waste and contaminated soil management in other prefectures, official communication (2015).
[296] TOKYO ELECTRIC POWER COMPANY, Mid-and-Long-Term Plans for Solid Waste Storage of the Fukushima Daiichi Nuclear Power Station (Draft) (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/l140407_05-j.pdf
[297] TOKYO ELECTRIC POWER COMPANY, Installation of Facilities for Temporary Storage Dry Casks (2014) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/pdf/120625/120625_02cc.pdf
[298] TOKYO ELECTRIC POWER COMPANY, A Mid-and-long-term plan for storage of solid wastes in Fukushima Daiichi NPS, official communication (2014).
[299] TOKYO ELECTRIC POWER COMPANY, "Radioactive Waste Management — Toward the decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[300] TOKYO ELECTRIC POWER COMPANY, Progress Status of Mid-and-Long-Term Roadmap Towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4 (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m120730-e.pdf
[301] SECRETARIAT OF THE TEAM FOR COUNTERMEASURES FOR DECOMMISSIONING AND CONTAMINATED WATER TREATMENT, Summary of Decommissioning and Contaminated Water Management (2014), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20140529-e.pdf
[302] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Reports from ICRP Dialogue Initiatives (2014), http://www.icrp.org/page.asp?id=189
[303] JAPAN EXTERNAL TRADE ORGANIZATION, 2011 JETRO Global Trade and Investment Report: International Business as a Catalyst for Japan's Reconstruction, JETRO, Tokyo (2011).
[304] FISHERIES AGENCY, The Leakage of Contaminated Water at TEPCO's Fukushima Daiichi Nuclear Power Station and the Safety of Fishery Products (2015).
[305] FOOD STANDARDS AGENCY, Import of Feed and Food Originating in or Consigned from Japan (2012), http://www.food.gov.uk/business-industry/imports/banned_restricted/japan#.UKS7deQ0V8E
[306] JAPAN EXTERNAL TRADE ORGANIZATION, JETRO Global Trade and Investment Report — Overview (2014), http://www.jetro.go.jp/en/reports/white_paper/trade_invest_2014.pdf
[307] Act on Compensation for Nuclear Damage, 1961, Act. Nr. 147, as amended by Act Nr. 19 in 2009.
[308] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, DISPUTE RECONCILIATION COMMITTEE FOR NUCLEAR DAMAGE COMPENSATION, Interim Guidelines On Determination of the Scope of Nuclear Damage Resulting from the Accident at The Tokyo Electric Power Company Fukushima Daiichi and Daini Nuclear Power Plants (2011) (in Japanese), http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/houkoku/__icsFiles/afieldfile/2011/08/17/1309452_1_2.pdf
[309] TOKYO ELECTRIC POWER COMPANY, Compensation for Additional Costs Resulting from Early Return after the Evacuation Order is Lifted (2014) (in Japanese), http://www.tepco.co.jp/cc/press/2014/1235026_5851.html
[310] PERKO, T., VALUCH, J., NAGY, A., LAMMERS, P., MAYS, C., Overview of Mass and New Media Treatment of Ionizing Radiation Topics: The Case of Fukushima, EAGLE Coordination Project (2013), http://eagle.sckcen.be/en/Deliverables
[311] FUKUSHIMA PREFECTURE, Steps for Revitalization in Fukushima, Fukushima Prefecture (2013).
[312] MINISTRY OF THE ENVIRONMENT, FUKUSHIMA PREFECTURE, Decontamination Information Plaza (2013).
[313] MINISTRY OF THE ENVIRONMENT, "Stakeholder communication overview for decontamination", paper presented at Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-site of the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.

[314] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency, IAEA, Vienna (2012).
[315] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Director General Calls for High Level Conference to Strengthen Nuclear Safety (2011), https://www.iaea.org/newscenter/news/iaea-director-general-calls-high-level-conference-strengthen-nuclear-safety
[316] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of the International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP (2011), http://www.mofa.go.jp/mofaj/saigai/pdfs/iaea_mission_1110_en.pdf
[317] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission to Review NISA's Approach to the Comprehensive Assessments for the Safety of Existing Power Reactor Facilities Conducted in Japan (2012), https://www.iaea.org/sites/default/files/nisamissionreport2012.pdf
[318] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japanese Earthquake and Tsunami (2012).
[319] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (2013), http://www.iaea.org/sites/default/files/missionreport220513.pdf
[320] Declaration by the IAEA Ministerial Conference on Nuclear Safety in Vienna on 20 June 2011 INFCIRC/821, IAEA, Vienna (2011).
[321] Measures to Strengthen International Cooperation in Nuclear, Radiation, Transport and Waste Safety, Resolution GOV/2013/32-GC(57)/RES/9, IAEA, Vienna (2013).
[322] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2012/11-GC(56)/INF/5, IAEA, Vienna (2012).
[323] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2013/8-GC(57)/INF/5, IAEA, Vienna (2013).
[324] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GOV/INF/2014/15-GC(58)/INF/7, IAEA, Vienna (2014).
[325] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).
[326] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Radiation Protection After the Fukushima Daiichi Accident: Promoting Confidence and Understanding, IAEA, Vienna (2014).
[327] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[328] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Strengthening Nuclear Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[329] Memorandum of Cooperation between Fukushima Prefecture and the International Atomic Energy Agency Following the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_04.pdf
[330] Practical Arrangements between Fukushima Prefecture and the International Atomic Energy Agency on Cooperation in the Area of Radiation Monitoring and Remediation (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_05.pdf
[331] Practical Arrangements between Fukushima Medical University and the International Atomic Energy Agency on Cooperation in the Area of Human Health (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_06.pdf
[332] Practical Arrangements between the Ministry of Foreign Affairs of Japan and the International Atomic Energy Agency on Cooperation in the Area of Emergency Preparedness and Response (2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_07.pdf

[333] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA and Japan Host Fukushima Ministerial Conference on Nuclear Safety (2012), https://www.iaea.org/newscenter/news/iaea-and-japan-host-fukushima-ministerial-conference-nuclear-safety
[334] Convention on Nuclear Safety, INFCIRC/449, IAEA, Vienna (1994).
[335] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).
[336] Convention on Nuclear Safety, Rules of Procedure and Financial Rules, INFCIRC/573/Rev.6, IAEA, Vienna (2015).
[337] Guidelines Regarding the Review Process under the Convention on Nuclear Safety, INFCIRC/571/Rev.7, IAEA, Vienna (2015).
[338] Guidelines Regarding National Reports under the Convention on Nuclear Safety, INFCIRC/572/Rev.5, IAEA, Vienna (2015).
[339] 2nd Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety: Final Summary Report, CNS/ExM/2012/04/Rev.2 (2012), http://www.iaea.org/sites/default/files/cns-summaryreport310812.pdf
[340] 6th Review Meeting of the Contracting Parties to the Convention on Nuclear Safety: Summary Report, CNS/6RM/2014/11_Final (2014), http://www-ns.iaea.org/downloads/ni/safety_convention/2014-cns-summary-report-w-annexes-signed.pdf
[341] Summary Report and Vienna Declaration on Nuclear Safety, CNS/DC/2015/3/Rev.2 (2015), https://www.iaea.org/sites/default/files/cns_summary090215.pdf

ABBREVIATIONS

μGy	microgray
μSv	microsievert
AC	alternating current
ALPS	Advanced Liquid Processing Systems
ANRE	Agency for Natural Resources and Energy
Bq	becquerel
BSS	Basic Safety Standards
CI	confidence interval
ConvEx	Convention Exercises
CRIEPI	Central Research Institute of the Electric Power Industry
CSC	Convention on Supplementary Compensation for Nuclear Damage
DC	direct current
EC	European Commission
EDG	emergency diesel generator
ENATOM	Emergency Notification and Assistance Technical Operations Manual
EPZ	emergency planning zone
ERSS	Emergency Response Support System
FAO	Food and Agriculture Organization of the United Nations
FW	fresh water
GPD	general psychological distress
Gy	gray
HP	hold point
HPCI	high pressure coolant injection
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
IC	isolation condenser
ICRP	International Commission on Radiological Protection
IEC	Incident and Emergency Centre
IEM	International Experts Meeting
IES	Incident and Emergency System
IGP	Institute of Geodesy and Photogrammetry
ILO	International Labour Organization
IMMSP	Institute of Mathematical Machines and Systems Problems
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Group
IRRS	Integrated Regulatory Review Service
IRSN	Institut de radioprotection et de sûreté nucléaire (Institute for Radiological Protection and Nuclear Safety)
JAEA	Japan Atomic Energy Agency
JAMSTEC	Japan Agency for Marine–Earth Science and Technology
JCNER	Joint Council for Nuclear Emergency Response
JCO	Japan Nuclear Fuels Conversion Company
JCOPET	Tide-resolving regional nested subsystem of Japan Coastal Ocean Predictability Experiment
JKEO	JAMSTEC Kuroshio Extension Observatory
JMA	Japan Meteorological Agency
JNES	Japan Nuclear Energy Safety Organization
JPLAN	Joint Radiation Emergency Management Plan of the International Organizations
JST	Japan Standard Time
KEO	Kuroshio Extension Observatory
KIOST	Korea Institute of Ocean Science and Technology
KNOT	Kyodo North Pacific Ocean Time-series

Kobe U	Kobe University
Local NERHQ	Local Nuclear Emergency Response Headquarters
MAFF	Ministry of Agriculture, Forestry and Fisheries
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
mGy	milligray
MHLW	Ministry of Health, Labour and Welfare
MITI	Ministry for International Trade and Industry
MO	motor operated
MOD (SDF)	Ministry of Defense (Self-Defense Forces)
MOE	Ministry of the Environment
MPa	megapascal
MSSG	Multi-Scale Simulator for the Geoenvironment
mSv	millisievert
NDF	Nuclear Damage Compensation and Decommissioning Facilitation Corporation
NERHQ	Nuclear Emergency Response Headquarters
NIES	National Institute for Environmental Studies
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPP-ERC	Fukushima Daiichi Emergency Response Centre at the NPP
NPS	Nuclear Power Station
NRA	Nuclear Regulation Authority
NSC	Nuclear Safety Commission
OECD/NEA	OECD Nuclear Energy Agency
OP	Onahama Port
PAHO	Pan American Health Organization
PBq	petabecquerel
PCV	primary containment vessel
PSA	probabilistic safety assessment
PTSR	post-traumatic stress response
RANET	Response and Assistance Network
RAPs	reference animals and plants
RCIC	reactor core isolation cooling
R&D	research and development
REMAT	Radiation Emergency Medical Assistance Team
SPEEDI	System for Prediction of Environmental Emergency Dose Information
Sv	sievert
SW	sea water
TEPCO	Tokyo Electric Power Company
TEPCO HQ-ERC	Emergency Response Centre at TEPCO Headquarters
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTC	Universal Time Coordinated
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization

CONTRIBUTORS TO DRAFTING AND REVIEW

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.V.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

WORKING GROUP 1 (WG1): DESCRIPTION AND CONTEXT OF THE ACCIDENT

Co-Chairs

Jammal, R.
Canadian Nuclear Safety Commission
Canada

Vincze, P.
Department of Nuclear Energy
IAEA

Scientific Secretary

Heitsch, M. (until August 2014)
Department of Nuclear Safety and Security
IAEA

Members

Dobrzyński, L.
National Centre for Nuclear Research
Poland

Dolganov, K.
Nuclear Safety Institute of the Russian Academy of Sciences
Russian Federation

Duspiva, J.
UJV Řež, a.s.
Czech Republic

Grant, I.
Federal Authority for Nuclear Regulation
United Arab Emirates

Guerpinar, A.
Senior Consultant
Turkey

Hirano, M.
Nuclear Regulation Authority
Japan

Khouaja, H.
Canadian Nuclear Safety Commission
Canada

Kim, H.T.
KHNP — Central Research Institute
Republic of Korea

Krijger, H.
N.V. Electriciteits-Productiemaatschappij Zuid-Nederland
Netherlands

Lequerica, I.
ENDESA
Spain

Noel, M.
European Commission Joint Research Centre

Orders, W.
Nuclear Regulatory Commission
USA

Urzua, G.
AREVA
France

Volkholz, P.
AREVA
France

Weidenbrück, K.
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
Germany

Weiss, S.
Global Research for Safety (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH)
Germany

Zheng, M.G.
Shanghai Nuclear Engineering Research and Design Institute
China

Invited experts

Dodo, T.
Japan Nuclear Safety Institute
Japan

Ihara, T.
Tokyo Electric Power Company
Japan

Kanno, M.
Nuclear Regulation Authority
Japan

Kawano, A. (until August 2013)
Tokyo Electric Power Company
Japan

Muftuoglu, K.
GE Hitachi Nuclear Energy
USA

Taira, J.
Tokyo Electric Power Company
Japan

Yamamoto, M. (August 2013 onwards)
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG1

Kang, K.-S.
Kilic, N.
Pagannone, B.
Yamada, K.
Yoshimoto, Y.

WORKING GROUP 2 (WG2): SAFETY ASSESSMENT

Co-Chairs

Chande, S.
Atomic Energy Regulatory Board
India

Hughes, P. (until August 2014)
Department of Nuclear Safety and Security
IAEA

Ulses, A. (August 2014 onwards)
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Aparkin, F.
Department of Nuclear Safety and Security
IAEA

Members

Alonso, J.R.
Nuclear Safety Council
Spain

Ayub, M.
Pakistan Nuclear Regulatory Authority
Pakistan

Bucalossi, A.
European Commission Joint Research Centre

Chaikiat, P.
Swedish Radiation Safety Authority
Sweden

Dermarkar, F.
CANDU Owners Group
Canada

Foucher, L.
French Nuclear Safety Authority
France

Gauntt, R.
Sandia National Laboratories
USA

Giannelli, I.A.
Slovenské Elektrárne, a.s. (subsidiary of Enel)
Italy

Godoy, A.R.
James J. Johnson and Associates
Argentina

Gonzalez, V.
Nuclear Safety and Safeguards National Commission
Mexico

Harrison, S.
Office for Nuclear Regulation
United Kingdom

Heppell-Masys, K.
Canadian Nuclear Safety Commission
Canada

Hoshi, H.
Nuclear Regulation Authority
Japan

Kajimoto, M.
Nuclear Regulation Authority
Japan

Kuivalainen, H.
Radiation and Nuclear Safety Authority Finland

Lankin, M.
Federal Environmental, Industrial and Nuclear Supervision Service of Russia
Russian Federation

de L'Epinois, B.
AREVA
France

Macchi, L.
Dédale
France

Mildenberger, O.
Global Research for Safety (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH)
Germany

Misak, J.
UJV Řež a.s.
Czech Republic

Perryman, L.
Eskom
South Africa

Ryser, C.
Swiss Federal Nuclear Safety Inspectorate
Switzerland

Song, J.H.
Korea Atomic Energy Research Institute
Republic of Korea

Weidenbrück, K.
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
Germany

Invited experts and contact points

Donges, A.
Institute of Nuclear Power Operation
USA

Haber, S.
Human Performance Analysis, Corp.
USA

Harter, R.
Boiling Water Reactors Owners Group
USA

Hatamura, Y.
University of Tokyo
Japan

Ihara, T.
Tokyo Electric Power Company
Japan

Iino, K.
SYDROSE
Japan

Kunito, S.
Tokyo Electric Power Company
Japan

Nakagawa, Y.
Tokyo Electric Power Company
Japan

Takizawa, S.
Tokyo Electric Power Company
Japan

Watford, G.
GE Hitachi Nuclear Energy
USA

Yamanaka, Y.
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG2

Beltran, F.
Earle, K.
Haage, M.
Haber, S.
Roveti, B.
Rycraft, H.
Skarbo, B.
Yllera, J.
Yoshimoto, Y.

WORKING GROUP 3 (WG3): EMERGENCY PREPAREDNESS AND RESPONSE

Co-Chairs

Drábová, D.
State Office for Nuclear Safety
Czech Republic

Buglova, E.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Shiraga, K.
Department of Nuclear Safety and Security
IAEA

Members

Aaltonen, H.
Radiation and Nuclear Safety Authority
Finland

Ahier, B.
Radiation Protection Bureau
Canada

Bardelay, J.
Institute for Radiological Protection and Nuclear Safety
France

Blackburn, C.
FAO

Byron, D.†
FAO

Chen, P. (until June 2014)
World Meteorological Organization

Chugunov, V.
State Atomic Energy Corporation 'Rosatom'
Russian Federation

Cortes Carmona, A.
Nuclear Safety and Safeguards National Commission
Mexico

Dela Rosa, A.
Philippine Nuclear Research Institute
Philippines

Harou, A. (June 2014 onwards)
World Meteorological Organization

Hernández, D.
Nuclear Regulatory Authority
Argentina

Homma, T.
Japan Atomic Energy Agency
Japan

Hubbard, L.
Swedish Radiation Safety Authority
Sweden

Kelly, N.
Senior Consultant
United Kingdom

Kenigsberg, J.†
National Commission of Radiation Protection
Belarus

Maree, M.
Eskom
South Africa

McClelland, V.
Department of Energy
USA

Molina, G.
Instituto Nacional de Investigaciones Nucleares
Mexico

Pascal, G.
European Commission Joint Research Centre

† Deceased

Sigouin, L.
Canadian Nuclear Safety Commission
Canada

Soufi, I.
National Energy Center of Sciences and Nuclear Techniques
Morocco

Sumargo, D.E.
Nuclear Energy Regulatory Agency
Indonesia

Takahara, S.
Japan Atomic Energy Agency
Japan

de la Vega, R.
Nuclear Safety Council
Spain

Invited experts and contact points

Taminami, T.
Tokyo Electric Power Company
Japan

Tanigawa, K.
Hiroshima University
Japan

Tominaga, T.
National Institute of Radiological Sciences
Japan

Wiley, A.
REAC/TS–WHO Collaborating Center
USA

Yamashita, S.
Nagasaki University
Japan

IAEA Secretariat staff supporting WG3

Callen, J.
Chaput, J.
Kaiser, P.
Martincic, R.
McKenna, T.
Mutluer, A.
Nestoroska Madjunarova, S.
Vilar Welter, P.
Yoshimoto, Y

WORKING GROUP 4 (WG4): RADIOLOGICAL CONSEQUENCES

Co-Chairs

González, A.
Nuclear Regulatory Authority
Argentina

Chhem, R. (until August 2014)
Department of Nuclear Sciences and Applications
IAEA

Meghzifene, A. (September 2014 onwards)
Department of Nuclear Sciences and Applications
IAEA

Pinak, M.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Müskens, P. (until August 2013)
Department of Nuclear Safety and Security
IAEA

Bevington, L. (September 2013 onwards)
Department of Nuclear Safety and Security
IAEA

Members

Akashi, M.
National Institute of Radiological Sciences
Japan

Betancourt, A.
Agencia de Energía Nuclear y Tecnologías de Avanzada
Cuba

Blumenthal, D.
National Nuclear Security Administration
Department of Energy
USA

Bromet, E.J.
State University of New York at Stony Brook
USA

Brown, J.
Norwegian Radiation Protection Authority
Norway

Coleman, C.N.
National Cancer Institute
USA

Demidchik, Y.
Belarusian Academy of Science and Belarusian Medical Academy of Post-Graduate Education
Belarus

Dobrzyński, L.
National Centre for Nuclear Research
Poland

Gallego, E.
Universidad Politécnica de Madrid
Spain

Haquin, G.
Soreq Nuclear Research Center
Israel

Jones, C.G.
Permanent Mission of the United States of America to the IAEA in Vienna
and Nuclear Regulatory Commission
USA

Lee, J.K.
Hanyang University
Republic of Korea

Magnusson, S.
Icelandic Radiation Safety Authority
Iceland

Mason, C.
BHP Billiton
Australia

McEwan, A.C.
Senior Consultant
New Zealand

McGinnity, P.A.
Environmental Protection Agency
Ireland

Ng, K.H.
University of Malaya
Malaysia

Niwa, O.
Kyoto University, and Fukushima Medical University
Japan

Pentreath, R.J.
University of Reading
United Kingdom

Perrin, M.L.
Nuclear Safety Authority
France

Rochedo, E.
Coordination of Nuclear Installations
Brazil

Shinkarev, S.
Federal Medical Biological Agency
Russian Federation

Sundell-Bergman, S.
Swedish University of Agricultural Sciences
Sweden

Thomas, G.
Imperial College London
United Kingdom

Valentin, J.
Jack Valentin Radiological Protection
Sweden

Invited experts and contact points

Brenner, A.
National Cancer Institute
USA

Chino, M.
Japan Atomic Energy Agency
Japan

Fukui, T.
Nuclear Regulation Authority
Japan

Ivanov, V.
National Radiation and Epidemiological Registry
Russian Federation

Makihira, A.
Tokyo Electric Power Company
Japan

Nagataki, S.
Nagasaki University
Japan

Ohtsuru, A.
Fukushima Medical University
Japan

IAEA Secretariat staff supporting WG4

Harms, A.V.
McGinnity, P.A.
Nies, H.
Osvath, I.
Sakai, K.
Yonehara, H.

WORKING GROUP 5 (WG5): POST-ACCIDENT RECOVERY

Co-Chairs

Williams, G.
Australian Radiation Protection and Nuclear Safety Agency
Australia

Mele, I.
Department of Nuclear Energy
IAEA

Proehl, G.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Delaunay, N.
Department of Nuclear Safety and Security
IAEA

Members

Al-Masri, M.S.
Atomic Energy Commission of Syria
Syrian Arab Republic

Balonov, M.
Institute of Radiation Hygiene
Russian Federation

Bassanelli, A.
Sogin — Società Gestione Impianti Nucleari
Italy

Brennecke, P.
Senior Consultant
Germany

Darko, E.O.
Ghana Atomic Energy Commission
Ghana

Gallay, F.
Nuclear Safety Authority
France

Howard, B.J.
Centre for Ecology and Hydrology
United Kingdom

Inoue, T.
Central Research Institute of Electric Power Industry
Japan

Kifanga, L.D.
Tanzania Atomic Energy Commission
United Republic of Tanzania

Nakayama, S.
Japan Atomic Energy Agency
Japan

Oughton, D.H.
Norwegian University of Life Sciences
Norway

Rowan, D.
Atomic Energy of Canada Limited
Canada

Seitz, R.
Savannah River National Laboratory
USA

Tokarevsky, V.
Institute for Chernobyl Problems
Ukraine

Zeleznik, N.
Regional Environmental Center
Slovenia

Invited experts and contact points

Belencan, H.
Senior Consultant
USA

Negin, C.
Project Enhancement Corporation
USA

Takizawa, S.
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG5

Izumo, A.
Fesenko, S.
Kumano, Y.
Monken-Fernandes, H.
Sakai, K.
Walker, J.
Yankovich, T.
Yonehara, H.

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization of the United Nations

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Mohammad Jais, A.
International Nuclear Safety Group

Niu, S.
International Labour Organization

Sharma, S.K.†
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

12–13 September 2013
3rd meeting of WGs 1 and 2, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

5–9 May 2014
6th meeting of WG 4, Vienna

26–30 May 2014
6th meeting of WG 5, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

6–7 August 2013
CS on Source Term, Vienna

29–31 October 2013
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 November 2013
CS on Human and Organizational Factors and Safety Culture, Atlanta

13–17 January 2014
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 March 2014
CS on Human and Organizational Factors and Safety Culture, Ottawa

24–26 March 2014
CS on Radioactivity in the Environment, Monaco

20–21 May 2014
CS on Radiation and Log-Normal Distributions, Vienna

23–27 June 2014
CS on Radiation and Log-Normal Distributions, Vienna

Bilateral meetings in Japan

14–21 October 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Remediation

25–27 November 2013
CS to Discuss Issues Related to Radiological Consequences in Connection with the Preparation of Chapter 4 (Radiological Consequences) and Chapter 5 (Post-accident Recovery)

25 November–4 December 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Decommissioning

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

23 January 2014
Meetings with Reconstruction Agency and Team in Charge of Assisting the Lives of Disaster Victims — Cabinet Office

24 January 2014
Meetings with the Institute of Energy Economics of Japan

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.

STI/PUB/1710

ISBN 978–92–0–107015–9 (set)

Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This Report by the Director General is prepared drawing on the detailed information provided in the technical volumes. Its content does not necessarily reflect the views of IAEA Member States or organizations nominating experts to the Working Groups for the preparation of the technical volumes.

Great care has been taken to maintain the accuracy of information contained in this report. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with the report.

This report is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from the report may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this report indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continuing existence of URLs for external or third party Internet web sites referred to in this report and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

15-1816



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)

GC(59)/14

The Fukushima Daiichi Accident



Technical Volume 1/5

Description and Context of the Accident

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 1
DESCRIPTION AND CONTEXT OF THE ACCIDENT

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 1
DESCRIPTION AND CONTEXT OF THE ACCIDENT

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.
STI/PUB/1710
ISBN 978–92–0–107015–9 (set)
Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This publication has been prepared from contributions submitted by many international experts to the five Working Groups for the preparation of the technical volumes. The content does not necessarily reflect the views of IAEA Member States, or the organizations nominating experts.

Great care has been taken to maintain the accuracy of information contained in this publication. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with this publication.

This publication is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from this publication may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this publication indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continued existence of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from this report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

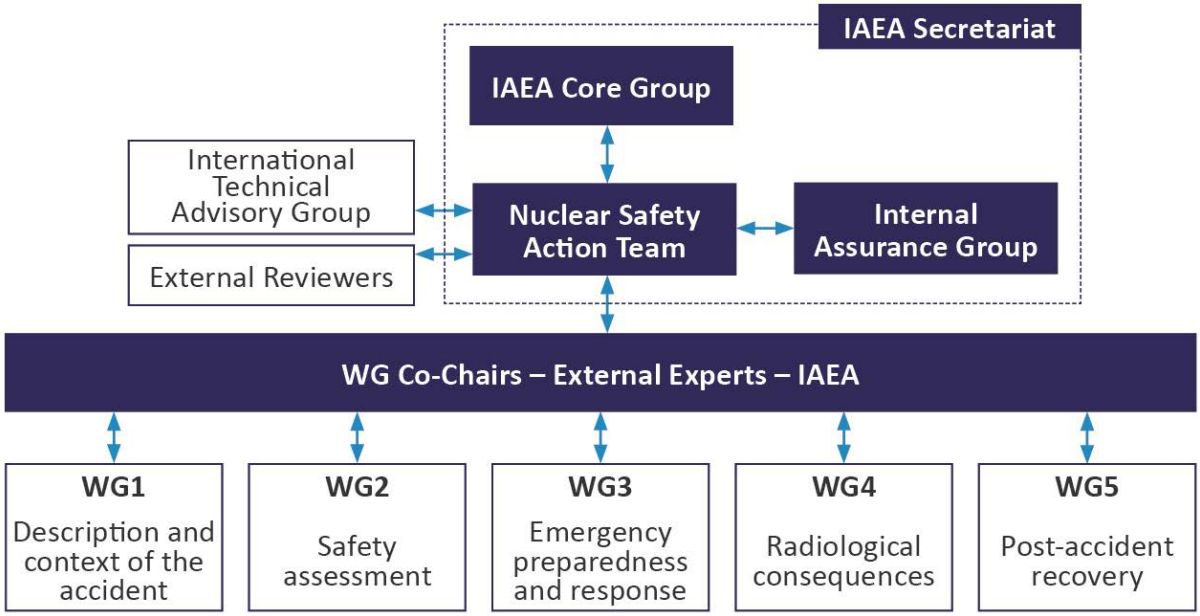


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

---

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

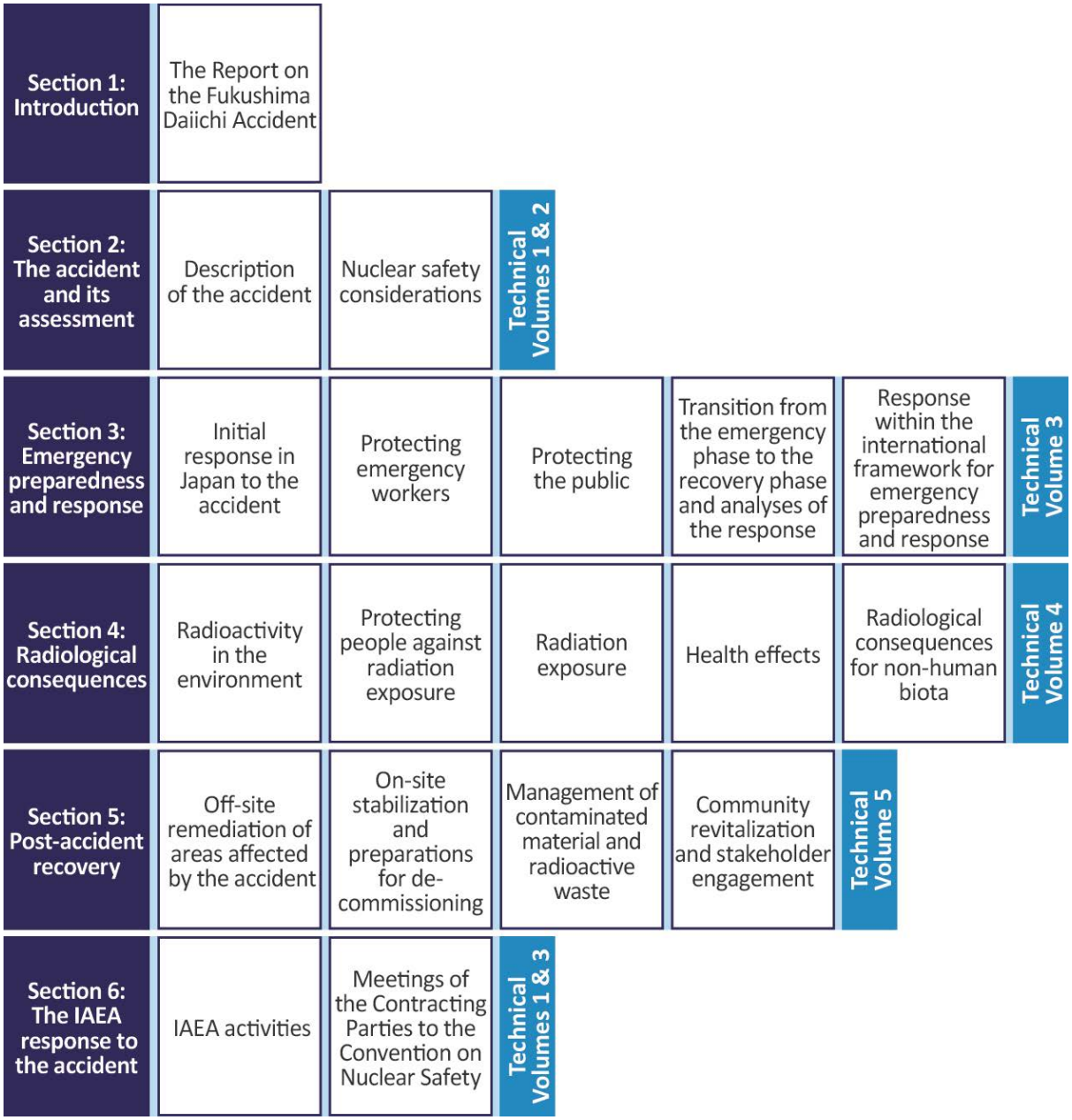


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

DESCRIPTION AND CONTEXT OF THE ACCIDENT 1

1. INTRODUCTION 1

1.1. SUMMARY OF THE ACCIDENT 2
1.1.1. Main occurrences 3
1.1.2. Accident initiation and response 5
1.1.3. Progression of the accident 16
1.1.4. Stabilization 32
1.2. CONTEXT WITHIN WHICH THE ACCIDENT OCCURRED 34
1.2.1. Nuclear industry structure 34
1.2.2. Governmental, legal and regulatory framework of nuclear safety prior to the accident 42
1.2.3. Stakeholder involvement and public communication 53
1.2.4. Training and qualification 55
1.2.5. Characteristics of the Fukushima Daiichi site 59
1.2.6. Description of the Fukushima Daiichi plant systems 64
1.2.7. Plant resources and capacity at the time of the accident 81
1.3. ONSET AND PROGRESSION OF THE ACCIDENT 86
1.3.1. Onset of the accident at the Fukushima Daiichi NPP 86
1.3.2. Sequence of events at Fukushima Daiichi Units 1–3 91
1.3.3. Sequence of events for the Fukushima Daiichi units in the outage (Units 4–6) 119
1.3.4. Sequence of events in the common spent fuel pool 130
1.3.5. Sequence of events for the dry cask storage facilities 131
1.3.6. Sequence of events for the Fukushima Daini Units 131
1.3.7. Site to site event comparison 133
1.4. RADIONUCLIDE INVENTORY AND RELEASES 134
1.4.1. Fukushima Daiichi Units 1–3 radionuclide core inventories at the time of accident 135
1.4.2. Radionuclide release mechanisms 142
1.4.3. Amount of radionuclides released 148
1.4.4. Atmospheric release 149
1.4.5. Groundwater and ocean release 154
1.4.6. Additional radiological release since the accident 158
1.5. ACTIONS BY ORGANIZATIONS OTHER THAN TEPCO 163
1.5.1. Structure and interactions of on-site and off-site organizations 163
1.5.2. Actions by the Prime Minister's Office and METI 166
1.5.3. Actions by NISA and the NSC 171
1.5.4. Actions by the local governments 173
1.5.5. Actions by international entities 174
1.6. ACTIONS TAKEN IN THE AFTERMATH OF THE ACCIDENT 179
1.6.1. Actions taken towards stabilization and restoration of the Fukushima Daiichi units 179
1.6.2. Actions towards a mid-term and long term roadmap for decommissioning 185
1.6.3. Government/regulatory actions 189
1.6.4. Other events at the Fukushima Daiichi site following the accident 193
1.6.5. International actions 195

REFERENCES 203
CONTENTS OF CD-ROM 216
ABBREVIATIONS 217
CONTRIBUTORS TO DRAFTING AND REVIEW 221
INTERNATIONAL TECHNICAL ADVISORY GROUP 224
MEETINGS 225

DESCRIPTION AND CONTEXT OF THE ACCIDENT

1. INTRODUCTION

This volume presents the key events that happened before, during and after the accident at the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO).

The description of the event in this volume is based on objective and factual information, and is presented largely in a chronological manner. The volume also describes the Fukushima Daiichi NPP site, the reactor designs, the structure of the nuclear industry in Japan and the Japanese regulatory framework at the time of the accident. It describes in detail the earthquake, the tsunami, the events at the Fukushima Daiichi NPP and the actions taken there and elsewhere for post-accident management up to December 2014. The description of the events is largely based on information provided by the Government of Japan to the IAEA [1, 2]; reports of the investigation committees established by the Japanese Government [3, 4], the National Diet of Japan [5] and TEPCO [6], including updates and supplements by TEPCO [7, 8]; the regulatory body [9]; and the IAEA missions listed in Section 1.6.5. Information is provided without judgement and evaluation, unless it is necessary to clarify a certain occurrence assessments are contained in Technical Volumes 2 to 5.

The volume begins with a summary of the accident (Section 1.1), which presents the main events in a chronological order to provide an overview that serves to demonstrate those events that occurred in parallel or affected actions at different parts of the site. In this manner, the accident description illustrates the integrated response to a multi-unit site accident from the perspective of emergency response centres (ERCs), shared main control rooms (MCRs) and the off-site organizations. There is some necessary repetition of information that is presented later in the volume, when events are described in more detail.

The second section (Section 1.2) describes the context within which the accident occurred. It describes the Japanese nuclear power programme, its nuclear industry and the governmental/legal/regulatory framework in place at the time of the accident. It then discusses the characteristics of the Fukushima Daiichi NPP and its six nuclear reactors. Finally, this section presents the plant's resources and its capacity with respect to the qualifications and abilities of its staff as well as the tools available to them at the time of the accident.

The third section (Section 1.3) deals with the start and the development of the accident. It explains how an extreme natural event, combined with some design and operational issues, led to a severe nuclear accident in which radioactive material was released to the environment. It describes the effects of the initiating event (the Great East Japan Earthquake) and its concurrent and dependent natural event (the tsunami) on the Fukushima Daiichi NPP site, as well as the response by personnel and equipment to the dynamic events on 11 March 2011 and during the following month.

The fourth section (Section 1.4) mainly describes the initial releases of radionuclides to the environment, resulting from the failure of the fission product barriers at the time of the accident. It also presents other events afterwards that caused additional radioactive releases from the accident site.

The fifth section (Section 1.5) addresses the response to the accident, as it progressed, by off-site entities, including the actions of Japan's national, prefectural and local governments, as well as those by the IAEA and other international and regional organizations.

Finally, Section 1.6 focuses on what has happened since the accident until December 2014.[1] It covers subsequent actions taken at the Fukushima Daiichi NPP, in governmental organizations, in Japan's nuclear industry and internationally to address challenges and issues after the accident, including current activities and plans on the site decommissioning and remediation. Annexes I, II and III provide the sequence of events in Units 1–3 in tabular form. These annexes are included on the CD-ROM attached to this volume.

Overall, as the general reference account of the accident and its aftermath, this volume forms the basis for analyses of the various aspects and causal factors of the accident. The specific investigations of these facts are presented in subsequent volumes. Sections 1.2 and 1.3 provide input to Technical Volume 2 in terms of technical and regulatory aspects; Section 1.4 provides input to Technical Volume 4 with regard to the amount of radionuclides released (source term); Section 1.5 mainly supports Technical Volume 3, with additional input provided by Section 1.2 on emergency response and regulations; and Section 1.6 furnishes information on the post-accident efforts towards remediation, stabilization and decommissioning and the management of radiological waste, explored further in Technical Volume 5.

1.1. SUMMARY OF THE ACCIDENT

On 11 March 2011, the tsunami waves generated by the Great East Japan Earthquake off the Pacific coast of Japan overwhelmed the tsunami barriers of Fukushima Daiichi nuclear power plant (NPP) site. They flooded the primary and backup power systems and equipment, as well as the ultimate heat sink systems and structures, of all six units on the site. Compounding the off-site power loss that occurred before the tsunami due to the earthquake damage to the transmission system, the flooding caused the loss of on-site power sources (and/or on-site power distribution systems). Units 1–5 of the Fukushima Daiichi NPP experienced extended station blackout (SBO) events, which exceeded nine days in Units 1 and 2, and 14 days in Units 3 and 4.

The nuclear units were unable to cope with the extended loss of electrical power and plant heat removal, and the reactors of Units 1, 2 and 3 suffered damage as the fuel overheated and melted. The reactor pressure vessels (RPVs) that enclose the reactor cores were eventually breached in those units, and radioactive material escaped from the reactors. The radioactive material confined in the primary containment vessels (PCVs) was further released directly to the environment either in a controlled manner, i.e. by venting of the reactors' PCVs, or in an uncontrolled manner upon damage and failure of the confinement structures. The radioactive releases resulted in radiological exposure of the workers at the site and the general public residing in the surrounding communities and caused radiological contamination of the environment in those areas. In order to reduce radiation exposures, people within a radius of 20 km of the site, as well as other specified areas, were evacuated, and restrictions were placed on the distribution and consumption of food and drinking water.

Although no loss of life has been attributed to the radiological releases, the accident caused social and economic impacts, especially in Japan. At the time of writing[2], people who were evacuated continue to live outside the evacuated areas or are allowed to return to their homes with limitations, and post-accident management efforts towards the recovery of the affected surrounding areas are ongoing. Following the stabilization of the conditions of the affected reactors, activities to prepare these reactors for their eventual decommissioning have also been initiated. These matters are discussed in detail in the subsequent volumes.

[1] In some cases information was available up until May 2015, and this was included, where possible.

[2] June 2015.

1.1.1. Main occurrences

The Great East Japan Earthquake occurred at 14:46 Japan Standard Time (JST)[3] on Friday 11 March 2011, off the eastern coast of Japan. It caused extensive damage to the infrastructure. The main shock, with a magnitude of M 9.0 [10], lasted for more than two minutes. This event was among the largest recorded earthquakes, most of which have also occurred in areas along the Pacific tectonic plate: the earthquakes of 1960 and 2010 in Chile, with a magnitude of M 9.5 and M 8.8, respectively, and those in Alaska (1964) and Sumatra (2004), both with a magnitude of M 9.2.

The large movement in the seabed also caused a series of tsunami waves that affected a wide coastal area of Japan. The earthquake and consequent tsunami caused widespread devastation and the loss of many lives. More than 15 000 people were killed, over 6000 were injured and, at the time of writing, around 2500 people were still reported to be missing [11]. These events also impacted residential and industrial establishments, including five NPP sites along Japan's north-eastern coast: Higashidori, Onagawa, Fukushima Daiichi, Fukushima Daini and Tokai Daini. As shown in Fig. 1.1–1, the epicentre was approximately 180 km north-east of the Fukushima Daiichi NPP and the Fukushima Daini NPP, and 130 km east of the Onagawa NPP.

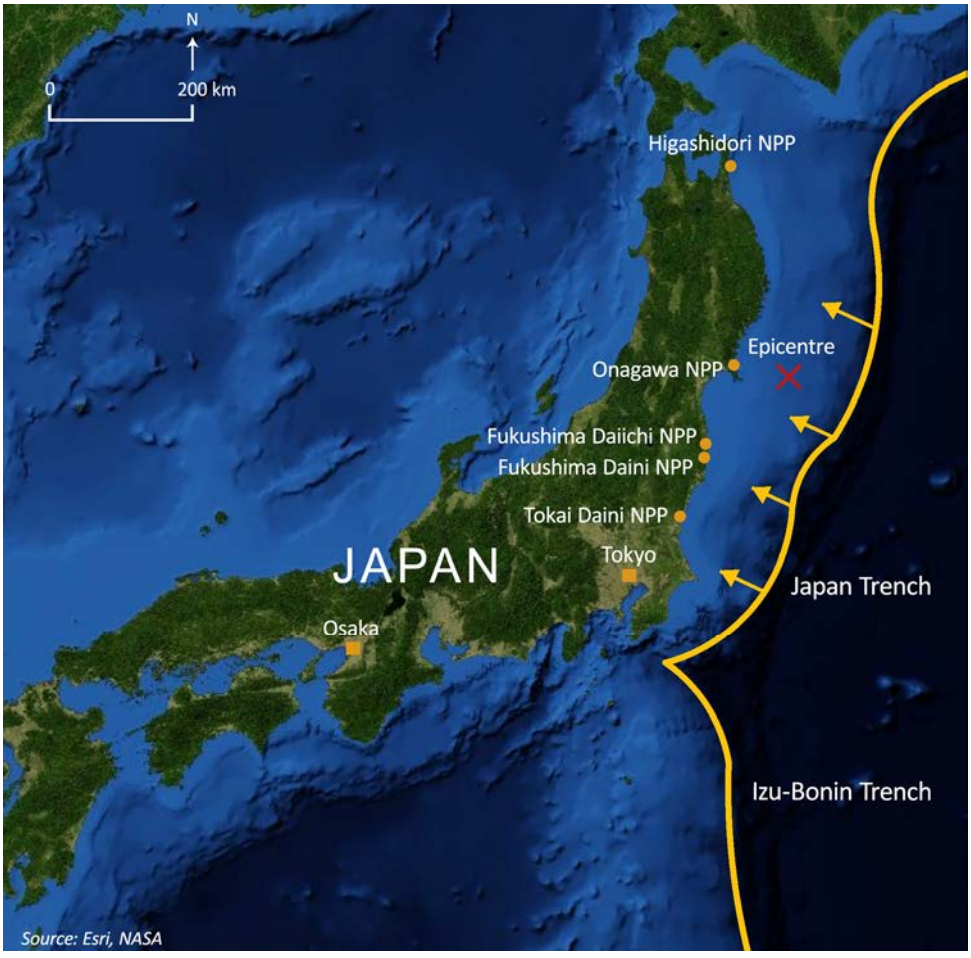


FIG. 1.1–1. The Great East Japan Earthquake and the NPPs nearby.

[3] All times in this narrative are in Japan Standard Time (JST) and all pressure values in units of bar absolute and megapascal (MPa). The times of events and values of plant parameters such as pressures, temperatures and water levels mentioned in this section are approximate. Though not explicitly mentioned individually, these values could have some uncertainty.

At one of these plants, the Fukushima Daiichi NPP, with six nuclear units, the effects of the earthquake and tsunami initiated a series of events, shown in Fig. 1.1-2, that led to a severe nuclear accident resulting in radioactive releases. Radionuclides were released to the atmosphere from the Fukushima Daiichi NPP and were deposited on land and on the ocean. There were also direct releases into the sea.

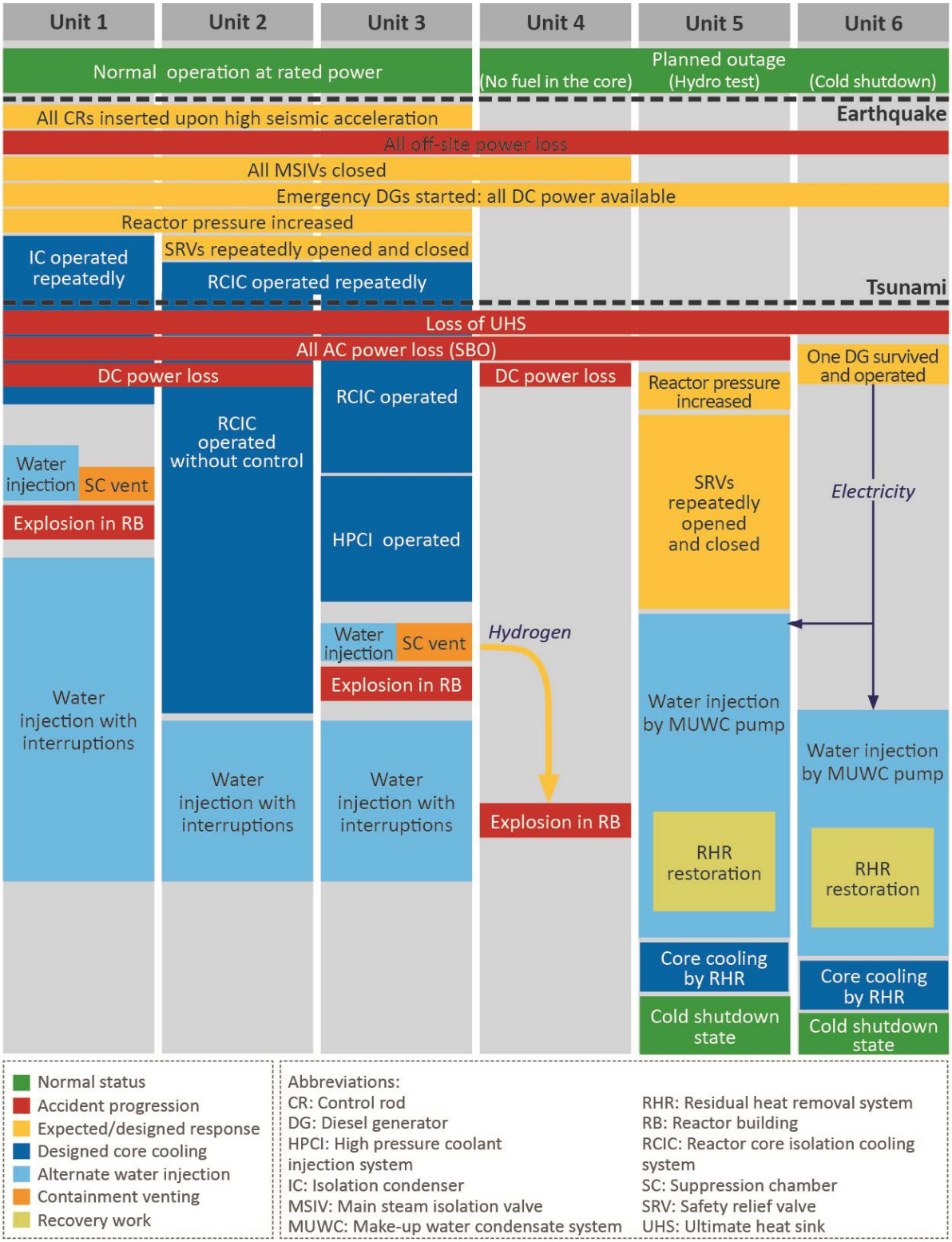


FIG. 1.1–2. Overview of the main event sequence at the Fukushima Daiichi NPP.

1.1.2. Accident initiation and response

1.1.2.1. Initiating event: The earthquake

The Great East Japan Earthquake occurred in the subduction zone off the north-east coast of Japan where the Pacific tectonic plate forces its way under the North American tectonic plate. It was caused by a sudden release of energy, as a section of the Earth's crust at the interface of these plates was ruptured and impacted an area in the fault zone estimated to be about 500 km long and 200 km wide.

The main shock, with a magnitude of M 9.0 [10], lasted for more than two minutes, with several significant pulses and aftershocks. The ground motion caused extensive damage to the infrastructure including the power transmission and transportation systems in Japan. Following the earthquake, local, regional and national 'general earthquake' emergency response organizations were activated to assess and coordinate the earthquake damage assessment and recovery. An ERC at TEPCO Headquarters in Tokyo was established for coordinating, overseeing and managing the response to the earthquake damage at all of the company's assets and the recovery from electric outages in the service area.

1.1.2.2. Plant status at the time of the earthquake

The Fukushima Daiichi NPP (Fig. 1.1–3), which comprises six units [12] with boiling water reactors (BWRs) (see Box 1.1–1), was located 180 km from the epicentre. When the earthquake occurred, the three reactors of Units 1, 2 and 3 were in normal operation at rated power, while Units 4, 5 and 6 were in various stages of periodic planned refuelling and inspection outage, as follows:

— Unit 1 was generating 460 MW electricity.
— Unit 2 was generating 784 MW electricity.
— Unit 3 was generating 784 MW electricity.
— Unit 4 had its fuel off-loaded from the reactor core to the fuel storage pool, the spent fuel pool (SFP), and no fuel assemblies were in the RPV, the vessel that houses the reactor. Both the SFP and RPV were filled with water.
— Unit 5 had fuel assemblies loaded in the reactor core. The fuel had relatively low decay heat due to the period elapsed since power operations. The RPV was filled completely with water and isolated (bottled up) and was being pressurized by a pump in preparation for the RPV pressure (leak) test. Its confinement structure, the PCV, was open, with its lid removed.
— Unit 6, which was under the cold shutdown state of the outage, also had fuel assemblies with relatively low decay heat loaded in the reactor core, and the RPV was filled with water to a prescribed height, sufficiently covering the reactor core. The main steam isolation valves (MSIVs) that, when closed, disconnect the RPV from rest of the power plant, were open, and the RPV was nearly at atmospheric pressure and ambient temperature.

There were approximately 6400 personnel at the site, among whom approximately 2400 TEPCO and contractor employees (750 TEPCO, 1650 contractors) were working in the controlled area. The majority (approximately 2000) of those were carrying out activities in support of the periodic planned refuelling and inspection outages.

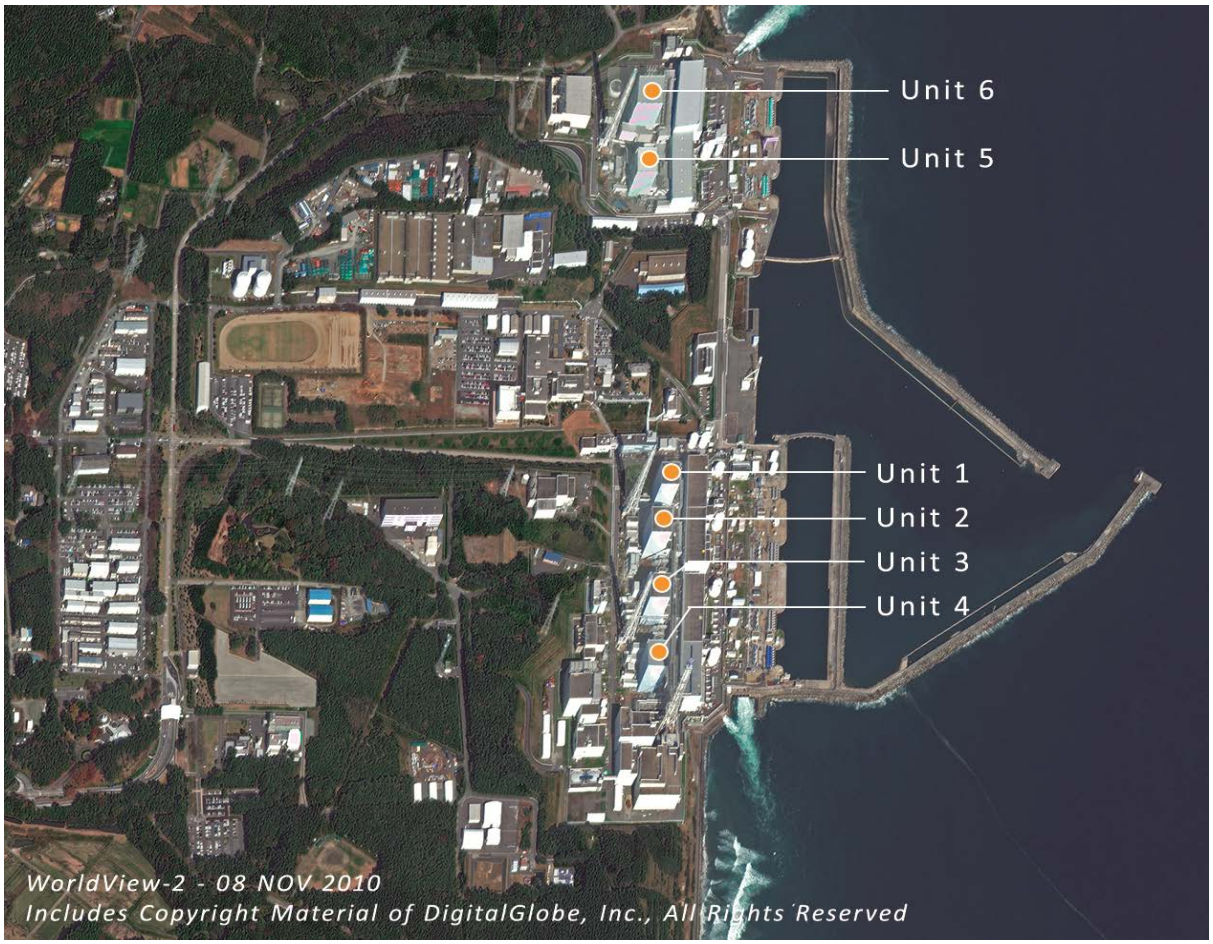


FIG. 1.1–3. An aerial view of the Fukushima Daiichi NPP site. The complex containing Units 1–4 is located at the south of the site and the complex of Units 5 and 6 is situated at the north.

1.1.2.3. Earthquake response and loss of off-site power

The operating reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. As the ground motion exceeded the value that was set to activate the reactor seismic protection, the insertion of control rods (blades) was automatically initiated, which stopped the nuclear reaction.

After shutdown, the nuclear fuel continued to generate heat (decay heat). To prevent the nuclear fuel from overheating, this heat had to be removed by cooling systems that were mainly run or controlled by electrical power. However, the earthquake caused damage to on-site switchyard equipment, off-site substation equipment and the power lines supplying off-site AC power to the plant, leading to the loss of all off-site electrical power for every unit at the Fukushima Daiichi NPP site. This is referred to as a loss of off-site power (LOOP) event and was within the design basis of the Fukushima Daiichi NPP.

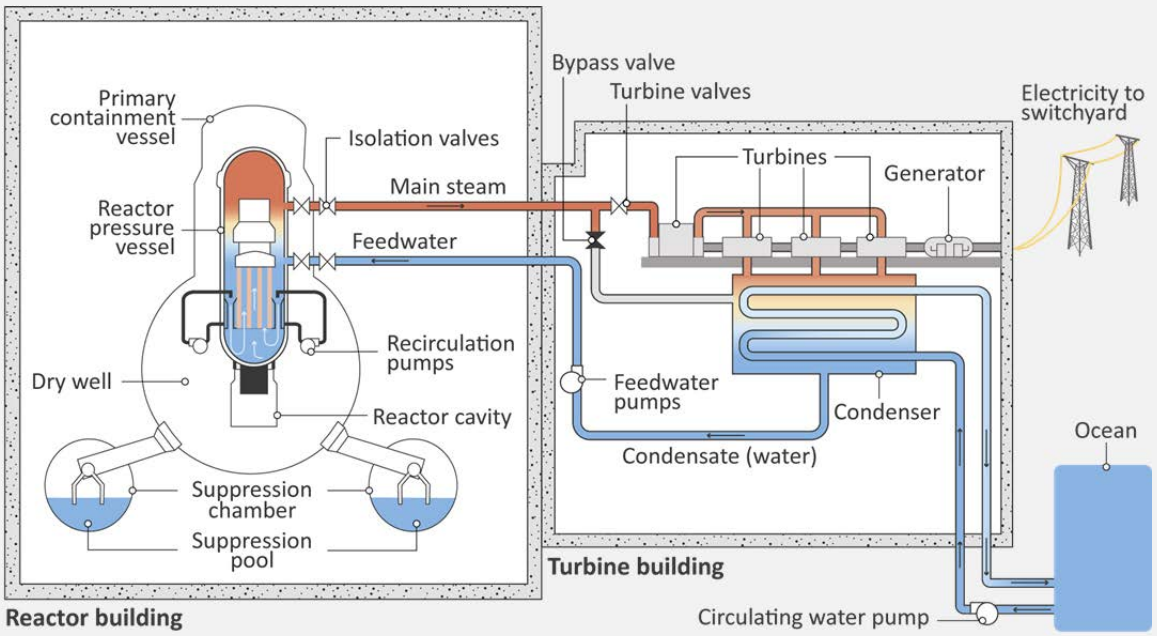
1.1.2.4. Plant response to loss of off-site power

In response to the LOOP, the on-site replacement power facilities — emergency diesel generators (EDGs) — which were designed for such LOOP situations, automatically started in order to restore

AC power in all six units.[4] The EDGs restored AC power to the emergency busses and to the direct current (DC) power battery chargers, as designed.

Box 1.1–1. Boiling water reactors

Boiling water reactors use a closed, direct steam cycle loop, as shown schematically below. The working fluid is water that is used both as the coolant to remove heat and the moderator for controlling reactivity. Coolant water boils in the reactor core at a pressure of approximately 7 MPa (70 bar), and the steam that is generated is used to drive turbines to generate electricity. After passing through the turbines, the steam is condensed back to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feed water.



As a result of the power interruption, the reactors of Units 1–3 were automatically isolated from their turbine systems by the closure of all MSIVs. This resulted in increases in the temperature and pressure of the reactors due to the decay heat. The cooling of these reactors after the reactor shutdown and isolation from their turbine systems was accomplished by means of the following design and operational provisions for heat removal at high reactor pressure (Box 1.1–2):

— In Unit 1, as the reactor pressure increased, both loops of the isolation condenser (IC) system started automatically and continued to cool the reactor. The operation of both IC loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the RPV that would be caused by the excessive cooling rate[5]. Afterwards, only one of the loops was used by the operators to control the reactor pressure in a range prescribed by the procedures.[6]

[4] One EDG of Unit 4 was under periodic maintenance, hence it was out of service.

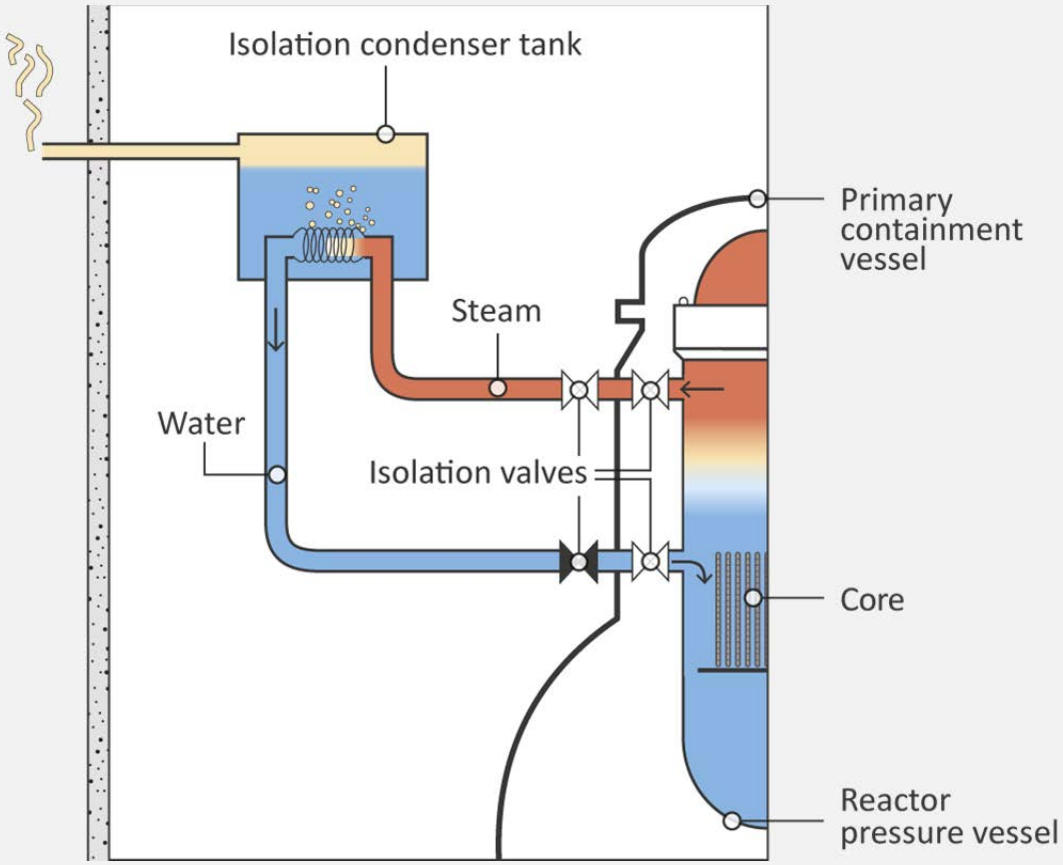
[5] In BWRs, the cooling rate is monitored and controlled by the reduction in reactor pressure, which, in turn, corresponds to the decrease in reactor temperature.

[6] In order to prevent opening of a safety relief valve (SRV) that would, in turn, result in loss of water in the reactor.

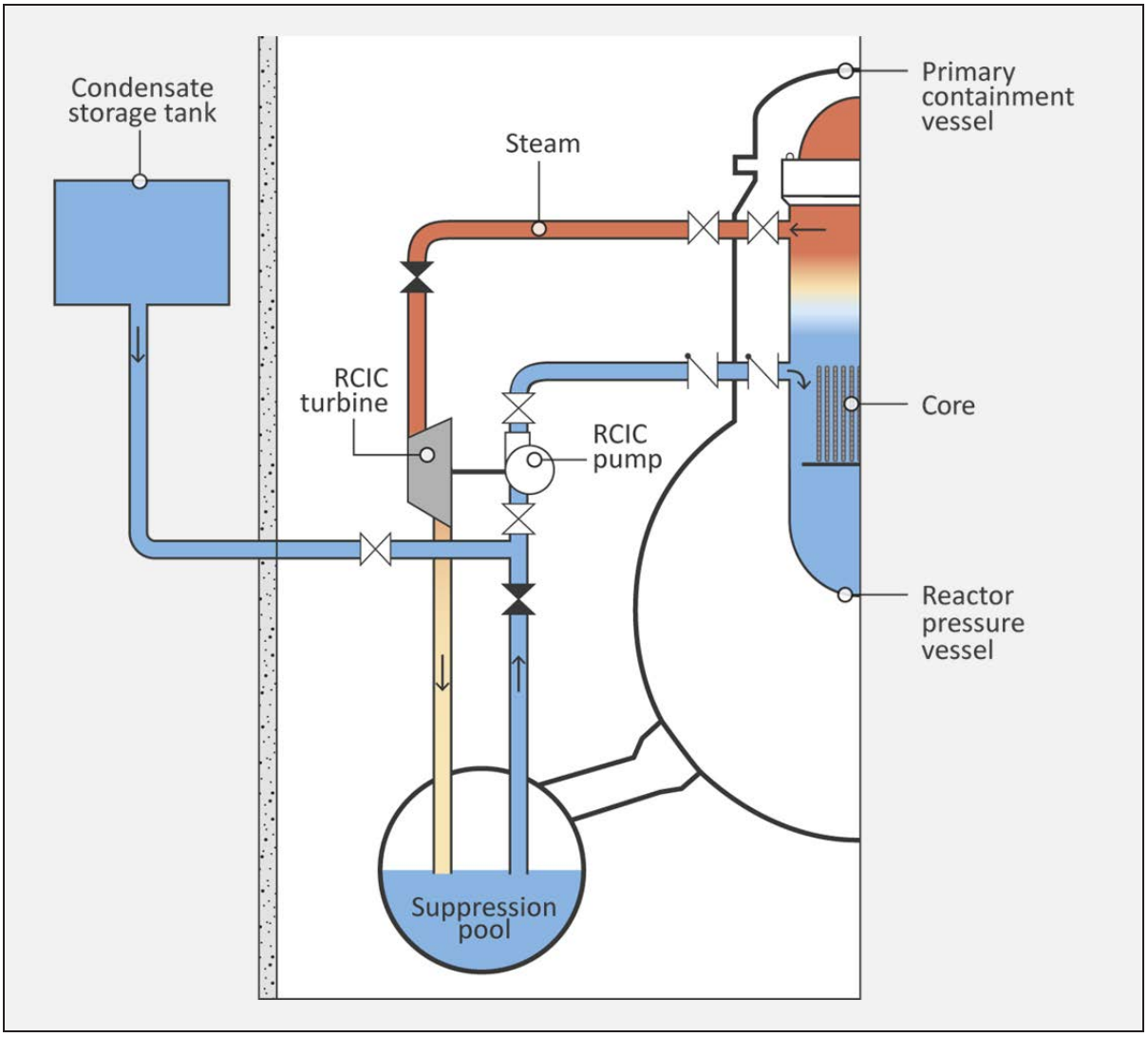
Box 1.1–2. Systems for cooling the core when the reactor is isolated from the turbines

Normal shutdown cooling of boiling water reactors at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 1.1–1). However, when the reactor is isolated, this path is not available, and core cooling is provided by the systems designed for an isolated reactor under high pressure conditions which exist after reactor shutdown. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser system for Unit 1 (the earlier design) and the reactor core isolation cooling system for Units 2–6.

Isolation condenser. In the Unit 1 design, there were two separate and redundant isolation condenser loops. In these closed loops, the primary side of the isolation condenser received steam generated in the reactor and condensed it by cooling inside the heat exchanger tubes that were submerged in colder water tanks (isolation condenser pools) located outside the primary containment vessel. Condensed steam was then sent as cold water back to the reactor by gravity (see the diagram below). Without mixing with the radioactive primary side water, the secondary side water in the isolation condenser pools boiled, and the evaporated steam was vented to the atmosphere, which served as the heat sink. The secondary side water volume of the isolation condenser (both trains together) was sufficient for eight hours of cooling before requiring replenishment from a dedicated water source.



Reactor core isolation cooling. In the design of Units 2–6, there were open cycle cooling systems that needed a source for adding water to the reactor system. In the reactor core isolation cooling systems, the steam from the reactor drove a small turbine which, in turn, ran a pump that injected water into the reactor at high pressure. The steam that ran the turbine was discharged and accumulated in the suppression pool section of the primary containment vessel, which served as the heat sink for absorbing waste heat. The water lost from the reactor was replenished by taking fresh water from the condensate storage tank (see the diagram below). When the tank emptied or the suppression pool became full, the water that accumulated in the suppression pool could be used, making the system essentially a closed loop cycle. The reactor core isolation cooling was designed to operate for at least four hours.



— In Unit 2, the operators manually activated the reactor core isolation cooling (RCIC) system in accordance with procedure. However, the RCIC automatically stopped almost immediately, since the reactor water level was higher than the pre-set water level point for RCIC operation. Increasing reactor vessel pressure eventually activated a safety relief valve (SRV), which was designed to protect the RPV from overpressurization by discharging steam into the water (suppression) pool in the suppression chamber (SC), or commonly referred as torus, section of the PCV. This resulted in a decrease in the reactor water levels. In response, the operators manually activated the RCIC system in accordance with procedures.
— In Unit 3, the reactor pressure increase first activated an SRV automatically, and the operators then manually activated the RCIC, in accordance with their procedure, upon decreasing reactor water level.

In Units 5 and 6, the decay heat from the fuel assemblies, which were loaded in the cores inside the RPVs, also had to be removed:

— In Unit 5, the reactor pressure, which was kept at an elevated level by the use of a pump for pressure testing at the time of the earthquake, initially dropped when the pump stopped as it lost power as a result of the LOOP. The pressure started to rise in the water filled RPV, as a result of

the decay heat, but, unlike in Units 2 and 3, it remained for some time well below the levels that would activate the SRVs[7].

— In Unit 6, the decay heat was also low, and the reactor was near atmospheric pressure and ambient temperature. Therefore, the increase in reactor pressure and temperature and the decrease of the reactor water level was slow, with less need for immediate heat removal after the LOOP.

The heat had to be removed not only from the reactor cores but also from the following systems and structures:

— In Unit 4, where the fuel assemblies had recently been moved from core to the spent fuel pool (SFP), the equipment for cooling and refilling of spent fuel pool water[8] stopped working as a result of the LOOP. The Unit 4 SFP, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among the SFPs of all the units.
— In the SFPs of the individual units and in the common SFP[9], all of which lost cooling and refilling capabilities upon the LOOP, the temperatures of the pool water started to increase due to decay heat.
— Since the normal containment cooling system stopped as a result of the LOOP, operators (in Units 1 and 2) also manually initiated emergency containment cooling systems to remove the residual heat discharged and dissipated from the RPV to ensure control of the confinement function.

In response to the earthquake and the LOOP, the operators activated the 'event based' abnormal operating procedures (AOPs) for a 'Natural Event' and a 'Turbine and Electrical Incident' in all three main control rooms (MCRs) [10] in keeping with post-earthquake and post-LOOP instructions, respectively. In line with the procedures, post-earthquake inspection and off-site power restoration activities were initiated. However, their implementation was continuously interrupted by the ongoing aftershocks.

An earthquake emergency response team was activated at the on-site emergency response centre (ERC) located within the seismically isolated building[11]. The Site Superintendent, as the designated on-site emergency manager, was responsible for directing the site response and for coordination with on-site and off-site organizations. Under the Site Superintendent's command, three shift superintendents, who were the licensed operators in each of the three common MCRs, were responsible for directing the actions of the shift teams in their units.

Therefore, the units at the Fukushima Daiichi NPP responded to the initiating event — the earthquake and the concurrent loss of off-site power — as intended by the designers and as stipulated in the operating procedures (Fig. 1.1–4).

---

[7] Although the pressure relief and reduction function of the SRVs were disabled (locked) as a prerequisite of the pressure testing, their automatic overpressure protection function was still available for one set of safety valves that consisted of three SRVs.

[8] The SFPs, which store the used and new fuel assemblies, are filled with water, providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of the fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

[9] As a shared auxiliary facility among the units, the common spent fuel pool, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[10] Each pair of units shared a control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[11] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

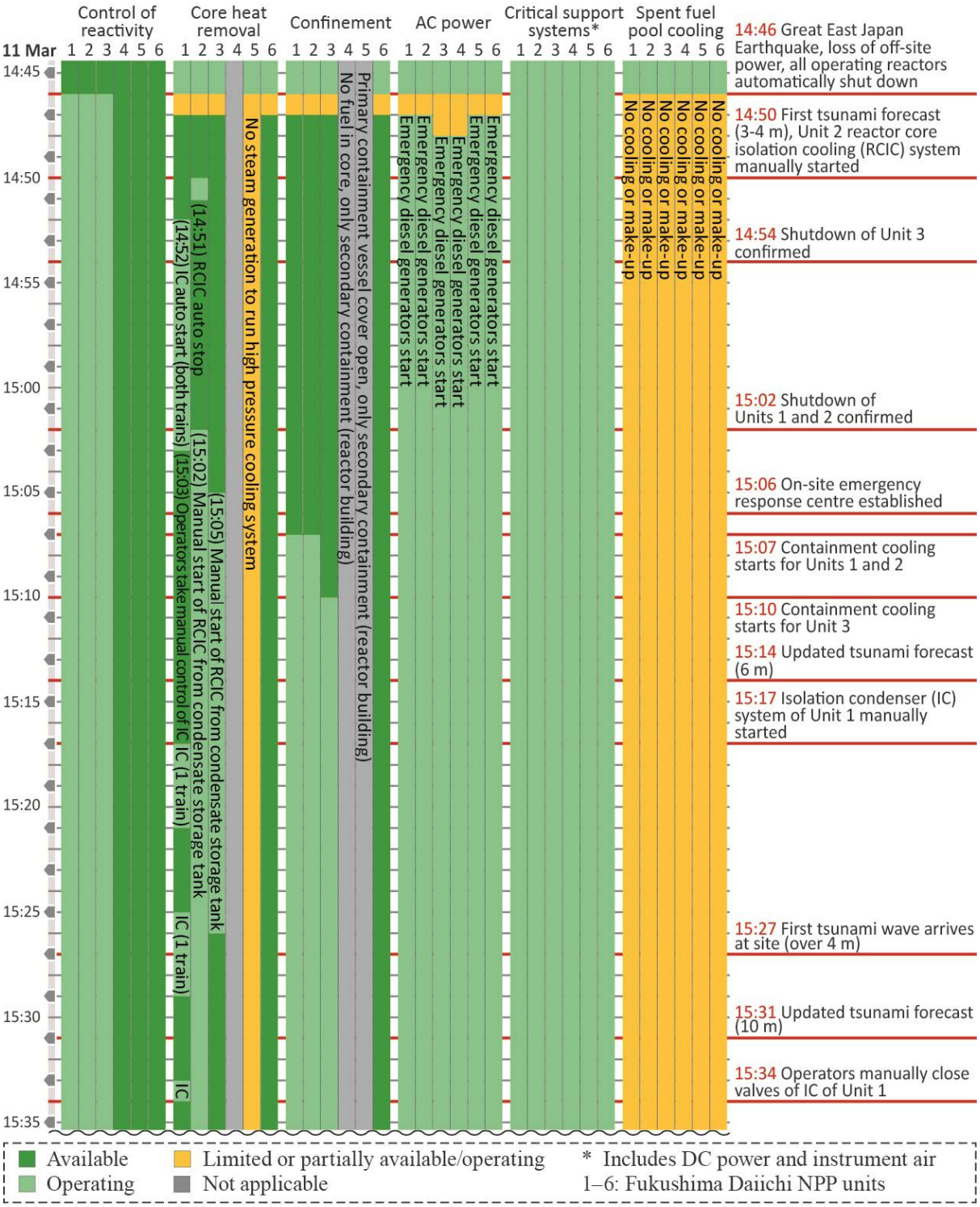


FIG. 1.1–4. Response of the Fukushima Daiichi NPP to the earthquake and the loss of off-site power.

1.1.2.5. Tsunami and station blackout

In addition to causing strong ground motion and infrastructure damage, the earthquake displaced a massive amount of water, giving rise to a series of large tsunami waves. When these tsunami waves reached the coast, they had a devastating effect over a wide area (Fig. 1.1–5).

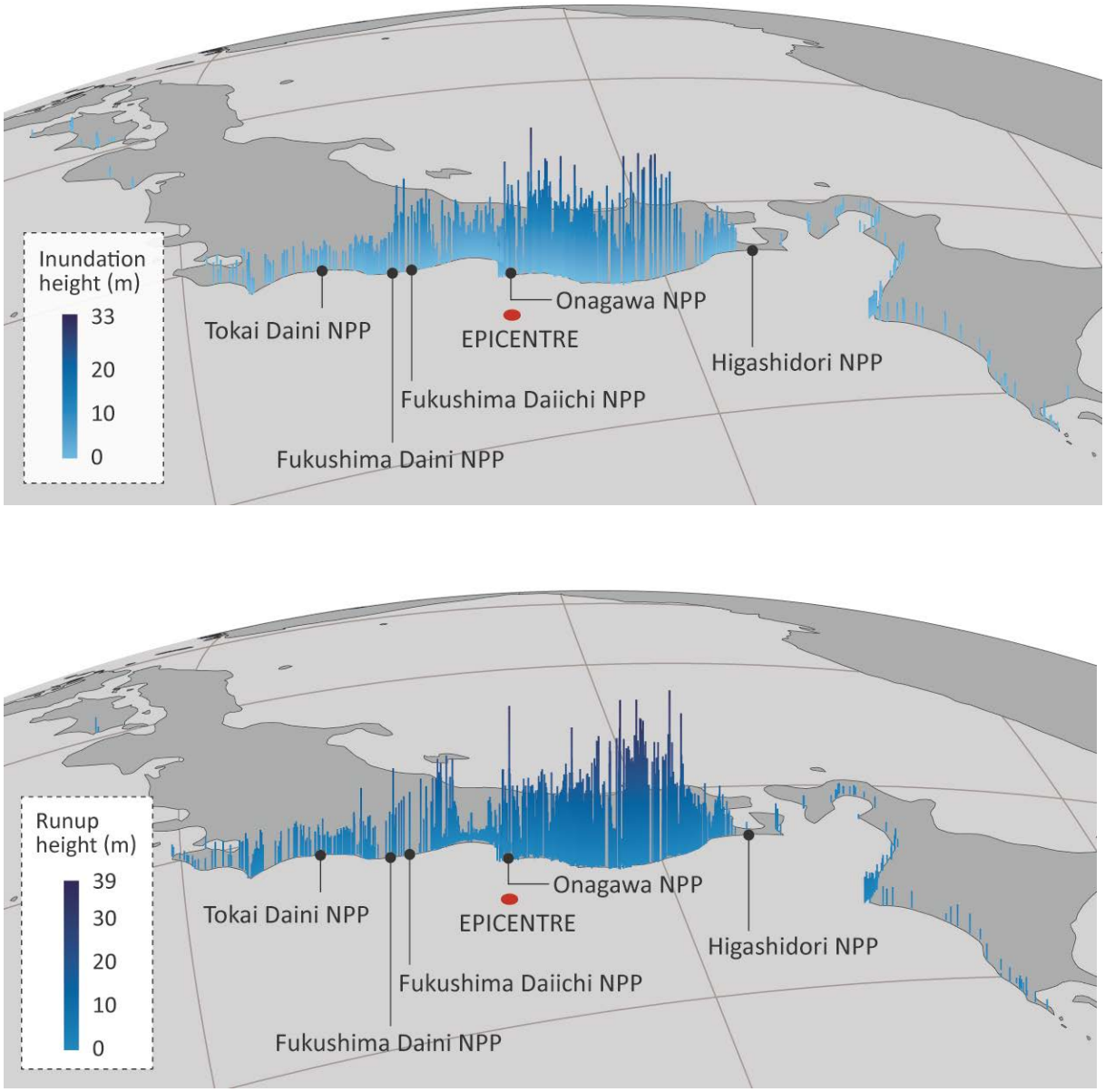


FIG. 1.1–5. The variation of tsunami wave impact, inundation (top) and runup (bottom), based on the coastal geography and topography [13].[12]

Shortly after the main earthquake shock, the Japan Meteorological Agency (JMA) issued tsunami warnings [14], initially forecasting a wave of 3–4 m high for Japan's east coast, on which the Fukushima Daiichi NPP site was located. This forecast was updated at 15:14 to 6 m and later, at 15:31, to 10 m. Upon this tsunami warning, an announcement was made from the MCRs via the PA system to the personnel to evacuate from the lower site elevations to higher positions.

The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake, at 15:27. The site was protected from the first wave, which had a 4–5 m runup height, by the tsunami barrier seawalls, the breakwater, that were designed to protect against a maximum

[12] Runup height is the height of the wave at the furthest inland point, and inundation height is the crest height of a wave compared to the sea level.

tsunami height of 5.5 m [15]. However, about 10 minutes after the first wave (between 15:36 and 15:37), the second and largest tsunami wave, with a run-up height of 14–15 m, reached the plant. The wave overwhelmed the seawalls and inundated the site. It engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations[13] (Fig. 1.1–6), causing the following sequence of events:

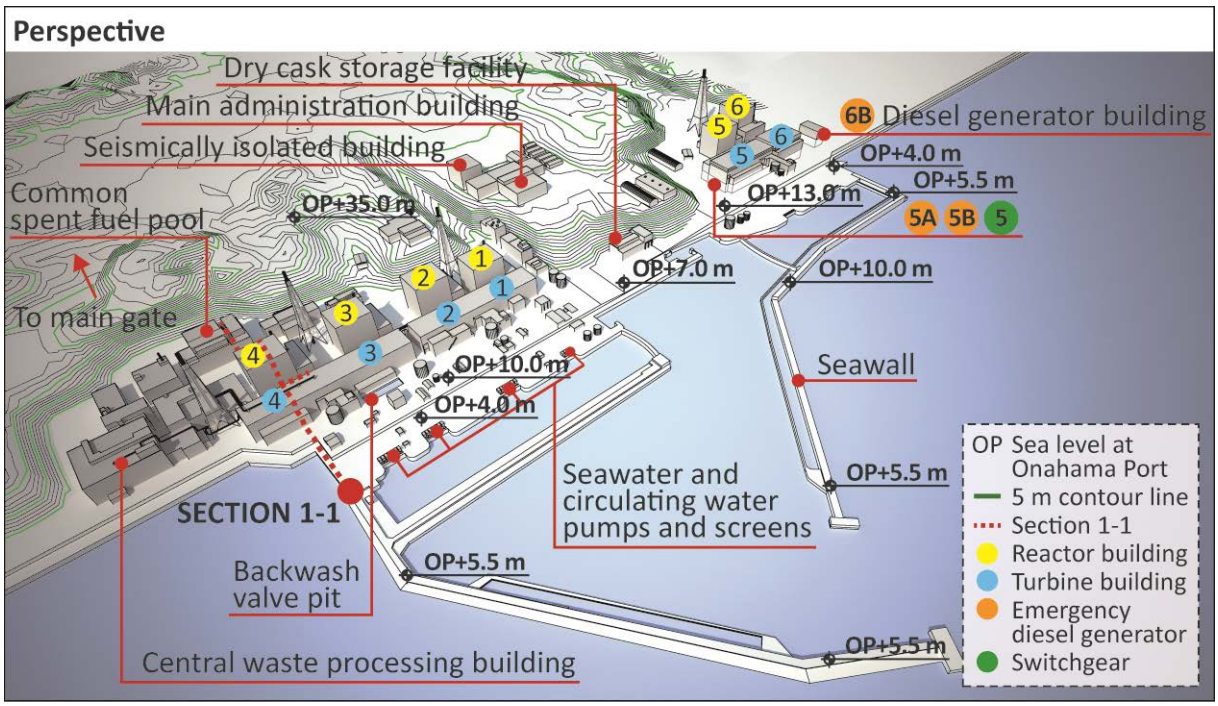


FIG. 1.1–6. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

— The wave flooded and damaged the unhoused seawater pumps and motors of all six units at the seawater intake locations on the shoreline, resulting in loss of ultimate heat sink events for all units. This meant that essential plant systems and components, including the water cooled EDGs[14], could not be cooled to ensure their continuous operation.
— The wave flooded and damaged the dry cask storage building located near the seashore between the Units 1–4 and Units 5–6 complexes. There were no significant impacts on the casks and the fuel stored in them, as was later confirmed [17].
— Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the EDGs or their associated power connections, power distribution panels and switchgear equipment (Fig. 1.1–7), which resulted in the loss of emergency AC power. Only

[13] The administration buildings and the seismically isolated building that contained the on-site ERC were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[14] Each unit had a pair of EDGs, and Unit 6 had an additional generator. Of those 13 EDGs, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

one of the air cooled EDGs — that of Unit 6 — was unaffected by the flooding[15]. It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

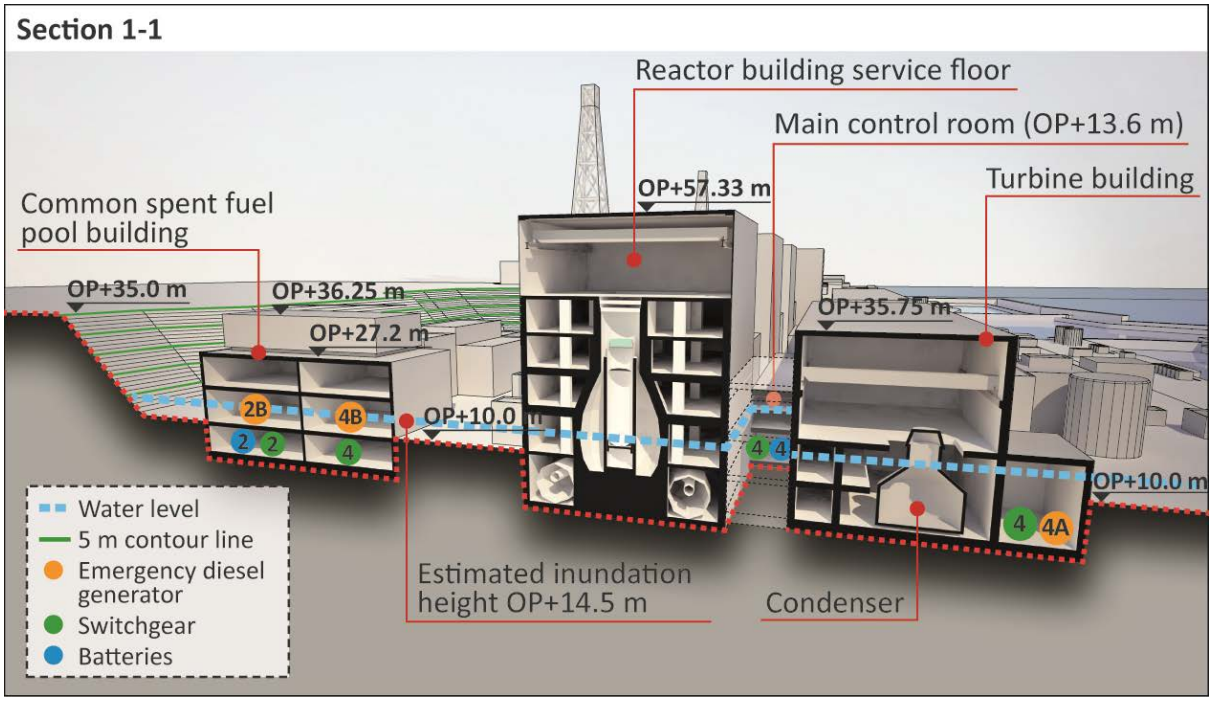


FIG. 1.1–7. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout (SBO). Only Unit 6, with its one remaining air cooled EDG supplying emergency AC power, did not. A 'specific event', as defined in the regulations[16] [18] associated with the Act on Special Measures Concerning Nuclear Emergency Preparedness (hereafter referred to as Nuclear Emergency Act)[17] [19] based on a 'station blackout'[18], was declared by the Site Superintendent, who was the head of the on-site ERC of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed, in accordance with the requirements of the Nuclear Emergency Act, within five minutes of the loss of all AC power, i.e. an SBO.

The Fukushima Daiichi NPP units, similar to other plants of the same age, had design provisions to withstand an SBO for eight hours, with response procedures for operators.[19] In Units 1–5, the event

[15] The air cooled EDGs of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be not affected by the flooding. However, the components (i.e. switchgears, power centres, panels, etc.) of the air cooled EDGs of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[16] Cabinet order in reference of the Nuclear Emergency Act.

[17] Act No. 156, adopted on 17 December 1999.

[18] Due to the loss of all AC power supplies for longer than 5 minutes.

[19] Nuclear power plants are generally equipped with on-site DC and additional backup AC power sources (i.e. gas turbine generators or diesel engines) to withstand an SBO for a limited period of time, varying between 4 and 72 hours. The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

based emergency operating procedures (EOPs) for 'loss of all AC power' [20] were initiated. As the emergency shifted from an earthquake situation to a nuclear situation, the ERC at TEPCO Headquarters and the Nuclear Emergency Headquarters of the Ministry of Economy, Trade and Industry (METI) were activated in Tokyo, along with METI's Local Emergency Headquarters at the Off-site Centre (OFC) in Okuma Town, located approximately 5 km away from the Fukushima Daiichi NPP site.[20]

1.1.2.6. Loss of DC power in Units 1, 2 and 4

All units at the Fukushima Daiichi NPP were equipped with on-site DC sources as an emergency power supply in an SBO situation, but the flooding also affected this equipment in Units 1, 2 and 4, inundating the DC batteries, power panels or connections. Consequently, DC power was gradually lost in Units 1, 2 and 4 during the first 10–15 minutes of the flooding, making it difficult to cope with the SBO.

Due to the loss of all electrical (AC and DC) power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the SFPs in all units was already lost following the LOOP. The additional loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the SFPs of these units.

In the absence of procedures addressing the loss of all (AC and DC) power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with an SBO under these conditions. The operators and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

1.1.2.7. Response in Units 3, 5 and 6

Although Units 3 and 5 were experiencing SBO, DC power was available in these units, and Unit 6 maintained its AC power supplied by the on-site emergency source, the EDG. Power availability enabled the operators to observe the plant status as the MCR indications and controls were functioning. This allowed the operators to continue with their applicable procedures in response to the events:

— In Unit 3, DC power was available from the DC batteries. The SRVs automatically opened and continued cycling to protect the RPV from overpressurization and, as a result, the reactor water level decreased. The operators manually restarted the RCIC system, controlling and monitoring the reactor water injection with the available DC power. They also shut off other non-critical equipment to maximize the availability of the DC batteries in order to extend the period of time for coping with the SBO in accordance with their event response EOP.
— DC power was also available in Unit 5. The residual heat removal by a high pressure cooling systems — the RCIC or high pressure coolant injection (HPCI) — was not possible, since the reactor was not generating steam to drive dedicated turbines to run the pumps. The reactor had to be depressurized to enable coolant injection by low pressure injection systems, such as the make-up water condensate (MUWC) and residual heat removal (RHR) systems. However, depressurization using the SRVs was not possible, since the depressurization function of the SRVs (except for three SRVs with the highest opening pressure) was disabled. Alternative

[20] The OFC at Okuma Town was later relocated to the Fukushima Prefecture Government office because of insufficient provisions by this office for an emergency situation caused by an earthquake and its inadequate arrangements for radiation protection for the radiation levels occurring during the accident.

options, such as discharging water from the RCIC and HPCI lines, were tried unsuccessfully, and the RPV, which was pressurized and filled with water, continued to heat up and pressurize.

— Unit 6 did not experience an SBO, since AC power was available from one operating EDG. Here, the efforts focused on maintaining fundamental safety functions[21] in response to the LOOP event as prescribed in the AOPs. The reactor was at atmospheric pressure, making it possible to utilize the low pressure systems to inject cooling water; however, some of the necessary components of those systems were damaged by the flooding and required restoration in order to provide water to the reactor. It was decided to inject water into the reactor via the MUWC system until the RHR system could be restored, since the air cooled EDG was operating and supplying AC power to the MUWC pump.

1.1.3. Progression of the accident

1.1.3.1. Presumed severe accident conditions in Units 1 and 2

As all electrical power was lost in Units 1 and 2, there were no indications available to the operators on the status of key systems and components to determine whether the safety systems were operating properly, or operating at all, in order to maintain the fundamental safety functions[22] and SFP cooling in Units 1 and 2.

Since the monitoring of the reactor water level status could not be recovered in the MCR and the status of water injection for core cooling remained undetermined, an emergency on the basis of the 'inability of water injection of the emergency core cooling system', as defined in regulations [18], was declared for Units 1 and 2 within one hour of AC and DC power loss, in accordance with the Nuclear Emergency Act's 'degrading nuclear emergency conditions' clause (Article 15). Consequently, at 16:45, the on-site ERC reported to the off-site organizations, TEPCO Headquarters and relevant government authorities, that the nuclear emergency conditions for Units 1 and 2 existed.[23] The Severe Accident Operating Procedures (SOPs) in the Unit 1 and 2 MCR and the severe Accident Management Guidelines (AMGs) in the on-site ERC were implemented, and the staff in the ERC and MCR began to establish a strategy for coping with the potential degradation of the fission product barriers.

1.1.3.2. Establishing the severe accident management strategy

Since the core cooling appeared to be compromised, the accident management strategy focused on injecting water into the reactors in order to prevent, or mitigate, potential damage to the nuclear fuel, in accordance with the AMGs and SOPs. Two options for injecting water into the reactors were identified:

— The use of systems that could inject water directly into the reactors even at high pressures, such as the standby liquid control (SLC) system and the control rod drive (CRD) system, which required the restoration of AC power.

---

[21] The control of reactivity, core cooling and confinement.

[22] The fundamental safety function of reactivity control had been confirmed before the SBO by indications showing that the control rods were inserted and the fission reaction had stopped.

[23] METI then reported Article 15 notification to the Prime Minister's Office, and, at 19:03, the Prime Minister declared a nuclear emergency situation. The Nuclear Emergency Response Headquarters (NERHQ) was established at the Prime Minister's Office, with the Prime Minister assuming responsibilities as the Director General, directing the national nuclear emergency response.

— The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump (DDFP) that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection (FP)[24] lines to inject water into the core.

The on-site ERC adopted a core cooling strategy that used the stationary DDFP and the fire engines via the fire protection system to inject water into the reactors, in addition to obtaining and connecting temporary AC power sources. Teams were dispatched to survey and assess the power equipment and the DDFP, to prepare the FP line arrangements and to dispatch the fire engines. This strategy considered not only Units 1 and 2, but all units, in anticipation of any further degradation of the fundamental safety function of core cooling in the other reactors.

This accident response strategy was given the highest priority for Units 1 and 2 and was applicable to all other units with some variations. For example, in Unit 5, the accident management (AM) action was to restore AC power using the available interconnecting line[25] to the operating EDG in Unit 6.

1.1.3.3. Confirmation of Unit 1 core cooling loss

Just before the tsunami struck, the Unit 1 IC was stopped by the operators in accordance with established operating procedures to control the reactor pressure. This was accomplished by closing the control valves (located outside the PCV and DC-operated, as shown in Box 1.1–2). About 2.5 hours after the loss of indications in the MCR, at 18:18 on 11 March, some of the status lamps for those control valves were found to be functioning, confirming that the control valves were closed and implying that the IC was not operating. The operators attempted to start the IC by opening those valves from the MCR (i.e. remote-manually), expecting that the isolation valves, located inside the containment on each line of IC loops, were in the open position, since their status was unclear[26]. After opening the outside containment valves of one IC loop, release of steam was observed above the Unit 1 reactor building (RB), which was thought to be coming from the IC system and would have indicated that the IC was operational; however, this assumption was short lived, as the steam release stopped, raising concerns about the integrity of the IC system. Since the system was not operating as expected, the valves that had just been opened were manually closed again to ensure that the IC was not operating. A team that was later dispatched to the RB confirmed that the IC was not operating, as indicated by the local readings of high reactor pressure. The 'non-operational' status of the IC was communicated to the MCR and relayed to the ERC. Thus, the fundamental safety function of core cooling at Unit 1 was lost when the IC was stopped by the operators just before the tsunami, and the Unit 1 core heated up from that time onward.

The team dispatched to the RB also confirmed that the DDFP was functioning and proceeded with establishing the core spray line-up for an alternative water injection via the FP system, as envisioned in the strategy. Additionally, local measurements (in the RB) at 20:07 indicated that the reactor was still near the operating pressure of 7 MPa (70 bar), which prevented water injection by alternative methods that would only be possible below 0.8 MPa (8 bar).

---

[24] The fire protection system was designed primarily for fire suppression and flooding of the containment vessel, not for injection of water into the reactor.

[25] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management. Sharing the functioning emergency power of Unit 6 was only possible for Unit 5, since these interconnections had been installed only between pairs of units, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[26] The valve positions were not clear to the operators owing to the uncertain timing and sequence of each type of power loss that would determine the operation of isolation condenser status of isolation valves. All the inside containment isolation condenser valves (AC operated) would keep their position when the AC power was lost, but they would close, by design, if the control power (i.e. DC power) was lost to the protection system — for the line break situation — that would have sent 'close signal' signals to those valves. The position of AC-powered isolation valves has not yet been confirmed by post-accident investigations.

After several notifications from the on-site ERC on the status of Unit 1 and the other units and discussions among the Prime Minister's Office, METI, the Nuclear and Industrial Safety Agency (NISA) and TEPCO, a national nuclear emergency was declared by the Japanese Government at 19:03 on 11 March 2011.

In Unit 2, which was also without any indications of operation of the core cooling system and core pressure and temperature, the operators assumed the worst case scenario that the RCIC system was not operating, and the Unit 2 core was heating up. At 21:01, the on-site ERC informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Following this prediction, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order at 21:23 on 11 March for the evacuation of the public within 3 km and for sheltering within 3–10 km of the site.[27]

The uncovering of the Unit 1 core was indicated when high radiation levels[28] encountered on the first floor of the Unit 1 RB by a team that was dispatched at 21:51 to confirm the status of the operation of the IC. This was an indication of the severity of the conditions at the Unit 1 reactor and the occurrence of possible core damage.

At 21:30, nearly six hours after the SBO, the operators tried to start the IC again. Although the water level in the Unit 1 reactor appeared to be increasing briefly, the IC did not function.[29]

At around 23:00 on 11 March, the radiation readings in the turbine building (TB), just outside the entry doors of the RB, were elevated (as high as 1.2 mSv/h at the north entry door). Shortly thereafter, an order that restricted entry to the Unit 1 RB was issued, and a report to the Government of Japan reporting the dose rates of 1.2 mSv/h in the RB and 1 mSv/h in the TB was sent at 23:49.

1.1.3.4. Deterioration in conditions at Unit 1 confinement

Following the confirmation of the loss of core cooling in Unit 1, further challenges to the other fundamental safety function — the confinement — became evident when the first reading of the PCV pressure became possible at 23:50 on 11 March. It showed that the Unit 1 containment pressure was 0.6 MPa (6 bar), exceeding the maximum containment design pressure of 0.528 MPa (5.28 bar). The pressures in the containments of other units were less adverse and were below the respective design pressures (local readings were 0.141 MPa (1.41 bar) in Unit 2 and 0.2 MPa (2 bar) in Unit 3).

The elevated Unit 1 PCV pressure prompted the declaration of an emergency based on 'abnormal rise in PCV pressure' for Unit 1 within one hour of the pressure measurements. The Site Superintendent also ordered preparations for Unit 1 PCV venting to relieve pressure in a controlled manner.

By 02:30 on 12 March, approximately 11 hours after the SBO, Unit 1 PCV pressure reached its highest value of 0.84 MPa (8.4 bar) before quickly decreasing to 0.8 MPa (8 bar) and stabilizing.

---

[27] Earlier, at 20:50, the local Government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

[28] The personal dosimeters of the team dispatched to the RB to confirm the status of the IC in Unit 1 recorded levels as high as 0.8 mSv in about ten seconds of their entry in the building.

[29] The reliability of level measurements was questionable at this point, since the water levels may have erroneously been caused by the evaporation of the water in the reference leg of the water level measurement.

1.1.3.5. Heating up of Unit 5 and restoration of AC power

During the time when core cooling and confinement functions in Unit 1 were the primary concern, the Unit 5 reactor had continued to heat up in the absence of heat removal measures. An SRV in Unit 5 automatically opened for the first time approximately 10 hours after the SBO, because the reactor pressure reached its opening set value, at 01:40 on 12 March. The valve automatically opened and closed several times to maintain the pressure in a range determined by the design.

The SRVs were operating automatically to limit pressure but could not be used to reduce pressure, since most of them had their depressurization function disabled for the test carried out before the accident. Reducing pressure by opening a small valve (the head vent nozzle) on the RPV was considered as an alternative because DC power was available for this purpose.

1.1.3.6. Confirmation of Unit 2's status and focus on recovery of Unit 1's safety functions

At 02:55 on 12 March, the local observations by the team dispatched to enter the Unit 2 RCIC room confirmed that the Unit 2 RCIC system was still operating, clarifying the previously unknown status of Unit 2 core cooling. Based on this information and the acute challenge to the confinement function of Unit 1, the Site Superintendent decided to give priority to the venting efforts of Unit 1.[30]

While the venting plans were being developed, the Unit 1 reactor pressure became low enough to allow alternative water injection.[31] The AM strategy to restore Unit 1's core cooling using the DDFP for water injection proved to be impossible to implement, because the pump was discovered to be inoperable at 01:48 on 12 March. The alternative, using fire trucks connected to the FP water injection port outside the TB, which had been installed in the previous year as a fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake, was put into action.

After a four hour effort of searching for and locating the FP water injection port among the debris, establishing the connection and getting the fire truck to the connection, the alternative water injection from the freshwater tank to the Unit 1 reactor via the FP system by using fire engine started about 12.5 hours after the SBO, at 04:00 on 12 March. Water injection from a single one-tonne truck continued intermittently, with the truck having to return to the freshwater tank periodically to be refilled. The water transport efforts were also interrupted by changing radiation conditions at the site.

1.1.3.7. Degrading on-site radiological conditions

Meanwhile, an attempt to enter the Unit 1 RB to conduct radiation measurements at 03:45 on 12 March was abandoned, when the team encountered white fog-like steam upon opening the airlock door, although the measurements at the radiation monitoring post near the site's main gate did not show any anomaly to indicate a release from RPV or PCV at 04:00. However, shortly afterwards, at 04:19, a drop in the Unit 1 PCV pressure was recorded, and an approximately ten-fold increase in the main gate radiation levels was observed (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23). Also, in the MCR, the radiation levels showed an increase requiring that the Unit 1 crew move to the Unit 2 side of the MCR, away from the entry door which was not completely closed to allow the laying of temporary cables.

[30] The plans for Unit 1 PCV venting were announced to the public by METI and TEPCO at a joint press conference at 03:06 on 12 March.

[31] Reactor depressurization had occurred without any operator or plant systems actions, indicating that an unknown path provided pressure relief.

In response to increased dose rates at the site and the contamination detected on the workers returning from outside area activities at the site, the ERC issued a brief evacuation of site personnel conducting outside activities, and subsequently a recommendation to resume the work with protective gear. Following up on the ERC's recommendation, the shift superintendent of Units 1 and 2 issued a mandatory order for the outside workers of these units to wear full-face masks with charcoal respirators and full-body suits. He also ordered that full-face masks with charcoal respirators be worn by the operators in the Unit 1 and 2 MCR.

TEPCO also notified the government agencies about increasing radiation readings at the site. This information, combined with the elevated containment pressure in Unit 1 necessitating PCV venting, prompted the Government to expand the evacuation zone to 10 km early in the morning, at 05:44 on 12 March 2011. The activities to configure venting of Unit 1's containment were set to start at 09:00 on 12 March.

1.1.3.8. Starting continuous freshwater injection into Unit 1

As the intermittent freshwater injection by fire engines continued, the work on establishing a direct line from the freshwater tank to the Unit 1 reactor, via the FP system for continuous injection, took approximately 5.5 hours. The work on the direct injection line was interrupted by changing radiation conditions at the site. At around 09:15 on 12 March, slightly over 17.5 hours after the SBO, continuous water injection to the Unit 1 RPV started directly from the FP tank through a connection between a fire truck pump and the FP system.

1.1.3.9. Depletion of freshwater source in Unit 2

Meanwhile, in Unit 2, the contents of the freshwater source to RCIC system, the condensate storage tank (CST), for reactor water injection was being depleted. At the same time, the water level in the suppression chamber (SC) was rising to necessitate action to prevent overfill of the SC. Thus, a crew was dispatched to the RCIC room to manually manipulate the valves, in order to switch the RCIC pump water supply from the CST to the SC pool, in accordance with procedures. The valve alignment was completed at 05:00, and Unit 2 reactor water injection from the SC via the RCIC continued afterwards. This closed-loop RCIC operation resulted in a faster increase in SC temperature than a once-through line, as anticipated.

1.1.3.10. Depressurization of Unit 5 and restoration of AC power

After four hours of SRV cycling (repeated opening and closing) to limit pressure, at 06:06 on 12 March, approximately 14.5 hours after the SBO, the head vent nozzle on Unit 5's RPV was remotely opened from the MCR and left open to relieve pressure from the water-filled RPV afterwards.

In addition, the power connection between Unit 5 and the operating EDG in Unit 6 was completed nearly 16.5 hours after the SBO, utilizing the interconnecting 'accident management bus tie'. This AC connection enabled the powering of some Unit 5 equipment, such as the pumps and valves needed for reactor heat removal. Power supply to operate the MUWC pump and valves continued to be available through the rest of 12 March. Also, the MUWC-RHR interconnecting pipe valves were to be opened, to establish a reactor water injection line to Unit 5's reactor via the RHR system.

1.1.3.11. Trip of Unit 3 RCIC and switch to HPCI

While the containment venting and core cooling of Unit 1 was being established, the SBO response in Unit 3 had to be modified when the RCIC system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation. The operators tried unsuccessfully to restart the system several

times in the following hour as the water in the reactor continued to boil and evaporate, and therefore the reactor water level continued to decrease. When the water level reached the set point at which the HPCI system — an emergency core cooling system — to activate, this system automatically started at 12:35 to maintain the reactor water level in the predetermined range. However, the operators took manual control to avoid repeated automatic starts and stops of the system in order to preserve DC power for a longer period, in accordance with the SBO response procedures.

As the SC pressure and temperature had increased as a result of more than 20 hours of RCIC operation, the Unit 3 DDFP was also started at 12:06, to spray the SC via the FP line in order to suppress the pressure and temperature increase in the SC.

1.1.3.12. Venting of Unit 1 containment for protection of confinement safety function

As soon as confirmation was received from the Fukushima Prefecture authorities, at 09:02 on 12 March, of the completion of evacuation of Okuma Town, the teams were activated to start manipulation of the valves in order to arrange the path for venting the PCV of Unit 1.[32] After 5.5 hours of efforts, the venting path (Box 1.1-3) was established when the final valve on the path was opened at around 14:00 on 12 March.

The success of the venting operation was confirmed by a decrease in containment pressure, as measured at 14:30, and was reported to the relevant government authorities. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29 by one of the monitoring posts located near the site boundary to the north-west of Unit 1.[33] Overall, it took 14.5 hours from the Site Superintendent's order around midnight to implementation owing to high radiation levels in the torus room, which houses the SC, where valves had to be manually manipulated, and the lack of compressed air supply to manipulate the valves.

1.1.3.13. Establishment of temporary seawater injection and power provisions in Unit 1

After approximately 11 hours of water injection into the Unit 1 core via fire truck and FP system, the fresh water in the FP water tank was almost depleted. As a result, freshwater injection to Unit 1 stopped at 14:53 on 12 March. The Site Superintendent then decided to inject sea water into the Unit 1 reactor from the Unit 3 backwash valve pit, where seawater had pooled after the tsunami, as it was the only available source of water at that time. In just over half of an hour, this arrangement for seawater injection was completed. Around the same time, work to connect the mobile voltage power supplies[34] to Units 1 and 2 using an undamaged power panel in Unit 2 as a transformer was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized at 15:30 on 12 March.

---

[32] Completion of evacuation to start the venting was agreed with the Fukushima Prefecture authorities.

[33] At 16:17, it was noted by the ERC that radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h, and the authorities were notified at 16:27, since this value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

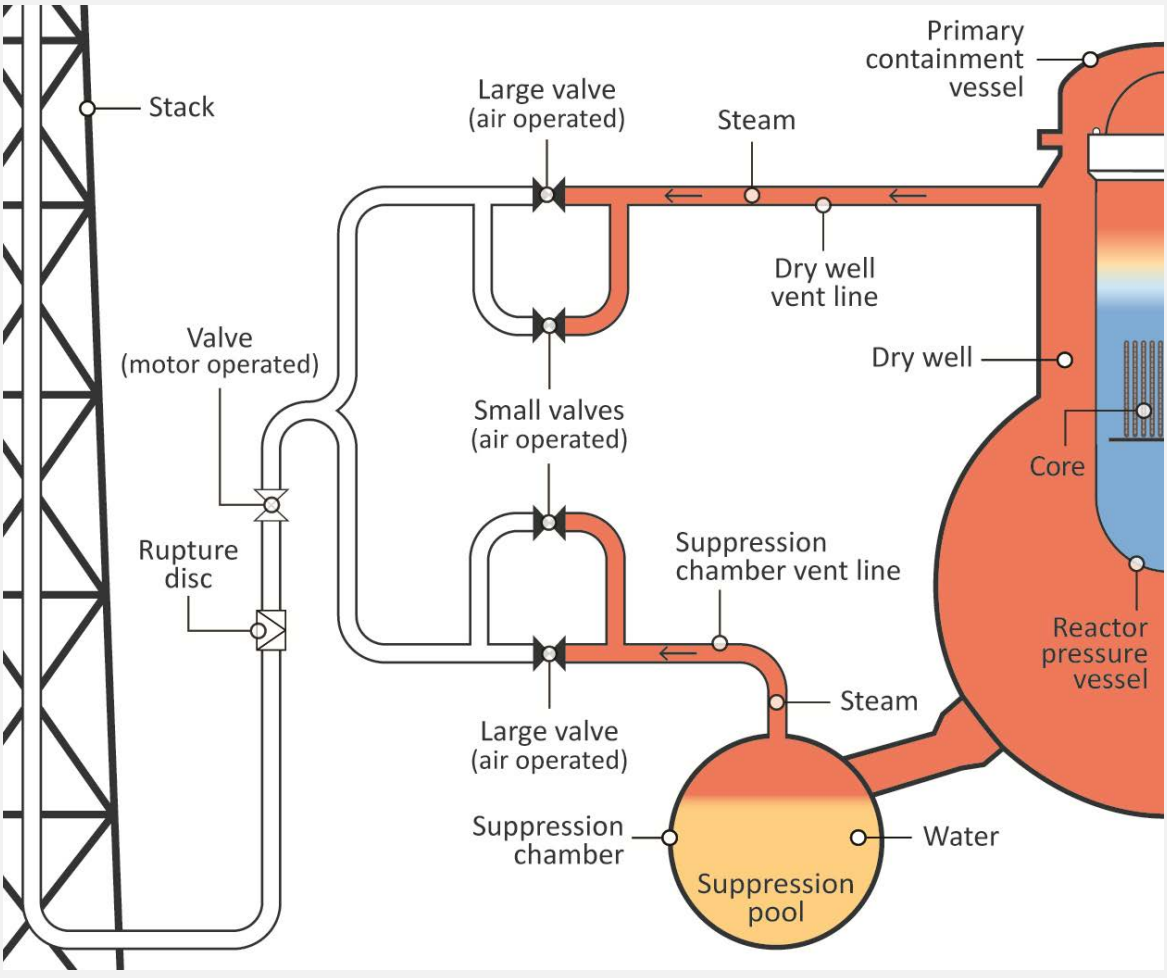
[34] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the Fukushima Daiichi NPP site.

Box 1.1–3. Containment venting

As a measure to improve the ability to cope with severe accidents, 'hardened vents' (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [21, 22]. The aim was to prevent overpressurization of the PCV by allowing venting (see the figure below) in order not to challenge the integrity of containment structure that maintains the confinement safety function.

Although the preferred path of venting was from the suppression chamber, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the drywell. Either path could be aligned by manipulating valves from the MCR, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to burst when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment.



Nearly 24 hours after the SBO, temporary seawater injection and AC power supply were connected to Unit 1. However, within minutes of connection, an explosion in the Unit 1 RB damaged both of these arrangements before they could be put in use.

1.1.3.14. Explosion in Unit 1 and destruction of alternative water and power provisions

At 15:36 on 12 March 2011, an explosion occurred on the service floor of the Unit 1 RB, causing extensive damage to the upper building structure. Although the explosion did not seem to have directly affected the primary containment (PCV), it damaged the secondary containment, the reactor building (RB) by destroying its steel framework and cover plates. The cause of the explosion was unknown to the plant staff, but it was suspected that hydrogen had been released from the core and had escaped from the primary containment via an unknown path. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4, including the crews of two MCRs except for the three most senior level MCR staff.

The explosion and the ejected debris also caused serious damage to the alternative seawater injection line assemblies and to the cables laid for the mobile high voltage power supply. It worsened the already challenging field conditions for emergency operations throughout the site, injuring workers and causing locally high dose rates around the site due to scattered contaminated rubble.

Shortly after the explosion, it was recognized that the radiation dose rates at the site boundary measured 1.015 mSv/h[35], and an emergency for 'abnormal rise in the site boundary radiation dose rate' was declared 40 minutes later. Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Although the relatively stable pressure inside the Unit 2 and 3 containments made venting of those units not an immediate necessity, the Site Superintendent ordered preparations for Unit 2 and 3 PCV venting to be started, benefiting from the relatively less adverse radiological conditions in those buildings, as the radiation conditions across the site were deteriorating quickly after the explosion in Unit 1.

1.1.3.15. Repair and restoration of water injection lines and seawater injection to Unit 1

Following the explosion in Unit 1, the area around the Units 1–4 had to be temporarily evacuated, delaying the repair of damaged temporary water and power equipment. The crew returned to repair or replace damaged equipment about 1.5 hours later.

After the replacement of damaged hoses and the start-up of the fire engine pumps, the injection of sea water into the Unit 1 RPV via fire engines from the Unit 3 backwash valve pit through the core spray line started at 19:04 on 12 March and continued afterwards.[36] Boric acid was added later to address recriticality concerns to ensure the fundamental safety function of reactivity control. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

1.1.3.16. Unit 3 HPCI manual shut-off and loss of core cooling

While Unit 1 was assigned the highest priority with respect to the maintenance of the fundamental safety functions during the first day and a half of the accident, the core cooling situation in Unit 3 became another cause of concern at 02:42 on the morning of Sunday 13 March.

---

[35] Later, this measurement was determined to have been taken at 15:29.

[36] On one occasion, according to the investigations [5], a TEPCO executive who was representing the company at the Prime Minister's Office asked the Site Superintendent on the telephone to stop the seawater injection to Unit 1. That directive was not followed, and seawater injection was not interrupted.

After 14 hours of continued operation of the HPCI system, the Unit 3 operators became concerned about the reliability and possible failure of the system's turbine powering the injection pump, which was by then already operating at low reactor steam pressure. The concern was related to the possibility of turbine damage and creation of a release path from the RPV. This would result in an uncontrollable release of radioactively contaminated steam, directly outside the PCV. This concern was heightened when the HPCI turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure.

Consequently, the operators decided to manually stop the HPCI system and instead use the alternative means of injection at low pressure (the DDFP). The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below the DDFP injection pressure and could be kept low by the use of SRVs. The Unit 3 HPCI was therefore turned off by the operators, who then proceeded to open the SRVs.

However, all attempts to open the SRVs failed, and reactor pressure quickly increased above the level at which the DDFP could inject, stopping the cooling of the Unit 3 core about 35 hours after the SBO. Faced with this setback, the operators unsuccessfully tried both from the MCR and local-manually, for nearly 45 minutes, to revert to injection via the HPCI system. Without any capability to cool the reactor, an emergency report for 'loss of reactor cooling function' as defined in the regulations [18] associated with the Nuclear Emergency Act [19] was issued for Unit 3, at 05:10 on 13 March. The Unit 3 core remained without cooling for the hours that followed, and Unit 3 became the next unit after Unit 1 to lose core cooling.

The overall effects of the HPCI shut-off and actions to recover the interrupted water injection were that the Unit 3 core was without cooling for seven hours. This interruption of core cooling was an adverse turning point for the Unit 3 conditions.

During this time, neutrons were detected between 05:30 and 10:50 on 13 March by a mobile radiation monitor near the main gate, which is around 1 km away from the RBs of Units 1–3.[37]

1.1.3.17. Unit 3 alternative core cooling and containment venting

After the loss of cooling of the Unit 3 core, an alternative water injection method utilizing the fire engines was ordered by the Site Superintendent at 05:15 on 13 March. In view of the deteriorating conditions, he also ordered the Unit 3 containment venting path, up to the rupture disc, to be lined up.

In order to establish Unit 3 core cooling by an alternative method, a fire engine from the Unit 5–6 complex was immediately dispatched to Unit 3 together with an additional fire engine that arrived from the Kashiwazaki-Kariwa NPP at 06:30. Also, the work to establish a temporary line for injecting seawater from the Unit 3 backwash valve pit to the Unit 3 core was immediately started. The water injection line was completed and connected to the FP line within one hour. However, its use was postponed by the Site Superintendent in accordance with a directive[38] from TEPCO Headquarters to continue injecting fresh water, not sea water, as long as fresh water was available. As a result, the injection line was changed back to the freshwater source. However, as the reactor pressure increased above the pump pressure of the fire engines, the injection did not occur.

---

[37] It has been estimated by TEPCO analyses after the accident that the neutrons came from spontaneous fission of actinides that had been released due to core damage in one of the three reactors, most probably from Unit 3.

[38] A TEPCO division director who attended a meeting in the Prime Minister's Office (PMO), asked the Site Superintendent on the telephone whether there was any fresh water available. The division director only informed the Site Superintendent of the views participants had expressed at their meeting. The Site Superintendent, however, took the discussions as directives.

The Unit 3 venting line arrangement was completed in a little more than three hours, at 08:41 on 13 March, but the containment pressure remained below the containment design pressure, and was not high enough to cause the rupture disc to burst.

The operators, meanwhile, continued their efforts to activate the SRVs in order to reduce the Unit 3 reactor pressure, using the DC batteries that were gathered from cars and collected in the common MCR of Units 3 and 4. As the opening of an SRV with those batteries was being tried, the operators in the MCR observed a drop in the reactor pressure in the Unit 3 reactor at 09:08, although the valve status indicators did not conclusively show whether or not the valves were in the open position.

Following the reactor depressurization, the reactor pressure fell below the fire engine pump pressure and injection of borated fresh water into the Unit 3 reactor, through the FP line using fire engines, started at 09:25, after more than four hours without core cooling.

Along with this depressurization of the RPV, there was a pressure surge in the SC section of the PCV, indicating a discharge from the RPV to the PCV. At 09:20 on 13 March, the containment pressure exceeded the maximum design pressure of the containment and, subsequently, the containment pressure dropped rapidly, indicating that the venting of the Unit 3 containment had occurred as a result of the bursting of the rupture disc. The venting of the Unit 3 containment, however, was short lived, when a valve on the vent line closed[39] because of the lack of sufficient air supply to keep it open. After 6.5 hours of effort, the valve was reopened by using a mobile compressor.

1.1.3.18. Unit 2 precautionary measures for fundamental safety functions

At approximately 10:15 on 13 March, as the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, the Site Superintendent ordered the containment vent path for Unit 2 to be pre-emptively established. This order was intended to take advantage of favourable radiological conditions by manually operating valves in the Unit 2 RB before any deterioration in line with the site wide trend.[40] The work was accomplished in 45 minutes, but venting did not occur because the pressure inside the Unit 2 containment was not high enough to cause the bursting of the rupture disc.

At around 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's operating normal cooling system, the RCIC, failed, as it was the case in Unit 3. For this purpose, fire engines were to be connected to the fire protection lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed.

1.1.3.19. Seawater injection and increase in radiation levels in Unit 3

As the fresh water from the FP tanks was depleted at around 12:20 on 13 March, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started about one hour later, at 13:12.

At 14:15 on 13 March, a radiation dose rate of 0.905 mSv/h was measured near the site boundary. This measurement exceeded the reporting criterion of 0.5 mSv/h as defined in the regulations [18] and the relevant government agencies were notified at 14:23 of an 'abnormal rise in the site boundary radiation dose rate' in accordance with the regulations associated with the Nuclear Emergency

[39] As discovered two hours later.

[40] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km from the reactor buildings of Units 1–4 near the main gate, indicating a possible breach of the containment vessel, although the source of the neutrons was unknown.

Act [19]. Fifteen minutes later, the radiation dose rate exceeded 100–300 mSv/h at the entry doors of the Unit 3 RB. Also, the dose rates on the Unit 3 side of the Unit 3–4 MCR exceeded 12 mSv/h by 15:28, and the shift team moved to the Unit 4 side. The on-site ERC inferred from these increasing dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common MCR of Units 3 and 4 and from the areas in the vicinity of Unit 3. The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

1.1.3.20. Establishing core cooling and confinement functions of Unit 5

At around 20:48 on 13 March, the power from the Unit 6 EDG was connected to the pump of Unit 5's normal, low pressure, non-safety heat removal system, the MUWC, and the pump was started at 20:54. The MUWC–RHR interconnecting pipe valves were remotely opened, completing a reactor water injection line to Unit 5's reactor via a train of the RHR system at 21:00, approximately 53 hours after the SBO. However, the reactor pressure had gradually risen and exceeded the RHR pump discharge pressure, which prevented water injection to the reactor. In response, the shift team, acknowledging that the pressure reduction by the head vent nozzle was not sufficient, decided to use the SRV set that was not locked, for additional RPV pressure relief. An SRV was opened, making use of available DC power and nitrogen supplies, reducing RPV pressure and allowing the water injection into the reactor at 05:30 on 14 March. This bleed (by SRV) and feed (by MUWC pump) operation continued afterwards.

In addition, the AC power to operate the standby gas treatment system (SGTS) for controlling RB pressure was supplied from Unit 6's EDG. The system was started up a little over two days after the SBO and kept the pressure inside the RB below the atmospheric pressure, ensuring secondary confinement.

1.1.3.21. Loss of seawater cooling in Units 1 and 3

As the injection of sea water into Units 1 and 3 from the Unit 3 backwash valve pit continued into Monday 14 March, the water in the pit fell to such a low level that injection to both units had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3, which resumed two hours later. Unit 1 core cooling was postponed until the pit could be refilled.

In the following hours, the Unit 3 containment pressure was found to be increasing, and the reactor water level indication continued to decrease. The reactor water level in Unit 3 went off-scale at 06:20 on 14 March, indicating to the operators that the core was uncovered. The Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the pit refilling activities.

The containment pressure in the drywell (DW) (see Box 1.1–1) in Unit 3 reached a maximum value of 0.52 MPa (5.2 bar) at 07:00, but was found to be slightly lower (0.5 MPa (5 bar)) at 07:20. It subsequently remained stable around 0.5 MPa (5 bar), which was below the maximum design pressure. The Site Superintendent then decided to resume the work to establish a line to refill the backwash valve pit from the ocean. In the next two to four hours, the seawater injection lines for all units were re-established, and refilling of the pit commenced, utilizing two fire engines pumping water from the ocean and seven tanker trucks from the Japan Self-Defense Forces (SDF), which arrived at the site at 10:26, to carry water to the pit.

Seawater injection into Unit 1 was ready to be resumed upon the refilling of the backwash valve pit, but all activities, including the ongoing seawater injection into the Unit 3 reactor, had to stop because of an explosion in Unit 3.

1.1.3.22. Explosion in Unit 3 reactor building

At 11:01 on 14 March, an explosion occurred in the upper part of the Unit 3 RB, destroying the building structure above the service floor and injuring workers. It also damaged the hoses and fire engines around the Unit 3 backwash valve pit. The cause of the explosion was unknown to the plant staff, but a hydrogen explosion was suspected.[41]

The explosion happened about one hour after the Unit 3 backwash valve pit levels had been restored and at a time when Unit 1 seawater injection was getting ready to be restarted. It necessitated a temporary evacuation of the workers from the outside areas, and hence interrupted the injection of water into Unit 3 and further delayed the injection into Unit 1.

In addition to the destruction of the alternative water injection arrangement, the ability of containment venting in Unit 2 was also lost as a result of the explosion, which affected the previously set up Unit 2 containment venting path. After the explosion, the isolation valve on the Unit 2 vent line was discovered to be closed and could not be reopened.

1.1.3.23. Restart of seawater cooling of Unit 1 and 3 cores

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. After the restoration of the injection lines, seawater injection was recommenced first for Unit 3 in the afternoon of 14 March and later in the evening for Unit 1. The cores had been without cooling water injection, for nearly 5 hours in Unit 3 and for 18 hours in Unit 1.

1.1.3.24. Loss of Unit 2 core cooling

At around 13:00 on 14 March, Unit 2 became the next unit to experience loss of core cooling, with measurements showing that the reactor water level had decreased and that the reactor pressure had increased since the previous measurements. This pointed to the possible failure of the Unit 2 RCIC system, as inferred by the MCR and the ERC. As a result, a 'loss of reactor cooling function' emergency was declared, now for Unit 2.

After the failure of the RCIC system, it was decided to apply seawater injection through the FP system via fire engines at 13:05. However, the reactor pressure was too high for the fire engine pumps and the RPV had to be depressurized first. It seemed likely that, without water injection, the core would be uncovered very soon. It was therefore decided to use the SRVs to depressurize the reactor in order to enable water injection at low pressure, while recognizing the potential adverse impact on the confinement function since this operation would have increased the pressure and temperature in the PCV, as a result of the release of steam from the reactor into the containment.[42]

[41] A team that was dispatched to check the status of the Unit 4 SFP at 10:30 on 14 March, just before the explosion, encountered high radiation levels, at the door of the Unit 4 RB and could not enter the building.

[42] The SC section of the PCV was already nearly filled and saturated.

After RPV depressurization through the SRVs and refuelling of the fire engines (which had meanwhile run out of fuel), seawater injection into Unit 2 through the FP system began shortly before 20:00 on 14 March, first by one fire engine, and soon thereafter by two fire engines.

1.1.3.25. Degradation of the Unit 2 confinement

At around 21:55 on 14 March, the recently restored containment atmospheric monitoring system (CAMS) — the radiation monitoring equipment inside the Unit 2 RPV — indicated that the radiation levels inside the containment had increased substantially since the previous measurements taken about eight hours earlier, prior to the CAMS going off-line: a 5000-fold increase in the DW (from 1.08 mSv/h to 5360 mSv/h) and an almost 40-fold increase in the SC (from 10.3 mSv/h to 383 mSv/h). Additionally, neutrons were detected after 21:00 on 14 March (until 01:40 on 15 March) near the main gate.[43]

Also, both the reactor and containment pressures showed an increasing trend after 22:30. The containment pressure measurement of 0.54 MPa (5.4 bar) at 22:50 exceeded the containment design pressure, prompting an emergency declaration of an 'abnormal rise in containment pressure' for Unit 2 in accordance with the regulations [18]. This condition was reported to the relevant government authorities at 23:39, in accordance with the Nuclear Emergency Act [19].

At the same time, the Unit 2 reactor pressure was 1.923 MPa (19.23 bar), and over the next three to four hours, more SRVs were opened to decrease the RPV pressure in order to allow water injection. As a consequence of these discharges from the RPV to the PCV through the SRVs, the containment pressure increased further while the unit operations team tasked with establishing the venting line to relieve containment pressure was unable to open the vent valves. In order to protect the confinement function and accomplish venting as soon as possible, TEPCO staff at the on-site and off-site ERCs agreed to vent directly from the DW, recognizing that this would substantially increase radioactive releases to the environment compared to venting from the SC. However, it was not possible to open the valves on the DW vent path either, and consequently, Unit 2 venting could not be accomplished.

At 04:17 on Tuesday 15 March, the relevant government agencies were notified that depressurization by venting of the Unit 2 containment and of the reactor had not been effective and that containment pressure continued to increase.

1.1.3.26. Blasts in Unit 2 and Unit 4 and site evacuation

At 06:14 on 15 March, an explosion was heard on the site, and tremors were felt in the common MCR of Units 1 and 2. This was followed by a drop in the pressure reading of the SC section of the Unit 2 containment. The staff in the MCR initially reported to the on-site ERC that the Unit 2 SC pressure had dropped to nearly atmospheric pressure, as zero bar was displayed in the MCR indicator, inferring a potential loss of the confinement function. After re-checking the readings, it was confirmed that the Unit 2 SC pressure went off the scale, but the Unit 2 DW pressure had not decreased significantly.

This information indicated a possible PCV failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site ERC was located.

[43] It was explained by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors.

Following the events in Units 2, all personnel, except those required for monitoring and for essential emergency response, were instructed by the Site Superintendent to go to a radiologically safe location. Approximately 650 people understood this order to mean a site evacuation, and they evacuated to the Fukushima Daini NPP site. An estimated 50–70 staff[44], including the Site Superintendent, remained at the Fukushima Daiichi ERC. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00 on 15 March.

At about the same time as the event associated with the Unit 2 SC, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[45]

About two hours later, at 08:25, white smoke (or steam) was observed being released from the Unit 2 RB near the fifth floor. A radiation dose rate measurement of 11.93 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

During this sequence of events, fundamental safety functions of Units 1–3 were lost or severely degraded (Fig. 1.1–8), and efforts focused on damage assessment and the restoration and stabilization of safety functions, starting with the SFPs of those units where explosions in the RBs had occurred.

[44] As noted by different investigation reports, the exact number of staff is not certain [4, 6]. It is also noted that the staff who evacuated to the Fukushima Daini NPP started to return to the Fukushima Daiichi site later on the same day.

[45] The personnel reported the Unit 4 explosion to the ERC after they arrived at the seismically isolated building, at around 08:11.

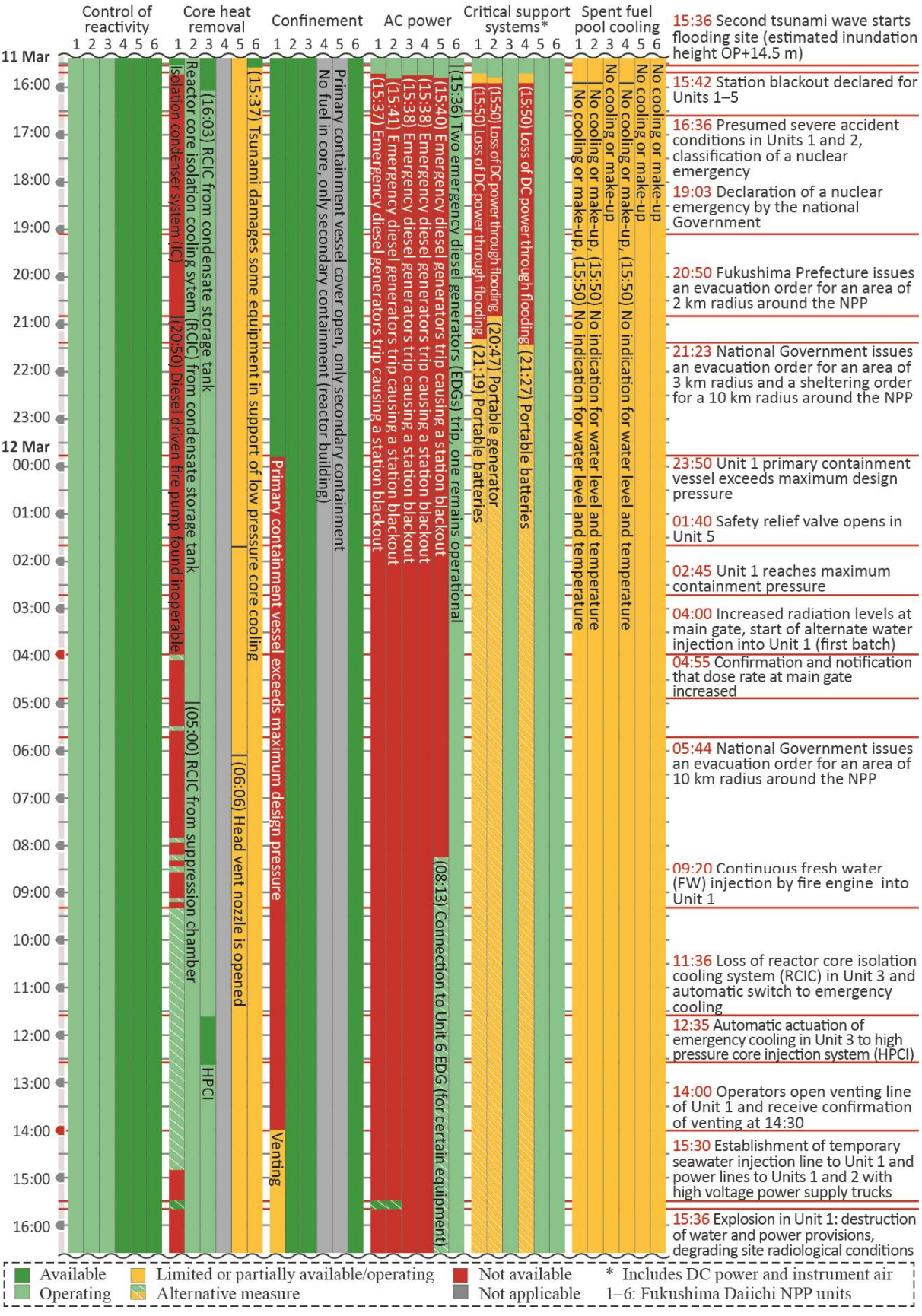


FIG. 1.1–8. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11-15 March 2011).

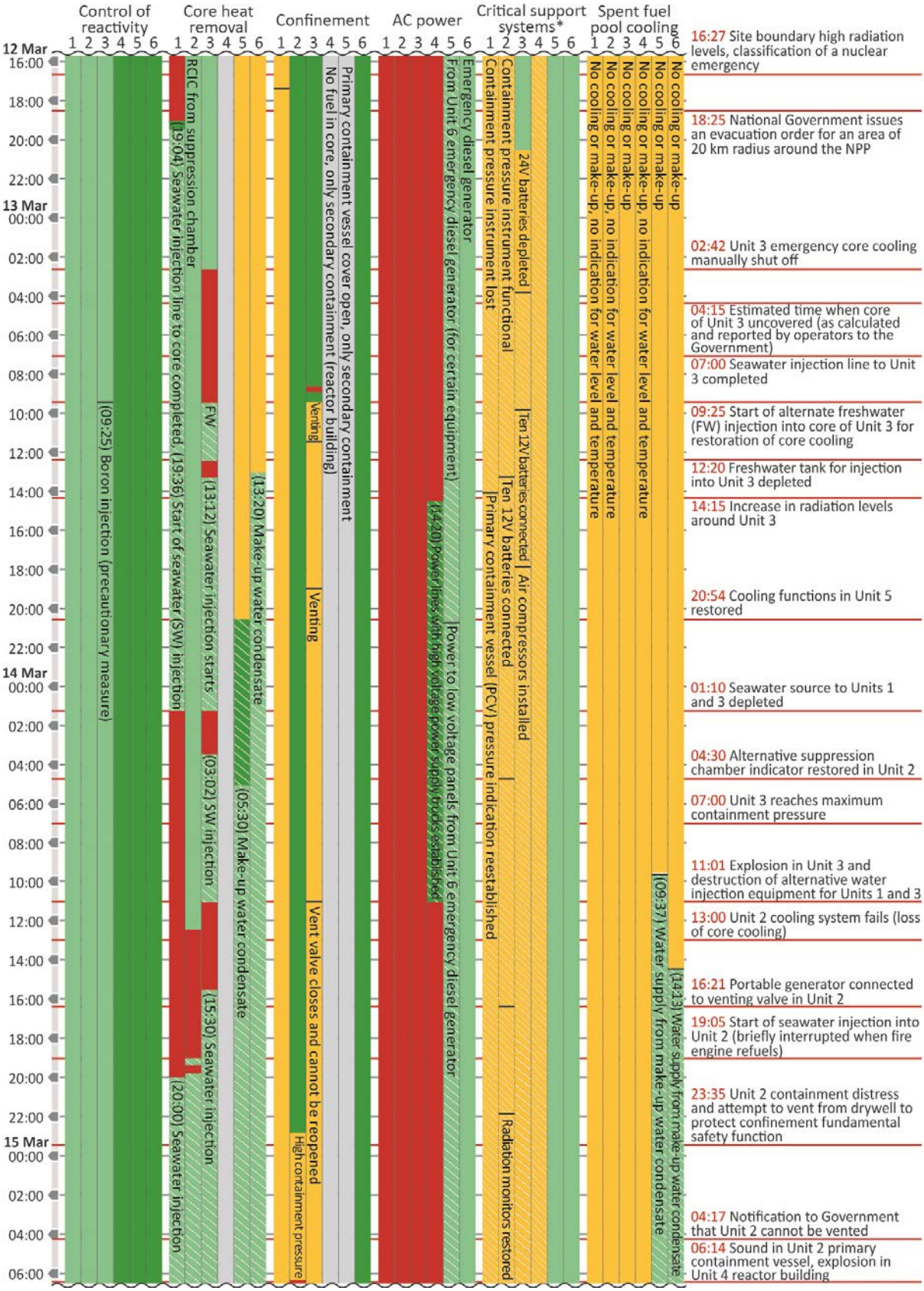


FIG. 1.1–8. Fundamental and supporting safety functions in the accident response at the Fukushima Daiichi NPP (11–15 March 2011) (cont.).

1.1.4. Stabilization

1.1.4.1. Replenishment of the spent fuel pools of Units 3 and 4

In order to perform an assessment of the reported Unit 4 fire, and to confirm the integrity of the SFP, a team attempted to enter the Unit 4 RB between 10:30 and 11:00 on 15 March, just over four hours after the explosion. The team encountered high radiation levels, in excess of 1000 mSv/h (the dosimeters hit the maximum scale of 1000 mSv/h).

A remote visual inspection from a helicopter to address concerns about the status of the Unit 3 and 4 SFPs was conducted in the afternoon of Wednesday 16 March. The inspection confirmed that there was sufficient water in the Unit 4 SFP to cover the fuel assemblies; however, observations were not conclusive for Unit 3's SFP, making its replenishment a high priority.

The first supply of water to the Unit 3 SFP was accomplished on the next day, 17 March, between 09:30 and 10:00, when helicopters dropped approximately 30 t of sea water on the Unit 3 RB. Freshwater was sprayed onto the Unit 3 SFP later on the same day, in five missions between 19:05 and 20:07, by the high pressure water cannon trucks from the Tokyo Metropolitan Police Department (44 t) and the fire engines of the SDF (30 t).

Seawater or freshwater spray into the Unit 4 SFP started on 20 March.[46] Later, on 22 March, a concrete pump truck with a boom was utilized for spraying the SFPs.

Spraying into the SFPs using water cannon and fire engine trucks or concrete pump vehicles continued intermittently in March to ensure that the spent fuel was not exposed. The fuel pool cooling (FPC) system — an SFP cooling and cleanup system — was also utilized in April and well into May 2011.

1.1.4.2. Restoration of power

In Unit 6, power was restored to the cooling system of the second, water cooled, EDG by connecting a power line to the operating air cooled EDG. The water cooled EDG started to operate again at 04:22 on 19 March, supplying AC power to Units 5 and 6.

Between 17 and 20 March, work was carried out on laying temporary power cables to Units 1 and 2, and, on 20 March, an auxiliary transformer was connected to the external grid. At 15:46 on Sunday 20 March, almost exactly nine days after the SBO, off-site power was restored to Units 1 and 2 through this temporary AC power system, ending the SBO in Units 1 and 2.

Lighting was restored in the MCR of Units 3 and 4 at 10:45 on 22 March, while the lighting for the MCR of Units 1 and 2 was re-established two days later, on 24 March.

The SBO at Units 3 and 4 ended, after more than 14 days, when temporary off-site power to these two units was restored on 26 March 2011.

Also during 23–25 March 2011, the water injection to the reactors was switched from sea water to borated fresh water. On 26 March, the fire pump was replaced by a stationary motor driven pump. On 3 April, the power supply to the pumps providing water to Units 1–3 was switched to off-site power.

---

[46] The same approach was followed for adding water to the SFP of Unit 1 later. Since the Unit 2 RB was still covering the Unit 2 SFP, the spray method could not be used for Unit 2.

1.1.4.3. Achieving safe or stable conditions

Unit 5 was the first unit to reach cold shutdown mode. Its shutdown heat removal system was put into service as the RHR system was aligned to the shutdown cooling (SHC) operation at 12:25 on 20 March. The reactor temperature decreased to below 100°C in approximately two hours, placing Unit 5 in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the earthquake.

The normal residual heat removal system of Unit 6 was put back in service, in a manner similar to that at Unit 5, at 18:48 on the same day. The reactor temperature decreased to below 100°C in less than one hour, placing Unit 6 in the cold shutdown mode at 19:27 on 20 March (Fig. 1.1–9).

For Units 1–3, TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

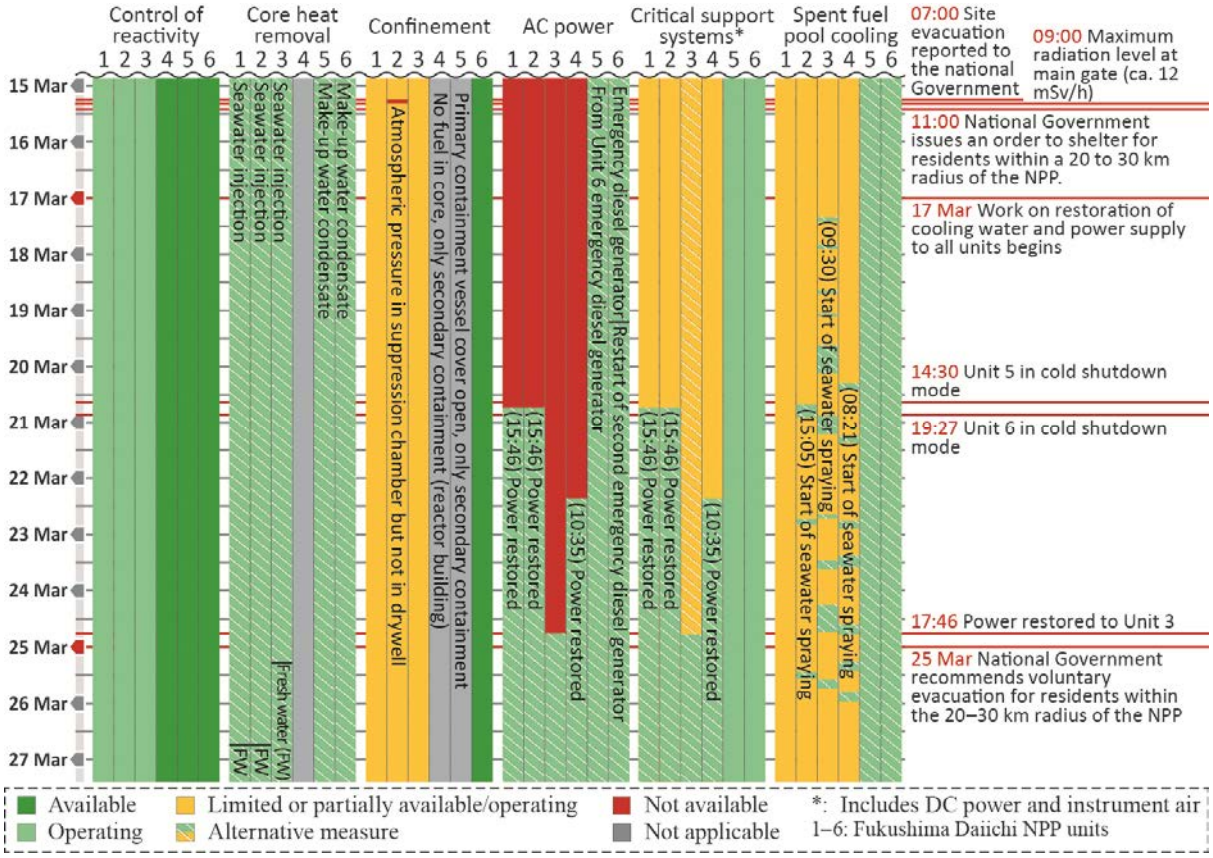


FIG. 1.1–9. Temporary restoration of fundamental safety functions at the Fukushima Daiichi NPP.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[47]: achievement of significant suppression of radiological releases and steady decline

[47] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap. The Government and TEPCO (through the Government–TEPCO Integrated Response Office[48]) announced on 19 July that the first condition had been achieved in Units 1–3, and on 16 December 2011, that the second condition had also been achieved for these units. This announcement brought the 'accident' phase of events at the Fukushima Daiichi NPP to a close, according to the criteria set by the Government of Japan at the time.

However, some unstable plant conditions continued, such as fluctuations in temperatures, which were explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued. Additionally, challenges in the management of waste, such as difficulties in dealing with the accumulation of radioactively contaminated water due to groundwater ingress to the buildings and occasional failures of equipment, continued. At the time of writing, the Government of Japan considered the Fukushima Daiichi NPP a 'specified facility as an accident site'[49].

1.2. CONTEXT WITHIN WHICH THE ACCIDENT OCCURRED

This section provides an overview of the status of the Japanese nuclear energy generation and the involvement of the various stakeholders, including legislators, governments, regulators, owners, operators, industry associations and suppliers. The description in this section details the structure and status of the relevant entities as well as the laws and regulations that shaped the nuclear energy strategy, the decision making process in the formulation of licensing arrangements, and the oversight and assurance procedures in Japan in or before March 2011.

After providing a general view of the structure and the interfaces of the Japanese nuclear industry's owners and operators, who had established a system that was aimed at the safe and economic generation of nuclear energy, information is presented on the development of the legal and regulatory framework and, in chronological order, the establishment of key laws, regulations and their associated entities.

The structures and roles of those entities that influenced the legislative, regulatory, and industrial environment in which the design, licensing, construction, operation and modification of the Fukushima Daiichi NPP occurred are analysed and evaluated in greater detail in Technical Volume 2 in the assessment of relevant factors.

1.2.1. Nuclear industry structure

1.2.1.1. Nuclear power in Japan

Nuclear power generation has been an important energy source in Japan for decades. In response to the oil crisis of the 1970s, the Government of Japan implemented a policy of reducing dependency on imported oil by encouraging energy efficiency and the diversification of power sources supplied by privately owned independent regional electric power companies. As a result of this government

[48] On 6 May 2011, the Integrated Countermeasures Headquarters for the Fukushima Nuclear Power Plant Accident, which had been established on 15 March 2011 by the Prime Minister's Office, was reformed into the Government–TEPCO Integrated Response Office under the Nuclear Emergency Response Headquarters (NERHQ) of the Japanese Government.

[49] In accordance with the definition of 'specified nuclear facility', i.e. a facility that would require special measures for safety or physical protection of specified nuclear material, established by the regulatory body, the Nuclear Regulation Authority (NRA), on 7 November 2012.

policy, the contribution of nuclear power to the overall Japanese energy supply grew significantly until the time of the accident at the Fukushima Daiichi NPP. In 1973, the nuclear power generation was just 9.7 TWh, and its share in total commercial power generation was just 3%. Growth in nuclear power generation accelerated in the 1990s, backed by government policy and the efforts of the power companies, and reached a historical high of 332.2 TWh in 1998. During the mid-2000s, nuclear power generation decreased because of the impacts of the extended periods of shutdown of a number of NPPs following the Niigata-Chuetsu-Oki earthquake in 2007. Even so, nuclear power generation in 2010 was 288.2 TWh, accounting for 29% of the total power generation in Japan. In the year before the accident, nuclear power had the largest share in total power generation in Japan, slightly more than natural gas fired power generation. These two sources of energy were followed by coal (25%), hydro (9%) and oil (6%).

By March 2011, 54 nuclear power reactors were operating in Japan, producing a licensed total output of 49 GW. Thirty of those 54 reactors included boiling water reactor (BWR) technology. Three additional nuclear power reactors were under construction, and three were being decommissioned in the spring of 2011. The location of the NPPs in Japan is shown in Fig. 1.2–1. To support the operation of the NPPs, Japan also developed a full spectrum of fuel cycle activities, comprising enrichment, conversion, fuel fabrication, reprocessing and radioactive waste management.

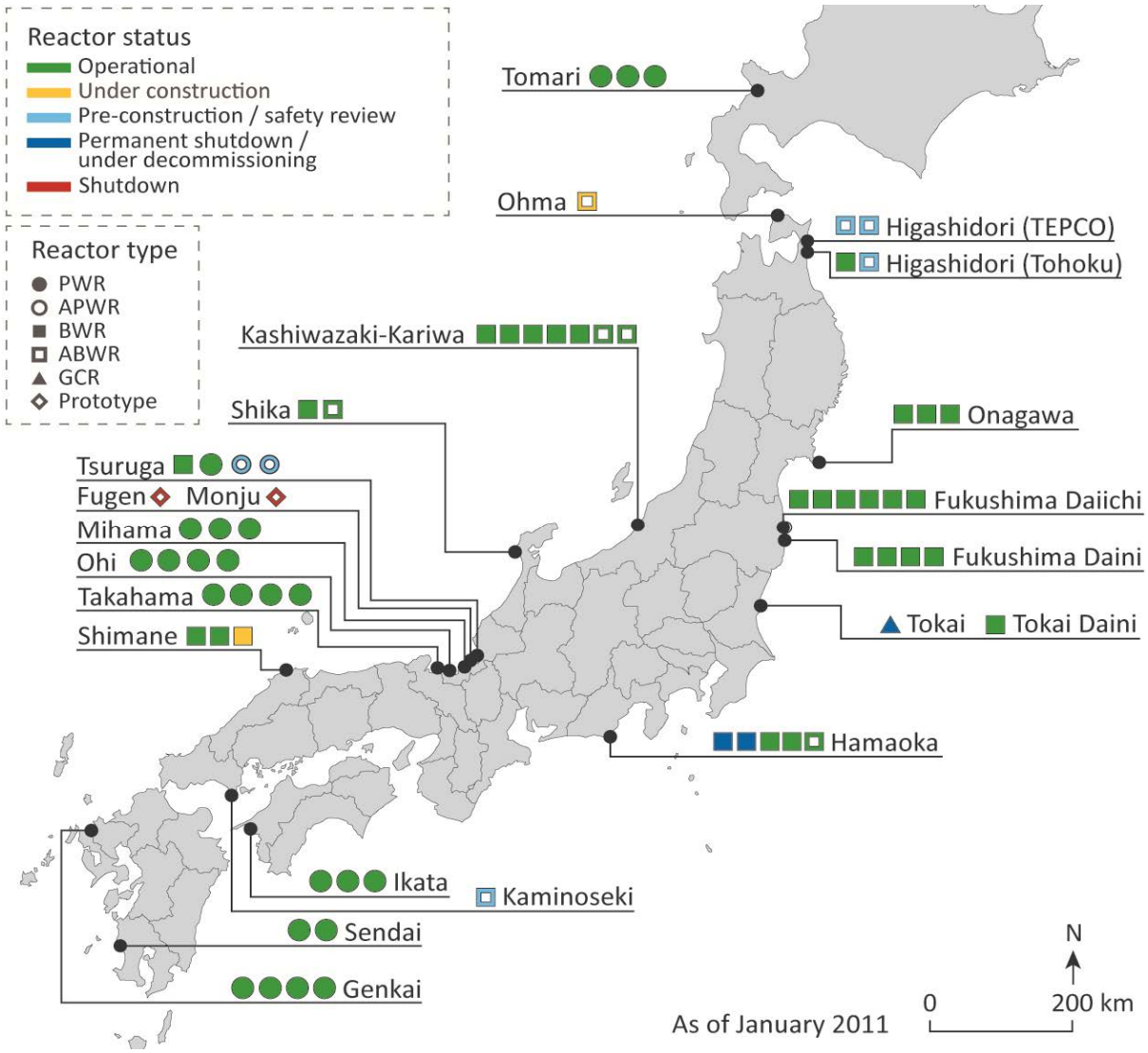


FIG. 1.2–1. Location of the NPPs in Japan [24].

The introduction of BWRs in Japan began with the construction, by the Japan Atomic Energy Research Institute (JAERI), of the Japan Power Demonstration Reactor, which ran from 1963 to 1976. Its construction and operation provided experience for the introduction of commercial light water reactors (LWRs) at the next stage. The first commercial BWR was constructed by the Japan Atomic Power Company (JAPC) in Tsuruga and started operation in March 1970.

Following the construction of the BWR in Tsuruga, TEPCO started to construct the first unit of the Fukushima Daiichi NPP in 1967. Both JAPC's Tsuruga and TEPCO's Fukushima Daiichi Unit 1 were imported under a turnkey contract with General Electric (GE). The necessary technology was transferred to the Japanese reactor vendors Toshiba and Hitachi under a system licence contract. After that, Units 2–5 of the Fukushima Daiichi NPP (designed as 780 MW(e) with a BWR/4 type) and Unit 6 (the first unit of 1100 MW(e) design in TEPCO) were also constructed under turnkey contracts with GE, GE/Toshiba, Hitachi or Toshiba. In parallel with Fukushima Daiichi Unit 6, Tokai Daini of JAPC was also constructed under contract with GE.

From the second half of the 1990s, there was a slowing down in the development of technology, and factors such as 'strong demands to reduce construction cost' and 'design changes based on external requests', in addition to 'project delays due to a protracted licensing and approval process' created an environment in which there was no additional technological consideration for further improvements in the reviewed and approved designs as they were confirmed to be safe and it was believed that the safety level was well established [25]. However, certain measures, which resulted from learning from significant events and became regulatory requirements, were implemented. Examples of these design improvements by TEPCO under regulatory guidance included changing the structure of the RB to incorporate lessons learned from the Niigata-Chuetsu-Oki earthquake and changing the design of the Higashidori NPP to improve the seismic tolerance above and beyond the previously reviewed and approved levels.

Efforts, such as the construction of a concentrated environment facility, i.e. seismically isolated building, the core shroud replacement, the augmentation of EDGs and the expansion of the SFP, were implemented mainly at the Fukushima Daiichi NPP. With the exception of the core shroud replacement[50], these were single-item work projects. Efforts to address technical research issues included: the introduction of mixed oxide (MOX) fuel (first introduced at Fukushima Daiichi NPP Unit 3 in 2010); the introduction of new designs with 1100+ MW(e) power (first operation at Kashiwazaki-Kariwa NPP Units 2 and 5 in May 2002); and long cycle operation (not yet introduced but intended for introduction at the Fukushima Daini NPP) [26].

1.2.1.2. Research and development organizations and institutions

In promoting the research and development (R&D) of the nuclear energy industry, the Government played a leading role in implementing projects that required long term commitments, specifically those aimed at identifying and commercializing potential capabilities of nuclear power as an energy option in the years ahead. Initially, the Japan Atomic Energy Commission (JAEC), as the most important Japanese nuclear energy policy making organ, provided advice on R&D policies, such as nuclear energy policy and development of new generation power reactors and fuel cycle facilities. These efforts were succeeded by the Framework for Nuclear Energy Policy (FNEP), which was first authorized by the Government in 2005.

[50] The world's first such project was completed at the Fukushima Daiichi NPP Unit 3 in 1998, and later performed at Units 2, 5 and finally Unit 1.

All Japanese utilities participated in R&D planning and funding of the Steering Committee of the Federation of Electric Power Companies (FEPC), and these R&D decisions were carried out as joint research among utilities and reactor technology vendors. The joint R&D by utilities and vendors was not limited to existing LWRs. They explored next generation LWRs, fast breeder reactors (FBRs), fuel cycle technology (reprocessing and uranium enrichment) and radioactive waste treatment. The amount of non-governmental R&D funding decreased in the late 1990s and early 2000s. In the late 2000s, this trend was reversed; however, the additional funds were applied mainly to improve the performance and enhancement of safety, in which only limited funds were allocated to severe accident R&D activities.

1.2.1.3. Industry codes, standards and collaboration

In Japan, four standard development organizations are working to develop the industry codes and standards focusing on their specific areas as follows:

— The Japan Society of Mechanical Engineers (JSME) mainly focuses on the areas related to structural integrity of components. Publications of the JSME include design and construction codes (published in 2001, and revised in 2005) for design and manufacturing of components, and fitness-for-service codes for in-service-inspection of components.
— The Atomic Energy Society of Japan (AESJ) addresses topics related to nuclear safety, including probabilistic risk analyses, plant life management and radioactive waste treatment.
— The Japan Electric Association (JEA) develops codes and standards related to quality assurance in plant operation, inspection and evaluation of integrity, including the seismic design rule.
— The Thermal and Nuclear Power Engineering Society (TENPES) creates guidelines and standards related to application of thermal and nuclear power generating technologies, including topics such as environmental fatigue.

In July 2002, a committee of the regulatory body, the Nuclear and Industrial Safety Agency (NISA), published a report concerning industry codes and standards. In that report, the committee recommended that the regulation should be changed to a 'performance base rule' and that 'voluntary consensus standards' should be applied as the acceptable approaches after endorsement by the regulatory body. This recommendation was intended to shorten the time between the discovery of new knowledge, or the development of new technologies, and their implementation in the NPPs.

Following this recommendation, NISA revised the regulation, namely Ordinance No. 62, which became effective in January 2006, and started the technical review mechanism for endorsement of industry codes and standards after review by its technical support organization. Responding to the new regulation, industrial and academic bodies developing industrial codes and standards modified their codes and standards review processes. They also improved the transparency of their review process and the balance of participating members.

1.2.1.4. Industry cooperation

Japan Nuclear Technology Institute (JANTI)

The Japan Nuclear Technology Institute (JANTI) was established in March 2005 as an initiative of the industry with the aim of supporting the voluntary safety improvement activities towards 'excellence in performance'. The charter of JANTI[51] was similar to those of other national and international industry self-regulating initiatives, such as the World Association of Nuclear Operators (WANO) or the Institute

[51] The Japan Nuclear Technology Institute (JANTI) was renamed and reorganized after the accident to Japan Nuclear Safety Institute (JANSI), with a revised charter to incorporate lessons learned from the Fukushima Daiichi accident.

of Nuclear Power Operations (INPO). JANTI's members included not only utilities but also vendors, component suppliers, fuel manufacturers, reprocessing and waste disposal facilities and construction companies.

JANTI's Operating Experience Analysis Division assumed and developed activities related to the collection, analysis and application of operating experience information that was previously handled by the Nuclear Information Center of the Central Research Institute of the Electric Power Industry (CRIEPI). Specifically, it conducted activities focused on providing recommendations, information for operation management and equipment maintenance activities, and support for the safety improvements of the utilities, based on information analysis results. Also, the division supported the safety activities of the utilities with regard to quality assurance and root cause analysis promotion and dissemination activities.

Japanese BWR Owners' Group (JBOG)

Since the introduction of BWRs in Japan in 1967, the utilities and vendors have cooperated, and this cooperation was formalized in 2006 with the establishment of the Japanese BWR Owners' Group (JBOG). JBOG's purpose is to enhance nuclear safety and plant reliability based on operating experiences and the examination of technical issues in the BWR technology. It also provides support in resolving common issues concerning BWR operation and design by cooperation.

JBOG is a private organization of seven utilities that operate BWRs: TEPCO, Tohoku, Tokyo, Chubu, Hokuriku, Chugoku and JAPC. Two BWR vendors, J-Power and Toshiba/Hitachi, are also members of JBOG.

Federation of Electric Power Companies (FEPC)

In 1952, nine electric power companies, including TEPCO, established the Federation of Electric Power Companies (FEPC) to promote efficient operations within the industry. Since then, FEPC has played a role as a base for close communication between the electric power companies and a forum for exchanging views on creating the electric power industry of the future. FEPC also undertakes various activities to ensure stable operations of the electric power industry.

1.2.1.5. International cooperation

Cooperation with the IAEA

Japanese NPP operating organizations have also solicited cooperation with the IAEA in the enhancement of safety and reliability, specifically by receiving the IAEA's Operational Safety Review Team (OSART) services through the invitation of the Government of Japan. Since the creation of OSART services in 1982, five OSART missions have been requested by the Government to be carried out in Japanese NPPs (TEPCO invited two missions), as listed in Table 1.2–1. The Fukushima Daiichi NPP has never been reviewed by an OSART mission.

TABLE 1.2–1. IAEA OSART MISSIONS TO JAPAN

Mission site	Mission date
Mihama	January 2009
Kashiwazaki-Kariwa	November 2004
Hamaoka	February 1995
Fukushima Daini	March 1992
Takahama	January 1988

Cooperation with the OECD/NEA

Japan is a member of the Organisation for Economic Co-operation and Development (OECD) and its specialized organization, the Nuclear Energy Agency (NEA). In this inter-governmental cooperation framework, Japanese owners/operators have participated in various activities representing Japan, such as the Task Group on Defense in Depth of Electrical Systems and Grid Interaction, the Working Group on Analysis and Management of Accidents, the Working Group on Risk Assessment, and the Working Group on Human and Organizational Factors; in addition, they have been members of other standing committees, ad hoc working groups and joint research projects.

Cooperation with the World Association of Nuclear Operators (WANO)

The Japanese industry cooperation with WANO started with a contribution to the founding of WANO and the establishment of its Tokyo Centre. The Japanese plants are affiliated with the WANO Tokyo regional centre. Cooperation is carried out through WANO's four main programmes: peer reviews, operating experience, technical support and exchange, and professional and technical development. Since the inception of the peer review programme in 1992, 31 peer reviews of the Japanese NPPs have been conducted. WANO peer reviews were conducted at the Fukushima Daiichi NPP in 2003 and 2009. Additionally, TEPCO was subject to a WANO corporate peer review in 2008. The main purpose of the corporate peer review is to identify areas for improvement at the corporate level in order to maximize the safety and reliability of NPPs.

1.2.1.6. Management systems

In 2003, the Japanese regulatory requirement for the establishment and implementation of a quality management system (QMS) for the installation, operation and maintenance of commercial power reactors in accordance with the JIS Q-9000 series[52] was introduced. In response to this requirement, the JEA established industry code JEAC 4111 and its associated guide JEAG 4121. This industry code and guide were based on JIS Q-9000 and adapted some of the IAEA's requirements and guidelines, including the application of graded approach, the independence of inspectors and the need for design verification by a third party.

After incidents of falsification of safety related records in 2002 (see Section 1.2.3), TEPCO implemented a series of additional programmatic countermeasures to prevent a recurrence of such events. These included the following corporate level commitments to improve corporate culture through a corporate system and climate of individual responsibility and initiative [6, 26]:

— Promoting the disclosure of information, ensuring transparency of nuclear operations and establishing an independent check of nuclear safety and quality control.
— Creating a work environment where proper operations could be carried out, strengthening functions that contributed to proper performance of job related duties.
— Strengthening internal audits, through a quality assurance/management system in the Nuclear Power Division, and building a corporate culture aimed to produce a cooperative atmosphere.
— Promoting observance of corporate ethics, with the support of education and training, and conducting internal and independent audits to keep a high degree of compliance.[53]

[52] JIS Q-9000 is very similar to the 9000 series of the International Organization for Standardization (ISO).

[53] http://www.tepco.co.jp/en/corpinfo/overview/restor-e.html

1.2.1.7. Safety culture

The Japanese industry started activities relating to safety culture after the Chernobyl accident in 1986. After the criticality accident at the JCO facility in Tokaimura in 1999, which was Japan's worst nuclear accident at the time (see Section 1.2.3), the nuclear industry established NS-net (Nuclear Safety network). This organization included not only NPPs but also nuclear fuel manufacturing facilities and carried out peer reviews of those facilities and other activities aimed at enforcing safety culture in its member organizations. NS-net's activities included three-day peer reviews intended mainly for the review of documentation and the development of methods to analyse organizational strengths and weaknesses.

In 2007, NS-net's activities were taken over by JANTI. The peer review process was redesigned to focus on field observations, with a prolonged duration of two weeks. Reviewers from WANO and/or INPO were invited to participate in these peer reviews.

In addition, JANTI developed a method, called 'Safety Assessment', in which the strengths and weaknesses of an organization were analysed on the basis of information gained through interviews with workers.

TEPCO received a WANO corporate peer review in 2008, in which some areas for improvement were identified. Particularly, WANO pointed out that further attention needed to be given to the enhancement of safety culture attributes, while recognizing that, in the previous years, TEPCO's primary emphasis had been placed on improving transparency.

In response to the WANO review results, TEPCO established an approach to foster safety culture through seven principles. They corresponded largely to WANO's eight principles for a strong nuclear safety culture, with the exception of WANO's eighth principle ('nuclear safety undergoes constant examination') [27]. TEPCO's approach to safety culture is analysed in Technical Volume 2.

1.2.1.8. Operational experience

The Japanese nuclear industry utilizes a variety of operational experience networks, both internationally and domestically. International networks include information exchange with the IAEA, OECD/NEA, INPO, WANO, technology (BWR/PWR) Owners' Groups, vendors and research institutions for collecting and disseminating operational experience. Furthermore, licensees have individual agreements on information exchange with overseas utilities and manufacturers. Within Japan, dissemination of information and feedback is conducted by the industry's own system, mainly by JANTI. JANTI shares the information among all licensees in Japan, carrying out analyses and assessments of incidents and issuing recommendations for corrective actions to prevent recurrence. All Japanese NPPs are expected to respond to these recommendations and, in accordance with the membership agreement, inform JANTI of their solutions. JANTI and the regulatory body's technical support organization, the Japan Nuclear Energy Safety Organization (JNES)[54], had cooperated in a parallel operational experience network. For example, operating experience from the joint IAEA/NEA International Reporting System for Operating Experience (IRS) to the industry was initially managed through JNES. Later, JNES provided direct access to the web based IRS, in which all licensees and JANTI have participated. JNES and the Japanese utilities also have monitored operational experience collected by the regulatory bodies of other countries with similar reactor technologies, such as the

[54] JNES was absorbed into the new regulatory body, the NRA, after reorganization based on lessons learned from the Fukushima Daiichi accident.

United States Nuclear Regulatory Commission (NRC), including the review of NRC Bulletins and Generic Letters.

TEPCO has monitored the operating experience information that was provided through these networks and has submitted its operating experience information to JANTI's database, the Nuclear Information Archives.

Technical Volume 2 further evaluates the effectiveness of Japanese nuclear industry's learning from operational experience.

1.2.1.9. Risk management

As most of the industry, TEPCO had in place a cross-functional risk management mechanism. In 2004, the Risk Management Committee was set up to comprehensively manage all risks that could have a serious impact on the company's business management. The risk management process was defined in three steps:

— Factors that hamper management and business goals were identified and a risk management table was prepared (recognition).
— A risk map was drawn up taking into account the level of impact and probability of each risk, setting the priority of further responses (evaluation).
— A response strategy was defined according to the evaluation (response).

The nuclear risk management meetings collected information on how risk management was handled at relevant departments in TEPCO and conducted verification and assessment from multiple perspectives.

In October 2010, at the last meeting before the accident, the Risk Management Committee assessed earthquakes and tsunamis as critical risks. The following risks, in particular, were noted: earthquake beyond design basis giving rise to seismic ground motion that causes difficulties with power supply due to long-term shutdown of multiple plants [6]. Tsunamis were also identified as having the potential for high impacts associated with receding tides and due to beyond design basis tsunamis.

More specifically, earthquakes were identified as a high impact risk with a medium possibility of occurrence, while tsunamis were identified as a high impact risk with a low probability of occurrence. In a follow-up, TEPCO concluded that this new knowledge had not yet been firmly established and that there was no proven adverse impact on the safety of nuclear power plants.

1.2.1.10. Knowledge management

Knowledge management at TEPCO, as in many other organizations, has been centred on collecting knowledge and placing it in shared media [28]. TEPCO's approach consisted of integrating knowledge management in its internal organizations through sharing of information, especially on non-conformances and operating experiences. This information was analysed to identify issues, such as operational risks, review the effectiveness of preventive maintenance, assess human performance strengths and weaknesses and supply evaluation reports to the TEPCO personnel concerned. For example, the 'just-in-time caution reports' to operating personnel were designed to supply the operators with timely and concise summaries of past operation experience, and were considered in procedure revisions and pre-job briefings. Similarly, TEPCO's plant technical support (i.e. engineering) teams stored key technical issues in the 'engineering notebooks' that were helpful to support and maintenance organizations, as these notebooks contained such information as important operating experience, engineering bases and tips for improvement of tasks.

1.2.2. Governmental, legal and regulatory framework of nuclear safety prior to the accident

From the initiation of nuclear power in Japan to the Fukushima Daiichi accident, three distinctive stages can be observed with respect to the adoption of legislative and regulatory rules, as well as the structures of governmental and public organizations for nuclear policy and regulations [24]. These three distinctive periods, marked by significant nuclear safety events, resulted in the review and revision and restructuring of the Japanese nuclear framework [29]:

— The first period (1955–1978) started with the launch of the Japanese nuclear energy programme and the enactment of nuclear laws. It covered the period until the radiation incident involving the nuclear powered ship 'Mutsu' in September 1974, which raised concern about the adequacy of the Japanese nuclear safety framework. The Fukushima Daiichi NPP, one of the earliest nuclear facilities in Japan, was licensed, constructed and put in operation during this first period of the governmental and regulatory framework [24].[55]
— The second period (1978–1999) started with the amendment of laws and organizational restructuring as a result of the findings of the 'Mutsu' incident by the Committee on Atomic Energy Administration, which had been commissioned by the Government as a result of public concern about the adequacy of the Japanese nuclear safety framework after the incident [29]. The results of this committee's review introduced a fundamental change in the regulatory framework and changes among the structures of the regulatory organization, including the creation of an independent entity, the Nuclear Safety Commission (NSC) [30].
— During the 1980s and 1990s, the regulatory enhancements reflected the lessons learned from the Three Mile Island accident in 1979 and the Chernobyl accident in 1986, including the review of requirements and enhancements of emergency and severe accident management. In 1986, a long term plan was established to meet energy requirements and security which included a programme for reinforcing nuclear safety enhancements through 2030 [24].
— The end of this period was marked by the JCO's Tokaimura criticality accident, which occurred in September 1999. The accident was at that time Japan's worst nuclear accident, which was classified as a Level 4 event on the IAEA's International Nuclear and Radiological Event Scale (INES) [31]. It resulted in two fatalities of workers from radiation exposure in addition to exposing hundreds of other workers and members of the public to radiation [32, 33, 34].
— The third period (1999–2011) started with the amendment of laws and organizational restructuring as a result of the lessons learned from the JCO's Tokaimura criticality accident and ended with the Fukushima Daiichi accident. The investigation committee looking into the JCO's Tokaimura criticality accident recommended in 2000, among other things, that the capacity and independence of the regulatory body be strengthened and that the regulatory standards and guidelines on the oversight of compliance be improved [33, 34]. These recommendations introduced another fundamental change in the regulatory framework and lead to modifications in the licensing of NPPs, the separation among the ministries of the supervision of research and power generation and changes among the regulatory organizations. Also in this period, the Nuclear Emergency Act was enacted and the regulatory guide on the technical aspects of nuclear emergency was revised [35].

The changes to the legislative and regulatory framework, as well as the revisions of the organizational structures and processes in each of these three periods, are discussed in detail in the following sections.

[55] Unit 6 started operation in 1979; however, it was licensed and can be considered under the regulations of this period.

1.2.2.1. Nuclear laws and regulations

In 1955, the Government of Japan established a legal framework for nuclear safety. The main laws applying to different aspect of the nuclear structure are expanded on in subordinate laws, cabinet orders (i.e. regulations), ministerial ordinances and statutes (i.e. rules), and ministerial public notices (i.e. notifications). The main structure of the legal framework is illustrated in Fig. 1.2–2 [36]. The effectiveness of the framework is assessed in Technical Volume 2. The following key aspects of the main laws and their evolution are of particular relevance to the Fukushima Daiichi accident.

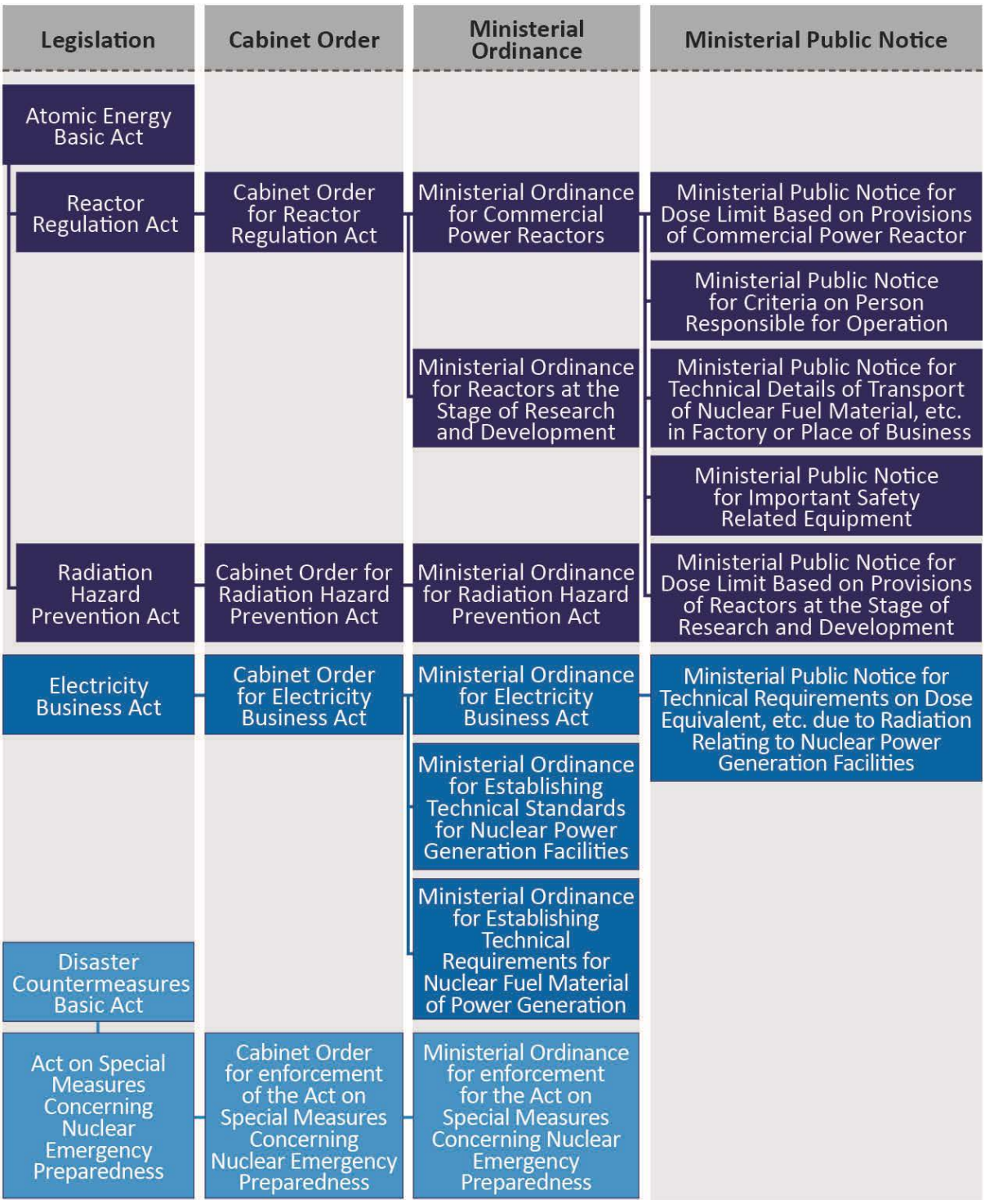


FIG. 1.2–2. Major legislation governing the safety regulation of nuclear installations [36].

The **Atomic Energy Basic Act**[56], first enacted in December 1955 (hereafter referred to as the Basic Act), is the foundation of the Japanese legal framework for nuclear energy. Its objectives are the security of energy resources, the promotion of research and development and the use of nuclear energy for peaceful purposes. The Basic Act establishes the framework for the regulation of nuclear activities. Its provisions deal with the mining of nuclear source materials, control over nuclear fuel materials, control over nuclear reactors, protection from radiation hazards, and compensation for damage caused by nuclear activities.[57] These broad provisions provide the state with the flexibility to exercise regulatory powers in these areas by means of subordinate legislation [33]. The Basic Act has two major subordinate laws, the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, which applies to the installation and operation of nuclear reactors, and the Law Concerning Prevention from Radiation Hazards due to Radio-Isotopes, etc. (Radiation Hazard Prevention Law), which applies to the use, sale, lease and disposal of contaminated material.

Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors[58] (hereafter referred to as the Reactor Regulation Act) regulates the utilization of nuclear source material, nuclear fuel material and reactors, i.e. the refining, fabricating and enrichment, storage, reprocessing and disposal of nuclear materials, and the installation and operation of nuclear reactors. The Reactor Regulation Act requires these activities to be limited to peaceful purposes, to be carried out in a planned manner and to ensure the safety of the public by preventing hazards and by providing for the physical protection of nuclear fuel material, in accordance with the Basic Act.

The Reactor Regulation Act specifies the processes of licensing and safety regulation in the construction and operation of nuclear facilities, including requirements for an establishment licence, approval of design and construction methods, pre-service inspection, facility periodic inspection, approval of an operational safety programme, operational safety inspection and decommissioning. It also defines violations and penalties, which consist of administrative measures such as the suspension or revocation of a licence, as well as criminal punishment, including imprisonment and fines.

Commercial nuclear power reactors are exempt from certain provisions of the Reactor Regulation Act. These exemptions relate to the approval of design and construction methods, pre-service inspection, welding methods, and inspection. These activities are subject to the 'Electricity Utilities Industry Law' (see below) [37].

Two of the ministerial ordinances issued under the Reactor Regulation Act directly apply to commercial nuclear power reactors:

— Ministerial Ordinance on Rules for the Installation, Operation, etc. of Commercial Nuclear Power Reactors (Ministerial Ordinance for Commercial Power Reactors). This ordinance implements the provisions of the Reactor Regulation Act and provides rules which apply to the majority of nuclear power plants in Japan.
— Ministerial Public Notice for Radiation Exposure Dose Limits. This ordinance mainly specifies the radiation exposure limits of workers and the radioactivity concentration limits.

The Reactor Regulation Act has been amended on several occasions following accidents and incidents that have occurred in Japan [38]:

---

[56] Act No. 186 of 19 December 1955; last amendment: Act No. 155 of 3 December 2004.

[57] At the time of the nuclear accident, Japan was not Party to any of the conventions on civil liability for nuclear damage [1] containing the basic principles on nuclear liability. Japan ratified the Convention on Supplementary Compensation for Nuclear Damage (CSC) on 15 January 2015.

[58] Law No. 166 of 1957, as last amended by Act No. 84 of 2007.

— Following JCO's Tokaimura criticality accident in September 1999, the Reactor Regulation Act was amended in 2000 to strengthen the nuclear safety requirements for the management, operation and inspection of nuclear power facilities and nuclear processing plants. The new amendment required regular review of the management and operational programmes of nuclear facilities. It also modified the licensing process for nuclear facilities and provided for the appointment of regulatory inspectors for safety management [39]. Furthermore, the amendment introduced the protection of employees who reported violations from being subject to discrimination.
— In response to falsification of safety records by TEPCO in 2002, the law was amended to require a quality assurance programme to be included in the licensees' operational safety programmes, and it required the programme's regulatory oversight [40].

Electricity Utilities Industry Law[59] (hereafter referred as the Electricity Business Act) is the legislation "to protect the interests of electricity users and to achieve sound development of Electricity Business by realizing appropriate and reasonable management of Electricity Business and to assure public safety and to promote environmental preservation by regulating the construction, maintenance and operation of electric facilities" [37]. The Electricity Business Act regulates all electricity businesses in Japan, including construction, maintenance and operation of nuclear power plants.

The ordinances related to the Electricity Business Act which apply to power generation facilities, including nuclear installations, are:

— Ministerial Ordinance for the Enforcement of the Electricity Business Act. It sets out the enforcement powers of the Minister of METI to require an electrical utility to submit reports on matters related to safety in the construction, maintenance and operation of facilities used for an electricity business.
— Ordinance Establishing Technical Standards for Electrical Equipment. It sets out the rules and standards applied to the approval of construction plans, pre-service inspection and periodic inspection of electricity generation facilities including, but not limited to, nuclear power plants.
— Ministerial Ordinance of Establishing Technical Standards on Nuclear Fuel Material for Power Generation. It sets the technical standards that apply to the approval of nuclear fuel assembly design and fuel assembly inspection.
— Ministerial Public Notice for Technical Standards on Dose Equivalent, etc. due to Radiation Relating to Nuclear Power Generation Facilities. It specifies details of doses provided in the Ordinance of Establishing Technical Standards for Nuclear Power Generation Facilities.

In addition to the Basic Act and the Electricity Business Act, two main laws relevant to emergency situations in nuclear installations are the **Basic Act on Disaster Control Measures** (hereafter referred to as the Basic Act for Emergency Preparedness) and **Act on Special Measures Concerning Nuclear Emergency Preparedness**[60] (Nuclear Emergency Act). The latter was enacted in December 1999, following JCO's Tokaimura criticality accident [41], much later than the Basic Act for Emergency Preparedness (enacted in 1961) in order to complement the provisions for emergency response for natural disasters. The main provisions of the Nuclear Emergency Act include: requirements for nuclear operators to prepare emergency plans and set up emergency management organizations; requirements for the responsible ministers to designate off-site centres in each prefecture where nuclear installations are located; and requirements for the participation in emergency drills by the national Government, local authorities and operators [33, 38]. It also provides requirements for roles

[59] Act No. 170 of 11 July 1964; last amendment: Act No. 87 of 2005.

[60] Last amendment: Act No. 118 of 2006.

and responsibilities in managing emergencies. Technical Volume 3 further discusses these laws for emergency measures and response.

1.2.2.2. Organization and responsibilities in the regulatory framework

The structures and roles of the governmental and regulatory organizations that are described in the nuclear laws and regulations have evolved since the enactment of the Basic Act in 1955. At the time of Fukushima Daiichi NPP licensing and construction, the structure was as set by the original laws of 1955. At the time of the Fukushima Daiichi accident, the structure had changed, mainly after major events, such as the Mutsu accident and JCO's Tokaimura criticality accident, towards enhancing regulatory effectiveness and assignment of responsibilities. These developments can be summarized chronologically as follows:

— Following the enactment of the Basic Act in 1955, the Atomic Energy Commission (AEC) was established as an independent body under the Prime Minister's Office to direct the national policy on research, development and utilization of nuclear energy. The Director General of the Science and Technology Agency (STA) was appointed as Chair of the AEC, while the STA served as the secretariat of the commission.
— The Reactor Regulation Act, enacted in 1957, gave the Prime Minister authority to approve licences for nuclear facilities. The Ministry for International Trade and Industry (MITI) was assigned responsibility for the development of nuclear power as an energy source, i.e. the promotion of nuclear energy in Japan.
— MITI was reorganized in 1966 to accommodate its increasing workload and to provide additional rules and regulations for the introduction of commercial LWRs in Japan [24]. The issuance of a construction permit for commercial nuclear power reactors required the consent of the Minister of MITI.
— Based on the findings of the Mutsu incident investigation, in 1978, the Japanese legislators amended the Basic Act and the Reactor Regulation Act and established the NSC [30]. The NSC was created as an advisory body on nuclear safety matters, separate from the AEC, although the STA commonly supported both organizations [29]. The NSC was composed of five commissioners appointed by the Prime Minister and provided comments and opinions to the relevant ministries.
— As part of the 1978 restructuring, the licensing of commercial nuclear power reactors was specifically assigned to MITI, and civilian marine reactors were regulated by the Minister of Transport. Research reactors, new reactor technologies and other aspects of the nuclear fuel cycle continued to be regulated by the Prime Minister.

Following the JCO's Tokaimura criticality accident, the investigation found that the direct causes of the accident were linked to human errors and inadequate procedures on the part of the operating organization. The contributing factors included the failure of the regulatory body, specifically STA, to adequately assess the hazards during the initial licensing of the JCO facility, and to effectively inspect its operation afterwards to identify non-compliance with the conditions of its licence. Hence, several organizational changes were implemented in the aftermath of JCO's Tokaimura criticality accident [32, 39, 41]. These principal measures, which established the structure that was in place at the time of the Fukushima Daiichi accident, can be summarized as follows:

— Strengthening the NSC: The NSC was moved under the Prime Minister's Office on 1 April 2000. The NSC's staff was increased from 20 to 92, and the NSC's involvement in regulatory oversight was anchored by adding a concurrent, 'double-check' review system [42].
— Reorganization of governmental bodies with responsibilities for nuclear safety: A reorganization of the Japanese Government took effect on 1 January 2001. This government reorganization was aimed broadly at reducing costs and improving the efficiency of government [43] and was unrelated to the JCO findings. However, a number of specific measures were taken in the

reorganization with the intention of strengthening the governmental and regulatory framework for nuclear safety. These arrangements can be summarized as follows [40]:

- Amendments to the Reactor Regulation Act provided for the appointment of inspectors for management of safety under the authority of the former STA and MITI.
- MITI was reformed as the Ministry of Economy, Trade and Industry (METI), with responsibilities for ensuring a stable and efficient energy supply, including the use of nuclear energy. Furthermore, METI was also assigned responsibilities for nuclear safety regulation and licensing of nuclear installations.
- Within METI, the Agency for Natural Resources and Energy (ANRE) was responsible for planning and overseeing the national energy supply. In implementing this responsibility, the Department of Electricity and Gas Industry administered the nuclear energy policy and radioactive waste management [33], while NISA regulated the safety of nuclear and other energy sources as well as industrial safety and emergencies at nuclear facilities.
- As the regulatory body, NISA's main functions were codified by the law [33, 38, 44] as: regulation of milling, refining, fabrication, storage, reprocessing and waste disposal activities; regulation of nuclear power generating facilities to ensure safety; control of explosives, safety of high-pressure gas, mining safety and other industrial safety matters under its jurisdiction.
- The Ministry of Education, Culture, Sports, Science and Technology (MEXT) was created through a merger of the STA and the Ministry of Education. The former responsibilities for nuclear safety regulation of the STA were reallocated between METI and MEXT. Accordingly, the regulation of nuclear fuel cycle facilities, including uranium refining and fuel fabrication, spent fuel storage, reprocessing, nuclear waste management, and related transportation of nuclear materials, were transferred from the STA to NISA [34, 42].
- MEXT retained responsibility for the science and technology aspects of nuclear energy, including policy and the development of nuclear technologies, safety regulations governing research reactors, protection against radiation hazards, the use and transportation of nuclear and radioactive materials and safeguards. MEXT also supervised the National Institute of Radiological Sciences (NIRS), the Japan Atomic Energy Research Institute (JAERI) and the Japan Nuclear Cycle Development Institute. The latter two organizations merged in 2005 to become the Japan Atomic Energy Agency (JAEA) [24, 45].
- The Ministry of Foreign Affairs (MOFA) was responsible for the international aspects of nuclear energy utilization, including the implementation of the related international treaties and conventions.

— The Nuclear Emergency Act set out the roles and responsibilities of the national Government, local governments, and licence holders in case of a nuclear emergency [40]. The Nuclear Emergency Law also provided that, in the event of a nuclear emergency, several organizations were to be activated. Within the Cabinet Office, the Nuclear Emergency Response Headquarters, led by the Prime Minister, were to be established in Tokyo; the Technical Advisory Organization composed of NSC commissioners and advisors for emergency response would give technical advice to the Prime Minister; the Nuclear Emergency Response Local Headquarters were to be set up at the concerned Off-site Centre (OFC) by the relevant ministries; and a Joint Council for Nuclear Emergency Response was to be established at the OFC in order to share information between the national Government and related organizations, such as local governments, licensees, and other relevant organizations, and, when necessary, to coordinate emergency measures by the respective organizations.
— Amendments to Ordinances for the Compensation Law and the Law on the Indemnity Agreement for Compensation of Nuclear Damage, which were implemented by a cabinet order in 1999, established the amounts for which nuclear operators were liable.
— In 2003, a METI ordinance established the process for notifying or reporting major events to NISA. NISA would assess the results of the licensee's investigations and the adequacy of countermeasures. In case of serious events, the NSC could set up its own investigation group. For coordinating the collection and evaluation of the domestic and international operating experience

on the regulatory side, and for considering its use in the development of regulations, NISA and JNES established a high level review group.

1.2.2.3. Staffing and resources of the regulatory body

To carry out its assigned functions, NISA, the regulatory body at the time of the accident, was organized in eleven divisions, which reported to the Director General at the headquarters. Nuclear safety inspectors and senior specialists for nuclear emergency preparedness were also stationed at each nuclear facility. NISA started in 2001 with approximately 260 staff working on nuclear safety [42]. By 2010, the staff dedicated to nuclear safety was 370 [37].

In 2003, the Japan Nuclear Energy Safety Organization (JNES) was established as a technical support organization for NISA by merging parts of the Nuclear Power Engineering Corporation, the Japan Power Engineering and Inspection Corporation and the Nuclear Safety Technology Center. The law establishing JNES was enacted by an extraordinary session of the National Diet of Japan, held in the autumn of 2002, at the time of a crisis in public confidence precipitated by the discovery of TEPCO's falsification of safety records [40]. JNES's main functions, as assigned by law, consisted of conducting inspections at nuclear facilities, review of licensees' periodic inspections, safety analysis and evaluation, nuclear emergency preparedness support, research and testing for code/standard development, and collection, analysis and distribution of safety information [37, 38].

JNES had approximately 400 employees as of 1 April 2010, and 60% of NISA's FY 2010 budget was allocated to JNES. JNES had the status of an 'incorporated administrative agency'. As such, JNES was free of the administrative rules that applied to Japanese Government departments. Consequently, JNES had more flexibility on matters of staffing and budget, which better enabled it to retain a cadre of professional experts [38].

The NSC was supported by its own secretariat, composed of a Secretary-General and four divisions with a total of about 100 staff members. Several advisory councils and committees on safety, emergency preparedness and other regulatory matters also supported the NSC [37, 38].

1.2.2.4. Regulatory guidance

The guidelines developed by NISA and the NSC were for their internal use to conduct reviews [46]. Technical standards and codes were prepared by industrial and academic bodies and endorsed by NISA (see Section 1.2.1).

Neither NISA nor its predecessor organizations had any legal authority under their respective statutes to issue regulations that were binding on applicants and licensees. Instead, the requirements for licensing, inspection and enforcement of nuclear power plants were described in detailed laws enacted by the National Diet of Japan and in ministerial ordinances, and the regulatory body issued requests to the licensees. For example, in case of severe accident management guidance, in accordance with the decision by the NSC[61], MITI requested, in July 1992, to consolidate accident management (AM) measures of the licensees. In response, the Japanese licensees, including TEPCO, prepared AM measures. Some of those measures, such as the primary containment vessel venting systems and accommodations for sharing emergency diesel generators between the units, were implemented over the period from 1994 to 2002. However, thereafter, it was deemed by the licensees without a

[61] "Accident Management as a Measure against Severe Accidents at Power Generating Light Water Reactors" (decision of the Nuclear Safety Commission, May 1992).

regulatory guidance that no further knowledge regarding severe accidents was found, and the existing and implemented AM measures were adequate.

1.2.2.5. Authorization of facilities and activities

The Fukushima Daiichi NPP, as noted above, is one of Japan's oldest nuclear sites, dating from the early days of the nuclear programme and licensing process in Japan. The establishment permit (EP) of the Fukushima Daiichi facility was issued on 1 December 1966 by the Prime Minister, after review of TEPCO's application by the AEC's Nuclear Reactor Safety Review Committee.

The AEC's Safety Review Committee, at that time, had the following five expert groups to conduct the safety review of the Fukushima Daiichi site:

— The Reactor Group, responsible for the review of physics, thermal and mechanical features and fuel and material properties;
— The Environment Group, responsible for review of meteorological and radiological effects;
— The Seismic Group, responsible for review of the seismic design;
— The Plant and Power Generation Group, responsible for the evaluation of plant performance;
— The Safety Review Group, responsible for the evaluation of accidents and emergencies.

The review was carried out in accordance with various guides prepared by the AEC's Committee on Nuclear Reactor Safety Standards, as well as the information from the 'draft' General Design Criteria regulation of the United States of America. After the EP was granted in 1966, TEPCO had to apply for approval of the construction plan under the Electricity Utilities Industry Law. MITI reviewed and approved the construction plan in September 1967 and then conducted the pre-service inspection tests before fuel loading, and the commissioning tests in accordance with the Electricity Utilities Industry Law. It should be noted that the construction of later units at the site was authorized through amendments to the same EP. There was no requirement for submission of a Final Safety Analysis Report (FSAR) for each unit, since the original EP as amended served as site safety analysis. The same authorization procedure was followed for facility modifications which had a significant safety impact on the basic design.

This authorization process was revised in 2007, to establish a 'double-check' approach consisting of a primary review that was performed by NISA and a secondary review that was performed by the NSC and AEC.

1.2.2.6. Authorization of long term operation

The establishment permits for Japanese NPPs were issued for an unlimited period. However the Ministerial Ordinance, under the Reactor Regulation Act, requires an 'ageing management technical review' for plants that reach 30 years of operating life, and Ageing Management Technical Assessments (AMTA) thereafter at 10-year intervals. The licensee is required to develop a ten year long term maintenance programme (LTMP) based on the AMTA results and submit it to NISA for review and subsequent oversight.

TEPCO submitted the report presenting the results of the AMTA for 40 years of operation and the LTMP for Unit 1 of the Fukushima Daiichi NPP to NISA on 25 March 2010. NISA reviewed the report with technical support from JNES, and approved the operation of Unit 1 for an additional ten year period on 7 February 2011, one month before the accident.

1.2.2.7. Requirements for periodic safety reviews

Licensees in Japan also conduct periodic safety reviews (PSRs) every ten years after the commencement of operation. Conduct of PSRs started as a voluntary activity in 1992 and became a legal requirement in 2003, through an amendment to the Ministerial Ordinance on 'Rules for the Installation, Operation, etc. of Commercial Nuclear Power Reactors' under the Reactor Law[62] [4]. Before the 2003 amendment, PSR reports were provided to the regulator for review and information to the NSC. After the 2003 amendment, PSRs, although mandatory, were regarded as 'self-assessments', and the licensees were not required to submit the results and implementation plans to NISA for review and approval. The regulatory body confirmed by its quarterly safety inspections that each licensee had adequately conducted its PSRs.

Furthermore, neither before nor after the 2003 amendment did the scope of PSRs involve the re-examination of the design or the reassessment of external hazards in light of new standards, data and/or methods. The Japanese National Report to the Fifth Review Meeting on the Convention on Nuclear Safety stated: "Periodic Safety Review in Japan covers the operator safety activities at nuclear installations in operation, but it does not cover the design review. The nuclear installations have been designed with sufficient safety margin, [rather] than...they just met the necessary design criteria so that back-fitting has not been institutionalized" [37].

1.2.2.8. Requirements for backfitting

There was no legal provision in Japan for 'backfits' of a plant, because of the understanding between the regulator and the industry that nuclear installations were designed with a sufficient safety margin, and hence a backfitting did not need to be institutionalized. Although NISA did not have a legal basis for ordering backfits, it had a policy to request 'backchecks' when technical standards were revised or new knowledge was gained. In response to NISA's request, the licensees' evaluation was carried out on a voluntary basis. For example, the Seismic Design Review Guide that was issued by the NSC in July 1978 (revised in 1981, 2001 and September 2006) provided the technical standards for review of the new plant EPs, including the revised acceptable methods for defining the design basis earthquake. After the 2006 revision of this guide, NISA requested licensees to conduct a 'backcheck' of seismic and tsunami hazards. TEPCO started the re-evaluation but had not finished its 'backcheck' before the accident at the Fukushima Daiichi NPP.

1.2.2.9. Inspections of facilities and activities

The inspection programme was structured by the Reactor Regulation Act, which prescribes the definite type and exact frequency of inspections of facilities and activities (see Fig. 1.2–3). Additionally, the Electricity Utilities Industry Law specifies the periodic plant inspection, while the Reactor Regulation Act specifies the inspection of compliance with the safety management programmes, both of which are to be conducted by METI.

The operators' safety management activities were governed by the operational safety programme that NISA reviewed and approved. NISA conducted quarterly operational safety inspections to check the operators' compliance with the programme. Periodic inspections were also conducted by NISA/JNES at intervals not exceeding 13 months, which focused on the operators' maintenance of structures, systems and components (SSCs) of the facility. Periodic inspections focused on the safety significant SSCs, belonging, for example, to the reactor shutdown system, the reactor coolant pressure boundary,

[62] All NPP units in Japan older than ten years were reported to have conducted at least one PSR at the time of the IAEA Integrated Regulatory Review Service (IRRS) mission in 2007.

the residual heat removal system and the containment system. These regulatory procedures were carried out in addition to the licensees' own inspection and maintenance management of nuclear installations, periodic safety assessments, and technical evaluations for ageing management [37].

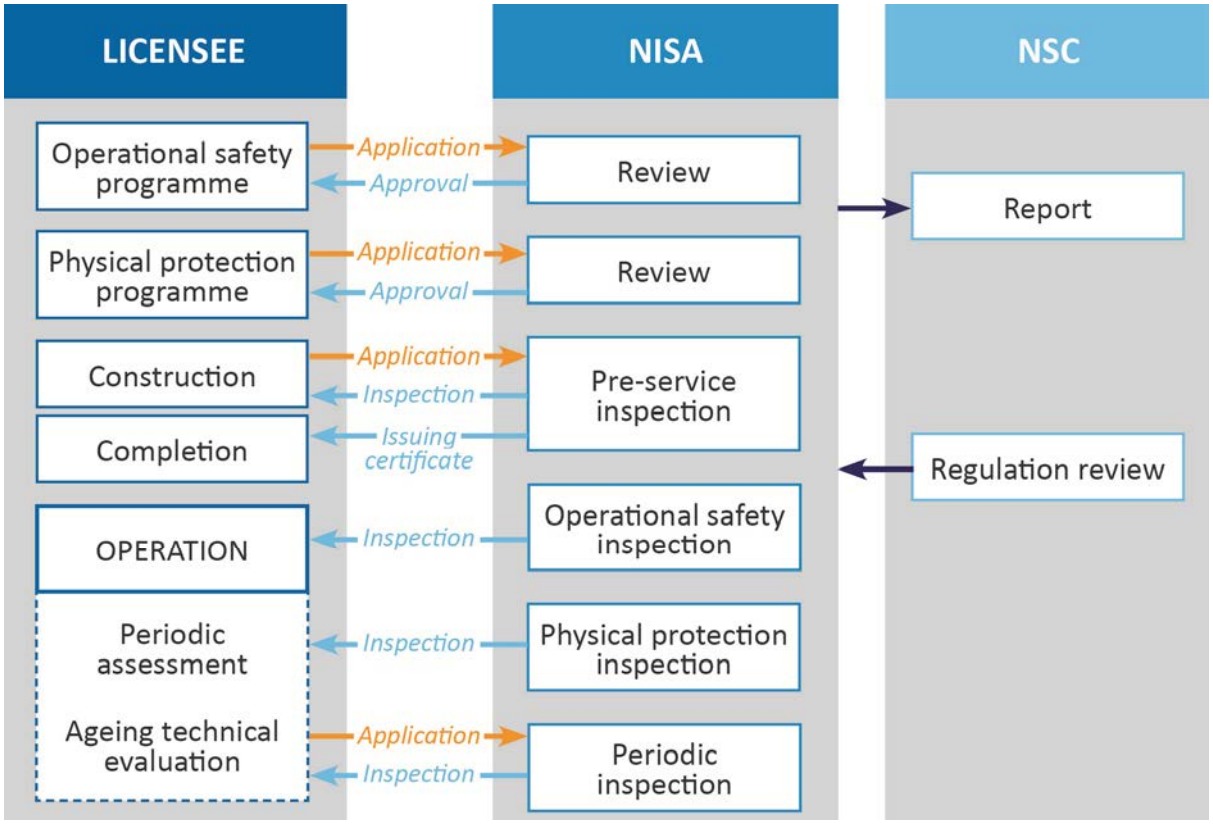


FIG. 1.2–3. The regulatory inspection process at the time of the accident for the operating stage of NPPs in Japan [37].

By law, the presence of NISA inspectors was required before the licensee could complete certain tests and surveillance. There were only specific periods at which inspectors were not allowed to be present and specific areas to which NISA was not permitted access for inspection because of the plant state and conditions restricting physical access. On 1 November 2006, the licensees accepted the request sent to them in NISA's formal letter for cooperation for the 'free access' of NISA inspectors to the facilities. On 8 May 2007, all the offices of the NISA inspectors started the operation of inspections with 'free access'. NISA was authorized to access the nuclear facility and examine the records, documents and other necessary matters at any time when the Minister of METI recognized it is necessary [37].

The repeated discoveries of non-compliance and falsification of test records that occurred in 2002 and in 2007 raised questions about the effectiveness of regulatory inspections and enforcement actions at that time. The initial falsifications were discovered as a result of allegations raised by former employees. However, in spite of follow-up inspections by NISA, regulatory orders to licensees and various other measures to strengthen self-checking and regulatory oversight, the true extent of the falsifications did not come to light for several years [38]. TEPCO's Fukushima Daiichi facility was also implicated in several cases, involving, for example, falsification of containment leak rate tests by employees at Unit 1, which resulted in a one year licence suspension by METI [40]. Consequently, improvements of the inspection system were ordered in January 2009 in a revision of the earlier ministerial ordinance. Greater flexibility was introduced considering the characteristics of individual

nuclear installations, and enhancements were made to the inspections during operation as well as at the time of plant shutdown in response to lessons learned from the data falsification events [37].

1.2.2.10. Requirements for qualification of reactor operators

Licensing of the plant operators was required by the Japanese regulation only for the shift managers, also called shift superintendents or shift supervisors (SSs), who would be in command and control of the shift team.

The licensing regulatory requirements for SSs were established by Ministerial Ordinance No. 77[63] of the Reactor Regulation Act, and the SS qualification and licensing process was implemented by the industry's self-regulating organization, JANTI. JANTI followed the industry guidance JEAC 4804 [47], which was issued on 12 February 2008, in the licensing of SSs after evaluating their knowledge and skills (Fig. 1.2–4) [48]. The SS licence had to be renewed every three years by completing the renewal training.

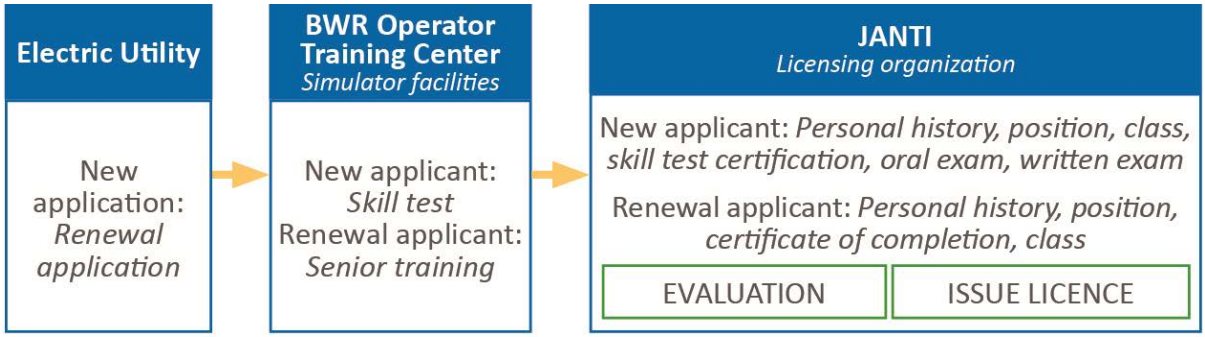


FIG. 1.2–4. Qualification and licensing process for shift supervisors in Japan [49].

The SS licence was issued upon the operator's demonstration of the necessary knowledge, skills and experience required in the position description, e.g. shift manager. These skills were listed in the governmental guidelines and included [50]:

— Ability to monitor the plant status during normal operation and accident conditions;
— Ability to manage and make accurate judgements and decisions during accident conditions;
— Knowledge of the laws and regulations concerning nuclear safety;
— Knowledge of nuclear reactor facilities and performance;
— Knowledge of leadership.

1.2.2.11. Operational experience

JNES managed the database containing domestic and overseas safety information, including incident and accident data, and shared it with NISA. The overseas information on reportable events was collected from international organizations such as the IAEA/NEA International Reporting System for Operating Experience (IRS) and from national regulatory agencies.

JNES performed the first screening of the incidents and, when needed, analysed them, assessing the applicability of the issues involved for domestic NPPs and proposed appropriate regulatory actions.

[63] The Reactor Regulation Act Article number was changed to No. 87 after regulatory system changes following the accident.

In case of operational experiences necessitating regulatory actions, NISA/JNES discussed the issue with the licensees. If necessary, NISA required the licensees to investigate and to take corrective actions. To ensure their implementation, NISA issued regulatory letters to recommend or require that the utilities take actions and requested them to report after the actions had been completed. The status of the recommended or required corrective actions was checked during the PSR of each plant by the licensee, and NISA confirmed, by its quarterly safety inspections, that each licensee had adequately conducted its PSRs, including the corrective actions. In case that operational experience constituted a change in laws, the laws would be amended by NISA, and codes and/or standards were established or revised by the appropriate codes and standards organizations.

1.2.2.12. International cooperation

The Japanese Government has been a Party to the following international conventions related to nuclear safety: Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, Convention on Early Notification of a Nuclear Accident (since 1987) and the Convention on Nuclear Safety (since 1995), as well as the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (since 2003). It has also supported the multilateral and bilateral cooperation activities within the IAEA framework by participation in the International Nuclear Safety Group (INSAG) and the Commission on Safety Standards. It has also contributed, through extra-budgetary programmes, to projects that are aimed, for example, at enhancing the safety of nuclear installations in South-East Asia, Pacific and Far East countries (since 1997), to the Asian Nuclear Safety Network (since 2002) and to the International Seismic Safety Centre (since 2008).

Japan's regulatory organizations received an IAEA Integrated Regulatory Review Service (IRRS) mission in 2007. At the request of the Japanese Government, a team of experts visited NISA and carried out a review of the legislative and governmental responsibilities; the authority, responsibilities and functions of the regulatory body; the organization of the regulatory body; the authorization process; review and assessment processes; inspection and enforcement activities; the development of regulations and guides; and the management system of the regulatory body. This mission report was made publicly available and the results are referred to in more detail in Technical Volume 2, Section 2.7 [38].

In addition to the international cooperation with the IAEA, the Government of Japan has been a member of the OECD/NEA and a participant in its Steering Committee and other committees, such as those on Nuclear Regulatory Activities, Safety of Nuclear Installations, Radiation Protection and Public Health and Radioactive Waste Management.

1.2.3. Stakeholder involvement and public communication

1.2.3.1. Stakeholder involvement and public communication in nuclear power in Japan

Since nuclear power was first introduced in Japan, the objectives of all communication activities were to make the public understand the need for nuclear power for the post-war reconstruction of the country as an engine for economic growth, and to emphasize the importance of nuclear safety.

The dialogue established by the Japanese nuclear sector was focused on the safety of the plants. As the Japanese Government supported nuclear power, it managed to counterbalance the concerns raised by the movement against nuclear power at national level (which had developed in the late 1960s) by supporting local communities that agreed to host NPPs with incentives and development initiatives [51]. In the early 1970s, the Government implemented the three energy source development laws, or so called 'Dengen Sanpo', which created a system of subsidies for local governments which accepted power plants, aiming at the promotion of nuclear power and its understanding.

The Chernobyl accident in 1986 seriously damaged public confidence in the safety of nuclear energy in Japan. Public concerns were addressed by the nuclear industry with a communications strategy emphasizing reassurance, based on the confidence that a severe accident could not happen in Japan.

1.2.3.2. Events that raised public concerns

The recent history of nuclear power in Japan includes several episodes that have had a negative impact on the public perception of the nuclear industry.

In 1974, high radiation leakage occurred during the initial voyage of Japan's first nuclear powered ship, the Mutsu, when it reached 1.4% of rated power. This accident affected the public's perception of institutions responsible for nuclear safety. Following the formal investigation, the final report that was submitted on July 1976 included the following recommendations for the reform and improvement of Japan's nuclear safety approach:

— Separation of the functions related to nuclear safety from those dealt with by the AEC and the establishment of a new independent commission to oversee nuclear safety and to 'double-check' the safety reviews carried out by the administrative agencies for enhancing and ensuring nuclear safety.
— Consistent implementation of safety regulations in accordance with the types of nuclear reactors — i.e. commercial power, marine, test and research applications and advanced technologies — with clear responsibilities among administrative agencies for ensuring their safety.
— Implementation of governmental and public checks and balances, including such measures as holding public hearings and discussions to dispel people's concern and to gain public understanding and cooperation for nuclear energy development [52].

In 1999, JCO's Tokaimura criticality accident led to the death of two workers and exposure to varying levels of radiation doses of hundreds of people [32, 34, 41]. Moreover, the local community was financially impacted by concerns about the safety of consuming local products. The report of the NSC investigation committee [53] identified three issues related to communication that have proved relevant to the Fukushima Daiichi accident:

— Lack of timely communications to the local residents from both JCO and NISA;
— Lack of coordination and understanding of their respective roles by the national, local and municipal governments;[64]
— Problems with the company's communication and emergency response systems.[65]

The NSC report also acknowledged the fact that the accident had a very significant social impact. A few months after the accident, the Japan Atomic Industrial Forum (JAIF) published a declaration on the reform of the nuclear industry, in which it admitted that "…the private-sector nuclear industry of Japan has betrayed the public trust, especially that of the people of Tokai mura" [54].

In 2002, TEPCO found 16 cases of misconduct in the management of nuclear inspections and repair work, which had been carried out systematically in an inappropriate manner for a long time [55], leading to the resignation of the TEPCO chairman and three other top management officials. TEPCO admitted to as many as 200 cases between 1977 and 2002 in which information had been falsified. In 2003, all 17 of its nuclear plants were shut down temporarily after a scandal over falsified safety

[64] For example, the mayor of Tokaimura recommended evacuation of the local residents without guidance or advice from the central and prefectural governments, creating confusion.

[65] The National Emergency Preparedness for Nuclear Disaster Law in Japan did not include fuel fabrication facilities; hence, there was no clear process for communication, or a point of contact to answer questions from the public.

inspection reports. In 2006 and 2007, there were further revelations of unreported and systematically false reporting of incidents that had occurred in the 1970s and 1980s.

In order to promote public understanding of the safety activities implemented by NPPs in light of these scandals, the Japanese nuclear industry, in 2003, established a publicly accessible database called 'Nuclear Information Archives', which covers the entire nuclear power generation history in the country and has recorded about 350–400 events per year.

In 2007, the Niigata-Chuetsu-Oki earthquake caused the shutdown of TEPCO's Kashiwazaki-Kariwa NPP. A review report by NISA stipulated that "NISA and plant operators must engage in communication with local communities on a regular basis via public hearings and PR activities". The NSC also indicated its opinion on various points, including the need to "constantly strive to secure transparency of information to the public and disseminate information related to radiation safety to ease public worry or anxiety concerning nuclear power safety" [56]. A subsequent IAEA report also highlighted the long time it took for TEPCO to report the event to the authorities [57]. Based on the lessons learned from the response to the earthquake, TEPCO assigned spokespersons to every key facility to provide accurate information quickly in coordination with the public relations department in the case of unusual events, incidents or accidents.

Also in 2007, the Hokuriku Electric Power Company announced that, in 1999, during a periodic inspection at the Shika NPP, the reactor had temporarily reached unplanned criticality and that this event had been covered up [58] without informing either the national Government or local municipalities of the incident [59].

1.2.3.3. Public perception of nuclear power

Public perception in Japan was generally in favour of nuclear power. However, even before the Fukushima Daiichi accident, public opinion had been influenced by various events, as confirmed by several surveys[66].

With respect to nuclear power in general, local communities that already hosted nuclear power plants were supportive of new construction; however, this was not the case with potential new localities. In one example from Maki in Niigata Prefecture, 66% of the population who participated in an official local referendum in 1996 voted against the siting of a nuclear power plant planned by Tohoku Electric Power Company, which eventually had to select another location. In general, the OECD/NEA public survey of 2010 showed that 61% of the Japanese respondents wanted to keep existing plants running, but only 21% supported new construction [58, 59].

With respect to the role of the regulatory authorities, in 2007, only 19% of the respondents to a survey conducted by Shin Joho Center Inc. agreed that current rules and regulations were sufficient to control nuclear power, showing a low level of trust in the regulation of nuclear power in the country.

1.2.4. Training and qualification

Training and qualification of operators in charge of plant activities and in command and control of the accident management played an important role in the accident and are described in the following sections.

---

[66] In particular, in a survey conducted at the end of 1999 by the local authority, the percentage of respondents who supported nuclear power after the JCO's Tokaimura criticality accident fell from 52% to 32%, and the number of respondents who said that nuclear power facilities were unsafe rose from 32% to 78%, according to an OECD/NEA 2010 survey published in: OECD NUCLEAR ENERGY AGENCY, Public Attitudes to Nuclear Power, OECD, Paris (2010), 45.

1.2.4.1. Operator training

As stated in Section 1.2.2, licensing for the operators was required by the Japanese regulation only for the shift manager or shift supervisor (SS), who would be in command and control of the shift team; there was one SS per control room. The SS qualification process was implemented by JANTI.

The Nuclear Power Training Center Ltd. (NTC) and the BWR Operators' Training Center Corporation (BTC) trained reactor operators and SSs by means of simulators of pressurized water reactor (PWR) NPPs and BWR NPPs, respectively. The NTC and BTC also carried out the qualification examinations for the SSs on behalf of the electric power companies. In addition, each electric power company has its own training facility. However, after JANTI started to implement the qualification process in accordance with the regulations, BWR SS and deputy SS (DSS) training for licensing were conducted by BTC.

Qualification and/or certification of control room operators other than the SSs was determined and performed by the individual NPP operating organization. In accordance with JEAG 4802, TEPCO also established a training programme similar to BTC's, including classroom, on-the-job, self-study, and simulator training (Fig. 1.2–5) that is described in the sections below. As such, both the initial and renewal training for Fukushima Daiichi operators were performed at the Fukushima site training centre and at the BTC facilities.

1.2.4.2. Reactor operator qualification and certification requirements

In-line with the Japanese nuclear industry practices, the operator certification programme by TEPCO primarily set different levels of training and qualification based on the required scope and skills for such positions as auxiliary operator (AO), senior operator (SO), system senior operator (SSO) and DSS:

— The AOs were expected to be able to 'walk down' in the nuclear facility and identify any early indication of an abnormality and promptly address or rectify the abnormality, to operate field equipment during start-up, shutdown and other plant conditions, and to report and describe equipment conditions to the control room (to the SS) in the case of an accident.
— The SOs/SSOs were expected to have the proficiency to operate and monitor the nuclear plant for startup, shutdown and other plant conditions and provide instructions for field operations; demonstrate a thorough understanding of emergency operating procedures (EOPs) and be able: to perform the necessary operations; to give instructions for field operations to mitigate and stabilize an equipment failure and/or accident; and to operate the plant appropriately to mitigate and stabilize the situation under the direction of the SS in the case of an accident or a severe accident.
— The DSSs were staff who had been selected for promotion to SS in the near future, and who were receiving on the job training prior to their SS licensing application. In addition to meeting all the proficiencies of SOs/SSOs, the DSSs were expected to demonstrate leadership skills and capabilities to manage, direct and control the shift team, with the understanding that their highest priority was on safety issues, including industrial safety and equipment integrity. They also had to demonstrate skills in taking decisions in the case of an accident and/or a severe accident. This included the determination of when to enter into or exit from EOPs or Severe Accident Operating Procedures (SOPs) and the ability to give directions for appropriate operation during an accident.

The operators (other than the SSs) were required by the TEPCO programme to renew their qualifications every four years.

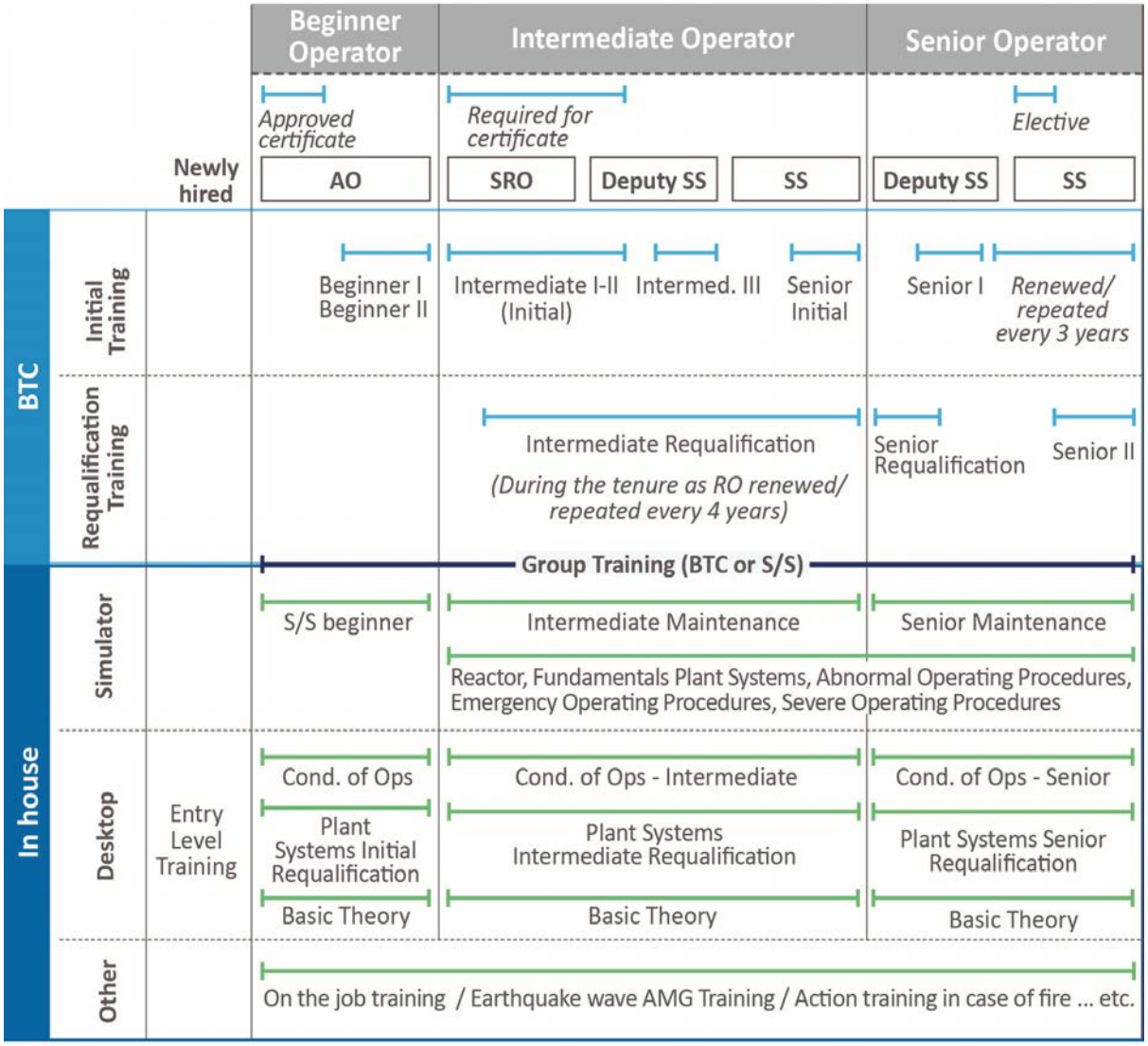


FIG. 1.2–5. TEPCO Operator Training and Qualification Programme.

1.2.4.3. Simulator training

Besides the classroom, on the job and self-study training, the training programmes of Japanese operating organizations also required operators to complete simulator training, either at on-site simulators or at BTC's simulators. There was no regulatory requirement for utilities in Japan to have full-scale unit specific simulators. However, every Japanese NPP had at least one full scope simulator at its site or in a nearby facility that was modelled after a specific unit or specific units at that site. These site representative simulators, which consisted of a replica unit from the site, had small and unique differences in design or equipment compared to other units on the same site.

Full-scale/full-scope simulator training for BWR reactor operators, especially for SSs/DSSs, was traditionally conducted at the BTC's full-scale simulator facilities.[67] The BTC provided simulator training for NPP operators with simulators that were modelled after selected reference plants,

[67] BTC's Fukushima Centre simulators went out of service following the accident, and replacement simulators were put in service at the Shimane provisional facilities.

including the Fukushima Daiichi NPP units (see Table 1.2–2). TEPCO operators also utilized and were trained in two full-scope BTC simulators, which were modelled after Fukushima Daiichi Units 3 and 4 (BWR/4) at a nearby facility.

TABLE 1.2–2. SIMULATOR TYPES AND LOCATIONS OF BTC TRAINING CENTRES [49]

Simulator No.	MCR type	Reference plant	Location	Training start year	Status at the time of accident	Current status
1	First Generation Control Panel 800 MW(e)	Fukushima Daiichi NPP Unit 3 (BWR/4)	Fukushima Centre	1974	In service	Closed
2	Second Generation Control Panel 1100 MW(e)	Fukushima Daini NPP Unit 3	Fukushima Centre	1983	In service	Closed
3	First Generation Control Panel 800 MW(e)	Fukushima Daiichi NPP Unit 4 (BWR/4)	Fukushima Centre	1989	In service	Closed
4	Second Generation Control Panel 1100 MW(e)	Kashiwazaki-Kariwa NPP Unit 4 (BWR/5)	Niagata Centre	1993	In service	Closed
5	Third Generation Control Panel 1356 MW(e)	Kashiwazaki-Kariwa NPP Unit 6 (ABWR)	Niagata Centre	1994	In service	In service

At the Fukushima Daiichi NPP site, there was one full-scale/full-scope simulator that was put in service in 2003. This simulator was modelled after the Fukushima Daiichi NPP Unit 3 (a BWR/4 and Mark-I containment) configuration.

Additionally, the Fukushima Daiichi NPP site housed a full-scale/limited-scope (compact) simulator based on the Unit 1 (BWR/3 with IC) configuration. After the activation of the full-scale/full-scope simulator in 2003, this compact simulator was utilized by the operators for self-study.[68] The Fukushima Daiichi NPP operators also utilized full-scope desktop training simulators (plant analysers) that individually modelled every unit at a given site for specific plant operation training.

1.2.4.4. Severe accident management training

In Japan, classroom and full-scope training simulators have been used for the training of operators for the prevention of core damage, i.e. mainly on design basis accident (DBA) procedures and scenarios. For the purposes of severe accident management (SAM) training of the TSC (Technical Support Centre) staff and operators, an education and training system (ETS), executed on personal computers, was developed by Japanese BWR utilities and vendors [60]. The ETS provided an interactive learning tool (both for individuals and for shift crews) for AM by visual means and utilized a commercial computer code.

[68] The site had another compact simulator modelled after Unit 4, which was used from 1996–2002 but was abandoned following the opening of the full-scale/full-scope simulator.

The computer simulations also included AM countermeasures based on the plant and equipment models, radioactive mitigation models and monitoring system models. Plant parameters calculated by the virtual simulator and the plant conditions were simultaneously displayed on several computer monitors connected over a network. Furthermore, core status, such as core damage and RPV failure, was mapped and displayed. Trainees could learn plant behaviour during severe accidents and the use of severe Accident Management Guidelines (AMGs) through the input of SAM actions during simulation. In the group training, the TSC staff and control room operators were able to perform emergency exercises simultaneously. These systems provided plant operators and TSC personnel with a training tool for AM. TEPCO conducted an emergency exercise simulating a hypothetical severe accident in March 2000, using the ETS tool.

TEPCO operators were required to complete the computer based SAM training every three years.

1.2.4.5. General emergency training and preparedness

Emergency training in the Japanese nuclear industry was guided by the Japan Electric Association Guide JEAG 4102 [61], which was the industry standard and was originally issued in 1996.

Following the JCO's Tokaimura criticality accident in 1999, when emergency plans of other countries were consulted as benchmarks, gaps in emergency preparedness and associated training were identified by Japanese regulators, utilities and international organizations. These were also raised in the IAEA report on lessons learned from the JCO's Tokaimura criticality accident [32]. The IAEA report also included recommendations concerning emergency preparedness.

In 2010, as a result of the trend in Western countries and the increased emphasis by the regulatory body, the Japanese nuclear operating organizations, through JANTI, initiated a revision of those guidelines and planned to implement enhanced nuclear emergency preparedness training. The JANTI task force started to prepare industry guidelines for emergency preparedness training, including the addition of the 'evaluation' concept to the 'conduct' aspect of training. Revision to JEAG 4102 was completed in September 2010. However, when the Fukushima Daiichi accident happened in March 2011, the guidelines had not yet been implemented.

1.2.5. Characteristics of the Fukushima Daiichi site

This section gives a general description of the Fukushima Daiichi site and its siting analysis for natural external hazards, such as earthquakes and tsunamis. It explains the site characteristics that were important for the course of the accident, such as the excavations that had lowered the site so that the reactors rested on bedrock and the placement of some essential systems at lower elevations.

The information in this section is derived mainly from the site description in the establishment permit (EP)[69], the Japanese equivalent of a safety analysis report (SAR) [15]. The EP was written almost 50 years ago, in accordance with the regulations at the time.

Although each of the six units at the Fukushima Daiichi site (Fig. 1.1–3) has its own site characterization in the EP, many parts of these are identical. The site characterization used for Unit 1 in 1966 was reused for Unit 2 in 1968, Unit 3 in 1970, Unit 5 in 1971 and Units 4 and 6 in 1972.

[69] Further information on Japanese terminology for licensing documentation is included in Section 1.3 and in Technical Volume 2.

1.2.5.1. Description of the site

The Fukushima Daiichi NPP site lies approximately 220 km north of Tokyo at almost the midpoint of the Pacific coast of Fukushima Prefecture (North latitude: 37°25', East longitude: 141°00'). It straddles Okuma and Futaba townships of Futaba County in the Fukushima Prefecture. Its area is approximately 3.5 km^2.

The population density around the site was sparse, with 9241 people living within 5 km of the site and 52 539 people within a 15 km radius.[70] The nearest inhabited homes were at least 0.9 km from the site. Three hamlets lie between 0.9 km and 3 km from the site, Ottozawa, Hosoya and Koriyama, and there are 18 hamlets within 5 km.

1.2.5.2. Weather

The region has an oceanic climate influenced by the warm waters of the Japan Current, which makes summers cooler and winters warmer than in inland areas.

No site specific long term weather data were collected at the site; year-round data were derived from weather stations nearby, mainly the Onahama Weather Station, which had similar meteorological characteristics.

The EP presented statistics on general weather patterns, including average annual temperatures, high temperatures, low temperatures, rainfall and wind speeds.

For extreme temperatures, precipitation and wind speeds, the EP used data from the previous 35 years from the nearest weather stations. It did not consider typhoons or tornadoes.

1.2.5.3. Topography

The sea floor next to the site consists of irregular protrusions approximately 2–3 m high that run parallel to the shoreline at approximately 600 m, 1000 m and 1300 m off the coast. The slope of the ocean floor is steep, approximately 1/60, until approximately 450 m offshore. Thereafter it is more gentle, approximately 1/130.

Before it was excavated, the site's elevation was approximately 35 m, and the elevation at the top of the cliffs was approximately 30 m. Since TEPCO selected grade levels of 10 m for the block of Units 1 to 4 and 13 m for the Unit 5 and 6 block, significant excavation was required, as shown in Fig. 1.2–6. The reasons for selecting grade levels of 10 m and 13 m are described in the section on 'Geology' below and are further discussed in Technical Volume 2, Section 2.1.

[70] At the time of accident, approximately 1900, 6000, 51 000 and 78 000 people resided in 2 km, 3 km, 10 km and 20 km radii, respectively.

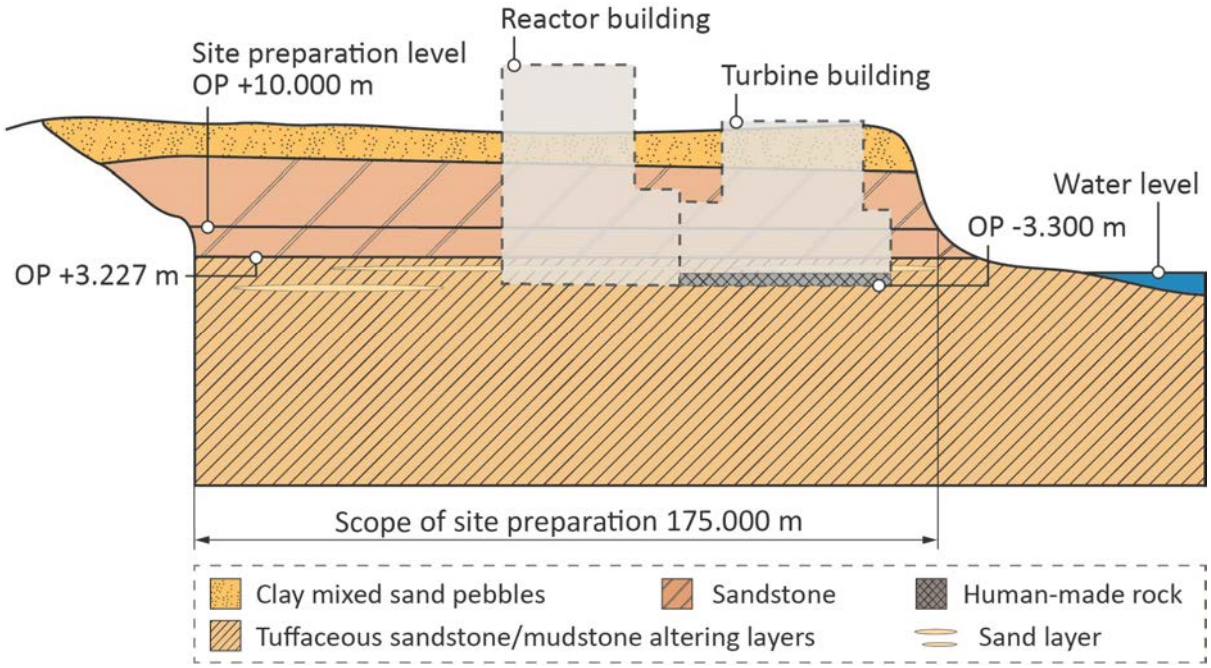


FIG. 1.2–6. Cross section of the Fukushima Daiichi construction site, including soil characteristics (Figure 1.3.2 of Establishment Permit [15]).

1.2.5.4. Geology

The site is made up of the Tomioka Formation, which is approximately 200–400 m thick and consists of sandstone and mudstone at the bottom and a lenticular sand layer sandwiched by tuffaceous fine grain sandstone and mudstone at the top. This is covered by coastal terrace sediments approximately 5–10 m thick and made up of pebbles, sand, silt and clay. In order to build the plant on an acceptable bedrock foundation, the site was excavated, and the main plant and buildings of Units 1–4 were built at an elevation of approximately 10 m.

The thick sediment of sandstone and mudstone was sufficient for bedrock supporting nuclear reactor buildings, so the primary structures were constructed directly on this mudstone.

1.2.5.5. Hydrology

There is groundwater in the 20–30 m thick layer of sand and clay immediately below the site's thin layer of topsoil. Underneath the layer of sand and clay is an impermeable Neogene mudstone layer; groundwater flows through the layer of sand and clay towards the coast (Fig. 1.2–7) at approximately 10 cm/d.

1.2.5.6. Oceanography

The tide measurements used in the design of the plant were recorded at the Onahama Port (OP), approximately 50 km south of the site.

In the EP, tsunami heights were considered as part of the maximum/minimum tidal level for plant design presented in Table 1.2–3. This gave a design basis tsunami height of 3.122 m above the OP level.

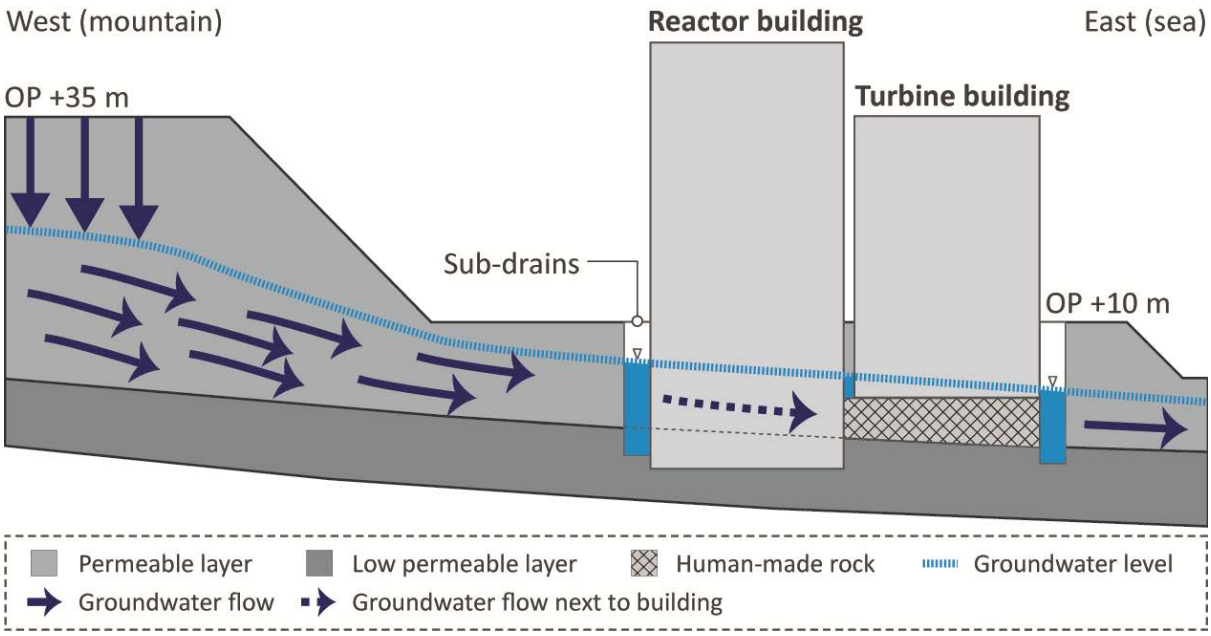


FIG. 1.2–7. Shallow layer groundwater cross-sectional diagram [15, 62].

TABLE 1.2–3. FUKUSHIMA DAIICHI ORIGINAL (EP) DESIGN BASIS TIDE LEVELS [15]

Tide level	Design basis height	Remarks
Maximum (High-high water level)	OP +3.122 m	Based on Chile earthquake and tsunami of 24 May 1960
Syzygy mean high (Mean high tide level)	OP +1.410 m	—
Mean (Mean tide level)	OP +0.824 m	—
Syzygy mean low (Mean low tide level)	OP +0.075 m	—
Minimum (Low-low water level)	OP −1.918 m	Based on Chile earthquake and tsunami of 24 May 1960

TABLE 1.2–4. SUMMARY OF FUKUSHIMA DAIICHI TSUNAMI RE-EVALUATIONS

Year	Tsunami height evaluation	Countermeasure
1966	Establishment Permit OP +3.122 m (observed height resulting from Chilean tsunami in 1960)	—
2002	Japan Society of Civil Engineers (JSCE) assessment method OP +5.7 m	Raise elevation of pumps Make buildings watertight
2007	Disaster Prevention Plan by Ibaraki Prefecture Government approx. OP +4.7 m	Unnecessary
2007	Disaster Prevention Plan by Fukushima Prefecture Government approx. OP +5 m	Unnecessary
2009	Latest bathymetric and tidal data on the basis of the JSCE assessment method OP +6.1 m	Raise elevation of pumps

This initial EP tsunami design basis was re-evaluated in 2002 following updated guidance from the Japan Society of Civil Engineers (JSCE) and re-evaluated again in 2009 using the latest bathymetric and tidal data. It was also re-evaluated twice in 2007 on the basis of the disaster prevention plans by the local prefectures at Ibaraki and Fukushima. Table 1.2–4 summarizes the results of the re-evaluations, and they are further discussed in Technical Volume 2, Section 2.1.

The EP did not consider combinations of tsunamis and other oceanographic events, such as storm surges or high winds.

1.2.5.7. Water for plant cooling

Seawater from the ocean was used for condenser cooling water and auxiliary equipment cooling water. A seawall was built in the ocean in front of the power station with open channels behind it that led from the power plant to the ocean. Water was drawn in through sluice gates and pump rooms installed for each unit and then transferred to the condenser by two pumps installed in the pump rooms.

Water from the condenser was discharged through a covered concrete culvert into the ocean in front of the south side of the sea wall.

1.2.5.8. Earthquakes and ground conditions

The subduction zone off Japan's Pacific coast has been the source of numerous earthquakes affecting Japan. It is part of the nearly circular subduction zone around the Pacific Ocean, the Circum Pacific Belt or so-called 'Ring of Fire'. It is the source of the world's largest earthquakes, including the Chilean earthquake of 1960 (M 9.5) and the Alaskan earthquake of 1964 (M 9.2), which occurred a few years before the Fukushima Daiichi NPP Unit 1 was designed.

The Fukushima Daiichi Unit 1 EP considered and analysed the following earthquakes as further discussed in Technical Volume 2, Section 2.1:

— Aizu earthquake, September 1611 (M 6.9)
— Sendai earthquake, June 1646 (M 7.6)
— Iwashiro-no-kuni Koori earthquake, October 1731 (M 6.6)
— Earthquake south-east off the coast of Shioyazaki, May 1938 (M 7.5)
— Earthquake east off the coast of Fukushima Prefecture, November 1938 (M 6.5)

Earthquakes in north-eastern Japan were grouped into: (1) those near the Japan Trench; (2) those near plate boundaries; (3) those within the Earth's crust under land; and (4) those within the sinking Pacific Plate. The following earthquakes were regarded as possible near the Fukushima Daiichi site:

— Earthquakes near the plate boundary: The largest earthquakes in the ocean near the site were in Rikuzen in 1646 and in Sendai in 1835. The Sendai earthquake had magnitude of M 7.6. The maximum potential magnitude for earthquakes in the area was estimated to be 7.75. It was therefore assumed that an earthquake with a magnitude of M 7.8 could occur near the plate boundary off the coast of Fukushima Prefecture (Δ = 50 km, epicentre depth (H) = 40 km).
— Land based earthquakes: The largest earthquake on land near the site was in Nikko in 1683. It was likely to have been between M 7.3 and M 7.5. Due to connections with active faults in the area, it was assumed that an M 7.5 earthquake could occur in the western marginal fault zone of the Fukushima Basin (Δ = 65 km).

Analysis of destructive earthquakes in these areas led to the following conclusions:

— M 8 class earthquakes occurring near the Japan Trench and further eastward had little impact at the power plant because they were so far away.
— Earthquakes around M 7.5 occurred offshore of Miyagi, Fukushima and Ibaraki prefectures near plate boundaries.
— Earthquakes around M 7.0–7.5 were thought to occur in the Earth's crust under land west of the Ou Mountains, the Kitakami River basin and near Nikko.
— No large earthquakes that could impact the Fukushima Daiichi site were likely to occur inside the sinking Pacific Plate.

Therefore, the EP concluded that the Fukushima Daiichi site was in an area of little seismic activity, and the design basis for the plant was based on large intra-slab earthquakes (up to M 7.1) beneath the site.

For Units 1 and 2, the original design basis for the seismic horizontal ground motion was calculated to be 250 Gals for the zero period ground acceleration (ZPGA), with 470 Gals static acceleration. The seismic design basis was re-evaluated under guidelines that were revised in 2006, and the results were submitted to NISA in 2008. The re-evaluation increased the design basis horizontal acceleration for all units except for Unit 6 and added a vertical acceleration design basis as shown in Table 1.2–5.

TABLE 1.2–5. DESIGN BASIS GROUND MOTION FOR FUKUSHIMA DAIICHI NPP UNITS [62]

Fukushima Daiichi NPP Unit	Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
	Revised design basis (2008)			Original design basis (1966)		
	N/S*	E/W**	U/D***	N/S*	E/W**	
Unit 1	487	489	412	245		470
Unit 2	441	438	420	250		470
Unit 3	449	441	429	291	275	470
Unit 4	447	445	422	291	283	470
Unit 5	452	452	427	294	255	470
Unit 6	445	448	415	495	500	470

Note: *North/South; **East/West; ***Upwards/Downwards.

1.2.6. Description of the Fukushima Daiichi plant systems

This section describes the Fukushima Daiichi NPP's BWRs. It focuses on the major structures, systems and components (SSCs) most relevant to preventing, protecting and mitigating accidents, specifically the systems for shutdown heat removal, overpressure protection, emergency core cooling, containment, off-site power configuration, on-site emergency power generation and fission product release prevention. Response and behaviours of these systems are evaluated in Technical Volume 2, Section 2.2.

1.2.6.1. General plant characteristics of the Fukushima Daiichi reactors

In general, BWRs use a closed, two-phase, direct steam cycle loop to remove heat from the reactor core, as shown schematically in Box 1.1–1. The working fluid is demineralized water that is used both as the coolant to remove heat and the moderator for controlling the reactivity. During normal

operation, bulk boiling of coolant water at a pressure of approximately 7 MPa (70 bar) takes place in the core, where the core exit steam quality reaches around 15% or less. This corresponds to a core exit void fraction of around 65% or less at the operating pressure of 7 MPa (70 bar). After passing through the turbines, the steam is condensed to water by being cooled by the condenser tubes that are filled with cold water taken from a heat sink, e.g. the ocean. The water resulting from condensation is then pumped back to the reactor as feed water.

The evolution of BWR technology during the 12 years from the start of construction on Unit 1 in 1967 to commercial operation of Unit 6 in 1979 was reflected in the six reactors of the Fukushima Daiichi NPP. After Unit 1, which was an earlier BWR/3 design, Units 2–5 were BWR/4 designs and Unit 6 was a BWR/5 design, which was the first unit with a capacity of 1100 MW(e). Some of the differences in design information and characteristic are noted in Tables 1.2–6 and 1.2–7.

TABLE 1.2–6. COMMERCIAL DESIGN INFORMATION FOR THE FUKUSHIMA DAIICHI NPP REACTORS [63]

Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Reactor type	BWR/3	BWR/4				BWR/5
Electrical output (MW(e)) (gross)	460	784	784	784	784	1100
Thermal output (MW(th))	1380	2381	2381	2381	2381	3293
Commercial operation start	March 1971	July 1974	March 1976	October 1978	April 1978	October 1979

Unit 1 licensed power (operating maximum power) was in 'MW-electric' output, while the other Fukushima Daiichi units were operated at licensed 'MW-thermal' power.[71]

TABLE 1.2–7. MAJOR DESIGN CHARACTERISTICS OF THE FUKUSHIMA DAIICHI NPP REACTORS [63]

Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Reactor pressure vessel inner diameter (m)	4.8	5.6	5.6	5.6	5.6	6.4
Reactor pressure vessel height (m)	20.0	22.0	22.0	22.0	22.0	23.0
Reactor pressure vessel total weight (t)	440	500	500	500	500	750
Reactor pressure vessels design pressure (gauge)	8.62 MPa (86.2 bar)					
Reactor pressure vessel design temperature (°C)	302					

[71] In Japanese regulation, for the Establishment Permit, the licensed power is the reactor system thermal output, while the Construction Plan review licences the electric output. Starting in 2000, it has been allowed to operate in larger electrical output than the licensed value in the Construction Plan, providing that thermal output is limited by the licensed thermal output of Establishment Permit. An evaluation showing that turbine and generator systems can be operated in these circumstances had to be completed and accepted by the regulatory body, NISA.

1.2.6.2. Heat generation

In BWRs, the heat is generated in the core that is composed of the fuel assemblies, which are the fuel pins bundled in square arrays and enclosed in a zirconium alloy fuel channel box[72], and the control rods, which are cross-shaped arrangement of blades containing boron carbide (B_4C) neutron poison. The fuel pins consist of low enrichment uranium oxide or mixed (uranium and plutonium) oxide (MOX) fuel pellets enclosed and sealed in zirconium alloy cladding tubes.

The BWR fuel design and reactor core arrangements evolved over the years. The reactor cores in the Fukushima Daiichi NPP units at the time of the accident had some differences in their arrangements as shown in Table 1.2–8. Section 1.4 provides further details of the fuel composition.

TABLE 1.2–8. THE FUKUSHIMA DAIICHI NPP REACTOR CORES [64, 65]

Description	1	2	3	4	5	6
Fuel assembly (No. of assemblies in the core)	400			548		764
High burnup 8 × 8 fuel assemblies	68	—	—	—	—	—
9 × 9 fuel (A type) assemblies	—	—	516	—	—	—
9 × 9 fuel (B type) assemblies	332	548	—	548	548	764
8 × 8 MOX fuel assemblies	—	—	32	—	—	—
Number of control rods	97			137		185

1.2.6.3. Shutdown heat removal

Normal shutdown cooling of BWRs at high reactor pressure is accomplished by directing the steam from the reactor to the main condenser, bypassing the turbines (see Box 1.1–1). However, when the reactor is isolated, i.e. the main steam isolation valves (MSIVs) are closed, the turbine bypass path is not available and shutdown cooling is provided by the systems designed for an isolated reactor under high pressure conditions. In the design of the Fukushima Daiichi NPP, those were: the isolation condenser (IC) system for Unit 1 (the earlier design) and the reactor core isolation cooling (RCIC) system for Units 2–6.

When the reactor temperature is lowered enough by depressurization[73] by high pressure shutdown cooling systems, the shutdown cooling at low pressure is provided by a shutdown cooling (SHC) system for Unit 1 and residual heat removal (RHR) systems for Units 2–6.

High pressure heat removal systems

Isolation condenser system

In the BWR/3 design (Unit 1), there are two separate and redundant IC loops (Trains A and B) with separate isolation logic circuits, each powered by a separate power supply. In these closed loops, the primary side of the IC received steam is generated in the reactor and is condensed it by cooling inside

[72] The functions of the fuel channel are to position the rod bundle, provide guide surfaces for the control rods that are inserted between the fuel assemblies, and allow for flow to the individual assemblies through orifices.

[73] In BWRs, the reactor cooldown is monitored and controlled by the reactor pressure which, in turn, corresponds to the reactor temperature.

the heat exchanger tubes that are submerged in colder water tanks (isolation condenser pools) located outside the PCV. Condensed steam is then sent as cold water back to the reactor by gravity (Fig. 1.2–8). Without mixing with the radioactive primary side water, the secondary side water in the IC pools boiled, and the evaporated steam is vented to the atmosphere, which served as the heat sink. The secondary side water volume of the IC (both trains together) is sufficient for eight hours of cooling before requiring replenishment [15] from a dedicated water source. Make-up of secondary water is provided from the fire water system or other suitable water source.

As shown in Fig. 1.2–8, there are two isolation valves on the steam lines going into each IC and two isolation valves on condensate lines coming out of each IC. The outboard valves (i.e. the valves outside the containment) on the condensate lines (MO-3 in the figure) are closed during normal operation. The inboard valves (i.e. the valves inside the containment) on the condensate lines (MO-4 in the figure), as well as the inboard and outboard valves on the steam lines (MO-1 and MO-2 in the figure) are normally kept open. The control of the IC is kept in automatic mode during normal operations, and if the pressure in the reactor exceeds and remains above the set point of 7.13 MPa (71.3 bar) (gauge) for longer than 15 seconds [63], the valves on the condensate line will open, enabling operation of IC.

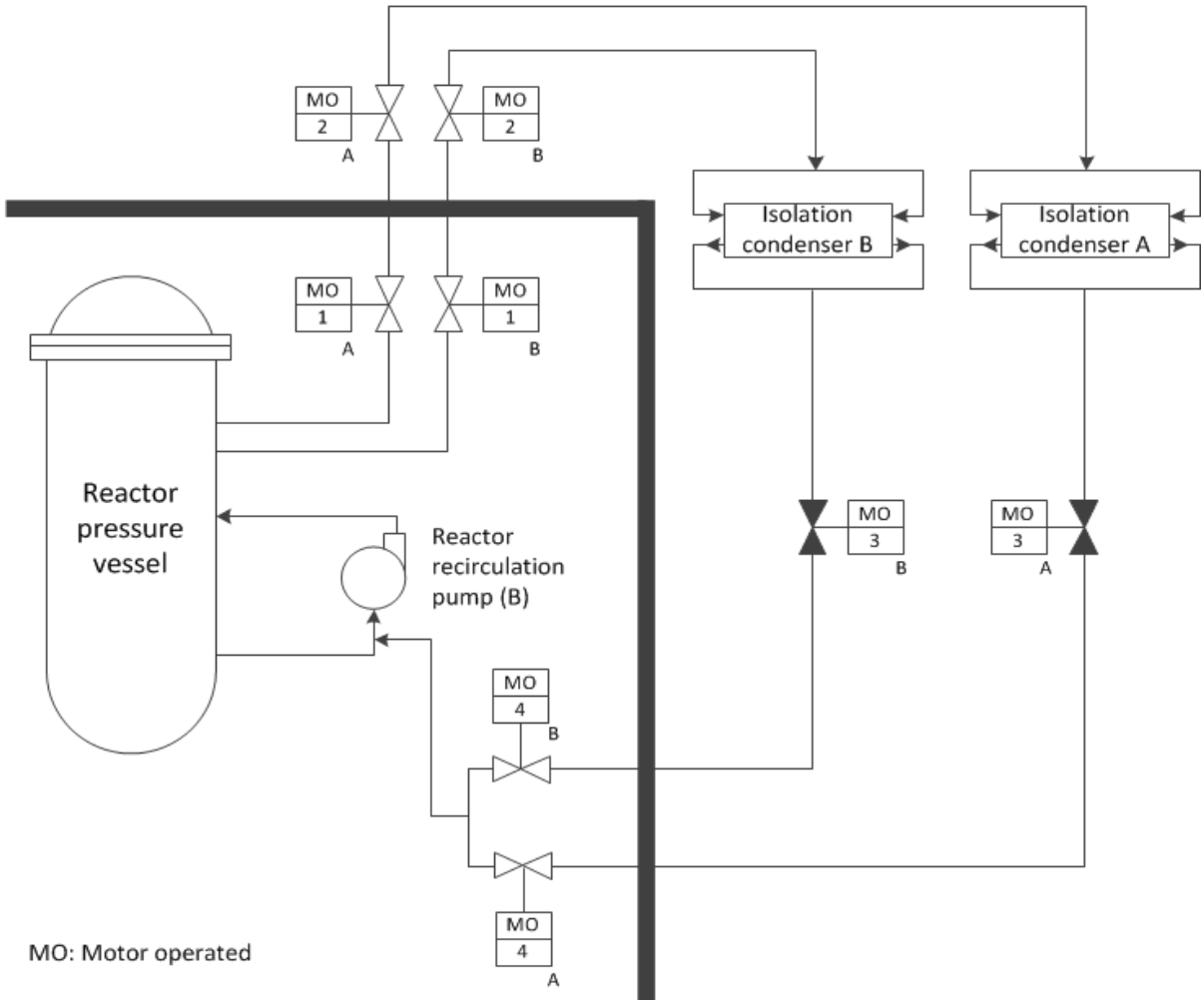


FIG. 1.2–8. Schematic of isolation condenser (IC) [1].

By conserving the water in the reactor pressure vessel (RPV), ICs eliminate the need for additional high pressure make-up systems. By removing decay heat, the system also limits reactor pressure

increases to below the safety relief valve (SRV) set points and prevents the SRV from being activated following reactor isolation.

All steam line valves and condensate line valves are designed to shut automatically to isolate the IC system if sensors detect high IC steam flow or high condensate return flow, either of which would indicate a line break.

The actuation of inboard steam supply and condensate return isolation valves are AC powered, and the outboard steam supply and condensate return isolation valves are DC powered. Both inboard and outboard isolation valves fail 'as-is' upon loss of actuation power. Also, if the power to control the system circuit is lost, all valves will fail 'close' as long as the actuation power is available.

The IC system instrumentation and control circuitry consists of initiation and containment isolation logic circuits. These circuits provide different functions, both of which are important to system reliability. The initiation circuitry provides for automatic and manual start of the system. The purpose of the containment isolation circuitry is to initiate closure of appropriate primary containment isolation valves to limit fission product release should a steam line rupture occur. The IC system is automatically isolated if high IC steam flow or condensate return flow is sensed, indicating a line break. This isolation shuts all the steam and condensate isolation valves and the steam line vent valves, rendering the IC system inoperable. The steam line vent valves will also automatically shut on a low vessel water level condition. Isolation of the vent valves for a prolonged period of time could render the heat exchanger inoperable due to the build-up of non-condensable gases. However, failure of this circuit to close the vent valves would not preclude operation of the system.

Reactor core isolation cooling system

In the BWR/4 designs (Units 2–6), shutdown cooling at high pressure is achieved by reactor core isolation cooling (RCIC) systems. These systems are open cycle cooling systems that consist of a turbine driven pump, associated piping, valves and instrumentation and control circuits, and a source for adding water to the reactor system. The system is designed to operate initially on an open cycle, taking water from a dedicated water source and injecting it into the RPV either through a main feedwater line (Units 2–5) or a reactor vessel head spray nozzle (Unit 6).

The steam from the reactor drives a small turbine which, in turn, runs a pump that injected water into the reactor at high pressure (Fig. 1.2–9). The steam that runs the turbine is discharged and accumulated in the suppression pool section of the PCV, which serves as the heat sink for absorbing waste heat. The water lost from the reactor is replenished by taking water from a dedicated water source.

During normal operations, the RCIC controls are kept in automatic. When the reactor is isolated, the pressure in the RPV increases and SRVs open to discharge steam and reduce the RPV pressure, resulting in the reactor water level decrease. The RCIC system is started automatically if low water level signals are detected in the reactor. Initially, the turbine-driven pump supplies make-up water from the condensate storage tank (CST) to the reactor vessel at the normal reactor operating pressure. When the CST water level is low or the suppression pool water level is high, the suction line from the CST is isolated and the RCIC pump takes water that has accumulated in the suppression pool, making the system essentially a closed loop cycle.

The start and operation of the RCIC system is independent of external AC power sources, since the primary motive energy is from the steam in the reactor vessel, while all the valves to control the amount of water injection are driven by DC power from the batteries. The required mission time for the RCIC in the Fukushima Daiichi NPP units in an SBO situation was four hours [8]. The RCIC can operate longer depending on the manipulation of plant systems consuming DC power.

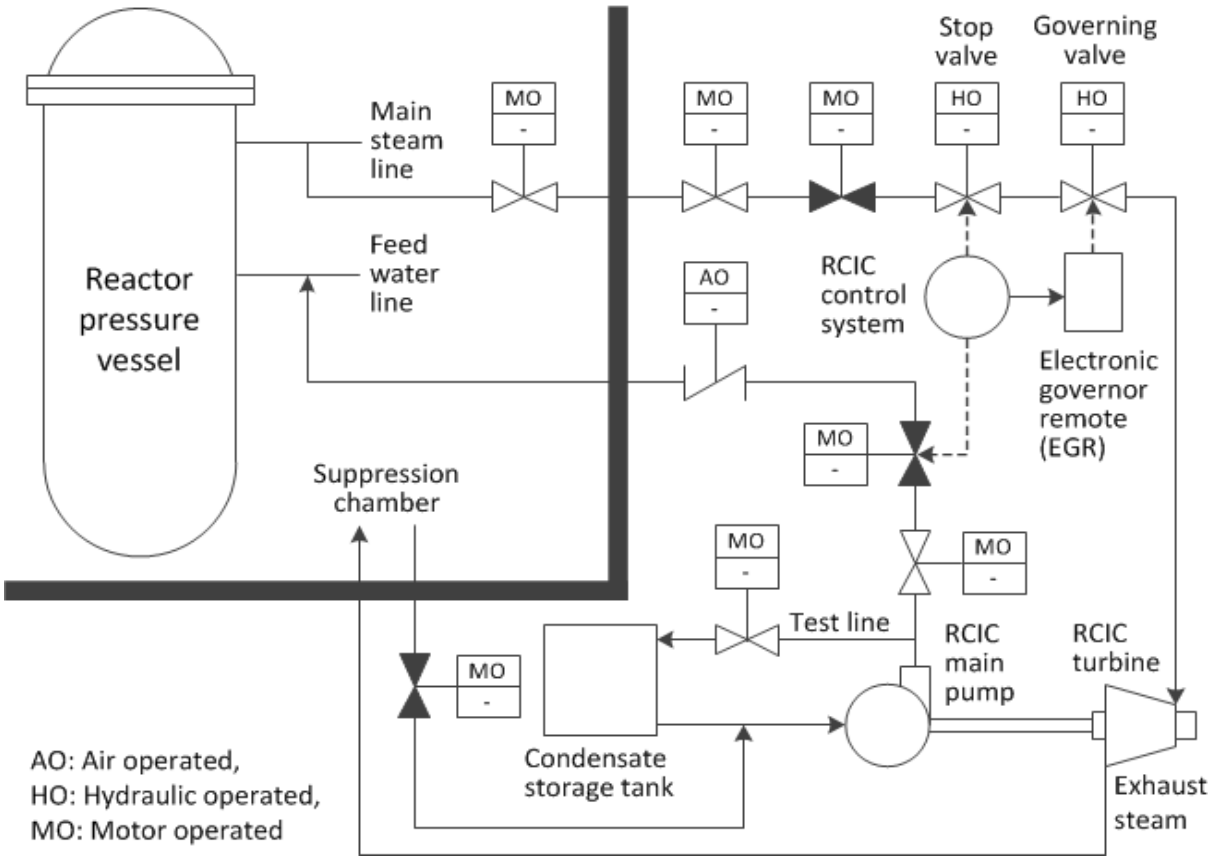


FIG. 1.2–9. Schematic of reactor core isolation cooling (RCIC) [1].

During the RCIC operation, the discharged energy to the SC will heat up the suppression pool. To keep the suppression pool temperature within prescribed limits under longer period of RCIC operation, the residual heat removal (RHR) system can be used to cool the suppression pool and complete the heat transfer path to the ultimate heat sink. However, the operation of the RHR systems' pumps and motor operated valves require AC power from off-site sources or on-site emergency AC power sources.

Low pressure heat removal systems

The Fukushima Daiichi NPP's Unit 1 had a shutdown cooling (SHC) system, and Units 2–6 had residual heat removal (RHR) systems to cool the cores after initial cool down by the high pressure heat removal system and depressurization to about 0.862 MPa (8.62 bar).

In the SHC system, hot water flows into the heat exchangers from a reactor recirculation loop, on the suction side of an idle recirculation pump. After being cooled in the heat exchangers, the water feeds back into either a main feedwater line or a recirculation line on the discharge side of an idle recirculation pump.

Similarly, the RHR system provides for post-shutdown core cooling after the initial cooldown and depressurization by the RCIC system. A residual heat removal and cooling seawater (RHRS) system, i.e. service water loop for the RHR system, supplies the cooling water to the RHR heat exchangers.

Because the RHRS system pumps have a relatively high discharge pressure (about 2.2 MPa (22 bar)), the system can also be utilized for an emergency flood of the core at lower pressures, or the PCV. This can be done by opening the cross-tie between the RHRS and the RHR return line to the reactor

coolant system (RCS). In a multimode RHR system, this return line branches to the RPV, the suppression chamber (SC) and the drywell (DW).

1.2.6.4. Overpressure protection

In the design of the Fukushima Daiichi NPP units, overpressure protection is provided by means of safety valves (SVs) and/or safety relief valves (SRVs), which are connected to the four main steam lines (Fig. 1.2–10).

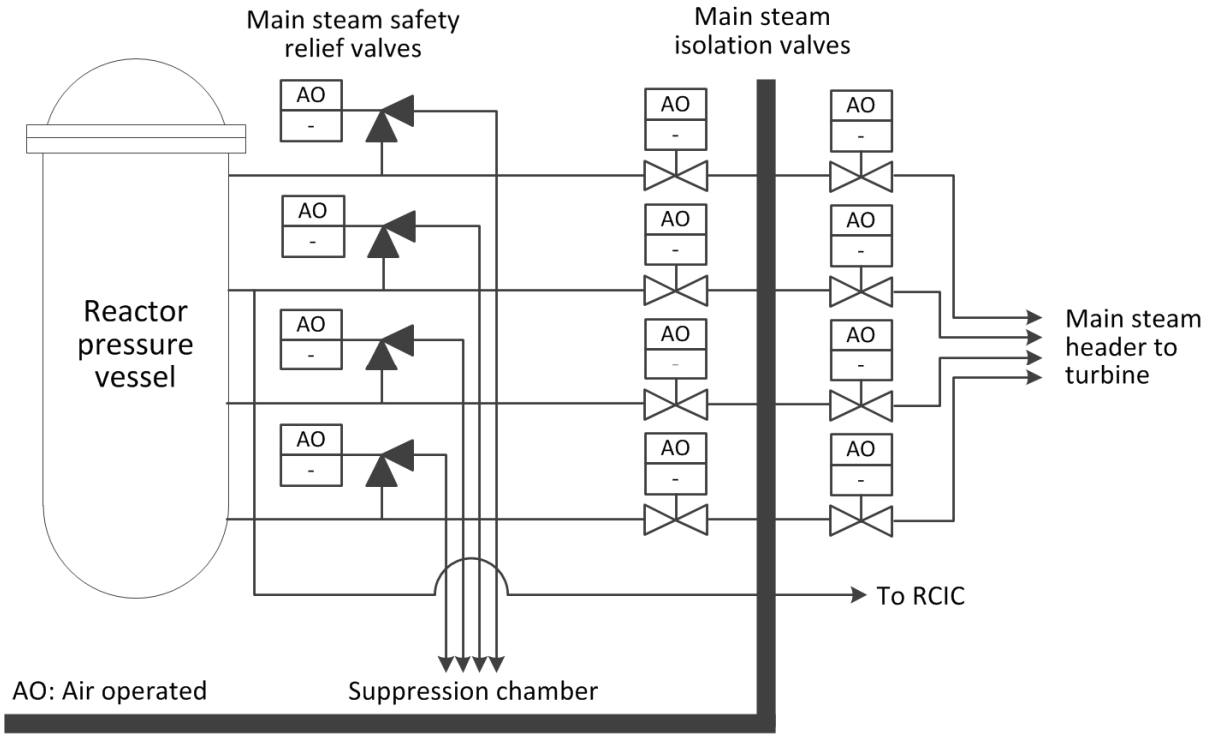


FIG. 1.2–10. Typical safety relief valve arrangement [1].

Fukushima Daiichi units provide for RCS overpressure protection, pressure relief, and RCS depressurization in various ways. The safety/relief valves are capable of both lifting mechanically on high pressure and being actuated at lower pressures to perform either the pressure relief or the automatic depressurization system (ADS) function.

— In the earliest plants (BWR/1 and some BWR/2 types) overpressure protection was provided by safety valves that mechanically open on high pressure in the RCS. In these plants, the automatic depressurization system (ADS) function is accomplished by 'Electromatic' type power-actuated relief valves (PARVs) that are controlled by a solenoid pilot valve.
— In the BWR/3 product line (Unit 1), the trend was away from PARVs to safety/relief valves that were capable of both lifting mechanically on high pressure and being actuated at lower pressures to perform either the pressure relief or the ADS function.
— In the BWR/4 product line (Units 2–5), the trend was away from safety valves to safety/relief valves for accomplishing the overpressure protection function.
— Later BWR/4 models, and all BWR/5 (Unit 6) plants only use safety/relief valves to accomplish the overpressure protection, pressure relief and ADS functions.

Based on their age and design, therefore, the Fukushima Daiichi NPP units had different overpressure protection configurations. Units 1–3 each had 3 SVs that discharged steam to the DW in addition to the SRVs (4 SRVs in Unit 1 and 8 SRVs in Units 2 and 3) that discharged to the SC. Units 4 and 5 had 11 and Unit 6 had 18 SRVs discharging to the SC. Some of the SRVs were also used for the ADS, as mentioned in the next section.

1.2.6.5. Emergency core cooling systems

BWRs are equipped with a safety grade emergency core cooling system (ECCS) to mitigate adverse effects of a loss of coolant accident (LOCA) by maintaining core cooling to prevent core damage. These systems also play a role in beyond design basis accidents (BDBA), and anticipated transient without scram (ATWS) and station blackout (SBO).

Depending on the age and design, the ECCS of a BWR may include various high and low pressure systems as well as the depressurization systems:

— A typical BWR/5 (Unit 6) employs high pressure core spray (HPCS), low pressure core spray (LPCS), ADS and low pressure coolant injection (LPCI) as parts of the ECCS.
— A typical BWR/4 (Units 2–5) employs high pressure coolant injection (HPCI), core spray (CS), ADS and LPCI as parts of the ECCS.
— As an earlier BWR/3 product line, Unit 1's ECCS does not include LPCI.

High pressure coolant injection system

The HPCI applies to the Fukushima Daiichi Units 1–5. It is a safety system designed to maintain adequate reactor vessel water inventory and core cooling during small break LOCAs. It also aids depressurization of the reactor vessel to allow low pressure ECCS to inject during intermediate break LOCAs. Under reactor vessel isolation conditions, it also serves as the backup to the non-safety RCIC system[74].

The HPCI system is an independent ECCS; it does not require AC power or instrument air to perform its function. The HPCI system consists of a turbine, turbine driven pump and the auxiliary systems required for turbine operation and associated piping and instrumentation.

The HPCI system initially operates on an open cycle, taking water from the CST, as illustrated-in Fig. 1.2–11, and injecting into the reactor vessel via a main feedwater line. When the CST water level is low or the suppression pool water level is high, the HPCI pump suction is aligned to the suppression pool and the suction line from the CST is isolated. Heat from the primary system is transferred to the suppression pool by the continuous or intermittent operation of the SRVs. Suppression pool cooling must be initiated to complete the heat transfer path to the ultimate heat sink. The HPCI system provides primary system make-up at RPV pressures ranging from the operating pressure to injection pressure of low pressure ECCS (Table 1.2–9). By supplying cool water and using the steam generated by the decay heat for driving the HPCI turbine, the reactor depressurizes and allows the injection by the low pressure ECCS. When the primary steam pressures are less than about 1 MPa (10 bar), the operation must be terminated because of poor steam conditions for the two-stage HPCI turbine drive that would affect the system's reliability.

[74] The flow capacity of an HPCI is about ten times higher than that of an RCIC.

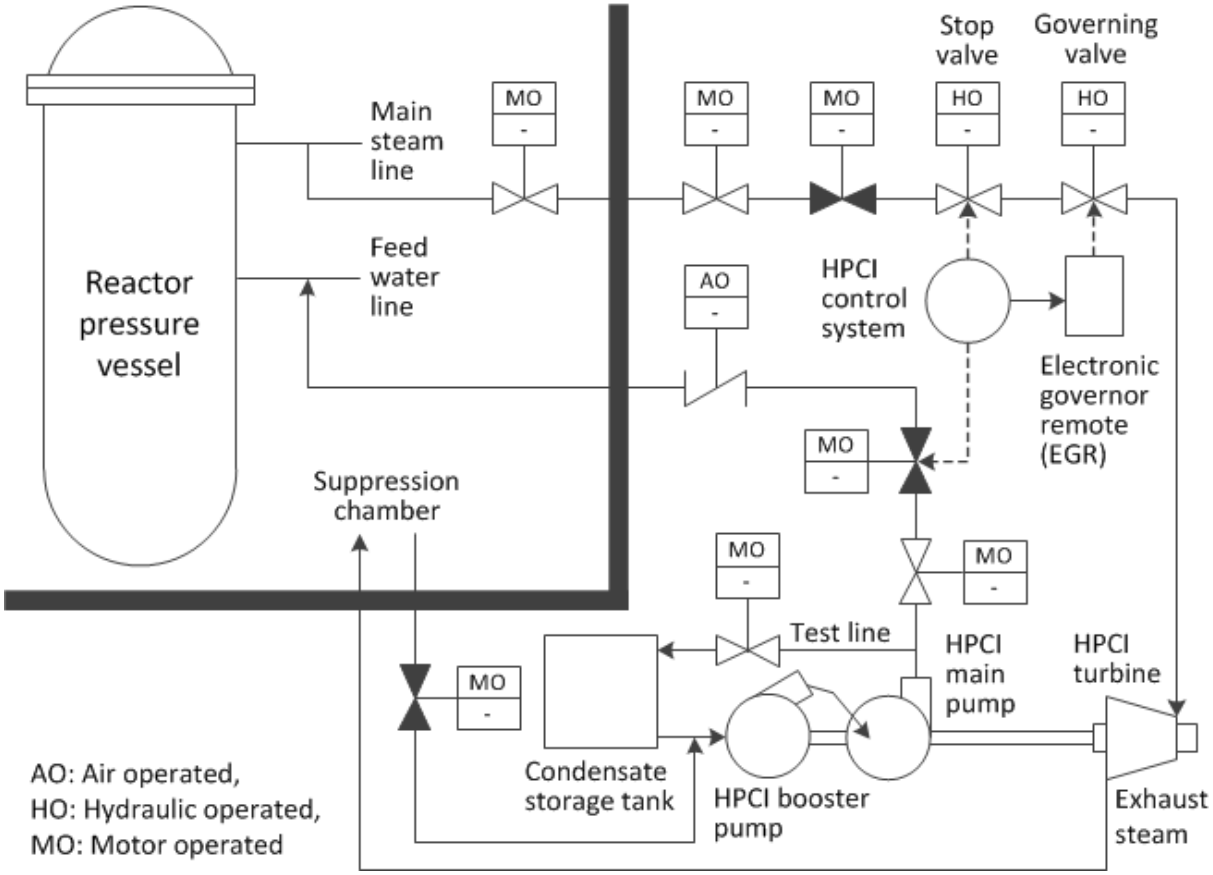


FIG. 1.2–11. Schematic of high pressure coolant injection (HPCI) system [1].

TABLE 1.2–9. HPCI PARAMETERS [63]

Description	Unit 1	Units 2–5	Unit 6
Reactor pressure (MPa)	72–10.3	72–10.3	72–10.3
Flow (m^3/h)	682	965	965

System initiation can be accomplished by automatic signals or remote-manually from the main control room (MCR). Receipt of either a low reactor water level or high drywell pressure indication will automatically start the HPCI system.

The 125 V DC power supply provides the energy for the controller, the motor operated valves; hence, if DC power is lost, the function to control the HPCI will cease.

In the Fukushima Daiichi Unit 6 (BWR/5), the high pressure ECCS subsystem was the HPCS system, which has a single motor driven pump that initially operates on an open cycle, taking water from the CST, as illustrated in Fig. 1.2–12, and injecting into the reactor vessel via a spray sparger located above the reactor core. Similar to the HPCI system, when the CST water level is low or the suppression pool water level is high, the HPCS pump suction is aligned to the suppression pool, and the suction line from the CST is isolated; suppression pool cooling must be initiated to complete the heat transfer path to the ultimate heat sink.

Automatic depressurization system

Under the scenario of a high pressure core cooling system failure, the ADS is designed to rapidly reduce the RPV pressure to allow the low pressure emergency core cooling systems to work upon a predetermined low reactor water level signal and high PCV pressure signal. The actuation signal of the ADS controls solenoid valves feeding nitrogen gas into the SRV cylinder from the ADS accumulator to open the SRV.

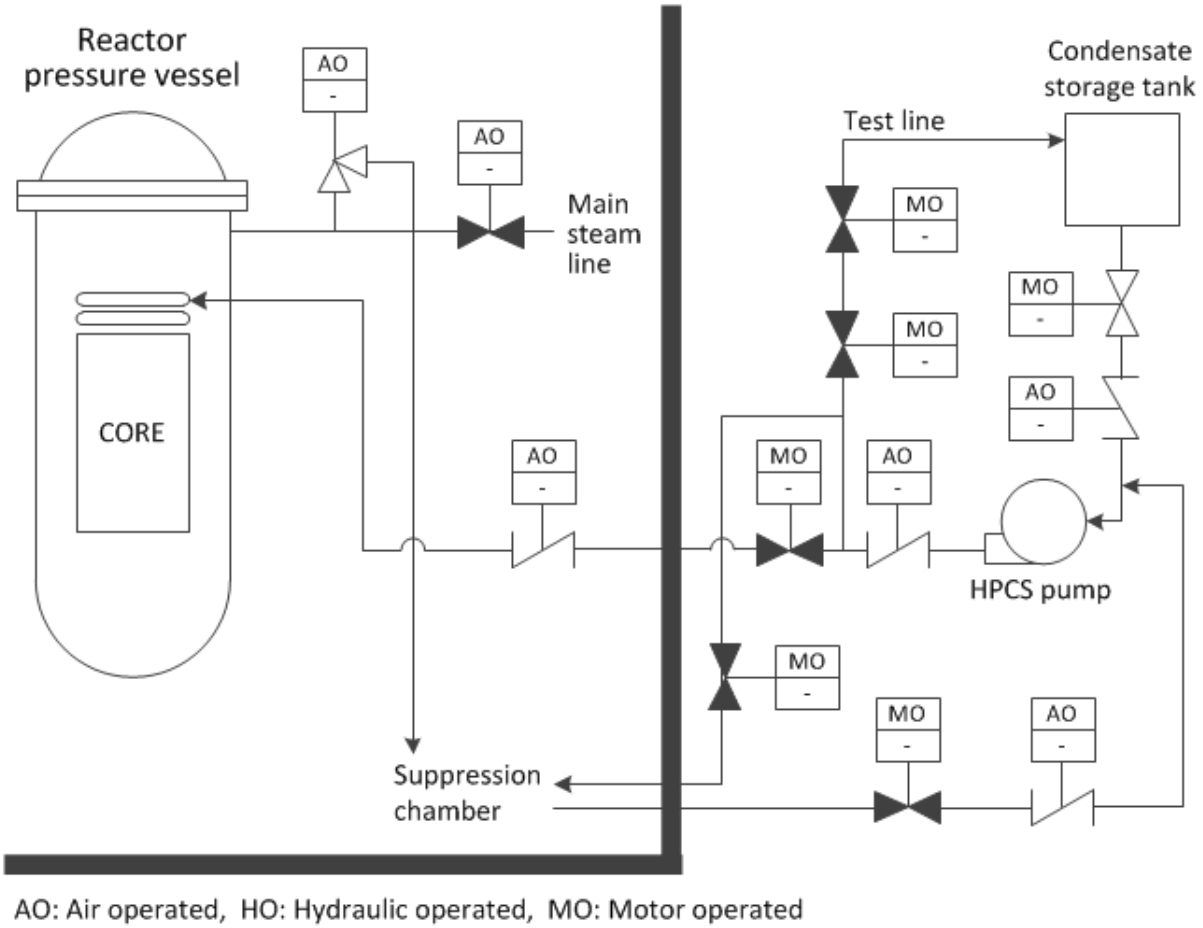


FIG. 1.2–12. Schematic of high pressure core spray system (HPCS) [1].

Core spray system

The purpose of the core spray (CS) system, which was in the design of all Fukushima Daiichi NPP units, is to provide low pressure make-up water to the reactor vessel for core cooling under LOCA conditions. All Fukushima Daiichi NPP units, like all BWRs, the core spray system was designed to inject water from the suppression pool to the core at low pressures using one or more spray spargers located above the core. The CS system automatically initiates upon receipt of either a predetermined low level reactor vessel water level signal or a high drywell pressure. The water was delivered by motor-driven pumps that required AC power to operate.

The CS system in the Fukushima NPP Units 1–5 (BWR/3 and BWR/4s), consisted of two 100% capacity trains with two separate spargers, while in Unit 6 (BWR/5), there was a single-train low pressure core spray (LPCS) system that was supplemented by a single-train HPCS system to provide a redundant low pressure core spray capability. These LPCS and HPCS systems in Unit 6 were

designed to inject through independent loops, each containing a low pressure pump, minimum flow line, test line, spray sparger and the associated motor operated valves and instrumentation necessary to perform its function.

Low pressure coolant injection system

In addition to the CS system, the ECCS of BWRs (except BWR/3, i.e. Unit 1) is equipped with an LPCI system that provides a core flooding capability at low pressures. This ECCS subsystem was introduced into a later BWR designs as a dedicated injection system (i.e. not integrated into a multimode RHR system) that delivered water from the suppression pool. The LPCI systems in the Fukushima Daiichi NPP Units 2–5 (BWR/4) were designed to inject via a recirculation loop, while the LPCI system in Unit 6 (BWR/5) had a direct injection path into the reactor vessel, inside the core shroud.

In the Fukushima Daiichi NPP Units 2–6, the LPCI system was an operating mode of the RHR system, constituting one of the ECCSs. In the LPCI mode for post-LOCA long term cooling, the RHR pumps take water from the suppression pool and feed back into the reactor. Spills from the break return to the suppression pool, establishing a closed loop for post-accident cooling.

The LPCI part of the ECCS was never utilized during the accident, since Unit 1 did not have an LPCI system, and, in other units, its operation required AC power.

1.2.6.6. Containment systems

Units 1–5 at the Fukushima Daiichi NPP had Mark-I containments, while Unit 6 had a Mark-II containment. Both designs use a common pressure suppression concept to condense steam from the RPV before it can create high pressure in the containment.

The BWR containments have two fission product barriers: the primary containment, or primary containment vessel (PCV), and the secondary containment, or reactor building (RB). The PCV has two major compartments. The compartment where the reactor vessel is located is the drywell (DW). The DW is connected to the second compartment, the suppression chamber (SC), which holds a large amount of water and enough space to suppress pressure increases and store increased amounts of water.

During normal operation, both the Mark-I and Mark-II containments are filled with nitrogen to provide prompt control of any hydrogen generated during an accident. If accumulation of hydrogen does build up, hydrogen recombiners equipped inside the PCV are started, if AC power is available, to avoid possibilities of hydrogen deflagration or detonation. They are not, however, installed in the RB outside the PCV.

If there is a severe accident in which the core is damaged, the suppression pool can also be used to ‘scrub’ some radioisotopes out of gases that might be discharged to reduce their radioactivity.

The RB surrounds the primary containment and provides the second fission product barrier and is commonly called as secondary containment. In case of an accident, the standby gas treatment system (SGTS), which needs AC power for operation, filters the gases and keeps the inside pressure below the atmospheric pressure to prevent radioactive materials release. Fig. 1.2–13 shows the containment configuration used in Unit 1. The same configuration, with some minor differences, was also used in Units 2–5.

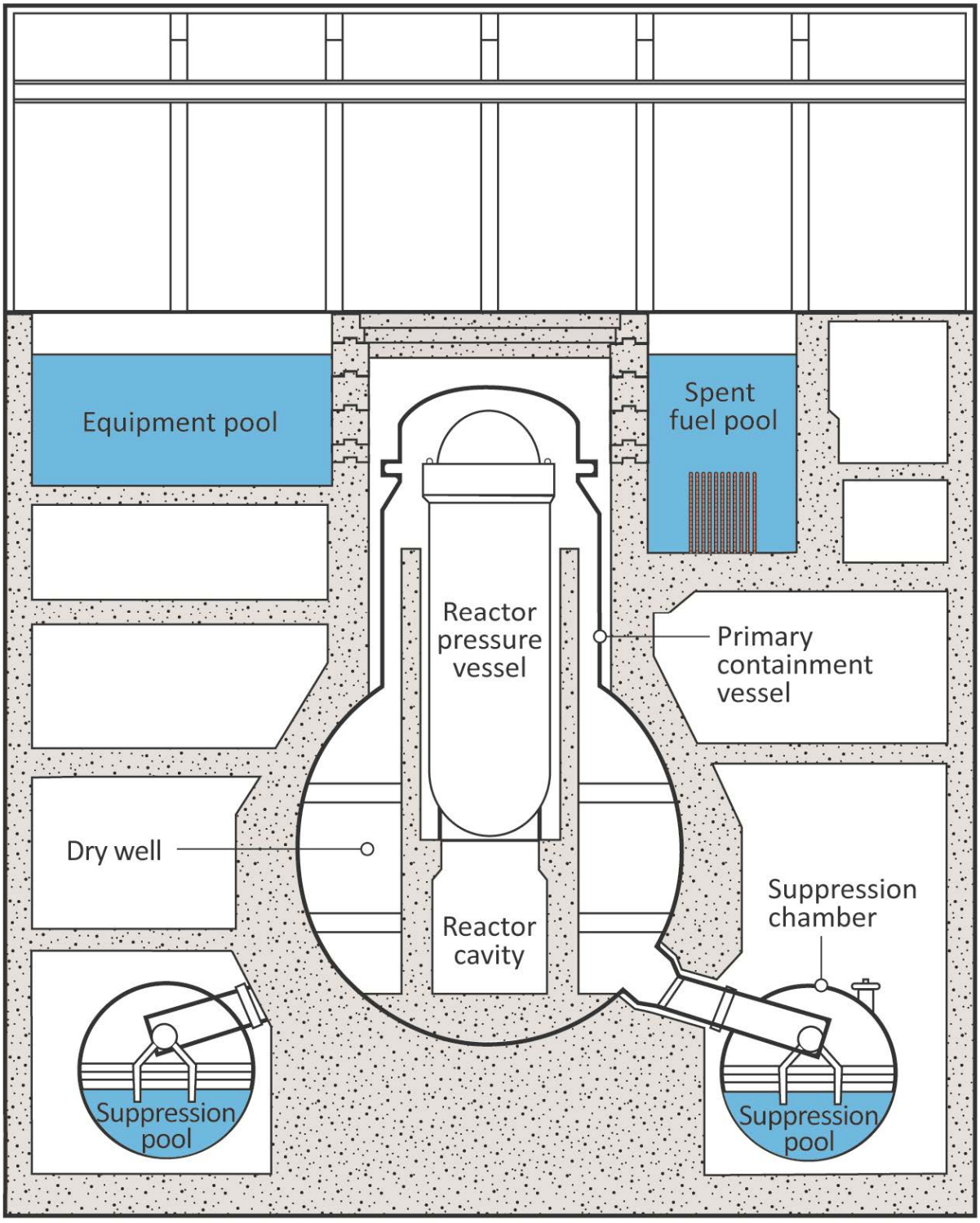


FIG. 1.2–13. Simplified representation of the Mark-I containment configuration [66].

The inverted light bulb shape of the DW is the distinctive characteristic of the Mark-I design. The DW is connected to a toroidal shaped compartment of the SC via large ducts. The torus contains a large amount of water, called the suppression pool. During a LOCA, the design allows hot steam to be vented through downcomer pipes and spargers to condense below the surface of the suppression pool water and reduce excessive pressure. The DW, the SC (including the suppression pool) and the connecting pipes are all part of the primary containment.

The Mark-II design uses the same pressure suppression concept as the Mark-I. Only Unit 6 at the Fukushima Daiichi NPP had a Mark-II containment, which is shown in Fig. 1.2–14.

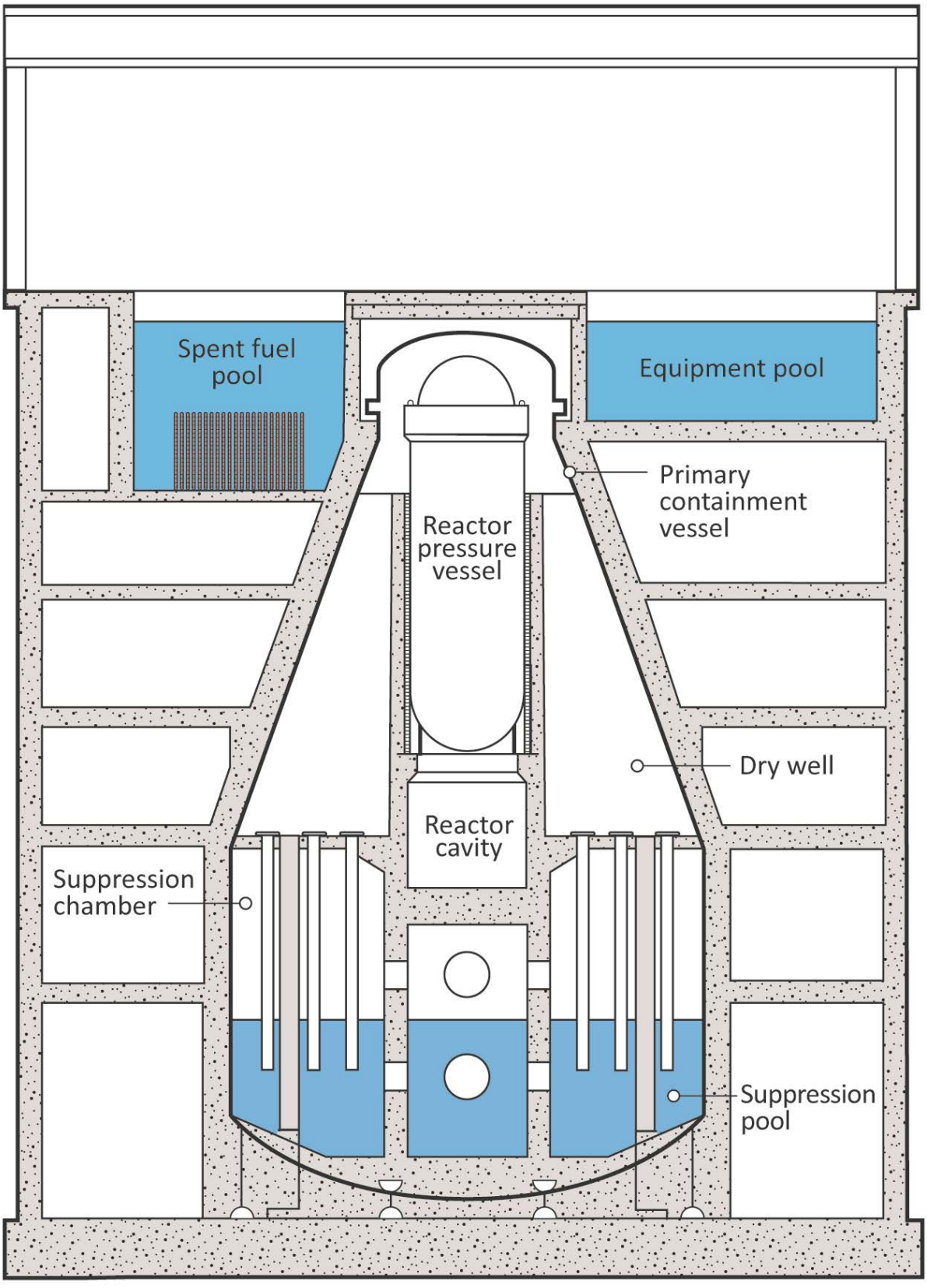


FIG. 1.2–14. Simplified representation of the Mark-II containment configuration [66].

1.2.6.7. Containment vents

As a measure to improve the ability to cope with severe accidents, 'hardened vents' (i.e. pressure relief devices with relatively thick walled discharge piping) were installed in the units at the Fukushima Daiichi NPP in the 1990s following a regulatory decision [21, 22]. The purpose of the containment venting system is to prevent overpressurization of the primary containment by allowing controlled release of energy inside the PCV. Although the preferred path of venting was from the SC, in order to benefit from the removal of radioisotopes by the water pool, the vent path included another route from the DW to allow rejecting higher energy from the containment to protect the integrity in a timely manner (Fig. 1.2–15). Either path could be aligned by manipulating valves from the MCR, controlling the amount and duration of the release through a stack shared between the pair of units.

In the Fukushima Daiichi NPP, the vent line also contained a rupture disc that was set to burst when the containment pressure exceeded a pre-set pressure, thereby preventing premature venting. The underlying philosophy in Japan was not to vent until it was inevitable, and as a last resort for maintaining the integrity of the primary containment in order to delay or prevent the direct release of radioactive material to the environment. In line with the delayed venting strategy, venting through aligning the valves was procedurally delayed until the containment pressure had reached a value that was twice the design.

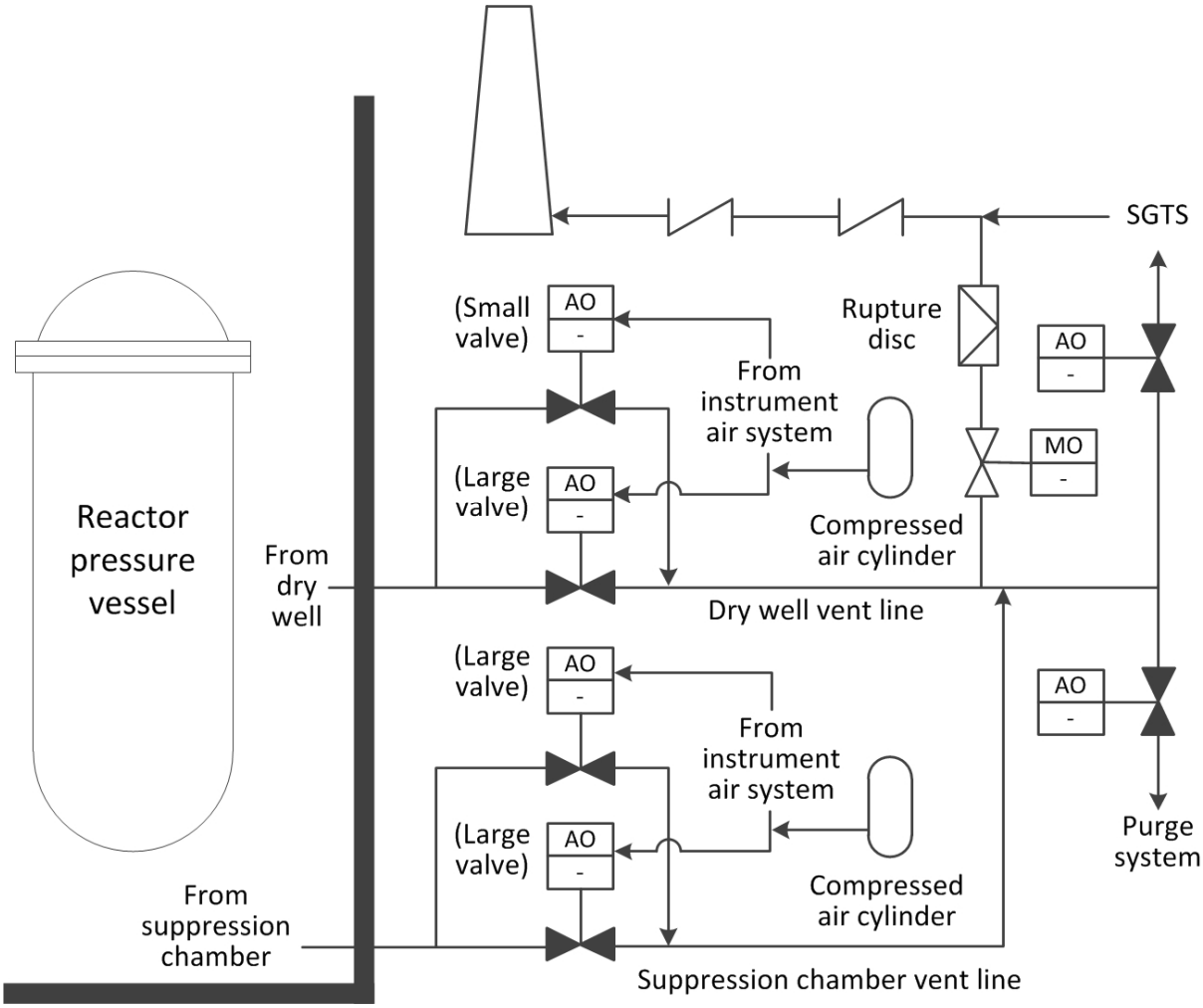


FIG. 1.2–15. Schematic of Fukushima Daiichi Unit 2 venting system [1].

1.2.6.8. Off-site power configuration

Off-site power for the Fukushima Daiichi NPP (Figs 1.2–16 and 1.2–17) consisted of a total of seven lines, with six transmission lines and one line feeding power to Unit 1 from Tohoku Electric Power Company (66 kV TEPCO Nuclear Circuit Line). Their supply to the units was as follows:

— Of the transmission lines from the Shin Fukushima Substation, Okuma Line 1L and 2L were connected to Units 1 and 2.
— Okuma Lines 3L and 4L were connected to Units 3 and 4.
— Futaba Lines 1L and 2L were connected to Units 5 and 6.
— The Yonomori Lines 1L and 2L were connected to Units 5 and 6.
— The TEPCO Nuclear Circuit Line was configured such that it could be connected, as a spare line, to the Unit 1 normal high voltage power panel.

Each line passed through a switchyard and fed on-site power systems.

Furthermore, in order to allow power to be supplied from (operating) main generators of adjacent units or transmission lines, the configuration allowed interconnection of normal high voltage power panels (metal clad switch gear, M/C) between Units 1 and 2, Units 3 and 4, and Units 5 and 6. However, there was no interconnection available across the Units 1–4 and Units 5–6 complexes.

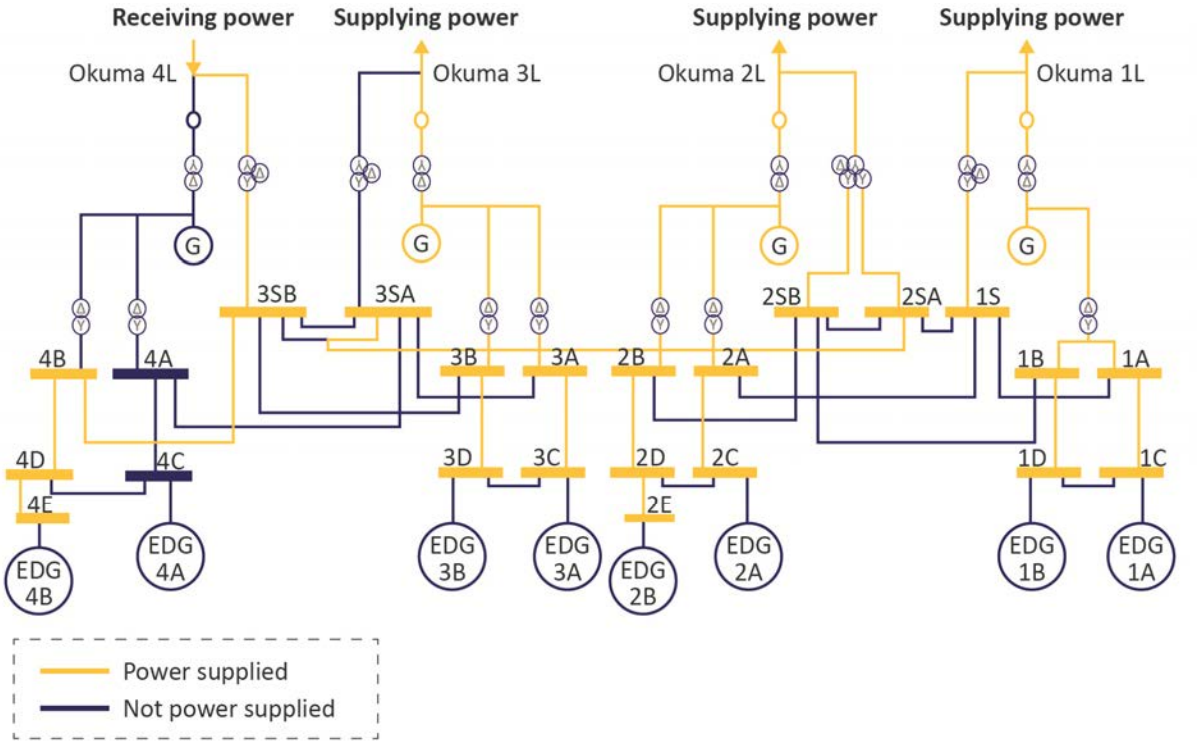


FIG. 1.2–16. Off-site power configuration for Units 1–4 [63].

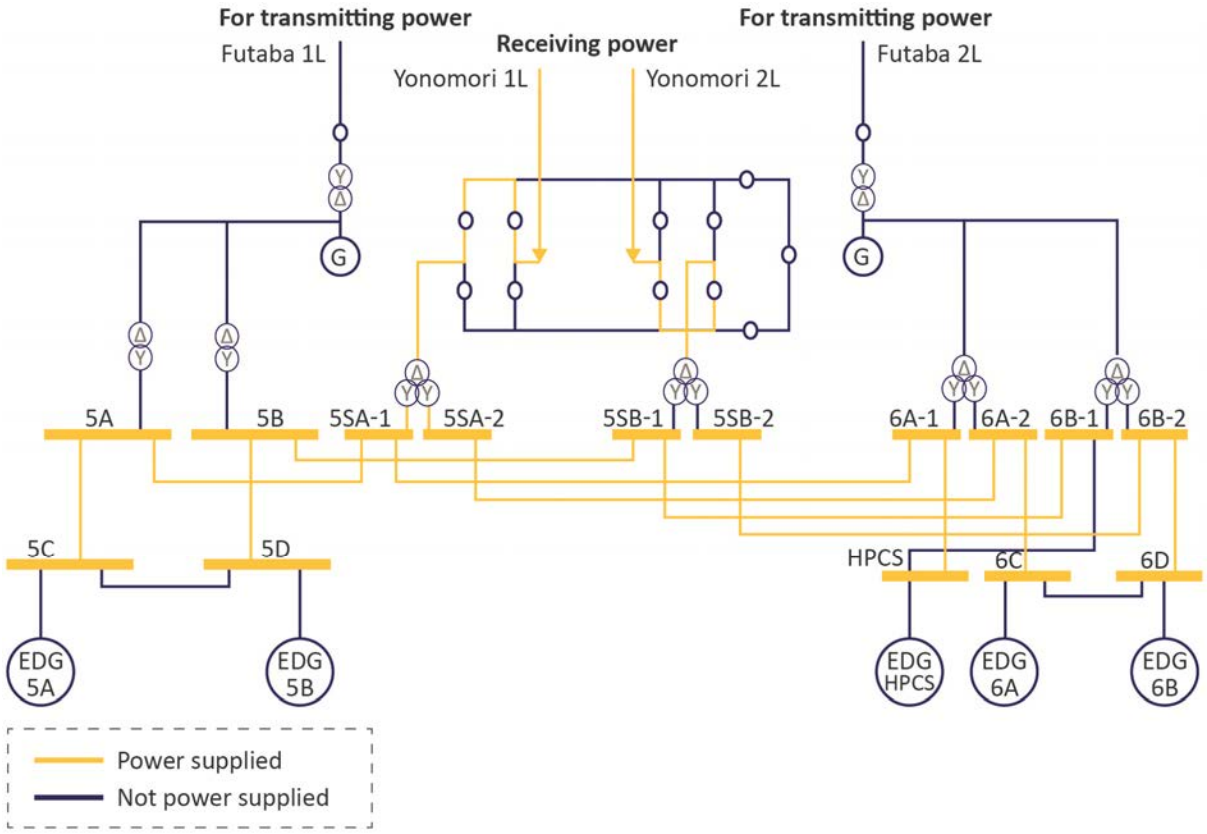


FIG. 1.2–17. Off-site power configurations for Units 5 and 6 [63].

1.2.6.9. On-site emergency power sources

Each unit at the plant was equipped with a redundant backup on-site power system composed of multiple emergency diesel generators (EDGs) to supply AC power, and a battery system to supply DC power.

During normal operation, the EDGs were idle, and the batteries were kept fully charged by battery chargers that also supplied the DC power loads. Nuclear power plants are designed to use their EDGs to withstand a loss of offsite power (LOOP) event and to use DC power sources (e.g. batteries) to cope with an SBO.

As shown in Table 1.2–10, Units 1–5 had two EDGs each and Unit 6 had 3 EDGs. In Units 2, 4 and 6, one of the EDGs was air cooled. These EDGs provided emergency AC power, if needed, to core cooling safety systems, as well as to charge the DC batteries. Most of the EDGs were located in the basements of the reactor or turbine buildings, i.e. 7–8 m below the plant grade.

NPPs are generally equipped with on-site DC and additional backup AC power sources (e.g. gas turbine generators or diesel engines) to withstand an SBO for a limited period of time varying between 4 and 72 hours[75]. The Fukushima Daiichi NPP units, similar to other plants of the same age, had design provisions to withstand an SBO with the DC battery capacity of eight hours. The batteries

[75] The determination of the coping period is based mainly on the time that it would take to restore AC power sources to the NPP and the capacity of the available measures. During that time, equipment such as DC batteries, DC/AC inverters and other secondary backup AC sources (e.g. gas turbines or diesel generators) is used.

were located in the basements of the control building (Units 1, 2 and 4) or in the mezzanine levels of the turbine buildings (Units 3, 5 and 6).

TABLE 1.2–10. TEPCO'S FUKUSHIMA DAIICHI ON-SITE AC POWER SOURCES

Unit	Number of EDGs	Type	Location	Floor level
Unit 1	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 2	2	Water cooled	Turbine Building	Basement
		Air cooled	Common Spent Fuel Pool Building	Ground
Unit 3	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 4	2	Water cooled*	Turbine Building*	Basement*
		Air cooled	Common Spent Fuel Pool Building	Ground
Unit 5	2	Water cooled	Turbine Building	Basement
		Water cooled	Turbine Building	Basement
Unit 6	3	Water cooled	Reactor Building	Basement
		Air cooled	DG Building	Ground**
		Water cooled	Reactor Building	Basement

* Was in maintenance and out of service.
** The ground level of the Unit 6 DG Building is higher than that of Unit 1–3 TBs and Common SFP Building.

1.2.6.10. Additional accident management systems

Several modifications had been carried out in order to utilize existing facilities for AM measures, including:

— A new automatic depressurization function had been added recently to Units 2–6 as one of AM measures. It triggers the ADS without a DW high pressure signal and enables low pressure core cooling systems to work swiftly. Unit 1 did not have this function because it had two high pressure core cooling systems, IC and HPCI.
— Connecting lines and motor operated valves were installed to allow for injection of cooling water into the RPV from the FP through the MUWC system to the CS (in Unit 1) or the LPCI (in Units 2–6) by operating from the MCR.
— In order to prevent failure of the PCV due to overpressurization and release of radioactive materials, a new vent line was installed. It allowed operators to release PCV pressure remotely from the SC or the DW to the main stack. In case of DW venting, the scrubbing effect of the suppression pool water is expected to remove a majority of radioactive materials (as mentioned in Section 1.2.6).
— Power source cross-tie lines were installed to adjacent units, i.e. between Units 1 and 2, Units 3 and 4, and Units 5 and 6, to provide electricity to each other in case of all power loss.

Based on the experience at the Kashiwazaki-Kariwa NPP during the Niigata-Chuetsu-Oki earthquake of July 2007, the seismically isolated building had been constructed, which was equipped with a gas turbine generator as an independent power facility, telecommunication systems, a video conferencing system and a ventilation system with filters. The station ERC was established in this building, serving as the central point for accident response.

Also from lessons learned from the fire at the Kashiwazaki-Kariwa NPP, caused by the Niigata-Chuetsu-Oki earthquake, TEPCO had deployed fire engines to all its nuclear power stations by February 2010. TEPCO's Fukushima Daiichi NPP had three fire engines within its premises. However, core injection using the fire engines through the FP system was not a part of the AM.

1.2.7. Plant resources and capacity at the time of the accident

This section provides information on the availability, capacity and capability of resources (both human and equipment) which played a role in responding to and managing the event. It is organized to give a snapshot of the plant personnel and the physical and administrative tools available at the time of the accident and in the immediate aftermath.

1.2.7.1. Plant staffing

On 11 March 2011, Fukushima Daiichi NPP Units 1, 2 and 3 were in power operation and Units 4, 5 and 6 were undergoing planned refuelling outages. Prior to the earthquake, approximately 6400 employees (including contractors) were at the Fukushima Daiichi NPP site [63].

Of these 6400 employees, approximately 2400 workers (750 TEPCO personnel and 1650 contractors) were working in the controlled area, with the majority of those (approximately 2000) carrying out activities in support of the planned refuelling outages. A breakdown of the number of staff present and their locations at the time of the event is shown in Table 1.2–11.

TABLE 1.2–11. PERSONNEL CAPACITY AT THE TIME OF THE EARTHQUAKE [6]

Number of staff	Assignment location within the controlled area				Total
	Units 1 & 2	Units 3 & 4	Units 5 & 6	Common facilities	
Unit personnel	160	1200*	800*	240	2400
MCR personnel	24	29	44	—	97
On-shift operators in MCR	14	9	9	—	32
Work management operators in MCR	10	8	8	—	26
Outage support operators in MCR	—	12**	27	—	39

* 2000 of the 2400 workers within radiation control areas were concentrated in Units 3 and 4, and Units 5 and 6. This was due to shroud replacement work at Unit 4 and RPV leak test evolution at Unit 5.

** Supporting Unit 4 outage.

After the second tsunami wave, 33 additional incoming shift operations personnel joined the initial response shift listed above (17 operators in Units 1 and 2, 7 operators in Units 3 and 4, and 9 operators in Units 5 and 6) on the evening of 11 March.

As Table 1.2–11 illustrates, 32 on-shift operators were distributed among the three MCRs for Units 1–6, with additional support from 26 work management team members, who were also operators. The units that were in planned refuelling outage and 39 additional operators were supporting the outage activities in and around the control rooms.

Following the earthquake, a tsunami warning was communicated by the MCR staff via the plant internal announcement system. The initial prediction for the tsunami was 3–4 m in height[76], thus evacuation and reassembly instructions were provided mainly for personnel who were working at lower elevations. Based on the assignment on essential or non-essential duties, most of the personnel from the 4 m elevation were moved to topographically higher elevations, and the emergency response duty personnel reported to the seismically isolated building and began to staff and activate the Earthquake Emergency Response Team.

After the earthquake and tsunami, many contractors returned home, except for necessary personnel. At 17:08 on 11 March, it was announced that TEPCO employees should return home if they could. The evacuation by busses to evacuation areas began at 05:15 on 12 March and continued until 13 March mainly for contractors and TEPCO female employees that had evacuated to the seismically isolated building.

Following the evacuation of personnel after the earthquake and tsunami, approximately 400 people (about 130 TEPCO employees and 270 contract personnel for maintenance and outage work) remained on site for the continuing accident response process; this number included personnel dispatched from other sites to provide assistance.

During the response and recovery phase in the following days, additional personnel, both TEPCO staff and contractors' employees who were called in by TEPCO Headquarters ERC in Tokyo, reported to the site. Those personnel included, among others: a crew for restoring power and monitoring equipment, fire brigade units (who also operated fire engines to inject cooling water into reactors), a health physics team that monitored radiation levels within the Fukushima Daiichi NPP site and its surroundings and a procurement team for needed supplies (see Table 1.2–12).

TABLE 1.2–12. PERSONNEL DISPATCHED TO THE FUKUSHIMA DAIICHI NPP BY TEPCO HEADQUARTERS AFTER THE ACCIDENT (NUMBER OF TEPCO EMPLOYEES GIVEN IN PARENTHESES) [6]

Function	Days				
	11 March	12 March	13 March	14 March	15 March
Response/recovery	245 (152)	332 (257)	374 (304)	439 (346)	272 (253)
Fire brigade	—	10	6	21	31
Health physics	—	25 (25)	66 (25)	158 (42)	162 (42)
Procurement	11	87	52	38	55
TOTAL	256	454	457	540	400

1.2.7.2. Shared facilities

The close proximity of the six units on the Fukushima Daiichi NPP site, and the various pieces of shared equipment, were both an advantage and a challenge in the accident response and recovery efforts. An event at one unit that had a physical connection to other units could affect the progress of the accident at all the units, benignly or adversely. For instance, emergency response activities at one

[76] The height of tsunami waves was forecasted by JMA to be 3–4 m at 14:50, then revised at 15:14 to 6 m, and revised again at 15:31 to 10 m.

reactor could be adversely affected by the progress of the accident at the adjoining units, while shared connections to available equipment could help operators respond to other aspects of the event.

In addition to the shared (common) equipment dictated by the design — e.g. off-site power lines, switchyard, electrical cross-ties, raw water tank, seawater intake structure, SGTS (common vent stack), fire protection system — there were other common structures that played a role in the response to and mitigation of the accident. These were:

— Common main control rooms (MCRs): For the Fukushima Daiichi site, one control room was shared between two units. Hence, each pair of units, Units 1 and 2, Units 3 and 4, and Units 5 and 6, shared a common control room. Although the unit control panels were separated, they were housed in one room, providing close interaction between the shift personnel controlling their respective unit under the command of one SS per MCR.
— Service building (SB) for unit personnel: Similarly, SBs in the controlled area were shared. Ingress/egress of personnel and equipment to the controlled area were through common gates, which included common exit personnel dose monitors/counters and common vehicle exit/entry gates.
— Seismically isolated building (activated after the earthquake): Emergency response functions for all six units at the Fukushima Daiichi site were conducted in the newly built earthquake hardened centre (built in response to lessons learned from the earlier Kashiwazaki-Kariwa seismic event).
— Firefighting equipment: The Fukushima Daiichi site had three fire engines and a nine person fire brigade that was shared among the six units at the time of the earthquake and tsunami.

1.2.7.3. Operating procedures

The procedures available to the operators determine the effectiveness, timeliness and appropriateness of actions to be taken during normal, abnormal, emergency and severe conditions. For design basis accident (DBA) response and management at the Fukushima Daiichi NPP, abnormal operating procedures (AOPs) and emergency operating procedures (EOPs) were utilized. The AOPs were event based, while the EOPs were symptom based and were primarily developed in accordance with the General Electric (GE) standard response procedures [67]. The EOPs also included the conditions for transition from EOPs to severe accident management procedures, to be applied after detection of core damage. EOPs were developed in Japan in the 1980s after the Three Mile Island accident in the United States of America in 1979. The AOPs were implemented, together with the installation of associated instrumentation and hardware (e.g. wide range monitors), around the same time [68].

For beyond design basis accidents (BDBAs), two sets of procedures were provided for utilization by the severe accident response and management personnel, inside and outside the MCR, respectively: (1) Severe Accident Operating Procedures (SOPs) for use in the MCR by the operators; and (2) Accident Management Guidelines (AMGs) for use in the technical support centre (TSC) in the ERC. The SOPs were designed for explicit actions to be taken on a given strategy, while the AMGs were designed for setting up the AM strategies. The AMGs contained figures and graphs of analytical results and provided the technical bases and criteria for the identification of plant conditions. Based on the AMGs, the TSC personnel established AM countermeasures and evaluated the outcomes. The SOPs contained the key action aspects of the AMGs and were prepared using a flow chart format to allow quick response by MCR staff to symptoms and facilitate recovery of systems (e.g. functional recovery procedures for RHR, EDGs, etc.).

Although the AOPs and EOPs were adopted from GE standard response procedures in Japanese BWRs, the development of severe accident response and management procedures, SOPs and AMGs,

took a different approach from the Severe Accident Management Guidelines (SAMGs) developed by the United States BWR Owners' Group (BWROG) in the 1990s.[77] Developed by Japanese BWR utilities and owners under the guidance of the regulatory bodies, the severe AM strategy was established. In development of severe accident response and management, Level 1 and targeted Level 2 probabilistic safety assessments (PSAs) were applied in Japan, both by the regulatory body and the industry. AM measures were developed to address mitigation strategies, such as the utilization of conventional systems, electric power supply from an adjacent unit, alternative measures for reactivity control, water injection and heat removal and recovery of failed components. These measures were identified on the basis of PSA results obtained in the 1990s [68]. The industry was to have implemented these AM countermeasures programmatically for both physical and procedural aspects around 2000. TEPCO had implemented them by 2002.

Procedures relevant to the accident

At the Fukushima Daiichi NPP site, each unit had its own unit specific set of AOPs, EOPs, SOPs and AMGs. The following procedures are relevant to the accident and the associated response:

— The event based AOP, 'Natural Disaster Accident', Section IV, Natural Disasters, Chapter 22 [69], specified the post-earthquake actions to be taken and provided instruction for carrying out those actions in response to an earthquake event. This procedure had three levels, based on the intensity seismic activity: 1–10 Gal; 10–45 Gal; and greater than 45 Gal. The seismic event on 11 March 2011 met the criterion for the highest level which, among other things, contained the following instructions: control room status check, responsibilities for performing structure, system and component (SSC) checks and general plant area walk-downs.
— Post-trip actions were implicit in the event based AOP for verification of reactor shutdown, e.g. verification of insertion of control rods and decreased reactivity.
— The event based AOP, Section II, Turbine and Electrical, Chapters 12, 13 and 14, addressed the external system fault, loss of off-site power and electrical system fault, respectively.
— The symptom based EOPs provided standard response actions for protection and/or recovery of key safety functions following the loss of all AC power after the tsunami. These included: reactor control, containment control, reactor water level recovery, rapid depressurization and loss of reactor water level indication. These EOPs described the actions to be taken from the MCR as well as the local-manual actions. However, these symptom based procedures were unusable when the MCR lost all its indicators.
— SOP (MCR severe accident procedure) and AMG (ERC severe accident procedure) procedures were activated upon the potential of core damage and provided a flow chart for AM using the available systems, and for mitigation of fission product barrier failures.

Procedural actions relevant to the accident

Some specific actions from the procedures noted above played important roles during the accident progress and station response. These actions (and related strategies) can be summarized as follows:

— PCV venting strategy: Although the Japanese BWRs were equipped with a hardened venting system to prevent containment vessel overpressurization, the underlying philosophy was to vent as late as possible (or not to vent until it was inevitable), in order to delay or prevent direct release of radioactive material to the public and the environment.

[77] Although foreign companies were participating in BWROG activities, BWROG is mainly composed of members from the United States of America. While TEPCO and several other Japanese utilities were members of BWROG, some Japanese BWR utilities were not and, hence, did not have access and permission to use BWROG products, compelling separate efforts to establish guidelines in Japan.

— PCV venting conditions: In line with the delayed venting strategy, the procedures instructed the operators to delay venting until the containment pressure had reached a value that was twice the design pressure (although the rupture disk was designed to burst at the design pressure), and a number of other conditions had occurred as the prerequisites for venting, e.g. the containment spray system was deemed to be unrecoverable or the water level in the SC was below the SC vent line.
— PCV venting operator actions: In addition to the rupture disk provided by design, remote-manual operation was necessary, and the SOPs instructed the operators how to line up the system for venting. However, the procedure did not contain instructions for local-manual actions in case of a total loss of AC and DC power, for loss of instrument air for air operated valves in the venting system, or for situations when the local conditions impeded access to those valves. Thus, additional procedures were improvised and developed for those situations as the accident progressed.
— SBO coping strategy: The (loss of all AC) procedure was designed to meet an 8-hour coping time which had been selected taking into consideration the availability or recovery of multiple off-site transmission lines, backup (AC and DC) power equipment, extensive features to cross-tie and share electric and water power sources among the units and equipment load shedding. The procedures to meet a specific coping time vary, in the strategies and instructions, among the NPPs.
— Hydrogen control/removal strategy: The AOP (Section I, Reactor, Chapter 2, LOCA) directed that the flammability control system (FCS) was to be utilized for hydrogen control to reduce the potential for hydrogen explosions during a design basis large break loss of coolant accident (LBLOCA) by maintaining the inert atmosphere in the PCV. However, the FCS and associated hydrogen monitoring systems were not operable, since the continuous AC power was unavailable for their function (i.e. similar to other NPP design basis accident conditions, LBLOCA did not consider a concurrent extended loss of AC power for flammability control). Thus, the AOP instructions did not deal with this specific event combination. Furthermore, for BDBAs, the instructions to remove hydrogen were not explicitly covered in the EOPs and/or SOPs/AMGs, on the assumptions that the flammability control during a DBA would be provided by the inert atmosphere, and that the venting strategy for pressure control during a severe accident would simultaneously serve this purpose.
— Loss of MCR indication response: There were no procedures that considered and addressed the event of a total loss of control room indications, including the safety parameter display, due to total and extended loss of AC and DC power.
— There were also other procedures that did not explicitly address certain strategies for mitigation or that were specifically intended to cover certain conditions; however, these procedures could be interpreted and utilized, with some modifications, to apply to those conditions. They were improvised to establish countermeasures, in some cases, without clear scope and evaluation of the system response to confirm whether they did or did not achieve the objectives. For instance, there were fire protection procedures instructing the utilization of fire engines to inject water via the external injection points. The intent of these procedures was ‘fire mitigation’ and ‘PCV flooding for fire suppression’ (modifications that had been installed following the lessons learned from the Kashiwazaki-Kariwa event). During the accident response, these procedures were considered and improvised for ‘core-cooling by RPV injection’. However, the system line up for ‘core-cooling’ was not intended or described in the existing procedure, and fire engine water was diverted from RPV injection via system backflows and bypasses which were intended for fire mitigation and PCV flooding.

1.3. ONSET AND PROGRESSION OF THE ACCIDENT

This section describes how an extreme natural event combined with design and operational issues led to a severe nuclear accident in which radioactive material was released to the environment. It describes the effects of the initiating natural event (the Great East Japan Earthquake) and the subsequent natural event (the tsunami) on the Fukushima Daiichi site.[78]

1.3.1. Onset of the accident at the Fukushima Daiichi NPP

1.3.1.1. Initiating natural event: The Great East Japan Earthquake

The Great East Japan Earthquake of 11 March 2011 occurred in the subduction zone off the Pacific coast of Japan's Tohoku region. It was a magnitude M 9.0 earthquake [10]. Its hypocentre was 24 km deep, and its epicentre was approximately 180 km north-east of the Fukushima Daiichi NPP[79], and 130 km east of the Onagawa NPP. Its duration was about 140–160 seconds, with 2–3 significant pulses. The rupture impacted an area in the fault zone approximately 500 km long and 200 km wide.

The closest NPP to the epicentre was the Onagawa NPP. It experienced the highest accelerations of all of Japan's NPPs (See Fig. 1.1–1).

The main shock at 14:46 JST had been preceded by a major foreshock two days earlier and was followed by numerous aftershocks. Table 1.3–1 lists the shocks that were magnitude M 7.0 or higher.

TABLE 1.3–1. SHOCKS AND THE ASSOCIATED EVENTS EXCEEDING M 7.0 OF THE GREAT EAST JAPAN EARTHQUAKE [62]

Shock	Date	Location		Magnitude
		Epicentre	Depth	
Foreshock	9 Mar. 11:45 (JST)	N38d20m, E143d17m	8 km	M 7.3
Main shock	11 Mar. 14:46 (JST)	N38d06m, E142d52m	24 km	M 9.0
Aftershocks	11 Mar. 15:08 (JST)	N39d49m, E142d46m	32 km	M 7.4
	11 Mar. 15:15 (JST)	N36d07m, E141d15m	43 km	M 7.6
Associated events	11 Mar. 15:25 (JST)	N37d55m, E144d45m	11 km	M 7.5
	7 Apr. 23:32 (JST)	N38d12m, E141d55m	66 km	M 7.2
	11 Apr. 17:16 (JST)	N36d57m, E140d40m	6 km	M 7.0

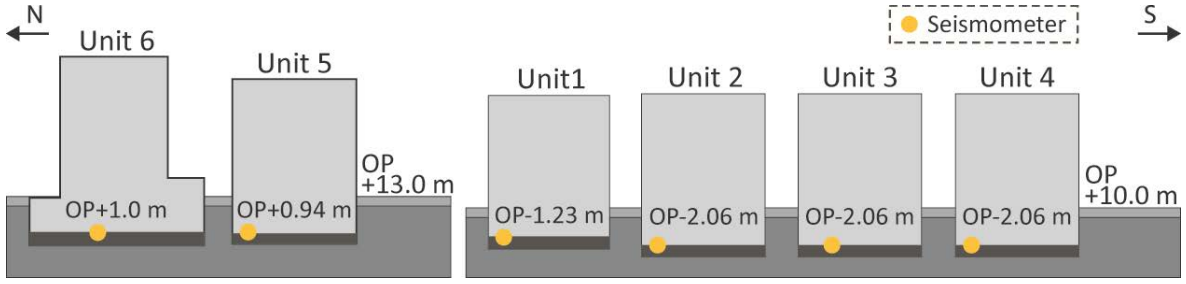
The ground acceleration from the earthquake did not exceed the design seismic ground motion limits for the Fukushima Daiichi Units 1, 4 and 6, but it did so for Units 2, 3 and 5, as shown in Table 1.3–2. The earthquake damaged the off-site power lines and switchyard equipment and caused extensive damage to the infrastructure at and around the site.

[78] All times in this narrative are in Japan Standard Time (JST) and all pressure values in units of bar absolute and megapascal (MPa). The times of events and values of plant parameters such as pressures, temperatures and water levels mentioned in this section are approximate. Though not explicitly mentioned individually, these values could have some uncertainty.

[79] The seismic intensity level of the Japan Meteorological Agency (JMA), showing the damage produced by the earthquake at towns near the Fukushima Daiichi and Daini sites, was 6+ (with the maximum level being 7 on the JMA scale).

TABLE 1.3–2. ACCELERATIONS EXPERIENCED AT THE FUKUSHIMA DAIICHI NPP UNITS AT INDICATED SEISMOMETER LOCATIONS[80] [62]

Fukushima Daiichi NPP Unit	Maximum measured acceleration value (Gal)		
	N/S*	E/W**	U/D***
Unit 1	460	447	258
Unit 2	348	550	302
Unit 3	322	507	231
Unit 4	281	319	200
Unit 5	311	548	256
Unit 6	298	444	244



Note: *North/South; **East/West; ***Upwards/Downwards.

1.3.1.2. Initiating event: Loss of off-site power (LOOP) due to the earthquake

The earthquake damaged the switchyard equipment and all six off-site power lines. Units 1–3 each experienced a reactor trip with a concurrent LOOP event. The reactors of Units 1–3 were shut down automatically when sensors at the plant detected the ground motion and triggered reactor protection systems in accordance with the design. As the ground motion exceeded the value that was set to activate the reactor seismic protection, the insertion of control rods was automatically initiated, which stopped the nuclear reaction. Because Units 4–6 were in outage modes, they experienced a LOOP event, i.e. no need for a reactor trip. The LOOP event automatically started all of the emergency diesel generators (EDGs) in order to establish AC power in all six units.

Also, as a result of the power interruption during the LOOP, the reactors of Units 1–3 were automatically isolated from their turbine systems by the closure of all main steam isolation valves (MSIVs). This resulted in increases in the temperature and pressure of the reactors due to the decay heat. Following isolation, the cooling of these reactors was accomplished by means of the following design and operational provisions:

— In Unit 1, as the reactor pressure increased, both loops of the IC system started automatically and continued to cool the reactor. The operation of both IC loops lowered the reactor pressure and temperature so rapidly that the operators manually stopped them, in accordance with procedures, in order to prevent thermal stress on the RPV. Afterwards, only one of the loops was used by the operators to control the pressure to keep the reactor pressure between 6 MPa and 7 MPa (60 bar and 70 bar).

[80] These records were obtained at the foundation basemat level and not at free field. The values are therefore likely to be lower than the corresponding free field maximum accelerations due to soil structure interaction effects.

— In Units 2 and 3, the increase in reactor pressure automatically activated SRVs, which were designed to protect the reactor from overpressurization by releasing steam from the RPV to the suppression pool of the SC section of the PCV. This resulted in a decrease in the reactor water levels. In response, the operators manually activated the RCIC system in accordance with procedures.

The decay heat from the nuclear fuel in Units 4–6 also had to be removed:

— In Unit 4, the equipment for cooling and refilling of SFP water stopped working as a result of the loss of off-site power. The Unit 4 SFP, containing more than 1300 spent fuel assemblies, had the largest amount of decay heat to be removed among all the SFPs of the units.
— In Unit 5, the reactor pressure, which was being kept elevated by the use of a pump for pressure testing purposes at the time of the earthquake, initially dropped when the pump stopped as a result of the LOOP. The pressure started to rise due to decay heat, but unlike in Units 2 and 3, it remained well below the levels to activate the SRVs.
— In Unit 6, the reactor was near atmospheric pressure and room temperature with fuel in the core, and the decay heat was low.

In the SFPs of all units and the common SFP[81], which lost cooling and refilling capabilities upon the LOOP, the temperatures of the pool water continued to increase due to decay heat.

In response to the earthquake and the LOOP, the operators activated the 'event based' AOPs in all three MCRs[82] of the six units. An earthquake emergency response team was activated at the on-site emergency response centre (ERC) located within the seismically isolated building[83]. The Site Superintendent was responsible for directing the site response and for coordination with on-site and off-site organizations, as the head of TEPCO's on-site ERC. Three shift superintendents in each of the main control rooms were responsible for directing the actions in their units under the command of the Site Superintendent.

1.3.1.3. Concurrent natural event: The tsunami triggered by the earthquake

The fault rupture that caused the earthquake deformed the seabed and the upper-plate crustal block, on which the islands of Japan are situated, moved about 50 m east-south-east and rose some 7–10 m upwards [70]. The seabed's deformation triggered several tsunami waves affecting almost the entire east coast of Japan as shown in Fig. 1.1–5.

The seabed's deformation triggered a two stage tsunami. The second wave was higher than the first wave and reached a run-up height of more than 30 m [13, 71].[84]

Shortly after the main earthquake shock, the Japan Meteorological Agency (JMA) issued tsunami warnings. At 14:50, the JMA forecast a wave with a height of 3–4 m arriving on the coast between 15:00 and 15:10 [14]. The height of the tsunami forecast by JMA was later revised at 15:14 to 6 m, and revised again at 15:31 to 10 m.

---

[81] As a shared auxiliary facility among the units, the common SFP, located in a separate building near Unit 4, stored over 6000 spent fuel assemblies, all of which needed to have their decay heat removed.

[82] Each pair of units shared a common control room, i.e. Units 1 and 2, Units 3 and 4, and Units 5 and 6.

[83] The seismically isolated building was built as a result of experience gained from the effects of the Niigata-Chuetsu-Oki earthquake at the Kashiwazaki-Kariwa NPP in 2007, and put into operation in July 2010. It was designed to withstand earthquakes and was equipped with backup power. Filtered ventilation and shielding were provided for protection from radioactivity.

[84] Survey results of coastal tsunami run-up, for example >30 m near the central Sanriku-Oki region.

At 15:27, approximately 40 minutes after the earthquake, the first tsunami wave reached the Fukushima Daiichi site [4]. It was over 4 m high. From 15:36 to 15:37, the second tsunami wave reached the plant. Its run-up height was 14–15 m. It exceeded the tsunami design basis for all six of the Fukushima Daiichi NPP units, and topped the tsunami walls which were designed for a maximum run-up height of 5.5 m. It flooded the site, damaged many of the plant's structures, systems and components (SSCs), and covered much of the site with sand, silt and debris. Additional damage was caused by the hydrodynamic force of the tsunami and the debris it swept along.

1.3.1.4. Concurrent event: Station blackout due to flooding from the tsunami

The tsunami waves started reaching the Fukushima Daiichi NPP site about 40 minutes after the earthquake. The second and largest tsunami wave engulfed all structures and equipment located at the seafront, as well as the main buildings (including the reactor, turbine and service buildings) at higher elevations (Fig. 1.3–1), causing the following sequence of events:[85]

— The wave flooded and damaged the unhoused seawater pumps and motors at the seawater intake locations on the shoreline. This meant that essential plant systems and components, including the water cooled EDGs[86], could not be cooled to ensure their continuous operation as all six units lost their ultimate heat sink (UHS).
— The wave flooded and damaged the dry cask storage building located near the seashore between the Units 1–4 and Units 5–6 complexes. There were no significant impacts on the casks and the fuel stored in them, as was later confirmed [17].
— Water entered and flooded buildings, including all the reactor and turbine buildings, the common spent fuel storage building and diesel generator building. It damaged the buildings and the electrical and mechanical equipment inside at ground level and on the lower floors. The damaged equipment included the EDGs or their associated power connections, which resulted in the loss of emergency AC power. Only one of the air cooled EDGs — that of Unit 6 — was unaffected by the flooding.[87] It remained in operation, continuing to supply emergency AC power to the Unit 6 safety systems and allowing cooling of the reactor.

As a result of these events, Units 1–5 lost all AC power, a situation referred to as a station blackout (SBO).

Because of the SBO in Units 1–5, the emergency operating procedures for 'loss of all AC power' [20] were initiated. A 'specific event', as defined in the regulations[88] [18] associated with the Nuclear Emergency Act [19] based on the condition of 'station blackout'[89], was declared by the Site Superintendent, who was the head of the on-site ERC of the operating organization, TEPCO. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

---

[85] The administration buildings and the seismically isolated building that contained the on-site ERC were on a cliff at an elevation of approximately 35 m (which was the original topographical site elevation before the site area was excavated for placing the units during construction).

[86] Each unit had a pair of EDGs, and Unit 6 had an additional generator. Of those 13 EDGs, Units 2, 4 and 6 each had one that was air cooled. Since they were air cooled, the operability of these generators was not directly affected by the loss of cooling water caused by the damage to the seawater pumps.

[87] The air cooled EDGs of Units 2, 4 (located in ground floor of the common spent fuel building) and 6 (located on the first floor of a separate diesel generator building at higher elevation) appeared to be not affected by the flooding. However, the components (i.e. switchgears, power centres, panels, etc.) of the air cooled EDGs of Units 2 and 4, which were located in the basement of the common spent fuel building, suffered water damage.

[88] Cabinet order in reference to the Nuclear Emergency Act.

[89] Due to the loss of all AC power supplies for longer than 5 minutes.

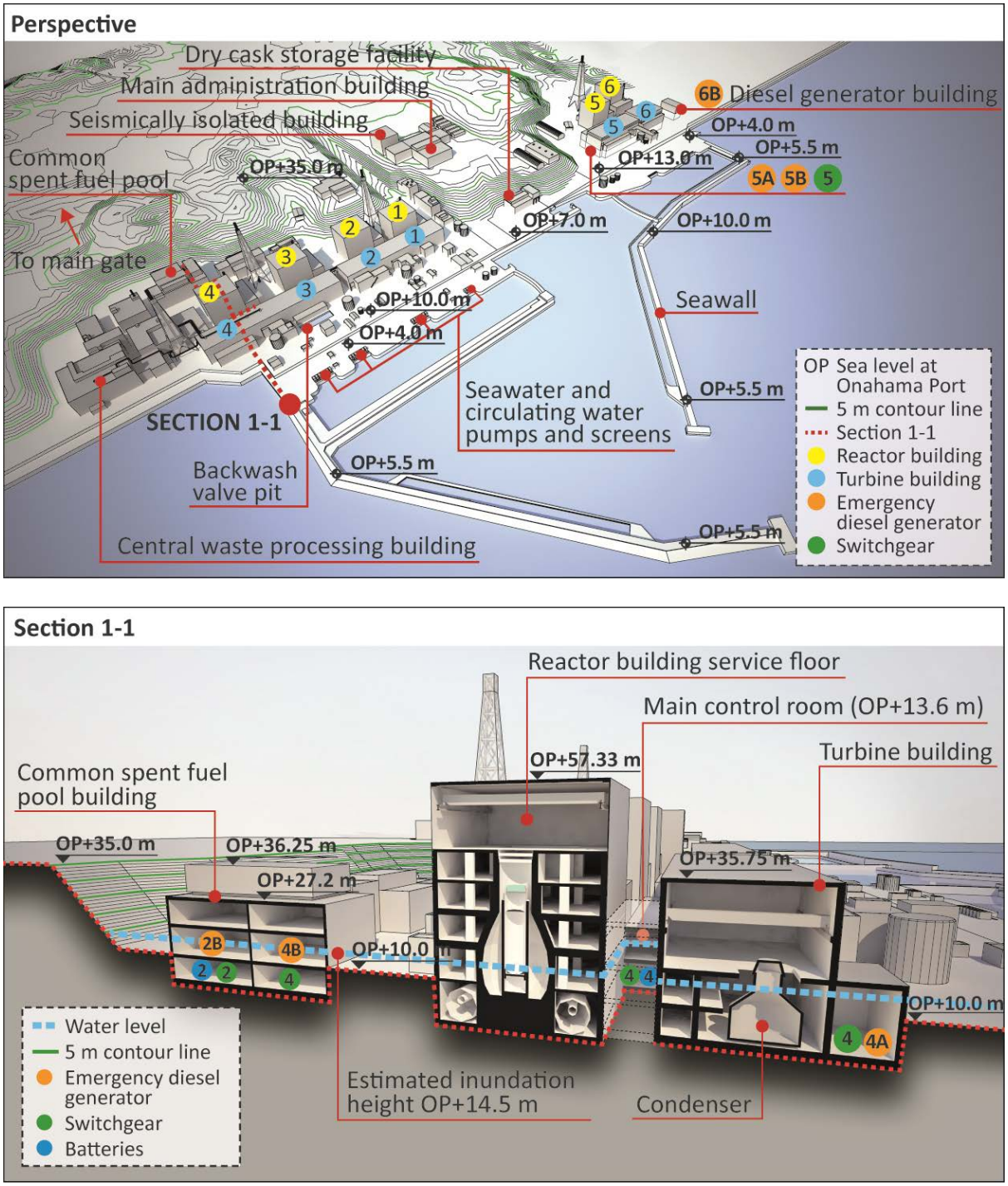


FIG. 1.3–1. The elevations and locations of structures and components at the Fukushima Daiichi NPP [16].

The flooding also inundated the DC power panels and batteries, and DC power was gradually lost in Units 1, 2 and 4 [4].

Due to the loss of all AC and DC power, the operators of Units 1 and 2 could no longer monitor essential plant parameters, such as the reactor pressure and reactor water level, or the status of key systems and components used for core cooling. As mentioned earlier, the heat removal capability for the spent fuel pool in all units was already lost following the loss of off-site power. The additional

loss of DC power in Units 1, 2 and 4 meant that operators could no longer monitor the water temperature and levels in the spent fuel pools of these units.

In the absence of procedures addressing the loss of all AC and DC power, the operators of Units 1, 2 and 4 did not have specific instructions on how to deal with an SBO under these conditions. The operators and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

1.3.2. Sequence of events at Fukushima Daiichi Units 1–3

As explained above, at the time of the earthquake, Units 1–3 were operating at their rated power, while Units 4–6 were in planned outage modes. The sequence of events associated with these units were therefore different and are dealt with separately.

All information presented in this section is based on the reports cited in Refs [3, 4, 6, 7, 72] unless indicated otherwise.

The event sequences for each unit includes those events from other units if they affected or were relevant to the overall event in the multi-unit site. Therefore, the same occurrences are sometimes repeated for different units to show this interface.

For reference, Annexes I, II and III provide the sequence of events in tabular form. Significant events are analysed in detail in Technical Volume 2, Section 2.2, together with management of the accident as discussed in Section 2.5.

1.3.2.1. Unit 1

Fukushima Daiichi Unit 1 was a BWR/3-type reactor with a Mark I containment. As has been described in detail, in contrast to the other units, Unit 1 was equipped with isolation condenser (IC) systems for shutdown cooling at high pressure instead of the reactor core isolation cooling (RCIC) systems found on the other units (see Section 1.2.6).

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 1 was operating at its rated electric power of 460 MW(e). The reactor water level was 950 mm, which corresponded to 4380 mm above the top of the active fuel (TAF), and the reactor pressure was 6.9 MPa (69 bar). The spent fuel pool (SFP) was fully filled with water at a temperature of 25°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 1. The trip set points of 100 Gal vertical and 135 Gal horizontal [73] were exceeded in two of four sensors, initiating an automatic reactor scram at 14:46. All control rods were fully inserted automatically at 14:47. The shift team confirmed the reactor trip based on the decrease in reactor power and the insertion of the control rods, and reported to the on-site ERC at 15:02 that the reactor was subcritical. The reactor scram rapidly reduced the steam generation in the core, causing a drop in the reactor water level by 800 mm and a drop of reactor pressure by 0.85 MPa (8.5 bar). The level was recovered by continued feedwater addition.

Since it was an ‘earthquake of greater than 45 Gal’, the operators began to implement post-earthquake actions according to the event based AOP, ‘Natural Disaster Accident’, Section IV, Natural Disasters,

Chapter 22 [20]. The Emergency Response Team was activated at the ERC located within the seismically isolated building. About one minute after the first shock of the earthquake, two workers witnessed the inflow of water into the fourth floor of the reactor building.[90]

From 14:46 to 14:47, the operators tried to switch the power for Units 1 and 2 to off-site power, but they were unsuccessful because the switchyard breaker had been damaged by the earthquake.

The LOOP meant that the emergency busbar lost power, with the result that the reactor protection system (RPS) lost power. This triggered a primary containment isolation signal (PCIS), which closed all the main steam isolation valves (MSIVs). The LOOP also stopped the heating, ventilating and air-conditioning (HVAC) system. In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

Both of Unit 1's EDGs started automatically at 14:47, and AC power to the emergency busbar was restored. The operators began to implement 'Natural Disaster Accident' Section II, Turbine and Electrical, Chapters 12, 13 and 14 of the AOP to address the LOOP.

The closure of the MSIVs isolated the reactor from the steam/power conversion system, thus preventing, as designed, normal core cooling using the main condenser. As the reactor pressure increased due to decay heat, both IC systems automatically started, also as designed.

The two IC systems decreased the reactor pressure and coolant temperature so rapidly that the operators manually stopped both loops of the IC systems at 15:03, in order to prevent the cool down limit of 55°C/h, set by the plant's operational limits and conditions (OLCs), from being exceeded.

Because the HVAC had stopped as a result of the LOOP, the PCV temperature and pressure began to rise. The operators therefore manually started the two trains of the containment cooling system (CCS) at 15:05 and 15:11, respectively.

To maintain the RPV pressure within the prescribed range, the operators manually turned the 'Train A' IC system on and off three times between 15:17 and 15:34 by opening and closing the DC powered outboard (i.e. outside containment) isolation valve on the condensate return pipe.

At 15:27, about 40 minutes after the earthquake, the first tsunami wave reached the site. It exceeded 4 m but did not affect any essential systems.[91] However, between 15:36 and 15:37, the second tsunami wave flooded the site. The tsunami damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). The flooding incapacitated both EDGs that were located in the basement of the turbine building (TB). All AC power was lost at 15:37, and operators entered the symptom based EOP for an SBO condition. In accordance with Article 10 of the Nuclear Emergency Act, TEPCO declared a station blackout at 15:42.

The DC power panel in the basement of the TB was also inundated, and DC power was lost between 15:37 and 15:50.

As a result of the loss of DC power, the shift team could not monitor plant parameters such as the reactor pressure and the reactor water level; the team was also unable to check lamp indicators for the

[90] The water is estimated to have come from the SFP on the fifth floor of the RB as a result of sloshing caused by the earthquake, and no available data show any leakages from the pipes connected to the RPV.

[91] At 15:29, some detectors at several monitoring points triggered an alarm on the 'high–high' set point of 430 nGy/h, which cleared later at 15:36. Meanwhile, more reliable monitors in that range at the same monitoring posts indicated a normal reading of 40 nGy/h.

operation status of major systems and components in the MCR of Units 1 and 2. All data recorders stopped, and the lights in the MCR gradually went out. Only the emergency lights on the Unit 1 side of the MCR remained on. Some of the most significant effects of the DC power loss were:

— Loss of reactor water level and pressure indications.
— Loss of valve status information for the IC systems.
— Loss of high pressure coolant injection (HPCI) activation and indication.
— Loss of SFP water temperature and level indications.

Since neither the status of the reactor nor the operability of the IC could be monitored, an incident according to Nuclear Emergency Act, Article 15, on 'ECCS cooling water injection function loss' was declared at 16:36, and the relevant government agencies were notified at 16:45.

The MCR operators moved to their SOPs. Accident Management Guidelines (AMGs) were implemented in the ERC upon the SBO and LUHS to identify a strategy for coping with the predicted degradation of the fission product barriers. The HPCI system was not available due to the loss of DC power. The residual heat removal (RHR) systems were also not available due to the flooding of the seawater pumps and the loss of AC power. Two options for injecting water into the reactor were identified, namely:

— The use of systems that could inject water directly into the reactors even at high pressures, such as the standby liquid control (SLC) system and the control rod drive (CRD) system, which required the restoration of AC power.
— The use of alternative equipment, such as mobile fire engines and the stationary diesel driven fire pump (DDFP) that could inject water at low pressures, which required depressurization of the reactors and alignment of the fire protection (FP) lines to inject water into the core.

For some time after the earthquake, frequent severe aftershocks and ongoing tsunami warnings made it impossible for the workers to leave protected buildings and/or approach lower plant site elevations. However, the ERC considered it necessary to check the condition of electrical equipment to assess the possibility of power restoration. To this end, a recovery team began a survey of off-site power equipment at around 16:00.

Meanwhile, the reactor water level indicators became available again[92]; the wide range (WR) monitor of the reactor water level indicated at 16:42 that the water level was −90 cm, which corresponded to 2530 mm above TAF. This was reported to the ERC. Consequently, at 16:45, the declaration under Article 15 was cancelled. At 16:56, the water level measurement went off-scale at the bottom range (i.e. −150 cm WR or 1930 mm above TAF), corresponding to a reactor water level loss rate of 2.6 m/h. At 17:07, the MCR informed the ERC that the reactor water level information was again unavailable and the Article 15 declaration was reissued. The relevant government parties were informed at 17:12.

At 16:55, a survey team was sent to activate the DDFP, but had to return to the MCR because of another tsunami warning.

At 17:12, the Site Superintendent ordered the review and preparation of water injection with fire engines in lieu of the injection of water through the fire protection (FP) system line as an alternative AM strategy.[93] Thus, the use of fire protection tanks and fire engines, which had been deployed after

[92] The reason for the recovery is unknown.

[93] Injection via the fire engines was not defined as one of the AM measures.

the Niigata-Chuetsu-Oki earthquake in 2007 as a fire suppression measure, was considered. The plan was to establish an alternative water injection flow path via the FP, MUWC and CS system lines by manually opening valves in the turbine and reactor buildings. This could only be done, however, after the reactor pressure had been lowered sufficiently to make fire pump injection possible. Yet, no specific action to consider the use of fire engines was taken until the early morning of 12 March until the respective roles and responsibilities of the function teams for these 'first time' activities were clarified.

At 17:15, the engineering team of the station ERC estimated that the reactor water level would reach the TAF in one hour.

At 17:19, operators went into the basement of the turbine building (TB), pushed the fault recovery button on the FP control panel and, at 17:30, confirmed that the DDFP had started. They started to work on the line to connect the DDFP to the core spray system, partly by manually opening the motor operated valves in the RB.

About 2.5 hours after the loss of indications in the MCR, some of the indicator lamps of the isolation valves were found to be working and, on the control panel, showed the status of the valves as 'closed'. Since the isolation valves on the IC lines were designed to 'fail–close' on loss of DC power to the control circuit, and to 'fail-as-is' on loss of AC/DC power to the valve actuator(s), this corroborated the fact that the valves had closed at the time of DC power loss, rendering shutdown heat removal by the IC impossible thereafter. It became clear that the outboard isolation valves (on the condensate return as well as the steam supply lines) of the IC Train A were closed. As the latter valve had been open prior to the arrival of the tsunami, the operators realized that the isolation valves had failed-closed due to the loss of the electrical power supply to the instrumentation.

The shift team opened the outboard isolation valves from the MCR (remote-manually) at 18:18, taking the chance that the other isolation valves were in an open position. After opening the outer isolation valves of Train A, a small amount of steam was observed above the RB of Unit 1, suggesting the onset of IC operation. However, these indirect signs of an operating IC disappeared after a short time. As there were questions concerning the soundness of the IC system, and as it was not operating as expected, the outboard isolation valve in the condensate leg of the IC was remote-manually closed again at 18:25, which was not reported to the ERC.

After several reports from the on-site ERC on the status of Unit 1 and the other units, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March.[94] At 20:50, the Government of Fukushima Prefecture issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

Given the continued unavailability of instrumentation and control, an operator entered the RB and read the RPV pressure locally as 7 MPa (70 bar) at 20:07. This pressure reading provided further evidence that the IC was not working.

Temporary lighting was partially re-established in the MCR by use of a mobile generator at 20:47.

Meanwhile, the line connecting the DDFP to the core spray system by manually opening the motor operated valves in the RB was completed at 20:50. However, the RPV pressure remained at 7.0 MPa

[94] At the same time, the NERHQ, located at the Prime Minister's Office, was established, and the Prime Minister assumed responsibilities as the Director General, directing the national nuclear emergency response.

(70 bar), which was much too high for the maximum pump head of the DDFP (0.79 MPa (7.9 bar)). Without an operable depressurization system, injection via the DDFP was impossible.

At 20:50, an evacuation order was issued by the Governor of Fukushima Prefecture to all residents within 2 km of the power station.

Temporary batteries and cables were gathered and carried to the MCR of Units 1 and 2 in order to energize the DC powered indicators. After confirming the wiring layout by referring to electrical diagrams, batteries were connected to instrument panels, and DC power to some indicators was recovered. The reactor water level indicator was restored at 21:19 and initially indicated a water level of 200 mm above TAF.[95]

At 21:23, the Prime Minister, as the Director General of the Nuclear Emergency Response Headquarters, issued an order requiring the evacuation of all persons within 3 km of the site and sheltering for those within 3–10 km of the site.

Reactor cooling via the IC Train A was attempted again at 21:30, since alternative water injection into the RPV was still not possible, and the DDFP was operable providing a means to refill the shell (secondary) side of the ICs. At least initially, the formation of steam at the IC vent pipe was again visually confirmed but it soon ceased. During later inspection, the water inventory on the shell side of the IC was discovered to be at almost normal level. At the onset of the accident the filling level of the shell side of the IC had been about 80% in Trains A and B.[96]

Two operators went to the RB to check the reactor water level and the IC pool water level. When one of them tried to enter the RB, his personal dosimeter indicated that he received a dose of 0.8 mSv in about 10 seconds. The operators immediately left the RB and returned to the MCR to give their report at 21:51. Subsequently, a radiation protection team measured local dose rates of 1.2 mSv/h and 0.5 mSv/h in the TB in front of the northern and southern airlock doors to the RB, respectively. At 23:05, entry to the RB was restricted by the Site Superintendent because of the increasing radiation levels. This was an indication of the severity of the conditions at the Unit 1 reactor and of possible core damage.

Because of the cable connection that had been established between the mobile generator and the MCR, it was not possible to completely close the MCR door, and the dose rates in the MCR increased together with the other areas of the control building. As the dose rates in the Unit 1 side of the MCR increased, operators had to move periodically to the Unit 2 side of the control room.

A mobile generator that had been used for MCR lighting was connected to the DW pressure instrumentation at 23:50. The first measurement of the DW pressure since the loss of DC power showed that the pressure in the DW was 0.6 MPa (6 bar), exceeding the maximum design pressure of 0.528 MPa (5.28 bar), and that it was increasing.

12 March 2011

At 00:06, the Site Superintendent ordered preparations for venting of Unit 1 (and Unit 2) and a notice was issued at 00:49 identifying an ‘abnormal rise in primary containment vessel pressure’ in

[95] The reliability of this measurement is questionable. It is likely that these water level indications resulted from the evaporation of the water in the reference leg of the water level measurement, prompting the operators to conclude that the reactor core was still submerged.

[96] After the accident, when the IC instrumentation was re-established on 3 April, as listed later in this section, the shell side water levels were determined to be 63% and 83% for Trains A and B, respectively.

accordance with Article 15 of the Nuclear Emergency Act. TEPCO informed the appropriate government agencies at 00:55 about the declaration of this Article 15 incident.

Completion of the 3 km zone evacuation was announced by the Government at 00:30 and re-confirmed at 01:45.

TEPCO informed the Prime Minister's Office, the Ministry of Economy, Trade and Industry (METI) and the Nuclear and Industrial Safety Agency (NISA) at 01:30 about the containment venting plans. Having received their agreement, TEPCO Headquarters ERC instructed the station ERC to start venting after it had been officially announced to the public at 03:00.

The crew that was dispatched at 01:25 to check the DDFP found out at 01:48 that the pump had not been working. After refilling the fuel tank and installing the temporary batteries carried for the pump, the attempts to start the pump failed and use of the DDFP for water injection proved to be impossible. The next strategy considered was the utilization of the station fire engines as an injection source for the reactor and the plans were initiated by the ERC at 02:03. The fire engines were to be connected to the injection port in the turbine building, which had been installed the previous year as a fire protection measure based on the experience of the Niigata-Chuetsu-Oki earthquake. The power recovery teams and the in-house fire brigade first had to clear access paths and mechanically open blocked truck bay shutters in order to gain access to the area where the fire protection system intake was located. At 02:10, the sea side of the TB was cleared sufficiently to allow access.

Meanwhile, at 02:24, the on-site ERC determined that the maximum stay time was not to exceed 17 minutes per person in the area where the venting preparation activities were to be conducted in order to remain below the dose limit for emergency personal of 100 mSv. This was based on the estimated dose rate of approximately 300 mSv/h in the area. The crew working on venting activities was advised to take potassium iodide (KI) tablets and to a wear breathing apparatus with a capacity of 20 minutes.

Reactor water level readings taken at 02:30 were 1300 mm and 530 mm above TAF in two different instrumentation channels, confirming that the reliability of those measurements was highly questionable. Around the same time, the DW pressure reached 0.84 MPa (8.4 bar) and then decreased to 0.8 MPa (8.0 bar) in the next 15 minutes, stabilizing between 0.7 MPa and 0.8 MPa (7.0 bar and 8.0 bar) afterwards.

Field observations at 02:55 reported to the ERC and the MCR that the Unit 2 reactor core isolation cooling (RCIC) was operating. This prompted the Site Superintendent to give priority to venting Unit 1 over Unit 2. However, when plans for primary containment vessel venting for Units 1 and 2 were announced to the public by METI and TEPCO at a press conference at 03:06, there was confusion about which unit would be prioritized.[97]

Connection to the FP system of Unit 1 was established at 03:30, and the injection of the contents of one fire engine into the reactor started around 04:00, about 12.5 hours after the SBO. Water injection from a single one-tonne truck continued intermittently for approximately 5.5 hours, with the truck having to return to the freshwater tank periodically to be refilled. At the same time, work on establishing a direct line from the tank continued. The operation of the fire engines and work to establish a direct line were interrupted periodically by the changing radiological conditions around the units.

[97] Immediately before the press conference, the NISA Director General received the information that the RCIC at Unit 2 was operating. He recognized that Unit 1 would be prioritized. In contrast, the TEPCO Managing Director did not have this information and believed that the IC of Unit 1 was operating. He thought, therefore, that Unit 2 would be given first priority.

Dose consequence predictions and release estimates for the venting operation were prepared by TEPCO and provided to the Government at 04:01 in order to determine on-site and off-site radiological consequences from the venting.

At 03:45 on 12 March, an attempt to enter the RB to conduct radiation measurements was abandoned, when the team encountered 'white fog-like' steam upon opening the RB airlock door, although the radiation readings main gate measurements at 04:00 had not shown any anomaly. However, shortly afterwards, a drop in the containment pressure was recorded. The measurement at 04:19 on 12 March showed that pressure in the Unit 1 primary containment vessel had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Subsequently, at 04:23, a significant increase was detected in the dose rate measurements at the main gate, namely 0.59 μSv/h compared with 0.069 μSv/h measured earlier at 04:00. This was also an indication of uncontrolled radioactive release from the primary containment, i.e. degraded confinement.

In response to these increased dose rates, the fire brigade working on water injection to the reactor had to evacuate the fire engine temporarily, halting freshwater injection. The MCR staff was equipped with high range (100 mSv) alarm pocket dosimeters (APDs) and full-face masks at 04:45 provided by the ERC, and TEPCO notified the Government about the increased radiation levels on the site at 04:55. In light of these increased dose rates and the contamination detected on workers coming back from outside activities, the ERC recommended, at 04:57, that workers performing outdoor task at the site should wear full face masks with charcoal respirators and full body suits. Radiation measurements began to be taken inside the seismically isolated building where the ERC was located. At 05:04, following up on the ERC's recommendation, the shift superintendent issued a mandatory order for the MCR staff to wear full face masks with charcoal respirators. Unit 1 operators had also moved to the Unit 2 side of the MCR where the radiological conditions were less adverse.

The evaluation of deteriorating radiological conditions at the site, combined with the elevated containment pressure in Unit 1, prompted the Government to expand the evacuation zone. Accordingly, a 10 km zone evacuation order was issued at 05:44 on 12 March by the Government based on the information from the site that the Unit 1 PCV venting was delayed and that its pressure remained elevated, above its design pressure.

At 05:46, after an interruption of more than one hour, the fire brigade restarted injection of cooling water using the fire engine. The fire engine was refilled from the nearest FP tank and returned to the connection point six times until 09:15. In the meantime, a hose connection between the FP tank, the fire engine and the intake was established so that continuous water injection became possible, injecting about 15 m^3 until 09:30. Additional fire engines from the Japan SDF arrived between 06:00 and 07:00, and one fire engine came from the Kashiwazaki-Kariwa NPP at around 10:30. These additional fire engines were used to refill the FP tank used for Unit 1 by carrying water from the other FP tanks.

The legal order for manual venting of the Unit 1 PCV, issued by METI via telephone, was received at the station at 06:50.

The Prime Minister arrived at the Fukushima Daiichi site at 07:11 on 12 March to be briefed by the Site Superintendent, and he left the site at 08:04 after a one hour visit.

At 08:03, the order to start venting in one hour was issued by the Site Superintendent. At 08:37, the Fukushima Prefecture Government was informed that venting would start at 09:00, and it was agreed that the evacuation status would be confirmed before performing venting.

Upon confirmation of the completion of evacuation of Okuma Town, that was received from the Fukushima Prefecture authorities at 09:02, teams were activated to start manipulation of the valves in order to arrange the path for the venting of Unit 1's containment. The first of three teams of two workers left the MCR at 09:04 to conduct the necessary field work. They were to manually open the motor operated valve (MOV) and either one of the two air operated valves (AOVs) that were on parallel lines, in order to align for venting of the PCV. The commencement of venting activities was made public via the press at 09:05.

The task of the first team was to manually open the PCV MOV on the 2nd floor of the RB. After opening the valve by 25% at 9:15, the team retreated. The operators received radiation doses of around 25 mSv. The second team left the MCR at 09:24 to manually open the small bypass AOV located in the torus room in the basement of the RB. However, high radiation inside, exceeding the personal dose of 100 mSv[98], forced the team to abandon the mission and return to the MCR at 09:32. In parallel, the operators unsuccessfully tried to remote-manually open the small AOV from the MCR three times, at 10:17, 10:23 and 10:24, assuming that there would be adequate residual pressure in the instrument air system. However, a brief increase in the radiation reading at the main gate and monitoring points at 10:40 was noted, potentially indicating that some venting had occurred. This venting could not be confirmed, since there was no associated decrease in PCV pressure. Also, the radiation readings started decreasing at the main gate and at the other monitoring points after 11:15.

At 12:30, the recovery team transported a portable air compressor to a connection point of the instrumentation compressed air system on the outside of the RB to try to open the large isolation AOV, rather than the small AOV whose opening had been previously attempted.

At 14:00, the recovery team connected and started the compressor, and opened the large AOV on the PCV vent line. Operators confirmed the decreasing trend in PCV pressure at 14:30. Within the next 20 minutes, the pressure inside the PCV decreased from 0.75 MPa to about 0.58 MPa (7.5 bar to about 5.8 bar), indicating successful venting of the Unit 1 PCV. The successful venting operation was reported to government agencies at 15:18. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29 by one of the site monitors located near the site boundary to the north-west of Unit 1 (MP4, located at the north-west of Units 1–4 and west of Units 5-6).[99] Overall, the venting process took 14.5 hours, from the Site Superintendent's order around midnight to vent, owing to high radiation levels in the torus room which houses the SC where valves had to be manually manipulated and the lack of a compressed air supply to operate the valves.

On the parallel attempts to inject water into the reactor via the DDFP, the crew working on the DDFP that had been out of service since 01:48 reported at 12:53 on 12 March that the DDFP was restored and available. The pump was started at 12:59, but stopped again at 13:21 due to a ground fault of the motor.

[98] A personal dose in excess of the 100 mSv limit received by one operator of the first team entering the torus room was reported to the Government at around 12:00.

[99] At 16:17, it was noted by the ERC that the radiation measurement taken at 15:31 near the main gate was 0.569 mSv/h; the authorities were notified at 16:27, since this value exceeded the legal reporting criterion of 0.5 mSv/h. The notification was corrected at 16:53, when it was realized that the radiation level measured at 15:29 was 1.015 mSv/h, i.e. after venting of Unit 1 (but before the explosion at Unit 1).

By 14:53, all the available fresh water in the FP tanks (80 m^3) had been injected into Unit 1, and the tank inventory had been almost completely depleted.[100] At 14:54, the Site Superintendent ordered the fire brigade to inject sea water into the reactor from the Unit 3 backwash valve pit, where seawater had collected after the tsunami, as it was the only available source of water at that time. The arrangements for seawater injection were completed in just over half an hour, by 15:30.

Also, by 15:30 on 12 March, a mobile 6.9 kV voltage power supply[101] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for the supply of AC power to Unit 1 was re-energized via an undamaged power centre (P/C) of Unit 2. Energizing a motor control centre (MCC) of Unit 1 enabled the starting of the standby liquid control (SLC) system, which was used to inject feedwater into the RPV.

Nearly 24 hours after the SBO, temporary water and power provisions, the seawater injection lines and the 6.9 kV AC, were connected to Unit 1 to recover core cooling. However, within minutes of connection, an explosion in the Unit 1 RB damaged both of these arrangements before they could be put in use.

The Unit 1 explosion, at 15:36 on 12 March, caused extensive damage to the upper RB structure, which consisted of a steel framework with inserted steel plates. Although the explosion did not directly affect the primary containment structure (the PCV), the damage to the secondary containment, or reactor building (RB), was significant. The cause of the explosion was unknown to the plant staff, but it was suspected that it was ignition of hydrogen that had been released from the damaged Unit 1 core and had escaped from the PCV to the RB via an unknown path.

Additionally, the explosion caused serious damage to the alternative seawater injection line assembly and to cables of the emergency high voltage power supply. It also worsened the already challenging site conditions for emergency response activities, blasting the windows of the fire engines, injuring workers and causing locally high dose rates on the plant site due to contaminated rubble and scattered debris from the building materials. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4. Considering that radioactive gases had been also released through the same path that allowed hydrogen outside the PCV, the ERC also ordered the evacuation of the staff from two MCRs (Unit 1 and 2, and Unit 3 and 4), except for the three most senior staff.

At 15:29, radiation dose rates at a station monitoring post along the site boundary showed 1.015 mSv/h. It was confirmed at 16:17 that the radiation level measured near a monitoring post (MP4) was 0.569 mSv/h as of 15:31. This situation was deemed to fall under Article 15 of the Nuclear Emergency Act, and government agencies were notified (the notification was corrected when, at 16:53, it was discovered, that radiation levels at 15:29 had been 1.015 mSv/h, as noted above). Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 containment), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Following the temporary evacuation of the Unit 1–4 area, lasting about two hours, the survey teams were redeployed at 17:20 and reported extensive damage to the seawater injection arrangement. After

---

[100] Note that not all the injected water went into the RPV because the water injection by fire engines was through the FP, MUWC and CS lines and there were several branches in the MUWC line to provide water for pump and valve seals, gland steam evaporators, etc.

[101] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

replacement of the damaged hoses, the fire engine pumps were started up and seawater injection into the RPV started at 19:04, from the Unit 3 backwash valve pit through the core spray line. Overall, between the end of freshwater injection and the start of seawater injection, the Unit 1 core was without cooling for nearly four hours.

After 20:45, boric acid was added to the sea water to address recriticality concerns.

By midnight, about 31 m^3 of sea water had been injected into the Unit 1 RPV.

13 March 2011

Seawater injection continued throughout the day on 13 March.

Early in the day, medical team leaders instructed all workers to take potassium iodide (KI) pills, making it mandatory for everyone under 40 years of age and optional for others.

At 13:37, measurement of the PCV pressure was re-established, having been lost after the hydrogen explosion the previous day. The measured pressure in the SC was around 0.6 MPa (6 bar) (0.595 MPa (5.95 bar) in the DW and 0.590 MPa (5.9) in the SC), slightly higher than before to the explosion. Measurements from 18:00 onwards indicated a decreasing trend in the SC pressure.

14 March 2011

At 01:10, the water in the Unit 3 backwash valve dropped below the suction level of the temporary hoses so that injection of sea water into the reactor coolant systems of Unit 1 (and Unit 3) had to be halted. After the intake hose was lowered deeper into the pit, the remaining pit water was reserved for injection into Unit 3 as a priority, and Unit 1 core cooling was postponed until the pit could be refilled. Refilling of the backwash valve pit started at 09:05 with seven tanker trucks from the Japan SDF, each with a capacity to transport five tonnes of water. After nearly two hours of refilling the pit, the seawater injection into Unit 1 was ready to be resumed at 11:01, when all activities had to stop because of the explosion in Unit 3. This damaged the hoses and fire engines around the Unit 3 backwash valve pit, including two fire engines forming a line to pump water directly from the ocean into the pit, and necessitated a temporary evacuation of workers from the outside areas.

The on-site ERC was informed at 14:04 by TEPCO Headquarters that it was agreed with the nuclear regulator, NISA, to increase the dose limit for emergency workers to 250 mSv.

The work to re-establish the seawater injection line, this time directly from the ocean, was started again after a break of two hours. Again, priority was given to restoring seawater injection into Unit 3 when the line was established. At around 20:00 on 14 March, seawater injection into the Unit 1 RPV resumed, using a new fire engine to pump water directly from the sea. Overall, this series of events caused a 19 hour suspension of water injection into Unit 1.

15 March 2011

At 06:14 on 15 March, the sound of an explosion was heard on the site and tremors were felt in the common MCR of Units 1 and 2. This was followed by a drop in the Unit 2 SC pressure, which reached atmospheric pressure at 06:30. In light of the possibility of failure of the Unit 2 PCV, all plant personnel including the Unit 1 MCR staff were ordered to temporarily evacuate to the seismically isolated building where the ERC was located. Subsequently, all personnel, with the exception of those

required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a 'radiologically safe location'. Approximately 650 people understood this order to be a site evacuation and evacuated to the Fukushima Daini NPP. An estimated 50–70[102] staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00.

About two hours later, white smoke (or steam) was observed being released from the Unit 2 reactor building near the fifth floor. A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

Between 17 and 20 March, temporary power cables were laid to Units 1 and 2. At 15:46 on Sunday 20 March, almost exactly nine days after the SBO, an auxiliary transformer of Units 1 and 2 was connected to the external grid, and temporary off-site power was restored to Unit 1 (and 2) through this AC power system, ending the Unit 1 SBO.

On 23 March, a fire engine pump was connected to the RPV feedwater system and seawater injection started at 02:30. This replaced the previous seawater injection via the RPV spray line.

At 11:30 on 24 March, lighting was restored to the common MCR of Units 1 and 2.

On 25 March, the water injected into the reactor was switched from sea water to fresh water and on 29 March, the fire engine pumps were replaced by electrical pumps powered by a diesel generator, to pump fresh water into the reactor.

In order to replenish the water in the Unit 1 SFP to ensure that the spent fuel was not exposed, spraying of sea water by concrete pump trucks was performed between 13:03 and 16:04 on 31 March.[103]

When the IC instrumentation was re-established on 3 April, the shell side water levels were determined to be 63% and 83% for Trains A and B, respectively, indicating that the IC was not utilized after the tsunami.

In order to avoid the possibility of futher hydrogen explosions, it was decided to purge the PCV with nitrogen. Therefore, a temporary nitrogen supply was connected to the DW inert gas supply system, and nitrogen injection started on 7 April.

TEPCO issued an action plan on 17 April 2011, the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23]. The roadmap included measures to be taken for: the establishment of stable cooling of the reactors and spent fuel; reduction and monitoring of radioactive releases; control of hydrogen accumulation; and prevention of return to criticality. These actions were implemented in the nine months following the accident.

---

[102] As noted by different investigation reports, the exact number of staff is not certain [4, 6]. It is also noted that the staff who evacuated to Fukushima Daini started to return to the site on the same day.

[103] Spraying the SFP with concrete pump vehicles was performed again on 14 May, this time using fresh water, and repeated almost weekly until an available plant system, namely the spent fuel pool cooling and cleanup (FPC) system, was first utilized on 29 May and continued to be used thereafter.

The roadmap established two conditions that would define the end of the accident state, or 'cold shutdown state'[104]: achievement of significant suppression of radiological releases and steady decline of radiation dose rates; and achievement of target values for certain plant parameters as prescribed in the roadmap.

On 17 and 18 April, remote controlled robots were used to check the conditions at ground level within the RBs of Units 1 to 3. Inside the Unit 1 RB, the temperature was 29°C and the humidity was approximately 50% on 26 April [74].

An air filtration system was installed on 5 May to lower the concentration of radioactive aerosols within the RB of Unit 1. The air contamination declined from 4.8 Bq/cm^3 on 26 April to 0.02 Bq/cm^3 on 7 May, and the airlock to the RB was opened at around 20:00 on 8 May.

During 9 May, 7 TEPCO employees, 2 NISA inspectors and 21 contractors entered the Unit 1 RB to check radiation levels, construct temporary shielding and install temporary lighting. In the following days, the pressure transmission lines, used for RPV pressure and water level measurement, were refilled. After refilling the lines, it was determined that the reactor water level was lower than the active core height. This measurement provided the first firm evidence, supported by temperature measurements, that the RPV had failed. Recalibration of the SC pressure measurement showed that the previously recorded pressure measurements could be considered reliable.

The Government and TEPCO announced on 19 July that the first condition had been achieved in Units 1–3 and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the 'accident' phase of events at the Fukushima Daiichi NPP Unit 1 to a close.[105] However, some unstable plant conditions continued, such as fluctuations in temperature, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.2.2. Unit 2

Fukushima Daiichi Unit 2 was a BWR/4-type reactor with a Mark-I containment.

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 2 was operating at its rated thermal power of 2381 MW(th). The reactor water level was 1150 mm, which corresponded to 5320 mm above TAF, and the reactor pressure was 0.7 MPa (70 bar). The spent fuel pool (SFP) was fully filled with water at a temperature of 26°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 2, initiating an automatic reactor scram at 14:47. All control rods were fully inserted automatically, and the shift team reported the reactor trip to the ERC at 15:01 and confirmed that the reactor was subcritical. The reactor scram caused a drop of the reactor water level by 1000 mm, which was recovered by feedwater, and a drop of reactor pressure by 0.6 MPa (6 bar).

---

[104] The term 'cold shutdown state' was defined by the Government of Japan at the time specifically for the Fukushima Daiichi reactors. Its definition differs from the terminology used by the IAEA and others.

[105] According to the criteria set by the Government of Japan at the time.

From 14:46 to 14:47, the shift team tried to switch the power house load of Units 1 and 2 to off-site power but this was unsuccessful because the switchyard breaker was damaged by the earthquake.

Due to the loss of all off-site power, the emergency busbar lost power, with the result that the RPS lost power. This initiated a primary containment isolation signal (PCIS), which caused all the MSIVs to close.

Both EDGs started automatically at 14:47, restoring AC power to the emergency busbar.

Following the MSIV closure, the shift team started the reactor core isolation cooling (RCIC) manually at 14:50, as required by procedures, but it stopped automatically at 14:51 because the RPV water level had reached the high level set point (+1485 mm, corresponding to 5655 mm above TAF, namely 'L-8').

The reactor pressure increased due to decay heat after the reactor isolation (i.e. the MSIV closure) until 14:52, when safety relief valve (SRV) 'F' started to open at 7.54 MPa (75.4 bar) and close at 7.2 MPa (72 bar), thus maintaining the reactor pressure by cycling. The reactor water level decreased as steam was released through the SRV into the suppression pool.

The shift team manually reactivated the RCIC at 15:02. The temperature of the suppression pool increased as the steam was discharged from the SRV and the RCIC turbine. The operators activated the SC spray mode of the residual heat removal chain (i.e. the RHR and RHRS systems) at 15:25 to cool down the SC. At 15:28, the RCIC stopped again automatically at the high level set point, and the operators restarted it at 15:39.

In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

Meanwhile, at 15:27, the first tsunami wave reached the site but did not impact any essential plant systems.

The second tsunami wave arriving between 15:36 and 15:37 flooded the plant site, resulting in a series of events. The tsunami damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). Seawater entered the basement levels of the buildings. The water cooled EDG located in the basement of the TB failed at 15:37 because of flooding of the EDG body. The other EDG, which was air cooled and located away from the ocean on the ground floor of the shared auxiliary facility (common spent fuel pool building), was not flooded. However, the metal clad switch gear (M/C) and the power centre (P/C) of that EDG were located below ground level in the basement of the common SFP building; hence, they were flooded, and subsequently failed at 15:41. This loss of backup AC power resulted in an SBO. The incident, in accordance with Article 10 of the Nuclear Emergency Act, was declared by TEPCO at 15:42, and plant operators entered symptom based EOP for SBO condition.

Furthermore, the DC power panel in the basement of the TB was also inundated, and so DC power was also lost during this time. With the failure of DC power, all alarm and status indicators in the MCR started to blink and then went out, the lighting went off and the alarm sounds ceased.

In the short period of RCIC operation prior to the loss of DC power, the RCIC injected water at up to 31 litres per second into the RPV, thereby causing a rise in the RPV water level [1].

After the loss of DC power, the operators were no longer able to confirm whether water injection into the RPV was taking place. Therefore, at 16:36, an incident 'ECCS cooling water injection function loss' according to the Nuclear Emergency Act, Article 15, was declared. The MCR operators moved

to their SOPs, and the team in the on-site ERC consulted the Accident Management Guidelines (AMGs) in order to identify a strategy for coping with the predicted degradation of the fission product barriers.

As mentioned earlier, the heat removal capability for the SFP had already been lost following the LOOP. The additional loss of DC power meant that operators could no longer monitor the water temperature and levels in the SFP.

In the absence of procedures addressing the loss of all AC and DC power, the operators did not have specific instructions on how to deal with an SBO under these conditions. The MCR and ERC staff started reviewing available options and establishing possible ways to restore power and thereby regain the ability to monitor and control the plant.

At 17:12, as part of an accident management (AM) strategy, the Site Superintendent ordered a review and the preparation for water injection using fire engines. This was seen as an alternative AM measure, in addition to injection by the DDFP through the FP, make-up water condensate (MUWC) and LPCI system lines. It was decided to line up the alternative system to Unit 1 first, because its radiation levels were increasing more rapidly than those of Unit 2. Thus, the Unit 2 line-up work started later, at around 21:00.

At 17:35, operators found that indicators on the trip channel were still alive and showing a stable reactor water level at 80%. The shift supervisor, therefore, reported to the station ERC that the reactor water level was stabilized at 80%.[106]

In spite of frequent aftershocks and ongoing tsunami warnings, recovery teams were dispatched at 16:00 and at 18:00 to survey the station power supply facilities. Following visual inspection, the team reported to the MCR at 20:56 that all M/Cs were inoperable but some P/Cs were available.

After several reports from the on-site ERC on the status of Units 1 and 2, and following the approval of the Prime Minister, a nuclear emergency was declared by the Government of Japan at 19:03 on 11 March. At 20:50, the Government of Fukushima Prefecture had issued an evacuation order for residents within 2 km of the plant after evaluating the national nuclear emergency declaration and discussing the uncertainty concerning the status of the NPPs with TEPCO officials.

Although partial lighting was re-established in the MCR at 20:47, the critical indications, such as reactor water level and the status of the RCIC, remained out of service. The operators had no direct indications of conditions in the reactor or whether the core cooling system was running or not. Without any indications of operation of the RCIC system and core pressure and temperature, the operators assumed the worst case scenario that the RCIC system was not operating and that the Unit 2 core was heating up. Assuming the RCIC was not operating, the reactor water level was calculated to fall below TAF and expose the fuel within approximately one hour. At 21:01, the on-site ERC informed government authorities that the Unit 2 core, without any cooling, was predicted to become uncovered at around 21:40. Upon this information, at 21:23, the Prime Minister's Office issued and evacuation order for residents within 3 km. The inhabitants within the 3–10 km zone around the site were also instructed to take shelter indoors.

As has been mentioned before, after the connection of temporary batteries to instrument panels, DC power to some indicators was recovered. At 21:50, the reactor water level measurement was

[106] Power to those indicators was later lost and, as of 18:12, the reactor water level could no longer be confirmed.

temporarily re-established and indicated a level of 3400 mm above TAF. This indicated that the RCIC was running, but this could not be controlled.[107]

At 22:00 a mobile high voltage power supply vehicle arrived on-site but could not be connected due to the damaged station electrical equipment.

The manual alignment of the FP injection line (via the MUWC and LPCI system lines), which had started at around 21:00, was completed in the RB. Flooding prevented access to the TB basement, so operation of the DDFP was confirmed by the smoke observed to be coming from its exhaust.

12 March 2011

Preparation for the required containment venting commenced at 00:06. Both Unit 1 and 2 containment venting plans were provided to the Prime Minister's Office, METI and NISA and were approved at 01:30.

At 01:20, it was discovered that the DDFP had stopped working, since the previously observed exhaust smoke was no longer visible.

Although flooding prevented access to the RCIC room, at 02:10 on 12 March, a team was able to enter the room in the RB where the RCIC instrumentation panel was located. The readings taken there verified that the RCIC was still functioning.[108] This was reported to the MCR and the station ECR at 02:55 and served to clarify the previously unknown condition of Unit 2's core cooling about 11 hours after the loss of monitoring in the MCR.

Meanwhile, the condensate storage tank (CST), for reactor water injection (via the RCIC) was being depleted. At the same time the SC water level was increasing to levels to initiate actions to prevent overfill. Upon low level indication in the CST, it was decided to switch the RCIC pump suction leg from the CST to the SC. The team was dispatched at 04:20 and switch of lines was accomplished at 05:00. As the RCIC was continuing to cool the Unit 2 core, the Site Superintendent ordered that priority be given to preparations for the PCV venting of Unit 1, as discussed earlier.

The measurement of Unit 1's containment pressure at 04:19 on 12 March showed that pressure in the containment had decreased since the last measurement (at 02:45) without any operator action and without an established vent path, indicating that some unintentional containment pressure relief had occurred through an unknown path. Furthermore, the radiation levels measured at the main gate around 04:23 showed an increase.[109] Combined with the unexpected decrease in the Unit 1 PCV, this indicated to the staff in the common MCR of Units 1 and 2 and the ERC of some uncontrolled radioactive release from the Unit 1 PCV.

The ERC provided, at 04:45, high range APDs and full-face masks to the MCR staff, and the relevant government organizations were notified at 04:55 about the increased site radiation levels. As the site wide and the MCR dose rates increased, the shift superintendent for Units 1 and 2 required at 05:04 that the MCR staff wear full face masks with charcoal respirators. Unit 1 operators in the MCR had also periodically moved to the Unit 2 side where the radiological conditions were less adverse.

---

[107] The reliability of level measurement was questionable.

[108] However, the RCIC could not be controlled because of the lack of DC power to operate the system.

[109] An increase of around ten-fold (0.000 069 mSv/h measured at 04:00 versus 0.000 59 mSv/h at 04:23).

At 05:44, the evacuation of a 10 km zone order was issued by the Government, based on the information from the site that the Unit 1 PCV venting was delayed and the PCV pressure in Unit 1 remained elevated well above its design pressure.

At 14:00, the large AOV of the PCV vent line was opened and the Unit 1 PCV venting occurred, as confirmed by the decreasing pressure measurements at 14:30 and 14:50. Although there was no significant immediate change in the radiation measurements within the site boundaries, about one hour later, a radiation dose rate reading of approximately 1 mSv/h was recorded at 15:29.

By 15:30 on 12 March, to restore temporary AC power, a mobile 6.9 kV voltage power supplies[110] to Units 1 and 2 using an undamaged transformer in Unit 2 was completed, and a low voltage grid for supply of AC power to Unit 1 was re-energized via an undamaged power centre (P/C) of Unit 2.

The explosion that occurred at 15:36 on the service floor of the Unit 1 RB damaged the newly installed high voltage cable. The blast probably also opened the blowout panel on an RB service floor wall of Unit 2.

The explosion also worsened the already challenging site conditions for emergency response activities, blasting the windows of the fire engines, injuring workers and causing locally high dose rates on the plant site due to contaminated rubble and scattered debris from the building materials. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4. Considering that radioactive gases had been also released through the same path that allowed hydrogen outside the Unit 1 PCV, the ERC also ordered the evacuation of the staff from two MCRs (Units 1 and 2, and Units 3 and 4), except for the three most senior level staff.

At 15:29, radiation dose rates at a station monitoring post along the site boundary showed 1.015 mSv/h. It was confirmed at 16:17 that the radiation level measured near a monitoring post (MP4) was 0.569 mSv/h as of 15:31. This situation was deemed to fall under Article 15 of the Nuclear Emergency Act, and government agencies were notified of 'abnormal rise in the site boundary radiation dose rate'. Approximately three hours after the explosion in Unit 1 (four hours after venting of the Unit 1 PCV), at 18:25 on 12 March, the Government extended the evacuation zone to 20 km.

Although immediate venting of Unit 2 was not considered necessary, at 17:30, the Site Superintendent requested considerations for venting to be started before the radiological conditions would worsen upon the site wide degradation of radiological conditions.

13 March 2011

On the morning of 13 March, at 08:10, operators entered the RB and manually opened the MOV on the PCV vent line to 25%. Complete opening of the AOV was deferred until the actual time when venting would need to be carried out.

As the conditions for maintaining the relevant fundamental safety functions in Units 1 and 3 became more difficult, at 10:15, the Site Superintendent ordered venting of the Unit 2 PCV by opening the large SC vent AOV. This order was intended to take advantage of relatively favourable radiological conditions by manually operating valves in the Unit 2 RB before any deterioration in line with the site

[110] Almost one hour after the SBO on 11 March, mobile power equipment (low and high voltage power supply vehicles) was dispatched to the Fukushima Daiichi and Fukushima Daini NPP sites. The first vehicle, from Tohoku Electric, arrived at around 22:00 on 11 March, i.e. nearly six hours after the SBO. More vehicles from other TEPCO and Tohoku Electric facilities and the Japan Self-Defense Forces arrived at the sites throughout the night. By 10:15 on 12 March, a total of 23 vehicles were at the site.

wide trend.[111] The AOV opening was accomplished in 45 minutes, at 11:00, but venting did not occur because the pressure inside the Unit 2 containment was lower than the set burst pressure of the rupture disc, 0.528 MPa (5.28 bar). In order to continuously maintain the venting path, instrumentation air was needed to keep the large SC vent open necessitating connection of a portable compressor.[112]

At 12:05, the Site Superintendent also ordered precautionary preparations for seawater injection into Unit 2 in case the unit's RCIC should fail. For this purpose, fire engines were to be connected to the FP lines of Unit 2 to inject water from the backwash valve pit of Unit 3, if needed. By the late afternoon, the fire brigade completed a seawater injection line to Unit 2. However, the ERC decided to prioritize water injection to Units 1 and 3, and the fire engine pumps were kept on standby.

Meanwhile, batteries gathered from various vehicles were connected to the SRV control panels in the MCR at 13:10, in order to allow RPV depressurization to be carried out if low pressure injection was needed.

At 14:15, after a radiation level of 0.905 mSv/h had been measured near one of the monitoring points, an 'abnormal rise in the site boundary radiation dose rate' incident according to the Article 15 of the Nuclear Emergency Act (radiation levels exceeding 0.500 mSv/h) was announced.

14 March 2011

The portable compressor, delivered from the Fukushima Daini NPP at 01:52, was connected to the air tank of the instrument air system in the TB and started to supply air after 03:00 in order to keep the large isolation AOV SC vent valve open.

At 04:30, a reinstated SC pressure monitor indicated that the SC pressure was 0.467 MPa (4.67 bar), suggesting that the pressure increase had slowed down and stabilized. As it was still below the rupture disc pressure, venting did not start.

At 11:00, the alternative seawater injection line assemblies for Units 1, 2 and 3 were completed but were kept on standby for Unit 2 as the reactor core isolation cooling (RCIC) system was thought to be still functional, while the injection to Units 1 and 3 was to resume.

At 11:01, an explosion occurred in the upper part of the Unit 3 RB. The explosion and the ejected building debris damaged fire engines and fire hoses located around the backwash valve pit of Unit 3. After a temporary evacuation of the plant site, recovery work to establish the seawater injection setup started at 13:05. However, due to scattered debris and high local radiation levels on-site, the backwash valve pit was no longer usable as a water source.

After the explosion, the large isolation AOV on the Unit 2 vent line was discovered to be closed and could not be reopened. The explosion in Unit 3 seemed to cause the valve to close, which affected the previously set up Unit 2 containment venting path, resulting in the loss of Unit 2 PCV venting capability.

Observing the reactor pressure and water level readings at 12:30 and 13:30, and comparing them to earlier readings, showed that the level was decreasing and the pressure was increasing. The unit

---

[111] Between 05:30 and 10:50 on 13 March, neutrons were detected about 1 km away from the RBs of Units 1–4 near the main gate, indicating a possible breach of the PCV, although the source of the neutrons was unknown.

[112] Portable compressors were requested through teleconferencing with TEPCO Headquarters at 22:22. They were dispatched from the Fukushima Daini and Kashiwazaki-Kariwa NPPs. A portable compressor was delivered later at 01:52 on 14 March from the Fukushima Daini NPP for Unit 2 venting arrangement.

operators and the on-site ERC inferred from this that the Unit 2 RCIC system had failed. As a result, a 'loss of reactor cooling functions' report as defined in the regulations[113] [18] associated with the Nuclear Emergency Act [19] was issued for Unit 2 at 13:25 and the government agencies were notified at 13:38.

The measured reactor water level continued to drop, and it was estimated (at 13:25) that the level would reach TAF at around 16:30; priority was therefore given to water injection efforts. The alternative water injection line to the reactor through the FP line via two fire engines was completed at 14:43. However, water injection was not possible without first depressurizing the RPV.

Last measured at 12:30, the suppression pool was near or at saturation conditions at 0.486 MPa (4.86 bar) and 149.3°C. The ERC, concerned about high PCV pressure and saturated conditions in the SC, hesitated to depressurize the RPV, as the PCV response to the mass and energy release from the RPV to the PCV could adversely affect the PCV's integrity. Therefore, the depressurization of the RPV was postponed until the containment venting line was re-established. This also postponed the water injection that would require depressurization.

The on-site ERC was informed at 14:04 by TEPCO Headquarters that it was agreed with nuclear regulator, NISA, to increase the emergency worker exposure dose limit to 250 mSv.

A revised estimation at 15:57 indicated that the reactor water level would reach TAF (uncovering the core) at around 17:30, based on the presumed time of the loss of the RCIC system. By 16:00, a containment vent path had not yet been re-established, and it was clear that achieving a successful venting was going to take some time. With uncovering the core predicted to be imminent, it was decided at 16:28 to depressurize the RPV by release through the SRV to the SC, to enable water injection, whilst recognizing the potential adverse impact on the confinement as a result of the release of steam from the reactor into the containment as there was no venting path to ensure PCV integrity in case of further over pressurization.

The first attempt to open the SRV from the switch in the MCR at 16:34 failed.[114] After several further unsuccessful attempts with five different SRVs, operators opened an SRV at 18:02. Additional SRVs had to be opened, before the RPV pressure dropped to about 0.65 MPa (6.5 bar) at 19:03 (from about 7 MPa (70 bar) at 16:34), which was below the fire engine pump discharge pressure. During this pressure relief, there was no apparent increase in the PCV pressure. On the other hand, the rapid pressure drop caused the water inside the RPV to flash to steam and, without make-up water injection, the water level continued to drop.[115]

Seawater injection could have started immediately after depressurization of the RPV, but the fire engine chosen for the injection ran out of fuel and stopped. After refuelling, two fire engines were started at 19:54 and 19:57, respectively, and seawater injection into Unit 2 RPV via the FP system could begin.[116]

---

[113] Cabinet order in reference to the Nuclear Emergency Act.

[114] As the work to open the SRV was ongoing, the shift crew heard noises that sounded like steam relief around the SRV area.

[115] Due to flashing of the water in the measurement pipes, the reactor water level measurement after the depressurization cannot be considered reliable. Thus, the magnitude of core uncovery, i.e. partial or complete, is not known. TEPCO estimates that the core was completely uncovered.

[116] Note that not all the injected water went into the RPV because the water injection by fire engines was through the FP, MUWC and LPCI lines and there were several branches in the MUWC line to provide water for pump and valve seals, gland steam evaporators and so on.

Meanwhile, re-establishing the PCV vent path continued. After confirming that the air tank was not empty and the outlet valve was open, it was suspected that the solenoid had failed by grounding, preventing the large SC vent AOV to open. Therefore, opening the small bypass SC vent AOV was also pursued and, by successful excitation of the solenoid, the valve was deemed to have opened at around 21:00.[117] As the PCV pressure remained below the bursting pressure of the rupture disk, the venting still did not start.

At 20:30, the RPV pressure started to rise again, exceeding 1.0 MPa (10 bar) at 21:00. Two more SRVs were opened, so that the RPV pressure started to drop at 21:20. The RPV pressure rose repeatedly afterwards, and water injection was considered to have been interrupted.

At 21:55, the containment atmospheric monitoring system (CAMS) — radiation monitoring equipment inside the PCV — was restored and its readings showed significantly elevated radiation levels in the DW and SC compared with the earlier readings at 15:15, prior to the CAMS going off-line. The radiation level increase was 5000-fold (from 1.08 mSv/h to 5360 mSv/h) in the containment atmosphere (the DW) and 40-fold (from 10.3 mSv/h to 383 mSv/h) in the SC section of the containment. Additionally, neutrons had been detected between 21:00 on 14 March and 01:40 on 15 March, by a mobile radiation monitor near the main gate (approximately 1 km away from the RBs of Units 1, 2 and 3). The measured neutron dose rates were 0.01–0.02 μSv/h.[118]

In the next three to four hours, more SRVs were opened to allow water to be injected into the Unit 2 reactor; hence, the containment pressure continued to increase due to mass and energy addition to the SC. However, the Unit 2 venting could not be accomplished.

Also, both the reactor pressure and the DW pressure continued to increase, and by 22:50, the measurements showed a reactor pressure of 1.923 MPa (19.23 bar) and a DW pressure of 0.54 MPa (5.4 bar). Since this DW pressure exceeded the design pressure, it constituted an incident of 'unusual rise of pressure in containment vessel' under Article 15 of the Nuclear Emergency Act as declared at 22:50 by the on-site ERC. The government agencies were notified at 23:39.

There was a mismatch between the pressure trends in the SC, in which the pressure remained between 0.3 MPa and 0.4 MPa (3–4 bar), and in the DW, where the pressure increased to 0.74 MPa (7.4 bar) by 23:40. The DW continued to over pressurize while SC pressure remained below rupture disc burst pressure. In order to protect the confinement function and permit venting (PCV pressure relief) as soon as possible, TEPCO staff at the on-site and off-site ERCs agreed to vent directly from the DW by remote-manually opening the small DW bypass AOV from the MCR. It was recognized that this would increase radioactive releases to the environment without suppression pool's scrubbing of radioactive isotopes. However, it was also not possible to open the valves on the DW vent path and consequently Unit 2 venting could not be accomplished.

15 March 2011

At 00:01, the DW vent bypass AOV was opened, but venting did not occur, although it is believed that the valve was open for a few minutes. The DW pressure remained close to 0.74 MPa (7.4 bar), while the reactor pressure increased from 0.753 MPa (7.53 bar) at 00:05 to 1.923 MPa (19.23 bar) at 00:45.

---

[117] Later, at 23:25, it was confirmed that the bypass AOV had not opened.

[118] It was thought by TEPCO that the neutrons came from the spontaneous fission of actinides that were released following core damage in one of the three reactors, probably from Unit 2 [5].

Opening further SRVs caused the reactor pressure to drop to 0.73 MPa (7.3 bar), at which it remained for some time before increasing again to 0.775 MPa (7.75 bar) at 02:22. At the same time, the DW pressure also increased slightly to 0.77 MPA (7.7 bar) at 02:45.

At 04:17, the relevant government agencies were notified that depressurization of the RPV and the PCV had not been fully effective.

At 06:14, the sound of an explosion was heard on site, and tremors were felt in the MCR. This was followed by a drop in the Unit 2 SC pressure indication, which went off scale. The MCR initially reported to the ERC that the indicated SC pressure was at nearly atmospheric pressure, as zero bar was displayed in the MCR indicator at 06:30, inferring potential loss of the confinement function. After re-checking the readings, however, it appeared that the DW pressure was still at 0.73 MPa (7.3 bar) and the SC pressure went off scale.

This information indicated a possible containment vessel failure and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units to temporarily evacuate to the seismically isolated building where the on-site ERC was located. At about the same time as the event associated with the Unit 2 SC, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[119]

After corroborating the damage and failure of the Unit 2 SC (PCV), as well as the rising radiation levels, all plant personnel were ordered to evacuate temporarily to the seismically isolated building where the ERC was located. Subsequently, all personnel, with the exception of those required for monitoring and emergency restoration were told by the ERC to move to a 'radiologically safe location', resulting in approximately 650 people understanding this order as a site evacuation and evacuating to the Fukushima Daini NPP. Relevant government agencies were informed of the evacuation at 07:00, with an estimated 50–70 staff, including the Site Superintendent, remaining at the Fukushima Daiichi site.

Only a limited amount of data and plant parameters were recorded between the evacuation and the return of operators to the MCR. These included DW pressure measurements of 0.73 MPa (7.3 bar) at 07:20 and 0.155 MPa (1.55 bar) at 11:25, and a dose rate measurement at the main gate of 11.93 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident and the government agencies were notified at 09:18.

At 08:25, white smoke (or steam) was observed being released from the Unit 2 RB near the fifth floor.

Given the increased radioactive releases, the Prime Minister issued an order at 11:00, requiring residents within a 20–30 km zone around the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

On 18 March, four workers entered the ground floor of Unit 2, where they encountered high temperature and high humidity and received a dose of about 3 mSv during their stay of approximately 14 minutes [75].

[119] It is reported in the event investigations that the Site Superintendent became aware of the Unit 4 explosion when it was reported to him at 08:11, when the evacuation personnel arrived in the ERC. Also, the evacuating personnel of the MCR for Units 3 and 4 reported scattered debris around Unit 4, and damage to the RB of Unit 4 on the fifth floor. Later seismic analyses indicated that the explosion originated from a location inside Unit 4.

On Sunday 20 March, an auxiliary transformer of Units 1 and 2 was connected to the external grid, and temporary off-site power was restored to Units 1 and 2 at 15:46. Almost exactly nine days after the SBO, off-site power was restored to Unit 2 through this temporary AC power system, ending the SBO.

Between 23 and 25 March, water injection to the reactors was switched from sea water to borated fresh water, and on 24 March lighting was re-established in the MCR. On the following day, the fire pump was replaced by a stationary motor driven pump [74].

Unlike in Units 1, 3 and 4, the Unit 2 RB was still covering the Unit 2 SFP, and consequently the spray method for replenishing pool water could not be used for Unit 2.

On 2 April, contaminated water was discovered to be flowing from the TB into the sea via the trench for power cables near the seawater intake channel of Unit 3. The high activity of the water ($^{134}Cs/^{137}Cs$: 1.8×10^9 Bq/kg, ^{131}I: 5.2×10^9 Bq/kg) indicated that this water originated from within the PCV of Unit 2. However, it was unclear why the water in the TB of Unit 2 had a much higher concentration of fission products than the water in the TBs of the other units [76].

On 3 April, the power supply to the pumps supplying water to Units 1–3 was switched to off-site power.

On 4 April, the Government of Japan issued permission for TEPCO to discharge 10 000 tonnes of low level contaminated water into the ocean in order to provide storage facilities for the highly contaminated water found in the Unit 2 TB basement.

The leakage of highly contaminated water to the ocean was stopped on 6 April by injecting concrete and polymer hardener into the soil surrounding the trench. On 21 April, the amount of released activity via this water leakage was determined to about 4.7×10^{15} Bq.

A survey of the RB ground floor by remote controlled robots started on 17 April 2011.

RPV temperature measurements were restored after 20 April. The temperature sensor at the RPV support skirt (restored on 30 April) showed temperatures in the range of 250–300°C.

The Government and TEPCO announced on 19 July that the first condition of the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] had been achieved in Units 1–3, and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the 'accident' phase of events at the Fukushima Daiichi NPP Unit 2 to a close.[120] However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.2.3. Unit 3

Fukushima Daiichi NPP Unit 3 was a BWR/4-type reactor with a Mark-I containment.

When the Great East Japan Earthquake occurred at 14:46 on 11 March 2011, Unit 3 was operating at its rated thermal power of 2381 MW. The reactor water level was about 1150 mm, which

[120] According to the criteria set by the Government of Japan at the time.

corresponded to 5320 mm above TAF, and the reactor pressure was about 0.71 MPa (71 bar). The SFP was fully filled with water at a temperature of 25°C.

11 March 2011

When the earthquake occurred, it triggered the acceleration sensors of Unit 3, initiating an automatic reactor scram at 14:47. All control rods were fully inserted automatically, and the shift team confirmed at 14:54 that the reactor was subcritical. The reactor scram caused a drop of the reactor water level by 1200 mm, which was recovered by feedwater, and a drop of reactor pressure by 0.7 MPa (7 bar).

Because it was an 'earthquake of greater than 45 Gal', the operators began to implement post-earthquake actions according to the AOP, 'Natural Disaster Accident', Section IV, Natural Disasters, Chapter 22. The Emergency Response Team was activated at the ERC.

Due to loss of all off-site power, the emergency busbar lost power with the result that the RPS lost power. This initiated a PCIS, which caused all the MSIVs to close. Both EDGs started automatically at 14:48, restoring AC power to the emergency bus bar.

The reactor pressure increased due to decay heat after reactor isolation (i.e. the MSIV closure) until 14:52, when safety relief valve (SRV) 'C' started to open at 7.54 MPa (75.4 bar) and close at 7.2 MPa (72 bar), thereby maintaining the reactor pressure by cycling. The reactor water level decreased as steam was released through the SRV into the SC. The SRVs continued to cycle to maintain the reactor pressure.

The shift team started the RCIC system manually at 15:05, as required by procedures. It stopped automatically at 15:25, when the RPV water level reached the high level set point (+ 1485 mm corresponding to 5655 mm above TAF, namely 'L-8').

In the SFP, which lost cooling and refilling capabilities upon the loss of off-site power, the temperature of the pool water started to increase due to decay heat.

The first tsunami wave reaching the site at 15:27 had a run-up height of 4–5 m and did not impact any essential plant systems. However, the second tsunami wave, with a run-up height of 14–15 m, flooded the plant site between 15:36 and 15:37, resulting in a series of events. The pumps for seawater systems were flooded and damaged, leading to the loss of ultimate heat sink (LUHS). Furthermore, sea water flowed into the RB, TB and other buildings. The two EDGs and associated M/Cs in the basements of the TB and the control building (CB) were flooded and lost their function, resulting in a total loss of AC power at 15:38. Station blackout (SBO) occurred and was declared by TEPCO at 15:42, and operators entered the symptom based EOP for an SBO condition.

After RCIC system stopped and SRVs continued to relieve RPV pressure, the reactor water level started to decrease again, and the shift team manually reactivated the RCIC system at 16:03. Unlike in Units 1 and 2, the flooding affected DC power systems partially, and the DC power remained available in Unit 3 for some time. The operators in the MCR were able to remote-manually start and control the RCIC system, using residual DC power and so ensured continuing, adequate core cooling. Monitoring of relevant plant parameters, such as water level and pressure inside the RPV, was possible at Unit 3. Chart recorders in the MCR continued recording plant data.

As the core cooling depended on the limited capacity of the station batteries, the operators tried to minimize the usage of DC power. This included disconnecting lighting and non-essential instrumentation at the MCR. Further, to avoid power consuming valve activations of the RCIC, resulting from automatic shutdown at high reactor water levels and automatic restart at low water

levels, the operators manually adjusted its RPV water injection rate to keep the reactor water level nearly constant. This was done by suitably distributing the pump discharge flow of the RCIC into the RPV and, via a test line, back into the CST.

At 21:27, the electrical lighting of the MCR of Unit 3 was restored through the use of a mobile generator. The operation of the RCIC and cycling of SRV activation transported decay heat from the RPV into the SC, causing a continuous temperature increase of the water in the SC. The DW pressure started to increase during the evening, exceeding 0.2 MPa (2 bar) by midnight.

12 March 2011

The SBO response that had been executed in accordance with the procedure had to be modified when the RCIC system ceased to operate at 11:36 on 12 March, after nearly 20.5 hours of continuous operation, and water injection into the RPV was consequently lost. Reactor pressure was between 7.4 MPa and 7.7 MPa (74 and 77 bar) at the time. The operators unsuccessfully tried to restart the RCIC several times.[121]

The SC pressure had, meanwhile, also increased to around 0.4 MPa (4 bar) due to the SRV and RCIC system operations, and the operators started the DDFP at 12:06 remote-manually (i.e. from the MCR) to provide an alternative SC spray to cool down the SC, with the result that the SC pressure stabilized [77].

Without core cooling, the water in the reactor continued to boil and evaporate, and with continuous SRV cycling, the reactor water level continued to decrease. At 12:35, the water level eventually reached the point (the 'reactor water level low' signal corresponding to 2950 mm above TAF) at which the high pressure coolant injection (HPCI) system — an emergency core cooling system — activated automatically. This system started and automatically maintained the reactor water level in the predetermined range. To avoid repeated stops and starts of the HPCI, which would have utilized much of the limited DC power remaining, the operators took manual control of the system by controlling the water injection rate into the RPV using the test line in accordance with the SBO procedure. Since the capacity of the HPCI is much larger than that of the RCIC system, the HPCI turbine consumed much more steam from the reactor.

At 15:36 on 12 March, an explosion occurred on the service floor of the Unit 1 RB, causing damage to the upper building structure and injuring workers and locally high dose rates due to contaminated debris. Consequently, the on-site ERC requested evacuation of staff from the areas in and around Units 1–4, including the common MCR of Units 3 and 4, except for the three most senior level staff.

Meanwhile, although the relatively stable pressure inside the PCVs obviated the need for immediate venting, the Site Superintendent ordered, at 17:30, preparations to start for PCV venting of Units 2 and 3. This decision was based on consideration of the relatively less harsh radiological conditions in the buildings as the site wide radiological conditions were deteriorating quickly.

Given the combined effects of water injection and steam consumption of the large capacity HPCI system, the reactor pressure decreased significantly, to around 1.0 MPa (10 bar) at 19:00. At low

[121] The operators reset the RCIC system turbine steam stop valve in the MCR and restarted the RCIC system, but it shut down immediately after the restart. They went into the RCIC room and confirmed locally that the stop valve was normal. They tried to restart the RCIC system again, but failed. There are two kinds of trip mechanisms: the electrical trip, which can be reset at the MCR control panel, and the mechanical trip, which needs additional recovery work in the RCIC system room. It is estimated that the trip of the RCIC system was caused by the electric trip detecting high discharge pressure because it was possible to reset only from the MCR.

reactor pressure, the inlet steam pressure of the HPCI turbine decreased to less than its designed range, causing the HPCI turbine rotational speed to fall below its specified operating range. The discharge pressure of the HPCI pump, therefore, gradually decreased, approaching the RPV pressure. This caused the operators to become concerned about reliability of the HPCI system now getting near the limits of the operational range.

At 20:36, the reactor water level monitor was lost due to depletion of the available 24 V DC batteries. It was restored at 03:51 on 13 March using batteries delivered from the Hirono Thermal Power Station.

13 March 2011

After 14 hours of continued operation of the emergency HPCI system, the concern about the reliability and possible failure of the HPCI turbine, which was by then operating at low reactor steam pressure, increased. The concern related to the possibility of turbine damage and creation of a release path from the reactor vessel resulting in an uncontrollable release of radioactively contaminated steam, directly outside PCV. This concern was heightened when the turbine did not automatically stop, as it was designed to, when the reactor pressure decreased below the automatic shutoff pressure of 0.8 MPa (8 bar) at 02:00 and reached 0.79 MPa (7.9 bar) at 02:30. This should normally have caused the automatic isolation of the HPCI, but it did not. The operators, in agreement with members of the ERC, therefore decided to stop the HPCI and switch the core cooling function from the HPCI to the alternative means of injection, DDFP.[122] The operators thought this could be achieved without interruption of core cooling, since the reactor pressure was already below that of the diesel driven fire pump and could be kept low by the use of SRVs.

A team was sent to the RB in order to verify the operation of the DDFP, which at this time was utilized to spray and depressurize the SC, and switch the DDFP connection from the SC spray line to the RPV injection line.

At 02:42, the HPCI was shut down remote-manually from the MCR.[123] The reactor pressure was measured as 0.68 MPa (6.8 bar) at the time. The shift team then proceeded to attempt to depressurize the reactor by opening SRVs at 02:45 and 02:55 from the MCR. However, the SRVs did not open although the valve status in the MCR indicated that they were functional[124] and the reactor pressure started to increase, reaching 0.87 MPa (8.7 bar) at 03:00. In parallel with attempts to open the SRV, the shift team started the DDFP. Although the discharge pressure of the DDFP reached 0.71 MPa (7.1 bar) by 03:05, it did not exceed the reactor pressure and so no water injection into the reactor was possible. By 03:44, the reactor pressure reached 0.42 MPa (4.2 bar).

Faced with this setback, the operators tried to restart the HPCI to revert to injection via the HPCI system at 03:35, but the restart attempts in the next 45 minutes were unsuccessful.[125] Between 03:37 and 05:08, they also unsuccessfully tried to local-manually activate RCIC (i.e. from the RCIC room). The reactor pressure continued to increase and exceeded 7.0 MPa (70 bar) by 04:30. Without any remaining system capable of injecting water into the RPV to cool the reactor, a ‘loss of reactor cooling function’ incident under Article 15 of the Nuclear Emergency Act was declared at 05:10 and

[122] This decision was not communicated to the Site Superintendent.

[123] Note that it was possible that the flow rate into the RPV with the HPCI had decreased before it was shut down.

[124] It is estimated that the battery capacity was enough to display the status indicator lamps, but not enough to operate the SRVs [78].

[125] It was presumably due to the fading DC power supply.

was reported to the government agencies at 05:58. Without core cooling, the Unit 3 reactor continued to heat up in the following hours.

After the loss of core cooling, an alternative water injection method to cool the Unit 3 core utilizing the fire engines was considered and the work began at 05:21 to establish a line for injecting seawater into the Unit 3 core from the Unit 3 backwash valve pit through the FP lines. Also, the fire engines located at the Unit 5–6 complex and an additional fire engine from the Kashiwazaki-Kariwa NPP (which was on standby at Fukushima Daini NPP) were dispatched.

In view of the deteriorating conditions without core cooling and projected containment heat up and pressurization by the use of SRVs to depressurize the reactor for cooling water injection, the Site Superintendent also ordered preparations for venting, at 05:15, by completing the Unit 3 containment venting path up to the rupture disk. Earlier, at 04:52, the operators had unsuccessfully attempted to excite the solenoid of the SC vent valve using the small portable generator that had been utilized for the MCR lighting. Upon receipt of the venting order, a team entered the torus room in the basement of RB, where the valves for venting were located. On investigation, the team discovered that instrument air provided by the air cylinder, needed to operate the large SC AOV, was not available, since there was no pressure in the tank. Replacement of the air cylinder with another available instrument air tank in the vicinity of the torus room began at 05:23.

Since the vent path had not been established, the on-site ERC decided to change the DDFP injection to SC spray line to control the pressure increase in the containment. The DDFP, that was previously aligned but had been unable to inject to the reactor, was changed back to the SC spray injection at 05:08.

At 06:00, a fire engine located at the Unit 5–6 complex was confirmed functional and was dispatched to Unit 3. An additional fire engine, requested earlier from off-site resources earlier, left Fukushima Daini NPP at 06:00. It arrived in the Fukushima Daiichi NPP at 06:30, and was directed to the Unit 3. A seawater injection line was completed by 07:00 with water intake for the fire engines changed to Unit 3 backwash valve pit from the fresh water FP tank, However, its use was postponed by the Site Superintendent as a result of a communication from TEPCO headquarters with directions to continue to inject fresh water, rather than sea water, as long as fresh water was available.[126] As a result, the injection line was changed back to the borated freshwater source. The efforts to reduce the reactor pressure below the fire engine pump pressure required the activation of the pressure relief valves. This was achieved by use of DC batteries from cars, which were collected in the common MCR of Units 3 and 4. In parallel, the efforts to establish temporary AC power to the SLC system for high pressure injection continued.

Meanwhile, the SC spray injection had not sufficiently supressed the containment pressure and the SC continued to heat up. As the containment venting became necessary to discharge heat, the ERC requested the expedited alignment of the vent path while minimizing the containment pressure increase. At 07:39, directed by the ERC, the shift team proceeded to switch containment spray line from SC to DW for containment pressure suppression and at 07:43 DW spraying by the DDFP injection started. The DW spray stabilized the containment pressure, while the teams worked on the

[126] A division director in the off-site ERC at TEPCO Headquarters who attended a meeting in the Prime Minister's Office earlier asked the Site Superintendent on the telephone whether there was any fresh water available. He informed the Site Superintendent of the views of meeting participants, who were inclined to continue freshwater injection as long as possible. The Site Superintendent interpreted this communication as a directive not to inject sea water as long as fresh water was available.

containment vent line. At 08:35 the operators opened manually the MOV in the RB to about 15%.[127] The venting line assembly was completed and kept open up to the rupture disc near the ventilation stack after 08:41. However, the pressure inside the containment vessel was lower than the pressure needed to burst the rupture disc, and so no containment venting occurred.

The established vent line and the stabilized containment pressure prompted the on-site ERC to stop the DW spray injection and use the DDFP for core injection. Between 08:40 and 09:10, the injection alignment was changed from the DW spray line to the alternative core injection line. As the AC power had not yet been restored to the high pressure injection system, the only injection method was DDFP or fire engines that required depressurization of the RPV.

The recovery team used batteries gathered from cars to actuate the SRVs from the MCR for reactor depressurization. As efforts continued to reduce the reactor pressure by opening an SRV, the operators in the MCR observed a drop in the reactor pressure at 09:08, although the opening of SRV was not confirmed by valve status indicators.[128] Upon the rapid RPV depressurization, borated freshwater injection into the reactor started through the FP line via the two fire engines at 09:25.[129] Overall, the Unit 3 core had remained without cooling for nearly six hours.

Along with this depressurization of the reactor, there was a pressure surge in the primary containment, confirming a discharge from the RPV to the PCV. This incidental depressurization of the RPV resulted in a surge in the SC pressure to over 0.63 MPa (6.3 bar), exceeding the maximum design pressure of the containment vessel, and eventually causing the rupture disc to burst at 09:20. Consequently, the containment pressure dropped rapidly, and the ERC judged that Unit 3 PCV venting had started. The venting of the Unit 3 containment was short lived when a valve on the vent line closed presumably because of the lack of sufficient air supply to keep it open.[130]

As the freshwater injection into the Unit 3 reactor from the FP tank via the fire engines continued for nearly three hours, available fresh water in the tanks was depleted at 12:20. As a result, the Site Superintendent decided to inject sea water into the Unit 3 reactor. The fire engines were repositioned, and seawater injection from the backwash valve pit of Unit 3 started nearly one hour later, at 13:12.

On the afternoon of 13 March, the site radiological conditions deteriorated.[131] At 14:15, an 'abnormal rise in the site boundary radiation dose rate' was declared, upon a radiation level measurement of 0.905 mSv/h at one of the site monitoring posts near the site boundary, in accordance with Article 15 of the Nuclear Emergency Act. At 15:28, dose rates exceeded 12 mSv/h at the Unit 3 side of the

---

[127] The operators had some concerns about the PCV buckling under negative pressure. Thus, they opened the valve 15%, instead of 25% as defined in the procedures and implemented in Units 1 and 2.

[128] The valve status indicators did not conclusively show whether or not the valves were in the open position as the indication lamps of two of the SRVs showed erratic behaviour. The reason of the RPV depressurization is estimated that the ADS was activated with a false signal. The establishment of the pump discharge pressure of the RHR or the CS was necessary to activate the ADS, and the increase of SC pressure might satisfy the condition because the RHR pump was then directly connected to the SC even though the pump itself did not function.

[129] Not all of the injected water may have reached the reactor because of back flows into the various branches in the pipe lineup.

[130] As discovered two hours after venting started, at 11:17. It is unknown how long the valve remained in an open position. In the following 6.5 hours, various attempts were made to open the valve but these were hampered by the high dose rate within the RB. At 17:52, the compressed air system was restored by the use of a mobile compressor, and the valve was kept open afterwards.

[131] Between 05:30 and 10:50 in the morning, neutrons were detected about 1 km away from the reactor buildings of Units 1-4 near the main gate although the source of the neutrons was unknown. The measured neutron dose rates were 0.01–0.02 μSv/h.

common MCR of Units 3 and 4, causing the shift team to move to the Unit 4 side. At 14:31, the radiation dose rate exceeded 300 mSv/h at the north side and 100 mSv/h at the south side RB doors.

The on-site ERC inferred from these dose levels that radioactive gases had escaped from the Unit 3 reactor, which in turn meant that hydrogen had also escaped. Mindful of the possibility of a hydrogen explosion similar to the one at Unit 1, the Site Superintendent decided, at 14:45, to temporarily evacuate the workers from the common MCR of Units 3 and 4 and from the areas in the vicinity of Unit 3.

The evacuated areas also included the Unit 3 backwash valve pit area, halting the activities for water injection. The evacuation order was lifted at 17:00, and workers returned to the Unit 3 backwash valve pit area to continue the activities for water injection and venting.

14 March 2011

As the injection of sea water from the Unit 3 backwash valve pit continued into Monday 14 March, the water in the pit fell to such a low level that injection into Unit 3 (and Unit 1) had to be halted at 01:10. After the intake hose was lowered deeper into the pit, the remaining water was reserved for injection into Unit 3, which resumed two hours later.[132]

In the following hours, the Unit 3 containment pressure was found to be increasing and the reactor water level indication continued to decrease. By 06:20, the DW pressure reached 0.47 MPa (4.7 bar) and the reactor water level indicators went off-scale, indicating to the operators, for the first time, that the core was uncovered. From around 06:30 until 06:45, the Site Superintendent ordered an evacuation of all workers because of concern about a possible hydrogen explosion in Unit 3, halting the Unit 3 backwash valve pit area refilling activities.

The DW pressure reached 0.52 MPa (5.2 bar) at 07:00, dropped to 0.5 MPa (5 bar) at 07:20, and remained at around that pressure. The Site Superintendent decided to resume the work of establishing a seawater injection line to the backwash valve pit and withdrew the evacuation order at 07:30.

At 11:01, an explosion in the upper part of the Unit 3 RB destroyed the building structure above the service floor. The explosion also injured workers, caused damage to hoses and fire engines around the Unit 3 backwash valve pit and required the temporary evacuation of the workers in the outside areas. The explosion happened about one hour after the Unit 3 backwash valve pit levels had been restored and at a time, when Unit 1 seawater injection was getting ready to be restarted, interrupting the injection of water into Units 2 and 3 and further delaying the seawater injection into Unit 1. The work to re-establish the seawater injection line was started again after a break of two hours. Again, priority was given to restoring seawater injection into Unit 3 when the line was established.

At 11:02, reactor pressure was measured as 0.391 MPa (3.91 bar) and 0.385 MPa (3.85 bar) at Trains A and B, respectively. The DW pressure was 0.48 MPa (4.8 bar), and the SC pressure was 0.47 MPa (4.7 bar). These measurements were reported to the on-site ERC and it was inferred that both the Unit 3 RPV and the PCV were stable.

At 13:05, work began to re-establish a seawater injection line, this time directly from the ocean since the damage caused to the fire engines and hoses by the Unit 3 explosion had damaged the previous injection line from the pit beyond repair.

[132] Unit 1 core cooling was postponed until the pit could be refilled.

Injection of seawater directly from the ocean to the reactor was started at 15:30 under the high radiation levels owing to the highly contaminated debris scattered by the Unit 3 explosion.

At 19:20, water injection had to be stopped, because a fire engine ran out of fuel, but it was restarted at 19:54. Water injection was interrupted again from 21:14 until 02:30 on 15 March in order to allow water injection into Unit 2.

15 March 2011

At 06:14, an explosion was heard on the site and tremors were felt in the common MCR of Units 3 and 4. Report from Unit 2 to the on-site ERC was indicating potential loss of the confinement function and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units, including in Unit 3, to temporarily evacuate to the seismically isolated building. At about the same time as the event associated with the Unit 2, an explosion in the upper part of the Unit 4 RB was observed by the evacuating personnel.[133]

Subsequently, all personnel, with the exception of those required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a 'radiologically safe location'. Approximately 650 people understood this order as a site evacuation and evacuated to the adjacent Fukushima Daini NPP, while an estimated 50–70 staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR. The relevant government agencies were informed by the on-site ERC of the evacuation at 07:00.

A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities two hours later, at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

16 March to May 2011

On 15 March 2011, the TEPCO Nuclear Line circuit breaker was energized, and five days later, the 480 V emergency low voltage switchboard (P/C 4D) was energized.

A remote visual inspection from a helicopter to address concerns about the status of the SFP was conducted on the afternoon of Wednesday 16 March. The inspection was not conclusive as to sufficiency of the water to cover the fuel assemblies in the Unit 3 SFP, making its replenishment a high priority.

The first supply of water to the Unit 3 SFP was accomplished between 09:30 and 10:00 on 17 March, when helicopters dropped seawater. Fresh water was sprayed by water cannon trucks later on the same day between 19:05 and 20:07.

Spraying into the pools continued daily in March, using water cannon and fire engine trucks or concrete pump vehicles, to ensure that the spent fuel was not exposed.[134]

---

[133] On the basis of the activity data and location in the charcoal filters of the standby gas treatment system (SGTS), it can be assumed that a gas flow from Unit 3 via its common chimney pipes into Unit 4 occurred, transporting sufficient hydrogen to account for the resulting explosion and building damages.

[134] Starting on 23 March, an available plant system, the FPC, was also utilized in the following months in addition to the spraying by vehicles.

At around 15:55 on 21 March, grey smoke coming from the roof of the RB was observed. The smoke continued until the next day and then stopped.

On 22 March, MCR lighting was restored at 10:45.

At around 16:20 on 23 March, black smoke coming from the RB was observed. Two observations at 23:30 on the same day and 04:50 on 24 March confirmed that the smoke stopped.

At 06:02, on 25 March, reactor water injection was changed from sea water to fresh water.

On 26 March, more than 14 days after the SBO, temporary off-site power to Unit 3 was restored.

Freshwater injection to the reactor from fire trucks was transferred to electrical pumps powered by a diesel generator at 08:30 on 28 March.

The Government and TEPCO announced on 19 July that the first condition of the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] had been achieved in Units 1–3 and on 16 December 2011 that the second condition had been achieved for these units. This announcement officially brought the 'accident' phase of events at the Fukushima Daiichi NPP Unit 3 to a close.[135] However, some unstable plant conditions continued, such as fluctuations in temperatures, which had been explained as being caused by instrumentation failures, or fluctuations in the measurement of fission products. More stable plant parameters were achieved between March and April 2012, while post-accident management efforts continued as listed in Section 1.6.

1.3.3. Sequence of events for the Fukushima Daiichi units in the outage (Units 4–6)

If not indicated otherwise, all information in this sequence of events can be found in the reports cited in Refs [3, 4, 6].

1.3.3.1. Unit 4

Unit 4 had been shut down for the planned refuelling outage since 30 November 2010. The reactor was disassembled, with the head removed at the time of the earthquake. The cavity gates were installed, isolating the SFP from the upper refuelling pools. All fuel assemblies had been transferred from the core to the SFP. In total, 1331 spent fuel assemblies and 204 new fuel assemblies were stored inside the SFP, having an estimated decay heat of 2.26 MW by 11 March. The SFP temperature was 27°C at the time of the earthquake.

11 March 2011

The earthquake damaged the open-air switchyards of Units 3 and 4, preventing recovery of the power supply via the main grid.

This LOOP initiated startup of the air cooled EDG to supply emergency power. The second EDG was unavailable due to maintenance outage at the time of the earthquake.

The SFP cooling and make-up water pump was not supplied by emergency AC power from the EDGs and, consequently ceased to function on the LOOP. As the SFP lost cooling and refilling capabilities

[135] According to the criteria set by the Government of Japan at the time.

upon the LOOP, the temperature of the pool water started to increase due to decay heat.[136] Alternative SFP cooling would have been possible via the residual heat removal system (RHR), which was supplied with power by the EDG. However, switching from RHR cooling to SFP cooling would have required manual actions, which had not taken place before the arrival of the tsunami.

At 15:27, the first tsunami wave arrived at the station but did not impact any essential plant systems. Between 15:36 and 15:37, the second tsunami wave arrived and damaged the seawater pumps, resulting in the loss of ultimate heat sink (LUHS). It flooded the TB basement, damaging the water cooled EDG, which was located on the first basement floor. The air cooled EDG was located on the first floor of the common fuel pool building and was not damaged by the tsunami. However, the associated regular and emergency metal-clad switch gear and power centres (M/C and P/Cs) located in the basement of the common fuel pool building and the basement of the TB were all damaged by the tsunami. On the other hand, the regular and emergency P/Cs associated with the water cooled EDG that were located on the first floor of the TB were not damaged.

Consequently, all AC power was lost and Unit 4 was under SBO conditions. Because of the SBO, the EOPs for 'loss of all AC power' [20] were initiated. A 'specific event', as defined in the regulations [18] associated with the Nuclear Emergency Act [19], was declared on the basis of a 'station blackout', due to the loss of all AC power supplies for longer than 5 minutes. Consequently, the relevant off-site agencies were informed in accordance with the requirements of the Nuclear Emergency Act.

The DC battery equipment, which was also located below ground in the TB, also suffered extensive water damage due to inundation. Consequently, DC power was gradually lost in Unit 4 during the first 10–15 minutes of the flooding. The additional loss of DC power meant that operators could no longer monitor the water temperature and levels in the SFP.

As the SFP lost cooling and refilling capabilities, the temperature of the pool water continued to increase due to decay heat without means to monitor the pool level and temperature.

13 March 2011

At 11:50, a water temperature of 78°C was measured inside the SFP of Unit 4, a rise of 51°C since the cooling function was lost after the tsunami on 11 March.

14 March 2011

At 04:08, the temperature in the SFP was measured as 84°C.

A team that was dispatched to check the status of the Unit 4 SFP at 10:30 on 14 March, just before the Unit 3 explosion, encountered high radiation levels, at the door of the Unit 4 RB and could not enter the building.

15 March 2011

At 06:14, an explosion was heard on the site and tremors were felt in the common MCR of Units 3 and 4. Report from Unit 2 to the on-site ERC was indicating potential loss of the confinement

[136] The SFPs are filled with water providing radiation shielding and removal of heat from the nuclear fuel located there. However, without cooling, the pool water would heat up and eventually start evaporating. If this situation continues without refilling, the cooling of fuel stops when the water level falls and exposes the fuel. Overheating and exposure causes damage to the fuel and the release of radionuclides.

function and the possibility of uncontrolled releases from Unit 2. On this basis, the on-site ERC ordered all personnel in all the units, including Unit 4, to temporarily evacuate to the seismically isolated building. At about the same time as the event associated with the Unit 2, an explosion in the upper part (around the fourth floor) of the Unit 4 RB was observed by the evacuating personnel[137]. The explosion destroyed large parts of the building structure and internal components on the third, fourth and fifth floors. The damage on the fifth floor was first confirmed at 06:55 on the fifth floor, and all relevant agencies were informed at 07:55. There were neither eyewitnesses nor images of the explosion, and the noise it had generated was first ascribed to a possible explosion in the suppression pool of Unit 2.[138]

All personnel, with the exception of those required for monitoring and emergency restoration, were instructed by the Site Superintendent to go to a 'radiologically safe location'. Approximately 650 people understood this order as a site evacuation and evacuated to the adjacent Fukushima Daini NPP, and an estimated 50–70 staff, including the Site Superintendent, remained at the Fukushima Daiichi ECR.

A radiation dose rate measurement of nearly 12 mSv/h was recorded at the main gate at 09:00 on 15 March, the highest measurement since the beginning of the accident. Because of the high radiation levels, an order was issued by government authorities, two hours later at 11:00, requiring all residents within a 20–30 km radius of the Fukushima Daiichi NPP to take shelter indoors.

At 09:38, a fire was reported on the north-west part of the Unit 4 RB. It was observed later that this fire had self-extinguished at 11:00.

The ERC recovery team tried to enter the RB at 10:30 in order to confirm the state of the SFP regarding to a reported fire, but abandoned the attempt because the dosimeter displayed a maximum rate of 1000 mSv/h upon opening the RB door.

16 March to May 2011

Another fire was reportedly observed on the fourth floor at around 05:45, but not confirmed upon investigation half an hour later.

A remote visual inspection from an SDF helicopter to address concerns about the status of the Unit 3 and 4 spent fuel pools was conducted on the afternoon of Wednesday 16 March. The inspection confirmed that there was sufficient water in the Unit 4 spent fuel pool to cover the fuel assemblies.

Between 08:21 and 09:40 on 20 March, the Japan SDF started to spray fresh water into the SFP using a fire engine. This operation was repeated between 18:30 and 19:46 on the same day and between 06:37 and 08:41 the next morning. By 21 March, approximately 250 m^3 of fresh water had been sprayed into the pool.

On the morning of 22 March, use of a concrete pumping truck to spray sea water into the SFP of Unit 4 was started and continued on daily basis for the next three days. Injection of water via the FPC system commenced on 25 March, and the level in the skimmer surge tank was observed to be rising, indicating that the SFP level was restored.

---

[137] On the basis of the activity data and location in the charcoal filters of the standby gas treatment system (SGTS), it can be assumed that a gas flow from Unit 3 via its common chimney pipes into Unit 4 occurred, transporting sufficient hydrogen to account for the resulting explosion and building damages.

[138] Later seismic analyses by TEPCO showed that there had been no explosion inside Unit 2 and ascribed the noise to the explosion in Unit 4.

On 26 March, more than 14 days after the SBO, temporary off-site power to Unit 4 was restored.

The MCR lighting was restored at 11:50 on 29 March.

The water level inside the SFP was measured by means of a concrete pumping truck to be 2100 mm above fuel assemblies on 12 April. Ten days later, water level measurement, again using a concrete pumping truck, displayed a water level of 1700 mm above the fuel. The decrease in water level was attributed to the result of the minimum amount of water being sprayed into the SFP and the evaporation of water by the decay heat of the stored fuel.

On 27 April, the water level in the skimmer surge tank rose from 4300 mm to 6050 mm, indicating a restored SFP level. Also, the water level in the reactor well was measured for the first time since the accident, showing 1800 mm above fuel assemblies. As the water level within the SFP dropped due to evaporation in the following days, fresh water was added intermittently to compensate for this loss by the concrete pump trucks spray.

The inspections conducted on 27 April and 7 May showed that the fuel was still adequately stored inside the fuel racks and the pool gate was in sound condition despite the debris that had fallen into the SFP during the explosion in Unit 4.

The water temperature measurements at the end of April were around 90°C.

Starting on 9 May, hydrazine was added to the cooling water in order to prevent corrosion.

1.3.3.2. Unit 5

Fukushima Daiichi Unit 5 was a BWR/4-type reactor with a Mark I containment.

At the time of the earthquake, at 14:46 on 11 March, Unit 5 had been in cold shutdown condition for routine inspections since 3 January 2011. The fuel for the new operation cycle was placed inside the core with all control rods inserted as a beginning of cycle RPV pressure leak test was being conducted. The pressure vessel head was therefore closed and RPV was filled with water and being pressurized by the control rod drive (CRD) pump. The reactor water temperature was 90.6°C and the reactor pressure was around 7.25 MPa (72.5 bar). The PCV cover was open with the lid removed.

As a prerequisite for the pressure test, the relief (depressurization) function of the SRVs was restricted as they were disabled (locked)[139], although their automatic overpressure protection function was still available. Also, the MSIVs outside the containment had also been left open while the inside containment isolation valves were closed.

11 March 2011

All off-site power to Units 5 was lost at 14:49 due to the earthquake damage. Both water cooled EDGs started up automatically and provided emergency AC power to the safety systems. The reactor pressure initially dropped to 5.0 MPa (50 bar) following the loss of power supply to the CRD pump due to loss of off-site power (LOOP), but rose again due to the decay heat of the fuel, but it was well below the levels to activate the SRVs.

[139] The depressurization function of the SRVs were locked prior to the earthquake by removal of the fuses on the MCR control panel for remote operation and deactivation the nitrogen supply lines in order to prevent the operator error of inadvertent opening of an SRV during the pressure leak test.

In the SFP, which lost cooling and refilling capabilities upon the LOOP, the temperature of the pool water started to increase due to decay heat.

When the tsunami hit the station between 15:36 and 15:37, both EDGs became inoperable because of water damage to the associated seawater pumps for component cooling. Also, all regular and emergency high voltage switchboards became inundated by the flood and were therefore rendered inoperable, resulting in an SBO at 15:40.

The lights on the Unit 5 side of the common MCR of Units 5 and 6 ceased to function, with only the emergency lighting operational.

Both trains of the DC power supply, located in the CB, were still operable and powered by DC batteries after the tsunami, supplying the monitoring instruments including the reactor pressure (narrow and wide range) and the reactor water level (narrow range) indicators. The AC powered shutdown range reactor water level indicator was not available owing to the LOOP. The reactor water level monitored by the DC powered narrow range water level indicator indicated the water level of at least 1500 mm above TAF.

As it was in the cold shutdown mode at the time of earthquake, the Unit 5 reactor was not generating enough steam to drive the turbines of the RCIC (or HPCI) system to run their pumps, so residual heat removal by high pressure coolant injection systems was not possible. The low pressure systems were also not operational: The residual heat removal (RHR) system ceased to function due to the loss of AC power supply to its pumps as well as the pumps of the residual heat removal and cooling seawater (RHRS) system; and, the make-up water condensate (MUWC) system was inoperable because its associated condensate transfer pump was no longer supplied with the required AC power. Furthermore, the FP system had been unavailable before the earthquake due to maintenance.

The MUWC system had an air cooled condensate transfer pump and did not require water cooled component cooling, and the shift team was more experienced in its use than other alternatives to be restored and aligned. The operators, therefore, decided on the pursuing low pressure core injection by the MUWC system, interconnected to the RHR system, which required the restoration of AC power and reactor depressurization[140]. Accordingly, activities to restore AC power using the available interconnecting line[141] to the operating EDG in Unit 6 were started.

Since it was not possible to reduce the reactor pressure using the SRVs as their relief function was disabled, alternative depressurization options were explored. At 21:00, depressurization of the reactor was attempted by discharging water via the RCIC and HPCI steam lines as well as via the HPCI exhaust line. Both methods were unsuccessful in reducing the reactor pressure, and the reactor continued to heat up and pressurize owing to the decay heat.

12 March 2011

The SRV automatically opened, as designed for the over pressurization protection safety function, when the RPV pressure rose to the activation pressure at 01:40 on 12 March, approximately 10 hours after the SBO. The SRVs continued to automatically open and close intermittently, maintaining the pressure between 8.1 MPa and 8.3 MPa (81 bar and 83 bar). The reactor had continued to heat up and

[140] The MUWC condensate transfer pump had a maximum discharge pressure of 0.98 MPa (9.8 bar), which necessitated a significant reduction of the reactor pressure to allow water injection to take place.

[141] Cross-tie lines had been installed at the Fukushima Daiichi NPP nearly a decade earlier as a design enhancement for accident management.

re-pressurize, in the absence of heat removal measures, prompting the need to expedite the power restoration and reactor depressurization efforts.

The work to supply power to instrumentation switchboards in the common Units 5 and 6 control building was conducted between 03:00 and 05:00. Temporary cables were laid from the Unit 6 instrumentation switchboard located in the basement of the Unit 5 TB, connecting the emergency AC power from the Unit 6 EDG. Subsequently, the AC powered shutdown range reactor water level indication became functional, confirming the water level prior to discharge from the RPV for depressurization.

For depressurizing the reactor, the on-site ERC and the MRC staff decided to use the nitrogen operated head vent nozzle (a small valve at top of the RPV) as an alternative method to depressurize the reactor because DC power was available from the 250 V emergency batteries for this purpose. The solenoid valve in the nitrogen supply line was opened at 05:00 on 12 March. Later, at 06:06, approximately 14.5 hours after the SBO, the vessel head vent nozzle was remotely opened. The reactor pressure dropped below the MUWC pump discharge pressure, ready for injection upon restoration of MUWC and RHR systems. Reactor pressure was down from 8.3 MPa (83 bar) to approximately to 0.2 MPa (2 bar) by 06:30.

Although the nozzle was left open to continue to depressurize the water filled RPV, the reactor pressure had gradually risen above discharge pressure of the MUWC pump as work continued to restore power to the pump from the Unit 6 EDG. When the pressure was approximately 1.5 MPa (15 bar) at around 07:31, the operators tried an alternative method to depressurize the reactor, via the RHR piping, but this method did not have notable effect on the reactor pressure.

Meanwhile, the laying of cable to connect power between Unit 5 and the operating EDG in Unit 6 was completed and the associated circuit breaker was closed at 08:13 connecting Unit 5 to Unit 6 emergency AC power supply. This supplied some power to be distributed to some Unit 5 equipment nearly 16.5 hours after the SBO. Installation of temporary power cables among the Unit 5 equipment, as well as between Unit 5 and Unit 6 continued throughout the day.

At 14:42, air filtration of the common MCR of Units 5 and 6 was restored for maintaining MCR habitability when the emergency ventilation system was manually started upon restoration of power from Unit 6 EDG.

Meanwhile, the 250 V DC batteries were depleted by around 16:52 on 12 March.

13 March 2011

A concern was raised regarding the water level in the Unit 5 SFP at 12:00 on 13 March, since the SFP water temperature had been displaying a constant value of 26°C. The shift supervisor explained that the water level had dropped below the temperature gauge (located 11.2 m above the SFP floor), resulting in the gauge displaying the ambient air temperature. This led to the application of alternate SFP make-up methods using the RHR interconnection.

Additional power cables among the Unit 5 equipment and between the Unit 5 and Unit 6 equipment were installed, restoring power to other Unit 5 equipment. After connecting the power supply to the Unit 5 low voltage power panel from the Unit 6 EDG, power was supplied to the Unit 5 MUWC system's condensate water transfer pump at 20:54. The pump was manually started and the MUWC–RHR interconnecting pipe valves and the RHR discharge valves were remotely opened at around 21:00, establishing a reactor water injection route via one train of RHR 53 hours after the SBO. However, water injection to the reactor did not occur, since the reactor pressure had gradually risen and exceeded the injection pressure.

The power supply to the SGTS also became available and the system was started up at 21:01, maintaining negative pressure within the Unit 5 RB in support of the confinement function.

14 March 2011

As the reactor pressure increased and remained higher than the MUWC pump injection pressure, the operators tried another alternative method to depressurize the reactor, via the main steam line. This method also did not have notable effect on the reactor pressure. In response, it was decided to use an SRV as the remaining effective option for depressurization.

To operate the SRV required reassembly of the fuses that had been removed from the MCR control panel prior to the earthquake to prevent inadvertent operation from the MCR during the pressure leak test. It also required manual opening of the nitrogen supply line inside the PCV.

After the restoration of SRV's 'A' function (i.e. the fuse in the MCR control panel was installed and a nitrogen line in the PCV was manually opened), SRV 'A' was remote-manually opened at 05:00, using the DC power supplied by the batteries. The reactor vessel pressure decreased to 0.9 MPa (9 bar) at 05:20. The water level which was 2200 mm above TAF prior to SRV opening, as measured at 05:00, dropped to 950 mm above TAF after the opening of SRV.

After reactor depressurization, the operators remotely opened the RHR Train B discharge valve and water injection to the reactor from the CST started at 05:30 on 14 March, over two and a half days after the SBO. The reactor water level increased to 2000 mm above TAF by 06:10 validating successful water injection into the reactor via the alternative system.

Using the accident management interconnection pipes, the MUWC system was also used to restore SFP cooling and make-up starting at 09:27. The operators locally opened the valves on the fourth floor of the RB and remotely (from the MCR) operated other valves needed to inject water into the SFP from the MUWC system via the RHR and FPC systems. Upon the water injection, the indicated SFP water temperature increased from 32.5°C to 48°C at 09:58. The water temperature gauge was therefore believed to be covered with water again and water injection was halted around 10:00. Later, when the operators went to the fifth floor of the Unit 5 RB, they visually noted that the SFP water level decreased again, the SFP pool water make-up by MUWC–RHR–FPC injection was repeated between 14:35 and 15:08.

16 March 2011

In order to maintain the SFP temperature, the ERC instructed MCR operators at 21:00 on 16 March to bleed and feed the SFP water. For this, SFP water was to be extracted to the SC[142] via the RHR system, while simultaneously injecting water from the MUWC system via the RHR and FPC systems, and the SFP water exchange started at 22:16 to prevent further increase in the SFP water temperature.

17 March 2011

The SFP water exchange continued until 05:43 on 17 March. During this process the SFP water temperature increase was successfully limited to 0.2°C.

[142] The capacity of the SC to perform its pressure suppression capability while taking SFP inventory was evaluated and confirmed.

At 11:00 on 17 March, one of the two RHR pumps on one RHR system train was deemed to be functional but did not have AC power to operate. Since flooding damaged the high voltage power panel inside the basement of Unit 5 TB, power could not be provided to the Unit 5 RHR pump via that panel. As a result, temporary power cables were laid connecting to the Unit 6 high voltage power panel (M/C) on 18 March to power Unit 5 RHR pump.

18 March 2011

On 18 March, the water cooled EDG of Unit 6 and its auxiliary systems were confirmed to be functional, but the component water cooling had to be provided for its operation. As the RHRS pumps were damaged by the tsunami and inoperable, the on-site ERC decided to use a mobile submersible pump to provide seawater cooling to the RHR system heat exchanger. The pump was procured and power to the pump and its control panels was supplied by a mobile high voltage generator when cables were connected on 18 March.

19 March 2011

After connecting pressure resistant hoses from the mobile submersible pump to the RHR system piping, the submersible pump was started at 01:55 on 19 March, providing component cooling including the water cooled EDG of Unit 6. The water cooled EDG was started at 04:22 on 19 March, and subsequently, AC power was supplied to Unit 5 via temporary cables from the Unit 6 water cooled EDG (Fig. 1.3–2). The RHR pump on the functional train of RHR system was started at 04:56.

Upon the availability of RHR system trains, the alternative RHR system arrangement was set for SFP water cooling mode and put in service at 05:00 on 19 March and continued into the next day.

Meanwhile, in order to avoid the accumulation of hydrogen, drilling holes in three parts of the RB roof was completed on 18 March.

20 March 2011

The alternative RHR system in the SFP water cooling mode was able to cool the SFP water temperature from 68.8°C, when the system was put in service, to 35.2°C in nearly one day. The ERC then decided to switch the cooling provided by the alternative RHR system from SFP cooling (the FPC mode) to reactor shutdown cooling (the SHC mode). After configuring the RHR for reactor cooling[143] by realigning the valves remote-manually from the MCR or local-manually in the RB, Train A of the RHR system started up in SHC mode at 12:25.

Unit 5 was the first Fukushima Daiichi NPP unit to reach cold shutdown mode. After the RHR system was put into service at 12:25 on 20 March to provide core cooling, the reactor temperature decreased below 100°C in approximately two hours. Therefore, Unit 5 was placed in the cold shutdown mode at 14:30 on 20 March 2011, nearly nine days after the beginning of the accident.

[143] The RHR system was used to cool the reactor and the SFP on an alternating basis after 20 March.

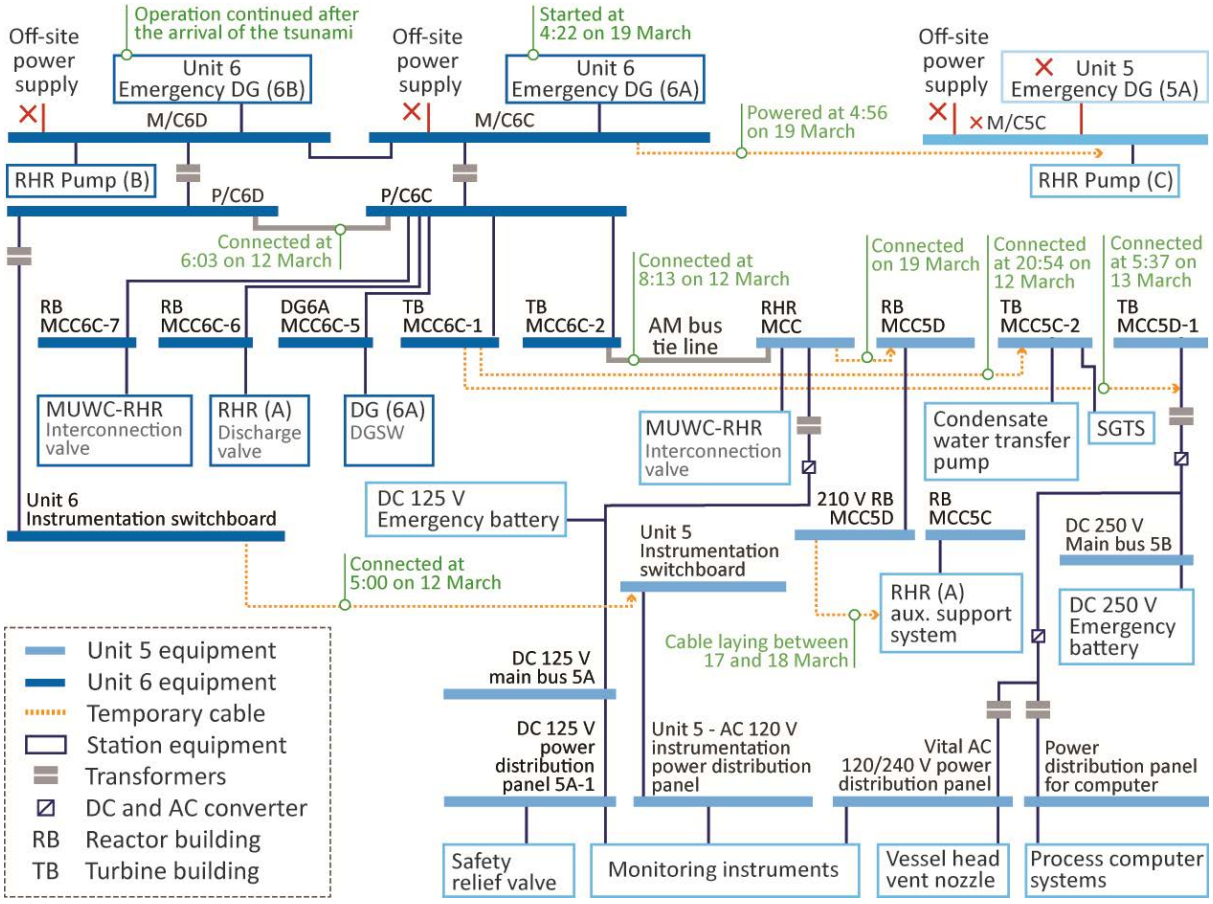


FIG. 1.3–2. Restoration of power for Units 5 and 6 [3].

1.3.3.3. Unit 6

Fukushima Daiichi Unit 6 was a BWR/5-type reactor with Mark II containment.

At the time of the earthquake, at 14:46 on 11 March, Unit 6 had been in outage mode since 14 August 2010. The reactor was in cold shutdown condition, with the fuel loaded and all control rods fully inserted into the core. The RPV head and the PCV cover were closed. The pressure vessel vent pipe[144] was left open and the MSIVs outside the containment had also been left open while the inside containment isolation valves were closed.

The reactor pressure was at atmospheric level, the reactor water temperature was 26°C and the SFP water temperature was 25°C. At the time of the earthquake, the 'upset range water level indicator' displayed a value of 1400 mm, which corresponded to the water level of 5596 mm above TAF.

11 March 2011

All off-site power to Unit 6 was lost at 14:49 due to earthquake damage. Upon the LOOP event due to the earthquake, two water cooled EDGs and one air cooled EDG started up automatically and provided emergency AC power to the safety systems.

[144] A pipeline that is connected to the RPV head in order to extract steam (or non-condensable gases) from the RPV when the reactor is not in shutdown condition.

In the SFP, which lost cooling and refilling capabilities upon the occurrence of the LOOP, the temperature of the pool water started to increase due to decay heat.

Because it was an 'earthquake of greater than 45 Gal', the operators began to implement post-earthquake actions according to Chapter 22 of the AOP, 'Natural Disaster Accident', Section IV, Natural Disasters. The Emergency Response Team was activated at the ERC. The operators also began to implement 'Natural Disaster Accident' Section II, Turbine and Electrical, Chapters 12, 13 and 14 of the AOP to address the LOOP.

When the tsunami hit the station between 15:36 and 15:37, the water cooled EDGs shut down (at 15:36) because of the damage inflicted to the seawater pumps, as well as the damage to the associated power panels and switchboards. However, the air cooled EDG, located on the first floor in the diesel generator building (DG building) did not suffer either water damage or loss of cooling (since it was air cooled). Its associated power panels had also not suffered water damage from the inundation. Therefore, the associated emergency high voltage switchboard on the first basement level inside the RB was still available for emergency power supply. Therefore, the operators continued with their AOPs for responding to the earthquake and LOOP.

The DC power equipment was also functional. Due to the loss of emergency AC power supply after the failure of the water cooled EDG, the power supply was switched over to one train of DC power supply. As the air cooled EDG was still operating, the Unit 6 side of the common MCR of Units 5 and 6 was still functioning.

The relatively low decay heat of Unit 6 and initial low reactor pressure meant that there was some time available to implement alternative methods for coolant injection and that there was no immediate need for reactor depressurization.

Pumps B and D of the low pressure heat removal system, RHR, were still supplied with emergency AC power, but the system itself was inoperable due to severe tsunami damage to the pumps of the RHRS. This also impacted the fuel pool cooling and cleanup (FPC) system, the high pressure core spray (HPCS) system and its associated components.

However, the condensate transfer pump of the MUWC system was still available, as it was powered by the air cooled EDG as an alternate reactor water make-up and heat removal at low pressure.

Train B of the standby gas treatment system (SGTS), also powered by EDG 6B, continued to function after the tsunami hit the station and negative pressure was maintained inside the RB.

The shift supervisor in consultation with the ERC decided to utilize the MUWC system for coolant water injection until the RHR system could be restored. In order to allow water injection via the MUWC–RHR piping, two valves on the RHR train had to be aligned. These valves were no longer supplied with emergency power since the water cooled EDG had ceased to function. However, by interconnecting the associated power panel, these valves could be remotely operated from the MCR.

12 March 2011

The restoration of power to Unit 6 systems (and cross-connecting the operating EDG to Unit 5) in order to supply power to instrumentation switchboards in the common Units 5 and 6 control building was conducted between 03:00 and 05:00.

The work associated with electrical system connection to operate the valves to align MUWC-RHR system for core cooling started at 06:03 on 12 March.

At 14:42, air filtration of the common MCR of Units 5 and 6 was restored for maintaining MCR habitability when the emergency ventilation system was manually started upon restoration of power from the operating EDG.

13 March 2011

A concern was raised regarding the Unit 6 SFP level at 12:00 on 13 March since the SFP water temperature had been displaying a constant value of 18°C. The shift supervisor elaborated that the water level had dropped below the temperature gauge (located 11.2 m above the SFP floor) resulting in gauge displaying the ambient air temperature. This prompted plans to arrange SFP make-up, in addition to the reactor from the MUWC system via the RHR and FPC systems.

Following the manual start of the MUWC condensate transfer pump at 13:01 on 13 March, water injection to Unit 6 core started at 13:20 and continued intermittently afterwards.

14 March 2011

Using the accident management interconnection pipes, the MUWC system was also used to restore SFP cooling and make-up at 14:13, when, after ensuring the cooling of Unit 5 SFP, the operators manually opened valves on the fifth floor of the Unit 6 RB and also remotely operated valves from the MCR to inject water into the Unit 6 SFP via the FPC. Upon the injection of water, the indicated SFP water temperature increased from 21.5°C to 50.5°C at 15:03 when water injection was stopped. At this point, it was assumed that the water level had again risen above the temperature gauge.

For the reactor core cooling, intermittent water injection continued on 14 March. At 21:30, when the water level[145] decreased to 1800 mm, the water injection was repeated and the restored the reactor water level to 3000 mm by 21:55. With the intention of maintaining a high water level, operators controlled the level just below the main steam line nozzle.

15 March 2011

The installation of an alternative emergency power supply from Unit 6 to Unit 5 has been described in the previous section. Starting on 15 March, the operators conducted inspection to verify the functionality and operability of the water cooled EDGs and its auxiliary systems.

16 March 2011

In order to maintain the SFP temperature, the ERC instructed MCR operators at around 13:00 on 16 March to bleed and feed the SFP water. For this, SFP water was to be extracted to the SC via the RHR system, while simultaneously injecting water from the MUWC system via the RHR and FPC systems. In order to circulate the SFP water, and therefore control the rise in the water temperature, the shift team operated the FPC pump between 13:10 and 21:44 utilizing the power supply from the air cooled EDG. During this period, the SFP water temperature increase was halted. This recirculation operation was stopped in order to avoid heat transfer from the uncooled pump to SFP water.

17 March 2011

The operators checked the functionality and operability of the water cooled EDGs and its auxiliary systems by visual inspection. The inspections also addressed the concerns regarding the rotation of

[145] Shutdown range reactor water level indicator

DGSW pump shaft as its shaft could be stuck. The inspection team reported to the on-site ERC that the water cooled EDG and its auxiliary systems were operable. As result, the ERC developed a plan for RHR restoration for Units 5 and 6 based on the fact that both EDGs were available and operable.

The TEPCO RHR system recovery team developed a plan to use a mobile submersible pump in the RHRS instead of the damaged RHRS pumps. The installation of an alternative RHR system assembly began in the early morning of 17 March. Simultaneously, attempts were made to clear earthquake and tsunami debris from the Unit 6 site to allow the alternative RHR restoration work to be carried out. Installation of the two procured submersible pumps in place of the damaged RHRS pumps continued throughout 17 March and the next day.

18 March 2011

At 17:00, in order to avoid the accumulation of hydrogen, drilling holes in three parts of the RB roof was completed.

The DG seawater pump was restored and activated at 19:07.

19 March 2011

After connecting pressure resistant hoses from the mobile submersible pump to the RHRS piping, the Unit 5 submersible pump was started at 01:55 on 19 March, providing component cooling including the water cooled EDG of Unit 6, and the second EDG was started at 04:22.

Power to the two submersible pumps, that were installed to replace the damaged the pumps of Unit 6 RHRS, and their control panels was supplied by a mobile high voltage generator when cables were connected at 21:26 on 19 March.

Upon the availability of RHR system trains, starting earlier at 11:00, alignment of the RHR Train A in the SFP cooling (FPC) mode was conducted, and SFP cooling was started at 22:14 on 19 March and continued into the next day.

20 March 2011

The operation alternative RHR system in SFP water cooling mode cooled the SFP water temperature from 67.5°C, when the system was put in service, to 27.5°C at 17.00 on 20 March.

The ERC then decided to switch the cooling provided by alternative RHR system from SFP cooling (FPC mode) to the reactor shutdown cooling (SHC mode) after switching the operating mode of the Unit 5 RHR system. To avoid the backflow of water from the reactor into the SFP cooling mode line, the shift team stopped the RHR system at 16:26. After configuring the RHR for reactor cooling by realigning the valves remote-manually from the MCR, the RHR was started in SHC mode to inject water into the reactor at 18:48.

After the RHR system was put into service at 18:48 on 20 March to provide core cooling, the reactor temperature decreased below 100°C in less than an hour. Therefore, Unit 6 was placed in the cold shutdown mode at 19:27 on 20 March 2011, little more than nine days after the beginning of the accident.

1.3.4. Sequence of events in the common spent fuel pool

At the Fukushima Daiichi site, there is a large shared pool to store fuel assemblies from all units, called the common spent fuel pool, located in a separate common pool building as a shared auxiliary

facility. It has been in service since October 1997, and at the time of the earthquake there were 6375 spent fuel assemblies stored in it.

Two air cooled EDGs associated with Units 2 and 4 were installed on the first floor of the common pool building. These EDGs themselves did not suffer direct water damage. However, their associated power panels which were installed on the basement floor of the shared auxiliary building, lost function when the basement flooded.

On 21 March, water was sprayed over the pool after the water temperature had risen to 61°C [79]. On 23 March, via a temporary line, water from SC surge tank A was injected into the common pool by a fire engine. On the next day, 24 March, common pool cooling was carried out using the FPC system and the SFP auxiliary unit cooling system pump. Power was supplied to the alternative cooling system on 24 March after off-site power had been restored to the Fukushima Daiichi site. The water temperature in the common pool had risen to 73°C by this time.

1.3.5. Sequence of events for the dry cask storage facilities

The dry cask storage facility at the Fukushima Daiichi site started operation in August 1995. It is located between Units 1 and 4, and Units 5 and 6. The storage casks are cooled by natural convection.

At the time of the earthquake, there were 408 spent fuel assemblies stored in nine dry storage casks (five large dry storage casks and four medium dry storage casks) in the cask storage building. After the earthquake, the entire nuclear power plant site, including the dry storage area, lost off-site power and an SBO occurred when the tsunami hit. The tsunami inundated the storage area floor and also carried a large amount of sea water, sand and scattered debris inside. Each cask was bolted to the floor and therefore did not move from its position. Subsequent inspections by TEPCO found neither significant damage to the casks themselves nor elevated radiation levels and the cooling of the casks by natural convection was not affected. The integrity of the casks was verified by leak tests [17].

1.3.6. Sequence of events for the Fukushima Daini Units

The Fukushima Daini site hosts four BWR/5 reactors with Mark II containments. Prior to the earthquake, all four units were operating at rated thermal power, off-site power was being supplied by three of four lines (one line was undergoing maintenance), all 12 EDGs (the number includes the HPCS-DGs) and all emergency core cooling systems were operable.

11 March 2011

When the earthquake occurred, all units automatically shut down due to the seismic instrumentation trip. Two of the three available off-site power sources were lost, but off-site power was maintained by the remaining line.

Approximately 35 minutes after the earthquake, the first tsunami wave reached the site, flooding the heat exchanger buildings, which were housing the seawater pumps and motors at the seawater intakes of all four units, and the EDG areas.[146] The flooding resulted in a loss of ultimate heat sink (UHS) at Units 1, 2 and 4.

[146] Unlike the Fukushima Daiichi NPP units, Fukushima Daini units had their seawater pumps and motors (of the RHRC, the RHRS and the emergency equipment cooling water (EECW) systems) and their PCs housed, i.e. relatively protected, in the 'heat exchanger buildings'.

The first tsunami wave also flooded main buildings including the RB and TB of Unit 1, the TB of Unit 3, and the SBs for Units 1 and 2, and Units 3 and 4.

Operators began reactor depressurization of all four units using the SRVs to control pressure and the RCIC systems to maintain the reactor coolant system inventory. This operation transferred the decay heat from the reactors to the water in the suppression pools.

At Unit 3, Train A of the RHR equipment was inoperable due to flooding, but the Train B equipment remained operable, including the UHS. This allowed the operators to take the unit to cold shutdown less than 24 hours after the tsunami reached the station.

ERC personnel knew that the critical issue was re-establishing core cooling capabilities to Units 1, 2 and 4. This required restoration of the residual heat removal and cooling seawater (RHRS) system and residual heat removal and cooling (RHRC) system functions. The temporary cables needed to supply power to the equipment were transported to the site by helicopter and trucks. The cables were installed to supply power from the radioactive waste (referred to as 'radwaste') building, Unit 3 heat exchanger building B, and mobile power supply trucks to the motors of the RHR system and RHRC pumps for Units 1, 2 and 4. Approximately 9 km of temporary cable were installed. Some pump motors had to be replaced on Units 1 and 4. Replacement motors were airlifted in by the SDF and were also transported from the Kashiwazaki-Kariwa NPP.

12 March 2011

By 05:00, the reactor pressure in all four units had been reduced to the point where low pressure alternate injection using the MUWC systems could be initiated and the RCIC systems were isolated. Both the RCICs and the SRVs had transferred reactor decay heat into the SCs. Since there was no alternative means for decay heat removal, SC temperatures on Units 1, 2 and 4 exceeded 100°C by 06:07, resulting in the inoperability of the SCs. After deliberation, the ERC directed the MCR to perform SC cooling by injecting MUWC cooling water into the SCs using the FCS drain line. MUWC was also used to spray the DW and the SC in order to suppress PCV pressure increase. As work continued to restore the RHRS at Units 1, 2 and 4, it was decided to align the PCV vents in all four units in case they were needed.

By 12:15, the Unit 3 reactor water temperature that had been lowered by the RHR system decreased below 100°C and the reactor was placed in cold shutdown. At 13:38, a second off-site power line was restored.

13 March 2011

On 13 March, a third off-site power source was restored, and at Unit 1 the seawater cooling pump for Train B RHR equipment was manually started at 20:17, followed by the Train D RHR equipment cooling pump at 21:03.

14 March 2011

Beginning in the early morning, RHR was sequentially restored to Units 1, 2 and 4. At Unit 1, by 10:15 the SC temperature had been reduced to less than 100°C, which restored the pressure suppression function, and by 17:00 the reactor was in cold shutdown when the reactor temperature decreased below 100°C. At Unit 2, by 15:52 the SC temperature had been decreased to less than 100°C and by 18:00 the reactor was in cold shutdown.

15 March 2011

At Unit 4, by 07:15 the reactor water temperature was reduced to below 100°C and the reactor was in cold shutdown. At 17:43, the fourth and final off-site power source was restored.

1.3.7. Site to site event comparison

In addition to the Fukushima Daiichi site, four other nuclear power plant sites on the east coast of Japan were impacted by the earthquake and tsunami. These sites are Higashidori, Onagawa, Fukushima Daini and Tokai Daini. Given that all of the reactors at these sites are BWRs but the plant response varied, it is illuminating to review each reactor's response in order to consider the factors which allowed some to cope better than others.

1.3.7.1. Higashidori nuclear power plant

The Higashidori site is home to one BWR/5 reactor with a Mark I containment. The reactor was undergoing a planned refuelling/maintenance outage at the time and the core had been removed from the reactor and placed into the SFP. When the earthquake struck, all three off-site power supply lines were lost. One of the facility's two EDGs had been removed from service and was undergoing routine planned maintenance, but the remaining EDG was operable, and it started and provided power to its associated safety systems. There was no onsite damage reported as the result of either the earthquake or tsunami. Off-site power was restored later on 11 March.

1.3.7.2. Onagawa nuclear power plant

There is one BWR/4 and two BWR/5 reactors at the Onagawa site, all of which have Mark I containments. Onagawa Units 1 and 3 were operating at full power when the earthquake struck; Unit 2 was in the beginning stages of a reactor startup.

The earthquake rendered four of the five off-site power supply lines inoperable, but off-site power was maintained by the remaining line. The first tsunami wave arrived at the site approximately 45 minutes after the earthquake. Onagawa experienced a tsunami with a 13 m run up height. Even though the site elevation 'dropped' from 14.8 m to 13.8 m as a result of the earthquake, the elevation was still adequate to prevent the site from being inundated. There was, however, significant tsunami induced flooding at Unit 2, as described below.

When the earthquake struck, Unit 1 tripped due to the seismic instrumentation, and both EDGs started but did not connect to their electrical loads since off-site power was available. Approximately 10 minutes after the earthquake, there was a failure of the unit's startup transformer due to earthquake induced damage to the high voltage circuit breakers. Loss of the startup transformer resulted in a Unit 1 LOOP, but the EDGs were available and provided power to their associated safety systems. The operators started the RCIC system to provide reactor coolant system make-up and used the SRVs to depressurize the reactor to the point that the RHR system could be used to provide decay heat removal. Cold shutdown was achieved shortly after midnight on 12 March. The startup transformer was restored to service at 02:05 on 13 March, which re-established off-site power to the unit.

Unit 2 was in the early stages of a reactor startup, but the reactor was not critical. When the earthquake struck, the seismic instrumentation system initiated a reactor trip. As a result, the unit immediately transitioned to cold shutdown since the reactor coolant temperature was only 78°C. The unit's EDGs automatically started, but remained in a standby mode since off-site power was available.

Unit 2 experienced significant flooding when the tsunami caused seawater to flow through penetrations in the seawater intake pump pit floor. The water flowed through a pipe/cable tray trench

into the reactor auxiliary building area basement, which flooded the Train B RCW heat exchanger and pump room and the HPCW heat exchanger and pump room, ultimately causing the shutdown of the Train B EDG and the HPCS DG. Train A safety systems were not affected by the flooding.

At Unit 3, the reactor tripped due to the seismic instrumentation and both EDGs started but did not connect to their electrical loads since off-site power was available. The operators started the RCIC system to provide reactor coolant system make-up and used the SRVs to depressurize the reactor to the point that they could use the RHR system to provide decay heat removal. Unit 3 was in cold shutdown at 01:17 on 12 March.

1.3.7.3. Fukushima Daini nuclear power plant

As described in Section 1.3.6, off-site power was maintained at the site after the earthquake by one remaining off-site source, but tsunami flooding resulted in the loss of the UHS at Units 1, 2 and 4.

The operators were successful in depressurizing the reactors using the SRVs and using the RCIC systems to maintain RCS inventory, but both the SRVs and the RCIC systems transferred heat from the reactors to the water in the SCs. With no decay heat removal capability, DW pressures climbed and the SC water temperatures on Units 1, 2 and 4 increased to the point where they became inoperable.

ERC personnel recognized that the critical issue was establishing decay heat removal for Units 1, 2 and 4. Based on equipment observations, the ERC prioritized inspection/maintenance of selected equipment in the heat exchanger buildings. This included replacing selected pump motors on Units 1 and 4 and installing approximately 9 km of temporary cables to route power from operable power panels and/or mobile generators to the required pumps.

Beginning in the early morning of 14 March, decay heat removal was sequentially restored to Units 1, 2 and 4. By 18:00, the Unit 1 and 2 reactors were in cold shutdown, followed by Unit 4 at 07:15 on 15 March.

1.3.7.4. Tokai Daini nuclear power plant

The Tokai Daini NPP site hosts one operating BWR-5 reactor with Mark II containment.

Prior to the earthquake, the Tokai Daini NPP unit was operating at full power. In response to the earthquake, the reactor automatically shut down due to the seismic instrumentation trip. All three off-site power sources were lost and all three EDGs started automatically. The first tsunami wave reached the site about 30 minutes after the earthquake. Ultimately, tsunami induced flood waters inundated one pump bay containing seawater pumps, which in turn caused the loss of one of the EDGs and its associated electrical loads. The other pump bay had been upgraded to be watertight and did not flood. The remaining EDGs provided power to the ECCS, which maintained core cooling. One off-site power supply source was restored at 19:37 on 13 March, and the reactor reached a state of cold shutdown at 12:40 on 15 March.

1.4. RADIONUCLIDE INVENTORY AND RELEASES

Radionuclides escaped from the cores of Fukushima Daiichi NPP Units 1, 2 and 3 as a result of failures of the fuel, cladding, and RPV and/or associated systems. These radionuclides were subsequently released to the environment either in a controlled manner, i.e. by venting of the primary containment vessel (PCV), or in an uncontrolled manner as a consequence of damage and failure of the PCV and RB during the accident sequence.

It is important to quantify the amount, type, distribution, dispersion, direction, and settlement of these radionuclides to be able to predict the public health and environmental consequences of the radiological release, as will be discussed in detail in Technical Volume 4, and to plan and implement remediation and recovery, as discussed in Technical Volume 5. There were limited radiation measurements made at and around the Fukushima Daiichi NPP during the accident[147], as well as larger scale atmospheric and oceanic measurements afterwards which continue up to the present day. Many organizations around the world continue to apply computational methods to model and describe the total releases into the atmosphere and the marine system from the Fukushima Daiichi NPP units.

Data on the initial radionuclide inventories in the cores of Fukushima Daiichi Units 1–3, and the release fractions of radiologically significant radionuclides, are essential for personal radiation dose and environmental consequence assessments. Their release mechanisms, paths, times and durations can be derived from knowledge of the event sequence. Information on the atmospheric and oceanic dispersion of radionuclides provides information necessary for the protection of people and the environment.

In this section, the initial radionuclide inventories of the Fukushima units at the time of the accident and those at the supposed start time of core degradation are provided. The fission product release mechanisms and the atmospheric, oceanic and terrestrial dispersion pathways are discussed. The principal features and main results of these analyses are also compared with Chernobyl accident releases.

To date, it is considered that there was no radioactive release from the SFPs at Units 1–4, because no voiding and fuel heat-up occurred during the accident and no damaged fuel was found after the accident. For this reason, the inventories of the SFPs at Units 1–4 are not provided and only core inventories of, and releases from, Fukushima Daiichi NPP Units 1–3 are discussed.

1.4.1. Fukushima Daiichi Units 1–3 radionuclide core inventories at the time of accident

The exact amount of each radionuclide in any reactor core at any given time is not precisely known. However, the inventory of isotopes can be calculated from knowledge of the core type and dimensions, the fuel enrichment and the reactor power history.

When comparing different inventory calculations for the Fukushima Daiichi NPP reactors the following points need to be noted:

— The composition and enrichment of the uranium/plutonium oxide fuel (MOX fuel) used at the Fukushima Daiichi NPP reactors is not publicly available due to security and commercial restrictions. Therefore, the inventory has to be calculated based on the known parameters (Table 1.4–1) [64, 65, 80], supplemented by assumptions derived and justified from similar fuel types (Table 1.4–2).
— The power history of Fukushima Daiichi Units 1–3 was made available publicly by JNES in 2011 [81]. The differences in the assumptions about power histories and fuel enrichment are linked to the unavailability of specific data for the cores of Units 1–3 when the early estimates were performed. When the average core burnups of the Units 1–3 cores became available, after the plant computer calculations and the operator logs [64, 65, 80] were disclosed by TEPCO, they provided a method for directly validating the power history used in the calculations.

[147] The Fukushima Daiichi NPP was not equipped with instrumentation scaled to record fission product releases in such severe accidents. Even if sufficient electric power had been available during the accident, the measurement range of the normal exhaust air screening equipment would have been greatly exceeded for data collection.

— Later calculations used more detailed information about the time at power and the cooling times, and the number of fresh fuel assemblies loaded into the core in each refuelling cycle, as well as the MOX fuel composition, which were published in a 2012 JAEA report (in Japanese) [82]. Although these data cannot be considered as exact in the absence of TEPCO's confirmation and concurrence, it is deemed to be sufficient to validate the properties and power histories used in the different calculations.
— Comparison of the initial core inventory from various calculations, using different methods and codes, gives confidence to the validity of the input assumptions. The majority of the fuel inventory calculations for Fukushima Daiichi NPP Units 1–3 utilized the ORIGEN family codes [83, 84] as their calculation method. A cross-comparison analysis was performed by JAEA with ORIGEN2 and SWAT codes [82]. IBRAE RAN made its calculation with the BONUS code [85, 86].

Table 1.4–1 presents the parameters of the six Fukushima Daiichi cores and Table 1.4–2 gives a summary of the input and assumptions used for estimating the radioactive inventories of Units 1–3.

TABLE 1.4–1. PARAMETERS OF THE FUKUSHIMA DAIICHI REACTOR CORES [64, 65, 80]

Fukushima Daiichi Unit		1	2	3	4	5	6
Reactor type		BWR/3	BWR/4				BWR/5
Full core power (MW(th))		1380	2381	2381	2381	2381	3293
Condition before earthquake		Operating	Operating	Operating	Refuelling outage (core off-loaded)	Refuelling outage (shutdown pressure test)	Refuelling outage (cold shutdown)
Core power at the time of accident (MW(th))		1380	2381	2381	0	Decay heat	Decay heat
Typical cycle length		~13 months					
Average reload batch size (No. of assemblies)		~100	~137	~137	~137	~137	~191
Core effective power days at the time of the accident (day)		~140	~80	~130	—	—	—
Fuel assembly (No. of assemblies in the core)		400	548	548	548	548	764
High burnup 8 × 8 fuel assemblies	Number	68	—	—	—	—	—
	Enrichment (Avg., w/o)	3.4	—	—	—	—	—
	Burnup (GW·d/t)	39.5 (Avg.) 50.0 (Max.)	—	—	—	—	—
9 × 9 fuel (A type) assemblies	Number	—	—	516	—	—	—
	Enrichment (Avg., w/o)	—	—	3.8	—	—	—
	Burnup (GW·d/t)	—	—	45.0 (Avg.) 55.0 (Max.)	—	—	—

TABLE 1.4–1. PARAMETERS OF THE FUKUSHIMA DAIICHI REACTOR CORES [64, 65, 80] (cont.)

Fukushima Daiichi Unit		1	2	3	4	5	6
9 × 9 fuel (B type) assemblies	Number	332	548	—	—	548	764
	Enrichment (Avg., w/o)	3.6	3.8	—	—	3.8	3.7
	Burnup (GW·d/t)	45.0 (Avg.) 55.0 (Max)	45.0 (Avg.) 55.0 (Max)	—	—	45.0 (Avg.) 55.0 (Max.)	45.0 (Avg.) 55.0 (Max.)
8 × 8 MOX fuel assemblies	Number	—	—	32	—	—	—
	Enrichment (Avg., w/o)	—	—	1.1–1.2 [U] 2.7–5.3 [Pu]	—	—	—
	Burnup (GW·d/t)	—	—	33.0 (Avg.) 40.0 (Max.)	—	—	—
Fuel rod active length (m)		3.66			3.71		

Note: MW(th): Megawatt (thermal); GW·d/t: gigawatt-day per tonne; w/o: weight percentage.

TABLE 1.4–2. SUMMARY OF INPUT AND ASSUMPTIONS USED IN THE CALCULATIONS OF INVENTORY OF RADIONUCLIDES IN THE CORES OF UNITS 1–3

Input/assumption	Kirchner et al., 2012 [84]	JAEA [82]	IBRAE RAN [87]	PNNL [83]
Code used	ORIGEN-ARP	ORIGEN2	BONUS	ORIGEN-ARP
Units modelled	Average core representing Units 1–3	Units 1–3 with specific core parameters	Units 1–3 with specific core parameters	Average core representing Units 1 and 3
Fuel type	GE-11 9 × 9	Unknown	—	GE 8 × 8
U-235 enrichment (%)	3.8	3.7	3.7	4.0
Pu-239 enrichment (%)	0	1.68	1.68	0
Power density (Units 1–3), MW/t HM	25.0	20.0/25.3/25.3	20.0/25.3/25.3	25.0
Irradiation history	Assumed: 5 × 360 days; Downtimes: 4 × 30 days	Realistic	Realistic, only last downtime is considered	Assumed: 3 × 400 days
Assumed power density distribution in the core	Kq = 1 Average over the core	Kq = var Linear across fuel groups at each cycle linear over cycles in each fuel group	Kq = 1 Average over the core	Kq = 1 Average over the core
Average core burnup (Units 1–3), GW·d/t HM	26.7	25.8/23.1/21.8	21.9/20.3/19.7	30
Average core burnup by operator logs (Units 1–3), GW·d/tHM	25.779 (Unit 1)/23.05 (Unit 2)/21.812 (Unit 3) [64, 65, 80]			

Note: t HM: metric tonnes of heavy metal; GW·d: gigawatt-days.

By way of example, the results of all the calculations of the inventory of Unit 2 are shown in Table 1.4–3 and summarized in Fig. 1.4–1.

TABLE 1.4–3. FUEL INVENTORY (Bq) CALCULATED FOR THE UNIT 2 CORE IN DIFFERENT ANALYSES [82-84, 87]

Nuclide	Kirchner et al., 2012	JAEA	IBRAE RAN	PNNL*
Am-241	3.4E+14	4.35E+14	Not calculated	3.37E+14
Am-243	2.2E+13	2.97E+13	Not calculated	2.50E+13
Ba-140	4.2E+18	4.35E+18	4.27E+18	4.30E+18
Ce-144	3.1E+18	2.31E+18	2.37E+18	3.36E+18
Cm-242	6.5E+16	8.94E+16	Not calculated	7.18E+16
Cm-244	1.5E+15	3.21E+15	Not calculated	1.69E+15
Co-60	3.9E+16	3.61E+12	Not calculated	Not calculated
Cs-134	2.6E+17	2.76E+17	2.49E+17	2.97E+17
Cs-136	9.4E+16	8.17E+16	5.83E+16	1.03E+17
Cs-137	3.0E+17	2.55E+17	2.29E+17	3.36E+17
H-3	1.5E+15	1.25E+15	Not calculated	1.70E+15
I-129	6.9E+10	7.47E+10	6.73E+10	Not calculated
I-131	2.4E+18	2.34E+18	2.71E+18	2.45E+18
La-140	4.5E+18	4.43E+18	4.28E+18	7.76E+18
Np-239	3.9E+19	4.32E+19	4.58E+19	Not calculated
Pu-238	3.9E+15	4.57E+15	Not calculated	4.24E+15
Pu-239	9.1E+14	8.83E+14	9.57E+14	8.39E+14
Pu-240	1.3E+15	1.04E+15	7.66E+14	1.37E+15
Pu-241	2.6E+17	2.81E+17	3.28E+17	2.74E+17
Pu-242	3.1E+12	3.41E+12	Not calculated	Not calculated
Ru-103	3.4E+18	3.00E+18	2.92E+18	3.50E+18
Ru-106	1.0E+18	8.71E+17	8.31E+17	1.15E+18
Sr-89	2.4E+18	2.21E+18	2.23E+18	2.44E+18
Sr-90	2.4E+17	1.91E+17	1.73E+17	Not calculated
Te-129m	1.1E+17	7.06E+16	5.88E+16	1.14E+17
Te-132	3.3E+18	3.36E+18	3.63E+18	3.67E+18
U-235	1.1E+11	7.16E+11	1.49E+11	Not calculated
U-238	1.1E+12	1.11E+12	1.11E+12	Not calculated
Zr-95	4.0E+18	3.40E+18	3.47E+18	4.12E+18

* PNNL in Ref. [83] indicated that the results were for Unit 3. However, they are presented here as for Unit 2 because the corresponding input data are a better match for the Unit 2 core.

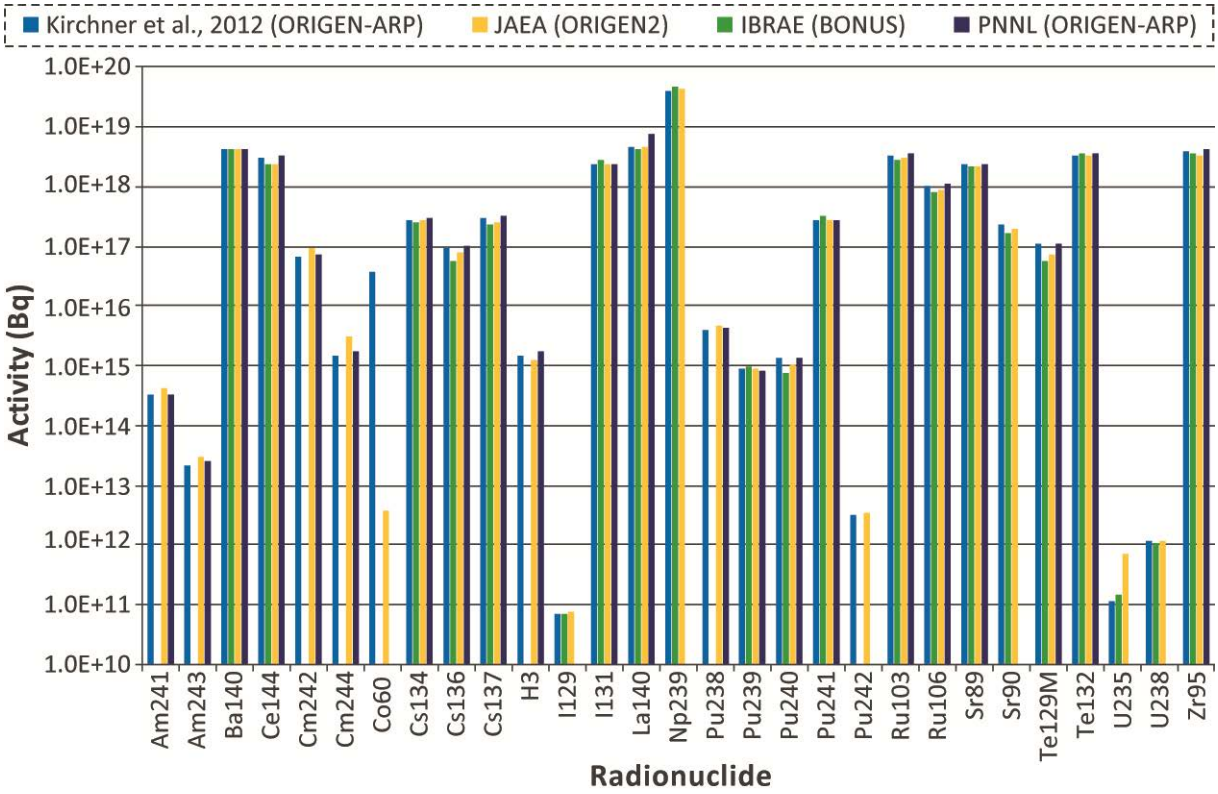


FIG. 1.4–1. Comparison of calculated activity of major radionuclides for the Unit 2 core [82-84, 87].

Tables 1.4–4 and 1.4–5 present the comparison of calculated inventories for Units 2 and 3 at two points in time: the time of reactor shutdown and the approximate time of core damage. It should be noted that, based on the current understanding of the accident progression, core degradation and major atmospheric releases occurred some 4–5 hours after Unit 1 tripped, some 70–80 hours after Unit 2 tripped and some 40–50 hours after Unit 3 tripped. At such times after reactor shutdown the shortest lived nuclides would have already decayed, so the tables only list those nuclides that have a half-life of at least 1 hour and which are major contributors to the radiological consequences.

TABLE 1.4–4. RADIONUCLIDE INVENTORY (IN Bq) IN THE UNIT 2 CORE AT DIFFERENT TIMES [82, 83, 87]

Nuclide	At time of scram			72 h after scram	
	JAEA (ORIGEN)	IBRAE RAN (BONUS)	PNNL (ORIGEN-ARP)	JAEA (ORIGEN)	IBRAE RAN (BONUS)
Cs-134	2.76E+17	2.49E+17	2.97E+17	2.76E+17	2.48E+17
Cs-136	8.17E+16	5.83E+16	9.59E+16	6.98E+16	4.97E+16
Cs-137	2.55E+17	2.29E+17	3.36E+17	2.55E+17	2.29E+17
I-131	2.34E+18	2.71E+18	2.16E+18	1.87E+18	2.15E+18
I-133	4.90E+18	4.91E+18	Not calculated	4.58E+17	4.60E+17
Te-132	3.36E+18	3.63E+18	2.69E+18	1.76E+18	1.92E+18
Te-127	1.74E+17	1.90E+17	1.85E+17	1.16E+17	1.34E+17
Te-127m	1.21E+16	2.62E+16	3.37E+16	1.23E+16	2.62E+16
Ba-140	4.35E+18	4.27E+18	3.98E+18	3.70E+18	3.63E+18
Sb-125	1.65E+16	1.52E+16	2.17E+16	1.65E+16	1.52E+16
Nb-95	2.88E+18	2.98E+18	4.14E+18	2.91E+18	3.00E+18
Sr-89	2.21E+18	2.23E+18	2.4E+18	2.12E+18	2.14E+18
Sr-90	1.91E+17	1.73E+17	Not calculated	1.91E+17	1.73E+17
La-140	4.43E+18	4.28E+18	4.28E+18	4.09E+18	3.99E+18
Zr-95	3.40E+18	3.47E+18	4.06E+18	3.30E+18	3.35E+18
Pu-238	4.57E+15	Not calculated	4.24E+15	4.60E+15	Not calculated
Pu-239	8.83E+14	9.57E+14	8.39E+14	8.90E+14	9.57E+14
Pu-240	1.04E+15	7.66E+14	1.37E+15	1.04E+15	7.66E+14
Pu-241	2.81E+17	3.28E+17	2.74E+17	2.81E+17	3.28E+17
Ag-110m	6.41E+15	Not calculated	3.89E+15	6.34E+15	Not calculated
Kr-85	3.11E+16	3.11E+16	3.42E+16	3.11E+16	3.10E+16
Xe-131m	2.57E+16	2.94E+16	Not calculated	2.53E+16	2.90E+16
Xe-133	4.67E+18	5.06E+18	4.54E+18	3.74E+18	4.02E+18
Xe-133m	1.37E+18	1.50E+17	Not calculated	8.11E+16	5.79E+16
Rb-86	4.50E+15	Not calculated	Not calculated	4.02E+15	Not calculated
Te-125m	5.38E+15	3.11E+15	4.72E+15	5.40E+15	3.12E+15
Tc-99m	3.88E+18	3.91E+18	3.27E+18	1.99E+18	2.02E+18
Mo-99	4.43E+18	4.46E+18	3.4E+18	2.08E+18	2.09E+18
Nb-95m	3.03E+16	2.06E+16	4.7E+16	3.02E+16	2.05E+16
Sb-124	7.91E+14	Not calculated	Not calculated	7.65E+14	Not calculated
Sn-123	1.33E+15	2.06E+15	3.11E+15	1.31E+15	2.03E+15
Sn-125	1.03E+16	2.18E+16	Not calculated	8.28E+15	1.75E+16
Ag-111	1.07E+17	1.02E+17	Not calculated	8.11E+16	7.71E+16
I-132	3.43E+18	3.70E+18	2.76E+18	1.81E+18	1.98E+18
Sm-151	8.87E+14	1.00E+15	1.02E+15	8.99E+14	1.01E+15
Np-239	4.32E+19	4.58E+19	Not calculated	1.80E+19	1.90E+19
Cm-244	3.21E+15	Not calculated	1.69E+15	3.21E+15	Not calculated
U-237	1.32E+18	Not calculated	1.35E+18	9.73E+17	Not calculated
Eu-156	3.21E+17	9.87E+16	3.38E+17	2.81E+17	8.70E+16
Y-90	1.95E+17	1.72E+17	2.75E+17	1.93E+17	1.73E+17
Pm-147	4.19E+17	3.89E+17	6.2E+17	4.21E+17	3.92E+17
Cm-242	8.94E+16	Not calculated	7.18E+16	8.89E+16	Not calculated
Ru-106	8.71E+17	8.31E+17	1.15E+18	8.66E+17	8.26E+17
Ru-103	3.00E+18	2.92E+18	3.41E+18	2.84E+18	2.77E+18
Ce-144	2.31E+18	2.37E+18	3.36E+18	2.30E+18	2.35E+18

TABLE 1.4–5. RADIONUCLIDE INVENTORY (IN Bq) OF UNIT 3 CORE AT DIFERENT TIMES [82, 87]

Nuclide	At time of scram		72 h after scram	42 h after scram
	JAEA (ORIGEN)	IBRAE RAN (BONUS)	JAEA (ORIGEN)	IBRAE RAN (BONUS)
Cs-134	2.52E+17	2.34E+17	2.51E+17	2.34E+17
Cs-136	8.18E+16	5.62E+16	6.99E+16	5.12E+16
Cs-137	2.41E+17	2.21E+17	2.41E+17	2.21E+17
I-131	2.33E+18	2.72E+18	1.86E+18	2.39E+18
I-133	4.90E+18	4.91E+18	4.57E+17	1.25E+18
Te-132	3.37E+18	3.65E+18	1.76E+18	2.52E+18
Te-127	1.78E+17	1.95E+17	1.20E+17	1.64E+17
Te-127m	1.33E+16	2.74E+16	1.34E+16	2.74E+16
Ba-140	4.35E+18	4.27E+18	3.69E+18	3.88E+18
Sb-125	1.57E+16	1.47E+16	1.57E+16	1.47E+16
Nb-95	3.26E+18	3.25E+18	3.28E+18	3.26E+18
Sr-89	2.35E+18	2.36E+18	2.26E+18	2.30E+18
Sr-90	1.81E+17	1.67E+17	1.81E+17	1.67E+17
La-140	4.42E+18	4.27E+18	4.08E+18	4.15E+18
Zr-95	3.68E+18	3.69E+18	3.56E+18	3.62E+18
Pu-238	5.53E+15	Not calculated	5.56E+15	Not calculated
Pu-239	1.04E+15	1.10E+15	1.05E+15	1.10E+15
Pu-240	1.36E+15	1.11E+15	1.36E+15	1.11E+15
Pu-241	3.15E+17	4.10E+17	3.15E+17	4.10E+17
Ag-110m	5.99E+15	Not calculated	5.94E+15	Not calculated
Kr-85	2.95E+16	2.99E+16	2.95E+16	2.99E+16
Xe-131m	2.60E+16	2.96E+16	2.55E+16	2.95E+16
Xe-133m	1.40E+17	1.50E+16	8.23E+16	8.61E+16
Xe-133	4.67E+18	5.06E+18	3.74E+18	4.59E+18
Rb-86	4.35E+15	Not calculated	3.89E+15	Not calculated
Te-125m	5.00E+15	2.95E+15	5.01E+15	2.96E+15
Tc-99m	3.86E+18	3.91E+18	1.99E+18	2.76E+18
Mo-99	4.42E+18	4.45E+18	2.08E+18	2.87E+18
Nb-95m	3.29E+16	2.20E+16	3.28E+16	2.20E+16
Sb-124	7.99E+14	Not calculated	7.72E+14	Not calculated
Sn-123	1.39E+15	2.14E+15	1.37E+15	2.12E+15
Sn-125	1.06E+16	2.24E+16	8.53E+15	1.97E+16
Ag-111	1.12E+17	1.07E+17	8.50E+16	9.09E+16
I-132	3.43E+18	3.72E+18	1.81E+18	2.59E+18
Sm-151	9.08E+14	1.03E+15	9.21E+14	1.04E+15
Np-239	4.30E+19	4.44E+19	1.79E+19	2.66E+19
Cm-244	2.71E+15	Not calculated	2.71E+15	Not calculated
U-237	1.28E+18	Not calculated	9.38E+17	Not calculated
Eu-156	3.12E+17	1.02E+17	2.73E+17	9.54E+16
Y-90	1.85E+17	1.66E+17	1.83E+17	1.66E+17
Pm-147	4.07E+17	3.80E+17	4.10E+17	3.82E+17
Cm-242	1.04E+17	Not calculated	1.03E+17	Not calculated
Ru-106	8.48E+17	8.16E+17	8.43E+17	8.14E+17
Ru-103	3.25E+18	3.15E+18	3.08E+18	3.06E+18
Ce-144	2.27E+18	2.29E+18	2.26E+18	2.28E+18

1.4.2. Radionuclide release mechanisms

1.4.2.1. Release from the cores to the RPVs

Fukushima Daiichi NPP Units 1, 2 and 3 experienced core meltdowns and radionuclides were released from the cores to the RPVs. With increasing fuel burnup, a certain fraction of the fission products migrate out of the fuel material into the gas space between the fuel pellets and the cladding tubes [88, 89]. Roughly 5–15% of the core inventory of noble gases, iodine and caesium are located in these gas gaps. In an accident when the core overheats, the fuel cladding fails and the contents of this gap are released to the RPV.

As the RPV pressurization is controlled by SRV cycling, from the outset of core degradation some radionuclides (mainly the noble gases) will be carried by steam to the SC pool of the PCV.

As the core degradation proceeds, leading eventually to melting of the core material, the fission products initially trapped within the nuclear fuel become volatile and released from the core material. The time and amount of release of the different fission product elements depends on their respective volatilization temperatures, as follows:

— Highly volatility elements like the noble gases, i.e. xenon (Xe), krypton (Kr), caesium (Cs), iodine (I), or tellurium (Te) and relevant chemical compounds of these elements, are released completely from the core in the early phase of core degeneration, when the core is still inside the RPV.
— Medium volatility elements like strontium (Sr) and barium (Ba) are released from the core during the in-vessel phase as well as during the ex-vessel phase. These medium volatile fission products dominate the release during the accident phase after RPV failure.
— Low volatility elements like zirconium (Zr), niobium (Nb), and the actinides (U, Pu, Np, Am) and their oxides, have a boiling point well above the temperatures reached in a core melt, and so only trace amounts of them are released. When the RPV fails and the core material falls into the reactor pit, the core melt no longer contains significant amounts of volatile fission products. Thus, the release of highly volatile fission products is expected to be low in this late phase of a core melt accident.

1.4.2.2. Transport to the PCV

After the fission products are released from the overheated reactor core, the noble gases, as well as the fission product vapours are transported by flows of gas or steam into cooler regions of the primary containment vessel (PCV). The fission product vapours start to condense to form small airborne particles (aerosols). These aerosols and the noble gases are then further transported by flows of gas or steam until they are either retained (e.g. by condensation, plate-out, scrubbing, etc.) inside the PCV or released into the environment through PCV leaks. The presence of very hot, high pressure steam in the RPV can create a number of possible leak paths, such as through the flanges of the SRVs or the seals of the recirculation pumps, for the other radionuclides to escape into the dry well and the SC of the PCV. While a fraction of the fission products released from the reactor core will be trapped in the water of the pressure suppression pool the remainder may be dispersed within the PCV and eventually released from the PCV to the outside atmosphere by either a controlled or an uncontrolled route. Finally, when high temperature core melt causes the RPV to fail, the molten debris is released directly to the RPV in the ex-vessel configuration.

Units 1–3 at Fukushima Daiichi NPP experienced radionuclide release both by steam transport from the RPV and by ex-vessel phenomena [7].

1.4.2.3. Release to the environment from the PCV

Those aerosols not trapped within liquid or on surfaces of structures, may be released from the PCV into the environment. Three different release paths can be distinguished at the Fukushima Daiichi nuclear power plant:

— Design leakage. In the Fukushima Daiichi containment design, the maximum design leakage was 0.5 vol. % per day at the design pressure. These leakages cause contamination of the reactor building (RB) relatively soon after the occurrence of core damage. This limits personnel access to the RB and thus hinders recovery actions. The RB is essentially a conventional structure with a design in-leakage of about 100 vol. % per day at a 5×10^{-5} MPa (0.5 mbar) sub-atmospheric pressure (the normal sub-pressure during power operation). Due to this low leakage rate, the aerosols escaping the PCV could remain for a long time inside the RB and a large fraction could settle out within that building, providing that the sub-atmospheric pressure could be maintained. To further reduce aerosol release from the RB, a filtered ventilation system keeps the building below the atmospheric pressure. Systems for maintaining sub-atmospheric pressure and filtered ventilation were inoperable due to loss of AC power.
— Containment venting. If there is an uncontrollable pressure buildup in the PCV, it can fail due to overpressurization. Therefore, the Fukushima Daiichi NPP units were equipped with a dedicated venting system to depressurize the PCV in a controlled manner. In Japan, the underlying philosophy was to vent as late as possible (or not vent until it is inevitable) in order to delay or prevent direct release of radioactive material to the public and the environment. As explained in Section 1.3, after the accident internal pressure rose rapidly in the PCVs of Units 1–3, and so the operators attempted to vent on several occasions, with mixed success. During venting of the PCV radioactive products were released unfiltered to the environment through the vent stacks. When venting took place from the SC, it is estimated that much of the vent gases were scrubbed within the water pool, resulting in a relatively lower release compared with the case where venting took place directly from the DW.
— Containment failure. The PCV can fail due to pressure buildup, by experiencing temperatures in excess of design values, or by transient phenomena such as hydrogen explosions. In the design of the Fukushima Daiichi nuclear power plant, PCV nitrogen inerting was used to prevent hydrogen combustion. The containment was designed to withstand an internal pressure and periodically tested at 115% of the design pressure. In addition to overpressure failure, the PCV can also fail if temperatures above design lead to failure of PCV penetrations, especially by thermal decomposition of the organic sealing materials. Venting or failure of the PCVs in three Fukushima Daiichi NPP units resulted in gas and steam escaping from the PCV and entering the RB. This gas/steam flow also transported a large volume of hydrogen into the building, resulting in hydrogen accumulation and several explosions that caused severe damage to the structure. Furthermore, this leakage released significant amounts of radioactive airborne aerosols into the building, and eventually into the environment.

1.4.2.4. Postulated atmospheric release pathways during the accident

Source term analyses indicate that the major releases that contributed most to the radiological consequences on Japanese territory occurred on 15 March. They were probably related to the release of activity from Unit 2 due to core melting and subsequent loss of PCV integrity early in the morning, or to PCV venting at Unit 3 that can be deduced from TEPCO information about operator actions and pressure drop readings in the DW after 16:00. Other large peaks of activity release are thought to have occurred in the afternoon on 12 March (explosion at Unit 1), at noon on 14 March (explosion at Unit 3), and late at night on the same day (probably due to venting of Unit 3).

However, Fig. 1.4–2 demonstrates that there is not an obvious correlation between the events thought to have produced the significant releases to the atmosphere and the dose rate measurements made by TEPCO during the accident at the measurement points (MP) shown in Fig. 1.4–3. Some dose rate peaks do not coincide with any event and some events seem to have had no impact on the dose rates.

Unit	Symbol in Fig.	Time of occurrence	Event
1	1a	12.03.2011 14:00	Venting No. 1
	1b	12.03.2011 15:36	Explosion
2	2a	14.03.2011 21:00	Venting No.1 or PCV leakage
	2b/4a	15.03.2011 06:15	Loud sound in torus room
	2c	15.03.2011 11:25	DW pressure drop
3	3a	13.03.2011 09:20	Venting No. 1
	3b	13.03.2011 12:30	Venting No. 2
	3c	13.03.2011 20:30	Venting No. 3
	3d	14.03.2011 05:20	Venting No. 4
	3e	14.03.2011 11:01	Explosion
	3f	14.03.2011 16:00	Venting No. 5
	3g	15.03.2011 16:05	Venting No. 6
	3h	16.03.2011 02:00	Venting No. 7
	3i	17.03.2011 21:30	Venting No. 8
	3j	18.03.2011 05:30	Venting No. 9
	3k	20.03.2011 11:25	Venting No.10
4	4a	15.03.2011 06:15	Explosion

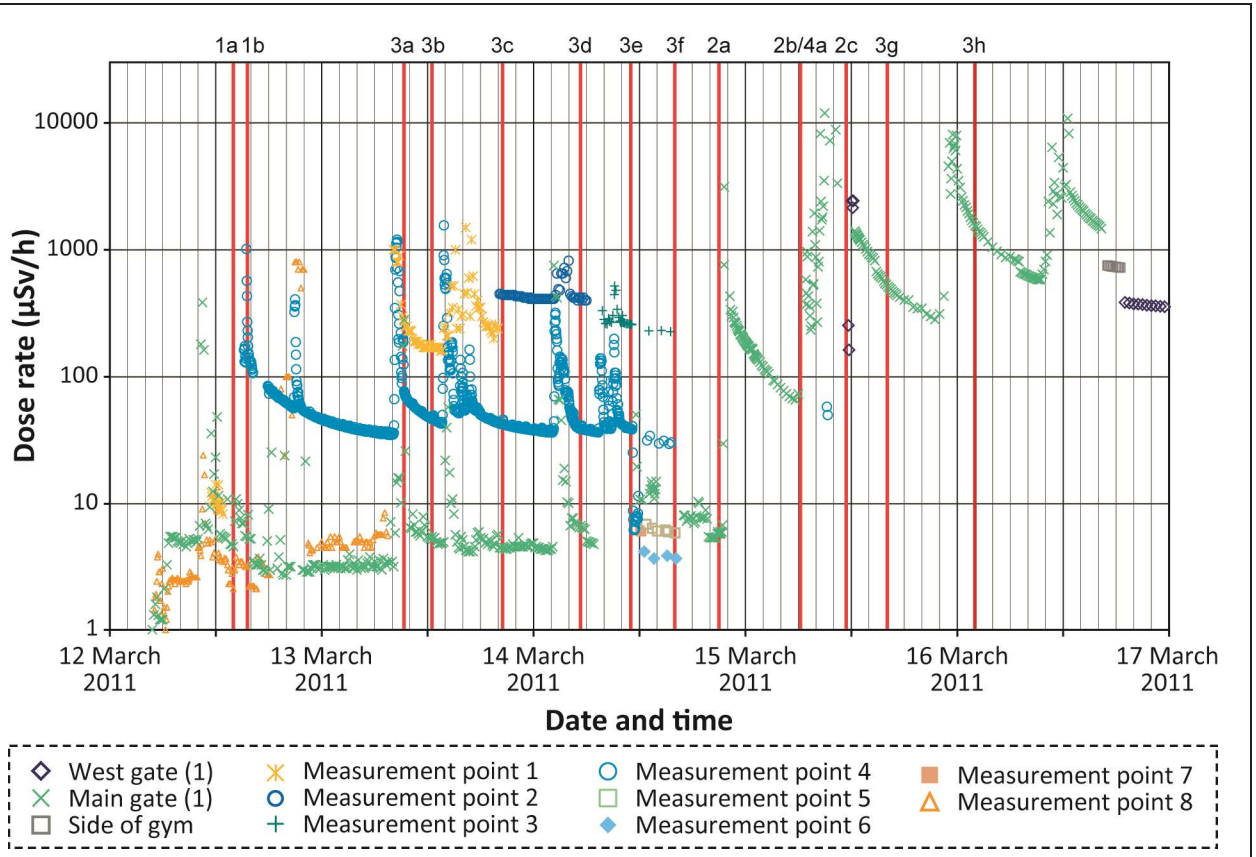


FIG. 1.4–2(a). Graph of dose rates measured at the Fukushima Daiichi site between 11 and 17 March 2011 (the vertical red lines indicate the major events registered during the accident).

Unit	Symbol at Fig.	Time of occurrence	Event
3	3i	17.03.2011 21:30	Venting No. 8
	3j	18.03.2011 05:30	Venting No. 9
	3k	20.03.2011 11:25	Venting No. 10

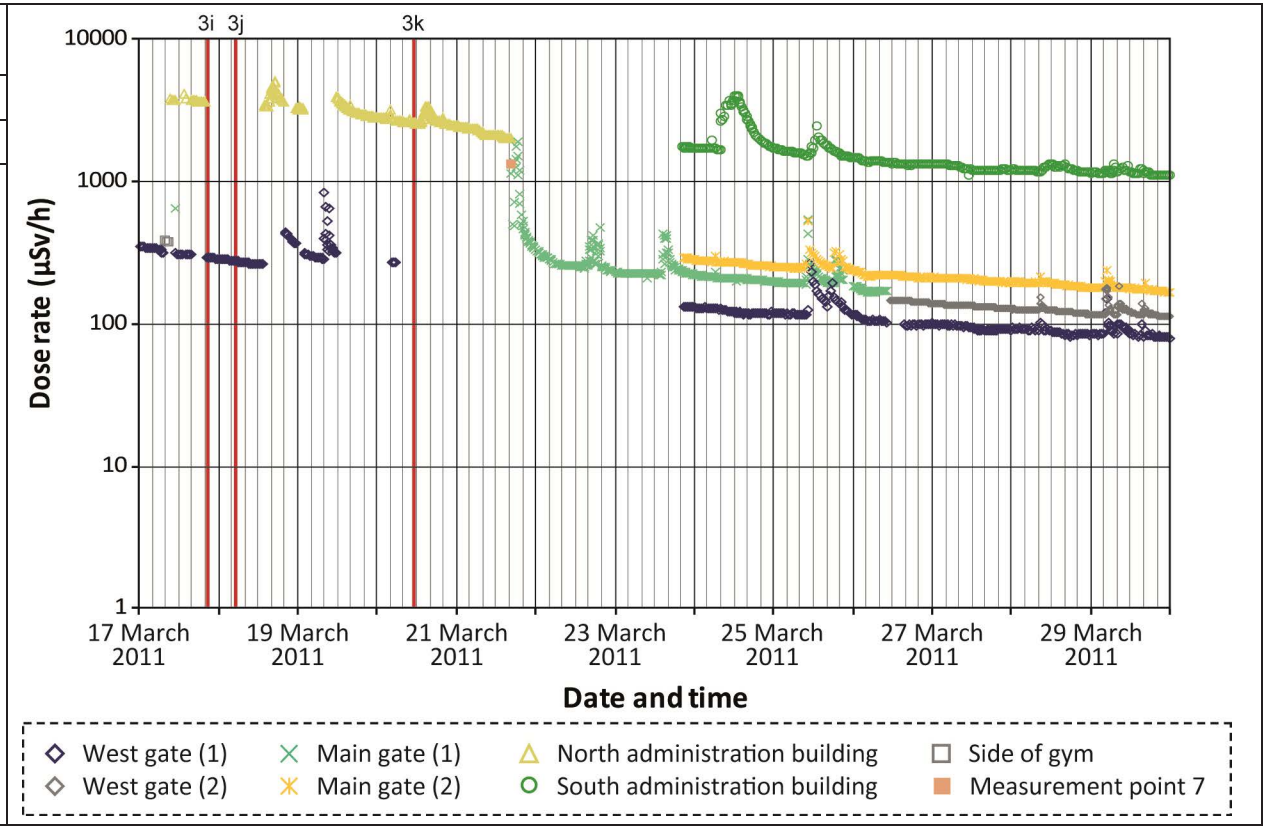


FIG.1.4–2(b). Graph of dose rates measured at the Fukushima Daiichi site between 17 and 30 March 2011 (the vertical red lines indicate the major events registered during the accident).



FIG. 1.4–3. Location of monitoring points at the Fukushima Daiichi site.

The first increase in dose rate at the site was measured near the main gate and the measuring point MP8 at 04:00–05:00 on 12 March. At around 10:00, the dose rate increased sharply at the same location. This can be correlated to Unit 1 SC venting, as multiple attempts to open the valves in the ventilation line were reported by TEPCO. However, the success of these attempts is unknown. The other postulated path besides venting could be a PCV leakage.

At 14:00, the PCV was vented at Unit 1 but it did not have a large impact on the dose rate readings available at this time. However, the first value measured at MP4 was about 0.16 mSv/h, well above the background level observed at the main gate and MP8. An abrupt peak of dose rate (~1 mSv/h) was measured near MP4 few minutes before the explosion at 15:36 at Unit 1, and explosion itself did not reveal any dose rate increase among readings available. The reason of this is currently unclear. Later, between 20:00 and 21:00, another release occurred and the dose rate increased to 0.4–0.6 mSv/h at MP4 and MP8. The cause of this release is not clear from the data.

On the next day, 13 March, the PCV at Unit 3 was vented at 09:20, giving a release confirmed by measurements made at the main gate measuring points MP4 and MP1 and by observation at the top of the vent stack by the live cameras. An identical peak was produced by another Unit 3 venting that was performed at 12:30, which was also accompanied by smoke coming from the vent stack. The success of the third Unit 3 venting at 20:30 is still questionable because it did not produce any dose rate change. Also, no events were observed at 02:00 on 14 March, when the dose rate increased at MP2, MP4 and the main gate.

The fourth venting operation at Unit 3 on 14 March (05:20) does not strictly coincide with the time of the peak (07:30–09:00) either. The explosion at Unit 3 (11:01) seems to have had a rather small effect on the measured dose rates, which only rose to 0.05 mSv/h at the main gate. A much larger reading (3 mSv/h) was registered at the main gate after the venting of Unit 2 PCV at 21:00 (success of venting is not confirmed). That event was followed by a drop in pressure in the SC, and an increase in pressure in the DW. The inconsistency in pressure changes in two connected parts of the PCV has not yet been explained, and it raises doubts about the efficiency of the venting as a postulated path of Unit 2 PCV leakage.

Neutrons were detected between 05:30 and 10:50 on 13 March by a mobile radiation monitor near the main gate which is around 1 km away from the RBs of Units 1–3. The measured neutron dose rates were between 0.01 μSv/h[148] and 0.02 μSv/h. Neutrons were also detected between 21:00 on 14 March and 01:40 on 15 March near the main gate. The measured neutron dose rates were again 0.01–0.02 μSv/h. These could indicate the core damage and inventory release from Unit 3 and Unit 2, respectively, following the loss of cooling function.

Early in the morning on 15 March, a loud sound came from the Unit 2 torus room, followed by a pressure drop first in the Unit 2 SC and a few hours later in the Unit 2 DW, which was confirmed by operators. About at the same time an explosion occurred at Unit 4. As a result, the dose rate reached a maximum value at the main gate of nearly 12 mSv/h. A large release to the Unit 2 reactor building compartments took place, followed by leakage to the atmosphere. This was confirmed by live camera images of an intensive steam flow through the orifice left in the Unit 2 reactor building wall by a previously broken blow-out panel.

On the evening of 15 March, the dose rate rose again to about 10 mSv/h at the boundary of the site, although there were no major events at around that time (21:00–22:00). A Unit 3 venting had taken place much earlier, at 16:05. The same inconsistency is seen at 09:00–10:00 on 16 March when the

[148] The lowest detectable limit of the neutron monitor.

level of 10 mSv/h was reached for a third time. There were no venting operations near that time, the closest being at 01:55 which, in any event, was not considered to have been successful.

In the following days, there were no more large releases, and dose rates did not exceed 1 mSv/h, with the average value being 0.35 mSv/h. In the north administrative building a background dose rate of 3 mSv/h was recorded, due to the deposition of radioactive material that was released earlier on 15 March. Venting operations were attempted several times at Unit 3 [90], but there is no clear evidence that they were successful or led to radioactive releases.

On 21 March, at 16:00–18:00, another fluctuation in the dose rate (~2 mSv/h) was registered near the main gate. This may have been related to the emission of smoke for a long time from the reactor buildings at Unit 3 (at 15:55) and Unit 2 (at 18:22).

After 21 March, the measurements showed a steady decline in the dose rates at the site, with some minor peaks. On 24 and 25 March, at around 13:00, the dose rate at the south side of administrative building increased twice to 4 mSv/h and 2.5 mSv/h, respectively. The second increase was also registered at the west and the main gates.

Further discussion of radiological release and their consequences is provided in Technical Volume 4, Section 4.1.

1.4.3. Amount of radionuclides released

The amount of radionuclides released, also called the 'source term', comprises radionuclides released from the cores and confining structures into the environment during and after the accident at the Fukushima Daiichi NPP. In this section, the radionuclide release is given either as a percentage of the core inventory, or in becquerels (Bq) or peta becquerels (PBq) (= 10^{15} Bq).

While the radioactive noble gases are diluted in the atmosphere, the aerosols formed and dispersed from the nuclear accident sooner or later deposit on surfaces. The isotopic composition of the deposit is relevant in two respects. On the one hand, it can give valuable information about core degradation and the mechanisms of fission product generation and release. On the other hand, it plays a vital part in the assessment of the radiological consequences for the environment as different radioactive isotopes and elements contribute differently to these consequences.

Gamma spectroscopic measurements of the deposition were analysed in various countries [91, 92] and radioactive isotopes of the following elements were detected: iodine, caesium, tellurium, lanthanum, antimony, technetium, barium and silver (I, Cs, Te, La, Sb, Tc, Ba and Ag).

1.4.3.1. High volatility elements

Isotopes of the elements iodine and caesium dominated the activity deposited on the ground by at least one order of magnitude, followed by the tellurium isotope, ^{132}Te [92]. The dominance of these elements originates from their low vapour pressure, which results in their virtually complete release from the nuclear fuel during a core meltdown.

1.4.3.2. Medium volatility elements

The deposited activity of the medium volatile barium (as isotope ^{140}Ba) lies about two to three orders of magnitude below Cs and/or I activity. Assuming a full release of Cs from the reactor core, this indicates a Ba release from the nuclear fuel of below 1%. Other medium volatile elements, such as antimony (Sb) and niobium (Nb), show similar release fractions [92]. The release of medium volatile fission products is therefore much lower than observed after the Chernobyl accident [93].

Of special scientific interest was the unexpectedly low release of ^{95}Nb, as it had been assumed previously that the chemical compound Cs_2XxO_4 (with Xx = early transition elements) contributed significantly to the fission product release from the nuclear core of a light water reactor. However, if this assumption were correct, a release of the early transition elements in the order of tens of per cent would have been expected, i.e. two to three orders of magnitude higher than observed.

The strontium isotopes ^{89}Sr and ^{90}Sr decay via beta decay, practically without emitting gamma radiation, making them invisible to gamma spectroscopy. Therefore, the strontium contamination was measured by radiochemical analysis which showed that the release of strontium was three to four orders of magnitude less than the release of caesium [94].

1.4.3.3. Refractory elements

In the gamma spectra of the deposited material, only the low volatile lanthanum isotope ^{140}La was detected. However, the observed ^{140}La is the daughter nuclide from the decay of ^{140}Ba, and not a sign of significant La release during the core meltdown. Further, there is the total absence of the ^{95}Zr line at 757 keV, showing that no significant amount of radioactive Zr was released [92].

1.4.3.4. Iodine and caesium

There were releases of long lived medium or low volatility fission products from the Fukushima Daiichi NPP reactors, but the atmospheric release was dominated by volatile isotopes of iodine and caesium. The chemical composition of the fission product release had the direct consequence on the land contamination. The contamination was dominated by the deposition of ^{131}I, ^{134}Cs and ^{137}Cs during the first days and weeks of the accident, and by ^{134}Cs and ^{137}Cs afterwards, when most of the iodine had decayed (with a half-life of 8 days). As caesium forms water soluble compounds, the land contamination decreases faster than would be expected by its radioactive decay alone. However, it persists in the environment for several years [91, 94, 95]. More information is provided in Technical Volume 4, Section 4.1.

1.4.3.5. Plutonium

Isotopes of plutonium can be major contributors to total radiological risk if they are inhaled or ingested. Most of the low volatility actinides are alpha emitters, which cannot be detected by gamma spectroscopy. Therefore, between 25 and 28 March 2011, several samples of soil, plants, litter and water were collected at different locations around the site to examine for contamination with plutonium. It should be noted that the isotopes of plutonium are still present in the environment due to nuclear weapon tests in the 1950s and 1960s, but their concentration is very low, about 0.15 Bq/kg in Japan [75] and ~1 Bq/kg in the USA [96]. Only a few samples collected after the Fukushima Daiichi accident showed the isotopic signature of reactor plutonium, in excess of the concentration ratios associated with historical nuclear weapon tests [97-99]. The concentration of plutonium isotopes found at the Fukushima Daiichi site (^{239}Pu and ^{240}Pu ~0.1 Bq/kg together [98, 99]) corresponded to the background level, indicating that the releases of plutonium from the Fukushima Daiichi units during the accident were limited. The isotopic ratios and concentrations of plutonium varied between neighbouring sampling areas (which indicates that the plutonium was in particulate form), resulting in a non-uniform deposition. There is possibility of locations with larger deposition, however, the data indicate that plutonium release due to the core melts in the Fukushima Daiichi NPP did not notably increase the environmental distribution of plutonium.

1.4.4. Atmospheric release

Multiple estimations of the atmospheric source term were made in 2011–2013 by different organizations around the world, as presented in Table 1.4–6. Most of them predict the total activity

released between 11 and 31 March 2011 in terms of ^{131}I, ^{137}Cs and ^{133}Xe. Figures 1.4–4 and 1.4–5 illustrate some of those estimated release rates of ^{137}Cs and ^{131}I extracted from the studies listed in Table 1.4–4. Some of the studies provide uncertainty ranges for their estimations, which are shown in these figures. Both figures include comparisons to the much higher total releases from the Chernobyl accident. A statistical analysis of the numerical studies for Fukushima Daiichi was performed. The major results of this analysis are the mean values and confidence limits for the major isotopes. Further discussion and results are given in Technical Volume 4, Section 4.1.

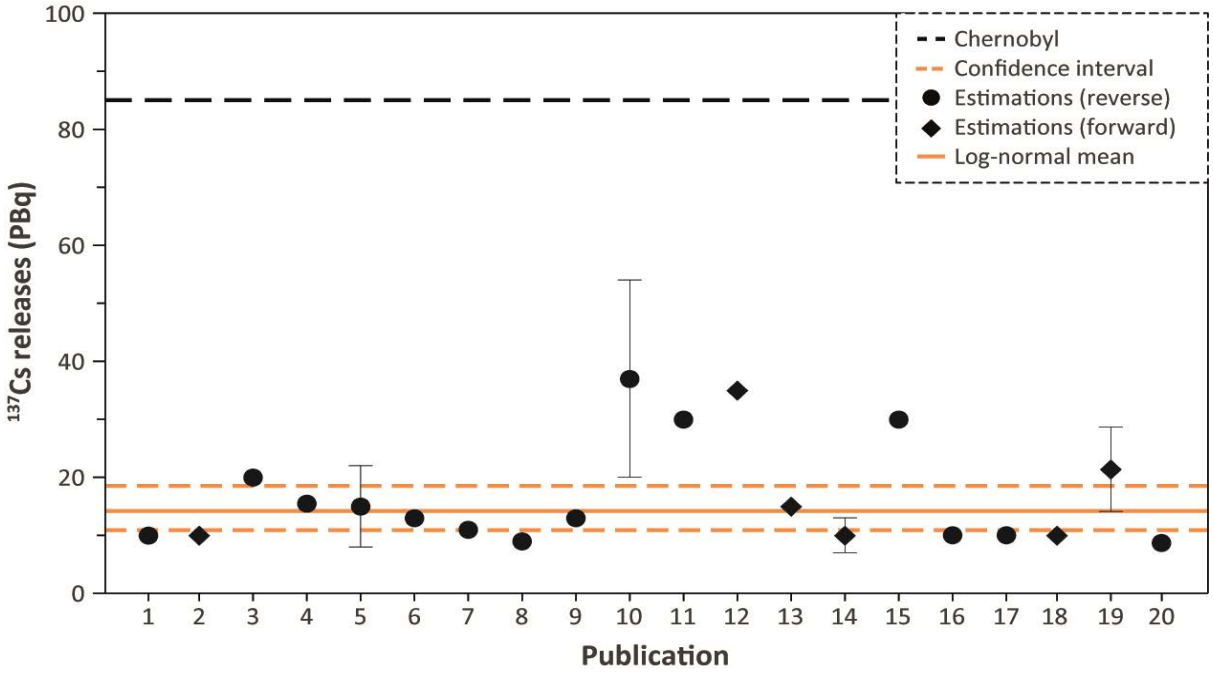


FIG. 1.4–4. Estimated atmospheric releases of ^{137}Cs (see Table 1.4–6).

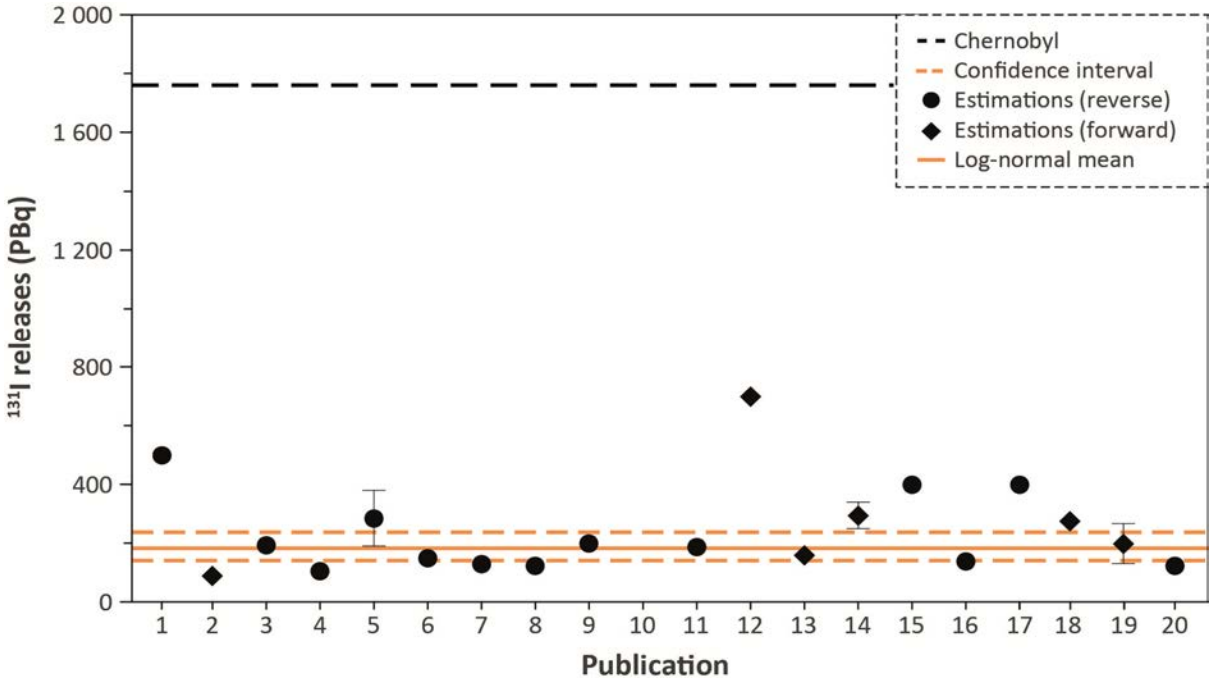


FIG. 1.4–5. Estimated atmospheric releases of ^{131}I (see Table 1.4–6).

TABLE 1.4–6. SUMMARY OF DIFFERENT ESTIMATES FOR THE ATMOSPHERIC SOURCE TERM IN 2011 (^{137}CS, ^{131}I, ^{133}XE), IN PBq

	Author publication	^{137}Cs	^{131}I	^{133}Xe	Release duration	Method used	Models or codes used
1	TEPCO, 2012 [6, 100]	10	500	0.5×10^3	12.03–31.03	Reverse modelling	Weather data (measurements on site and AMEDAS)/ DIANA
2	IRSN-1, 2011 (Emergency Response) [101]	10	90	2×10^3	11.03–22.03	Estimate of reactor state, analysis of information	Available operational data about the accident progression and reactor state
3	IRSN-2, 2012 [101-103]	20–21	190–197	5.9×10^3	11.03–27.03	Forward + reverse modelling	ECMWF + ARPEGE + local observations/ C3X (ldX+pX)/ ASTRID
4	IRSN-3, 2013 [104]	15.5	105.9	12×10^3	11.03–27.03	Reverse modelling	ECMWF/ C3X (ldX)
5	CEREA, 2012 [105, 106]	12–19, uncertainty 15–20%	190–380, uncertainty 5–10%	—	11.03–27.03	Reverse modelling	ECMWF, WRF/ Polair3D (polyphemus platform)
6	JAEA-1, 2011 (Chino et al.) [107]	13	150	—	12.03–05.04	Reverse modelling	SPEEDI (PHYSIC/ PRWDA21); WSPEEDI-II (MM5/GEARN)
7	JAEA-2/NSC, 2012 (Katata et al.) [2, 108, 109]	11	130	—	12.03–05.04	Reverse modelling, refinement of JAEA-1 source term	WSPEEDI-II (MM5/GEARN) + JMA data (WRF)
8	JAEA-3, 2012 (Terrada et al.) [110]	8.8	124	—	12.03–30.04	Reverse modelling, refinement of JAEA-2 source term	WSPEEDI-II (MM5/GEARN) + JMA data (WRF)
9	JAEA-4, 2013 (Kobayashi et al.) [111]	13	200	—	12.03–30.04	Reverse modelling	Same as JAEA-3 + SEA-GEARN
10	NILU, 2012 [112]	37, uncertainty 20–53	—	15×10^3, uncertainty (12–18) $\times 10^3$	11.03–05.04	Reverse modelling	ECMWF + NCEP GFS/ FLEXPART
11	IBRAE, 2012 [87, 113, 114]	30	188	0.4×10^3	15.03	Forward + reverse modelling (iterations)	SOCRAT/ ARW-WRF/ NOSTRADAMUS
12	SEC NRS, 2011 [115]	35	700	—	11.03–17.03	Estimate of fuel inventory, reactor state, analysis of information	SCALE6 (ORIGEN-ARP)/ WASH-1400/ NUREG-1150
13	NISA, 2011 [2, 116]	15	160	11×10^3	11.03–15.03	Forward modelling	MELCOR

TABLE 1.4–6. SUMMARY OF DIFFERENT ESTIMATES FOR THE ATMOSPHERIC SOURCE TERM IN 2011 (^{137}CS, ^{131}I, ^{133}XE), IN PBq (cont.)

	Author publication	^{137}Cs	^{131}I	^{133}Xe	Release duration	Method used	Models or codes used
14	JNES, 2012 [117]	7.3–13	250–340	9×10^3	11.03–17.03	Forward modelling	MELCOR
15	ZAMG, 2011 [118]	30	400	—	11.03–15.03	Reverse modelling	ECMWF/ FLEXPART
16	NIES, 2011 [119]	9.9 (100%–particulate, 1 μm)	142 (80%–gaseous form)	—	11.03–30.03	Reverse modelling	Models-3 CMAQ/ WRF + JMA data
17	CEA, 2012 [120]	10	400	6.0×10^3	12.03–01.05	Reverse modelling	MM5, WRF, NCEP GFS/ FLEXPART
18	SNL, 2013 [115]	10	276	7.9×10^3	11.03–15.03	Forward modelling	Fractional releases, ORIGEN core inventories
19	ENEA, 2014 [121]	21.4	199	5.56×10^3	11.03–16.03	Forward modelling	RASCAL 4.2
20	UNSCEAR, 2014 [122]	8.8	124 (50%–gaseous form)	7.3×10^3	Same as in JAEA-3	Reverse modelling	Same as in JAEA-3
	Chernobyl source term, IAEA, 2006 [93]	85	1760	6.5×10^3			

Comparing the various estimations of the atmospheric source term, shown in Table 1.4–6, illustrates between one and seven orders of magnitude for particularly relevant isotopes. Normally, it is impossible to draw conclusions from data with such a large scatter. However, the application of Bayesian statistics may help in some cases and can be applied to the analysis of release data from the Fukushima Daiichi accident. Assuming log-normal distribution of the data measured (or estimated) by various groups, the Bayesian analysis in which the quoted uncertainties are treated as the minimal ones, results in the values presented in the Table 1.4–7.

TABLE 1.4–7. UNCERTAINTIES IN ATMOSPHERIC SOURCE TERM ESTIMATES FOR KEY ISOTOPES

Isotope	Accuracy (%)	Normal		Log-normal	
		Mean (PBq)	Standard deviation (PBq)	Median (PBq)	Range (PBq)
^{131}I	25	144	32	183	141–237
	46*	144	36	200	154–259
^{133}Xe	25	469	238	9 425	4 879–18 208
	46	502	359	7 721	4 040–14 757
^{137}Cs	25	12.2	2.2	14.2	10.9–18.5
	46	12.4	2.5	15.7	12.1–20.4

* The largest uncertainty that was estimated by authors of the source term provided in Table 1.4–6.

The following conclusions can be drawn from these results:

— The differences between the estimations obtained within normal and log-normal distributions are not large; the means and medians coincide within the standard deviations.
— The estimated range of medians obtained for log-normal distributions (see last column of Table 1.4–7) includes the values corresponding to the maximum probabilities calculated for normal distribution; therefore, these ranges could be treated as representing our real knowledge of the releases (see also Figs 1.4–4 and 1.4–5).
— The log-normal distribution demonstrates the scatter of results better than the normal distribution, and so is more appropriate for considering possible health effects of the release.
— The data for ^{133}Xe are so dispersed that the normal distribution cannot be applied.

However, even with these uncertainties the different estimates of the releases of ^{131}I and ^{137}Cs are consistent and fall within a relatively narrow range: 90–700 PBq for ^{131}I, 7–50 PBq for ^{137}Cs. If the very first estimates made in March–April 2011 (when very limited information was available) are discarded, the range becomes narrower: 100–400 PBq for ^{131}I and 7–20 PBq for ^{137}Cs. The preliminary estimates of the source term for ^{133}Xe were more uncertain and were between 500 and 15 000 PBq. However, in more recent calculations this uncertainty has also decreased to give a range between 6000–12 000 PBq. For isotopes of elements other than iodine and caesium the range of the estimates is larger, because there were almost no direct measurements of these isotopes around the site.

1.4.4.1. Comparison with the atmospheric release from the Chernobyl accident

The total amount of aerosol based fission product releases from all of the Fukushima Daiichi NPP units was about one order of magnitude smaller than that from the Chernobyl accident [93]. Based even on the most conservative estimates, the releases of iodine and caesium did not exceed 25% and 45% of the Chernobyl release, respectively. The radionuclide release from Fukushima Daiichi NPP contained much less medium volatility isotopes such as ^{90}Sr, ^{103}Ru and ^{140}Ba, and practically no refractory elements like zirconium (^{95}Zr) [92] and plutonium (Pu) [75]. The releases of semi-volatile elements and non-volatile elements are estimated to be ~0.01–0.1% of those resulting from the Chernobyl accident. The release of plutonium isotopes from Fukushima Daiichi was estimated by UNSCEAR to be 10^{-6} GBq [123], which was four orders of magnitude lower than that released at Chernobyl [99]. The isotopic signature of the releases from the Fukushima Daiichi accident is a direct indication that core temperatures during the core degradation phase were lower than those from the Chernobyl accident.

The amount of radioactive noble gases released from the Fukushima Daiichi NPP exceeded the corresponding release from Chernobyl. The release of the noble gas ^{133}Xe is estimated in the later studies to be larger than the corresponding release at Chernobyl by a factor of 1.5–2. The explanation for this is the larger total fuel inventory of ^{133}Xe in the cores of Fukushima Daiichi NPP Units 1–3 compared with the Chernobyl core. However, as the noble gases do not contribute to deposition, their release had only a minor influence on the radiological consequences of the accident.

The smaller total atmospheric release in the Fukushima Daiichi accident compared with Chernobyl stems from the different accident scenarios and mechanisms of radioactive releases. In Chernobyl, the release started with a nuclear criticality accident which triggered an in-core steam explosion, causing an intensive ejection of the overheated core material and extensive burning of graphite and reactor materials over a long period of time. The core degradation could not be limited by the safety systems, and the release was not confined because RMBK reactors did not have a containment structure. The fast power spike or explosion not only overheated and fragmented the fuel, producing aerosols and particles containing all kinds of isotopes (including those that were non-volatile), but it also opened a direct path for radioactive product release to the environment, enhanced by entrainment in the smoke from graphite burning. At the Fukushima Daiichi NPP, there were no explosions within the cores, but

progressive heating, oxidation and meltdown of the cores. The energy in the cores was produced over a much longer time, so it did not instantly destroy all fission barriers and safety systems. The radioactive products were thus released from the core much more gradually, and some of the radioactive material was confined by containment structures which partially retained their general function. Also, scrubbing of radioactive products by the water in the suppression pool reduced the atmospheric release at the Fukushima Daiichi NPP. However some medium to non-volatile products were released to the atmosphere during the accident [97, 98]. The lack of measurements of these isotopes around the Fukushima Daiichi NPP site does not allow for a consistent analysis of the corresponding source term. The data available include the ratios of specific isotopes to key radionuclides, e.g. iodine and caesium. Such ratios are consistent for the isotopes of the same element, but may change over distance from the source because the isotopes of different elements may have different properties influencing their deposition.

1.4.5. Groundwater and ocean release

The oceanic release from the Fukushima Daiichi NPP was the largest release of radionuclides from a nuclear accident into an ocean based on the measured radionuclide concentrations. There were several ways by which radioactive material entered the ocean following the Fukushima Daiichi accident:

— Direct release from the flooded trenches and shafts;
— Atmospheric deposition onto the surface of the ocean during March–April 2011;
— Drainage of contaminated groundwater;
— Drainage of contaminated water from rivers;
— Planned release of low level wastewater;
— Runoff of deposited radioactive material following rains, typhoons, tides, etc.

Among these, the largest contributing factors to ocean contamination are thought to be the direct release of radioactive liquid effluents and atmospheric deposition.

During the accident and at a subsequent stage of molten core cool down, water was injected into the RPVs of Units 1–3. Some of it flowed from the RPV into the PCV through the possible openings, such as SRVs, gaps in flanges and/or RPV breaches which occurred during core heat up and melting, and then it drained from the PCV to the bottom compartments of the RB. On its way, the injected water came into contact with melted fuel and leached any soluble material and particulates. The flow rate of injected water was 350–400 m^3 per day.

Multiple estimates of the source term to the ocean were performed in 2011–2013 (Table 1.4–8). There is considerable variation between different analyses. The levels of radionuclides in the ocean were evaluated by sampling water, sediments and biota, together with numerical modelling of the dispersion of radioactive material. Numerical reconstruction of the marine source term was mainly based on measurements of ^{137}Cs and ^{131}I, two isotopes that are representative of dissolved substances. At the time of writing, most of the analyses provided the estimated radioactivity levels of ^{137}Cs, although some also estimated the levels of ^{134}Cs. Only few analyses provide a source term of ^{131}I, because its short half-life makes it difficult to determine from measurements undertaken in May 2011, when extensive measurements began. Activities of other radionuclides detected in sea water are usually referenced to ^{137}Cs or ^{134}Cs activity, with consideration of their decay. The activity ratio of ^{134}Cs to ^{137}Cs was close to 1. The presence of another gamma emitting isotope ^{110m}Ag with ratio ^{134}Cs:^{110m}Ag about 0.8–4.7 was found in zooplankton [124]. Activities of some other isotopes were found to be much lower than ^{137}Cs activity. Thus, for beta-emitting isotopes ^{90}Sr and ^{99}Tc the activity ratios were 0.02–0.24 [125, 126] and about 0.01 [125], respectively. The large uncertainty in the release of ^{90}Sr is explained by the scarcity of measurements in sea water.

As westerly winds were dominant during the initial atmospheric releases, wet and dry deposition of the airborne ^{137}Cs over the Pacific Ocean has to be accounted for in studies of the radionuclide levels in the ocean. As there were no measurements of dose rates above the ocean surface during atmospheric releases in the first weeks of the accident, the estimates of radioactive deposition are uncertain and vary over a wide range, from about 0.18 PBq to 10 PBq (Table 1.4–8). The fraction of the deposition over the ocean to the total level of deposit is also uncertain, with different studies ranging from 40–80% [112, 127].

TABLE 1.4–8. SUMMARY OF DIFFERENT ESTIMATES FOR THE MARINE SOURCE TERM

Study	Source term (PBq)/release duration (in 2011)	
	Direct release	Atmospheric deposition
TEPCO [1, 128]	Near water intake of Unit 2 4.7 (^{131}I+^{134}Cs+^{137}Cs) 0.94 (^{137}Cs) 05:38, 1–6 April	—
	Near water intake of Unit 3 0.02 02:00, 10 May and 19:00, 11 May	—
	Planned low waste release: 1.5×10^{-4} 4–10 April	—
IRSN, 2011 [129]	2.3 (^{137}Cs) 1–6 April	10 (^{137}Cs) 12 March–23 March
IRSN (Bailly du Bois et al.), 2012 [101, 125]	22 (uncertainty 10–34, ^{137}Cs) 26 March–8 April 27 (uncertainty 12–41, ^{137}Cs) 26 March–18 July	0.076 (within a radius of 80 km)
JAEA-1, 2011 [130]	0.9496 (^{137}Cs) 1 April	7.5 (^{137}Cs)
Buesseler et al., 2011 [131]	1.9–2.1 (^{137}Cs), total over 150 000 m^2 March–June	
Kawamura et al., 2011 [127]	11 (^{131}I) 4 (^{137}Cs) 21 March–30 April	57 (^{131}I) 5 (^{137}Cs) 12 March–30 April
Nakano and Povinec, 2012 [132]	Same as Kawamura (^{137}Cs) 5 (^{134}Cs) 21 March–30 April	Same as Kawamura (^{137}Cs) 6 (^{134}Cs) 12 March–30 April
Tsumune et al., 2012 [133]	3.5 ± 0.7 (^{137}Cs) 26 March–end of May	—
Estournel et al., 2012 [134]	5.1–5.5 (^{137}Cs) 12 March–30 April	5.7–5.9 (^{137}Cs) 0.23–0.33 (^{137}Cs) within a radius of 80 km
Honda et al., 2012 [135]	3.7 (^{137}Cs) 21 March–6 May	0.18 (^{137}Cs) 12 March–May
IFM-GEOMAR [136]	2.3 (^{137}Cs) 1 April instant	—
Byung-Il Min et al., 2013 [137]	Same as TEPCO (^{137}Cs)	5.8 (^{137}Cs) within (138°–145°E, 34°–40°N) 12 March–6 April
Rossi et al., 2013 [138]	Same as Bailly du Bois (^{137}Cs) 1 month (mid-March–mid-April)	—
Stohl et al., 2012 [112]	—	28

TABLE 1.4–8. SUMMARY OF DIFFERENT ESTIMATES FOR THE MARINE SOURCE TERM (cont.)

Study	Source term (PBq)/release duration (in 2011)	
	Direct release	Atmospheric deposition
JAMSTEC-1, 2012 [139]	14.8 (^{137}Cs) 21 March–6 May	—
JAEA-2 (Kobayashi et al.), 2013 [111]	11 (^{131}I) 3.5 (^{137}Cs) 26 March–30 June	99 (^{131}I) 7.6 (^{137}Cs) 12 March–1 May
WHOI-1, 2013 [140]	11–16 (^{137}Cs) early April 2011	—
WHOI-2, 2013 [141]	9.1–17.8 (^{137}Cs) mean 16.2; 1σ 1.6	0–11 (^{137}Cs) mean 0.5; 1σ 2.7
Sirocco, 2012 [139]	4.2 (^{137}Cs) 20 March–30 June	—
JAMSTEC-2, 2013 [142]	5.5–5.9 (^{137}Cs)	5.5–9.7 (^{137}Cs)
Kanda et al., 2013 [143]	2.27 (^{137}Cs) — from harbour to open ocean by water exchange (3 April 2011–30 September 2012) 2.25 (^{137}Cs) (1 April–31 May 2011)	—
UNSCEAR [122]	9–18 (^{131}I) 3–6 (^{137}Cs)	60–100 (^{131}I) 5–8 (^{137}Cs)

If the direct release from the site to the ocean had ended in May 2011, and assuming that the mixing processes in the ocean did not appreciably change, ^{137}Cs activities would have decreased by a factor of 1000 from May to June 2011 [124]. As per the concentration decrease, the change in slope of ^{137}Cs activity occurred approximately in late April. Some analyses of ocean contamination provide not only the integral value of the source term but its kinetics as well.

Most analyses estimate the source term of direct release based on numerical modelling of ^{137}Cs dispersion in the ocean and using the measurement data as validation basis. In the study presented in Ref. [134], the observations of ^{137}Cs concentrations near the outlets of the power plant were used in the inverse method to calculate the amounts of radionuclides released after the accident. IRSN [129] interpolated the individual measurement made in a period from 11 April to 12 July 2011. TEPCO used photographs, calculations of the flow rate, and measurements of activity concentrations in the leaking water to directly estimate the released activity.

The uncertainty in the direct release source term is generally smaller and most analyses show results in the range from 1 PBq to 5.5 PBq of ^{137}Cs (Table 1.4–8), except for the most conservative integral estimation given by IRSN (27 PBq, with an uncertainty band of 12–41 PBq) [125]. However, in 2013 new studies by the Woods Hole Oceanographic Institution in the USA [140, 144] partly confirmed this large IRSN value, thus making the uncertainty broader. The lower bound of the release range corresponds to estimates by TEPCO based on calculation of leakage flow rate and concentration readings (0.94 PBq in case of the leakage near the water intake of Unit 2, other leakages being much smaller).

The variability in the predictions of total direct ocean discharges of Cs is due to large uncertainties in the different oceanic circulation and radionuclide dispersion models and inversion processes used by each study and the lack of spatially distributed observations in the surrounding region. In much the same way as in atmospheric releases, the uncertainty of results was analysed using Bayesian techniques. The results are presented in Table 1.4–9.

TABLE 1.4–9. UNCERTAINTIES OF MARINE SOURCE TERM ESTIMATES FOR THE MAIN ISOTOPES (ALL VALUES IN PBQ)

Isotope	Accuracy (%)	Normal		Log-normal	
		Mean	Standard deviation	Mean	Range
^{137}Cs, deposition	25	1.24	1.33	6.34	3.81–10.53
	40*	1.77	1.55	6.43	3.94–10.52
^{137}Cs, direct inflow	25	2.70	0.76	3.79	2.73–5.28
	40	1.54	0.72	4.00	2.82–5.69
^{137}Cs, total	25	8.67	1.95	10.5	6.4–17.0
	40	6.79	2.23	10.5	6.4–17.3

* The largest uncertainty that was estimated by authors of the source term provided in Table 1.4–8.

Based on the results presented in Table 1.4–9, the following conclusions can be drawn:

— When normal distribution of the original data is assumed, the maximum likelihood values tend to be smaller than those for log-normal distribution. This follows from the higher weights ascribed to low values of releases and is a direct consequence of the mathematical model.
— The log-normal distribution is preferable in this kind of calculation. It is also less sensitive to the assumptions about the relative accuracy of the original results. For conservatism, the uncertainty range may be taken from the smallest value to the largest one. For example, in the case of direct deposition of ^{137}Cs to the sea, one could accept a mean value of 3.9 PBq within the range 2.7–5.7 PBq.

Before 25–26 March 2011, atmospheric deposition was the major source of radionuclides in the ocean arising from the Fukushima Daiichi accident, as the direct releases were likely to have been much lower in comparison. It has to be noted, however, that no observations of the concentration were available before 21 March 2011 near the southern outlet, or before 23 March near the northern outlet. Therefore, it is difficult to evaluate the direct release in these days. The impact of the importance of a no-observation period in the total release assuming two options was discussed in Ref. [134] as: a nil release and a release rate equal to the first measured value. The difference between two alternative scenarios demonstrated that the amount of ^{137}Cs released to the ocean before 21 March was 8% of the total liquid release. Most studies consider that the major direct release occurred in the period between 23 March and 8 April 2011. For example, the results obtained in Ref. [134] show a strong increase in direct release rate (>0.1 PBq/L) on 25 March. Another study [133] concluded from the analysis of the ^{131}I/^{137}Cs activity ratio that the contribution of direct release to the measured ^{137}Cs concentration became larger than atmospheric deposition after 26 March 2011.

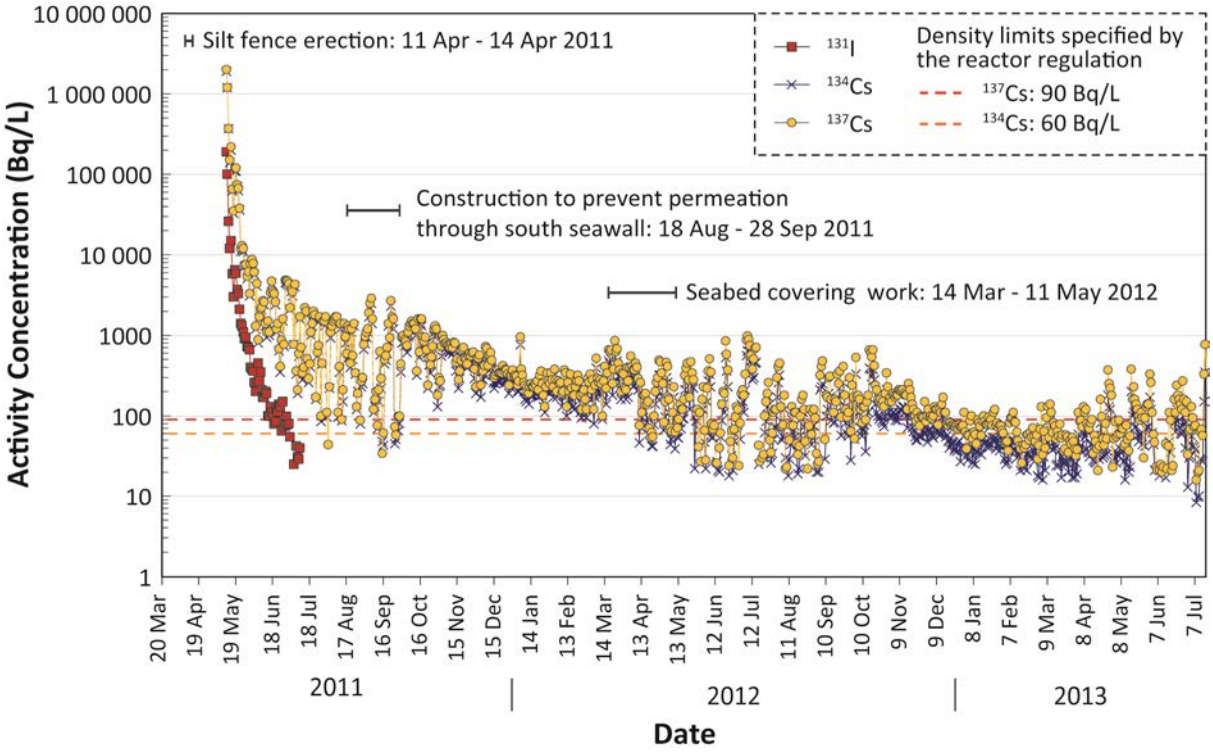
The relative contributions of direct release and deposition from the atmospheric release to ocean contamination over the full time period from 12 March 2011 to May 2011 are judged very differently by different studies. The ratio of the corresponding values of the source term (Bq released directly versus Bq deposited) varies from 0.13 [130] to 300 [125], while some analyses demonstrate equal contributions [127, 134].

Measurements of concentrations in ocean water close to the Fukushima coast show that, while the release rate has decreased over the first two years, radioactive material is still being discharged into the ocean. The possible sources of continued releases are likely to be drainage of groundwater transferring radioactive material from the basements of reactors, trenches or, to a lesser extent, leakage from a storage tank, and runoff of sediments from the ground during rains.

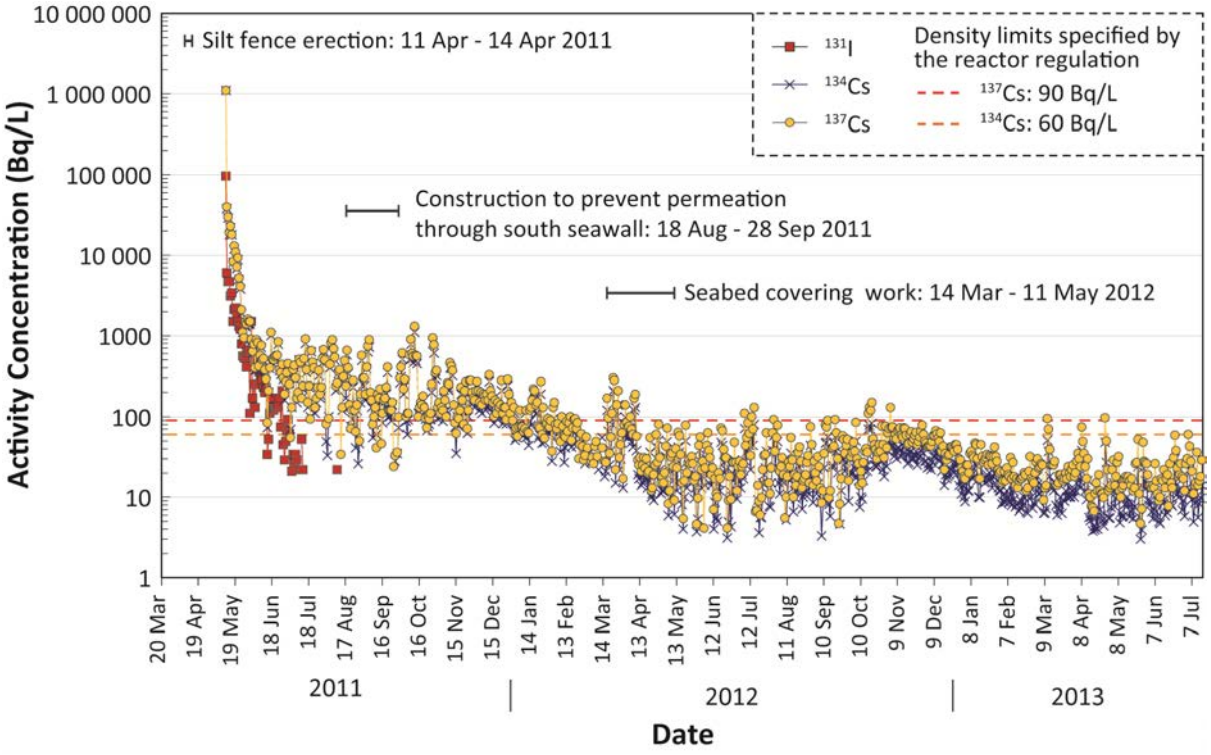
Radioactive materials deposited at the site may also be washed out to the ocean by the discharge of groundwater and river runoff, so an addition of radioactivity to the ocean from the contaminated watersheds also needs to be taken into account in long term analyses. According to Ref. [143], the release of ^{137}Cs from small rivers between April and September 2012 was estimated to be not more than 0.32 TBq/month. The study by IRSN [129] provides almost the same value, but only for the Ukedo River, the largest of the small rivers in the affected region of Japan. The larger Abukuma River has been estimated to release up to 0.87 TBq/month of ^{137}Cs [145]. Releases from other rivers (Naruse, Nanakita, Natori, Kuji and Naka) are of the same order of magnitude. A later study, in 2013 [146], showed that heavy rains during Typhoon Roke on 21–22 September 2011 transferred large amount of particulate ^{134}Cs and ^{137}Cs, deposited on the land, to the watersheds of the Natsui and Same Rivers and coastal marine environments. The rate at which radiocaesium was transported was estimated to be 0.020–0.026 TBq/d in the Natsui River and 0.007–0.009 TBq/d in the Same River, which is 30–50% of the total annual river transport from 11 March to 31 December 2011.

1.4.6. Additional radiological release since the accident

The concentration of radioactivity in the seawater of the port at Fukushima Daiichi has decreased since immediately after the accident. In 2013, the concentrations inside the port (water intakes, open culvert, inner side of the silt fence) fluctuated, but did not exceed the values measured in the summer of 2011 (Fig. 1.4–6). This is believed to be due to continuous leakages of contaminated groundwater, leakages of deposits from the seawall, changes in the tides and precipitation.



(a)



(b)

FIG. 1.4–6. Temporal change of measured radioactivity concentrations in the seawater inside (a) and outside (b) silt fence at Unit 3 intake [147].

The landscape features of the NPP site favour groundwater flow from the west-side hills to the eastern shore (Fig. 1.4–7). According to estimates by TEPCO, the flow rate of groundwater is approximately 1000 m^3/d. Because of the lack of water sealing in the basements, some groundwater enters the RBs and TBs of Units 1–4 and the auxiliary buildings that house the cleaning systems. TEPCO estimates that the daily contribution of groundwater to the flooding of these buildings is about 400 m^3.

This influx of groundwater and the water injected into the RPVs have created large pools of contaminated water in the RB basements with radioactivity concentrations of about 10^7 Bq/L [148]. As of 25 March 2014, the volume of these pools at Units 1, 2 and 3 was 13 700 m^3, 21 100 m^3 and 21 000 m^3, respectively, totalling 55 800 m^3. The basement of Unit 4 RB was flooded with 15 900 m^3 of water. Water also leaked from the RBs to the two TBs basements which are shared between pairs of units (Units 1 and 2, Units 3 and 4). Directly contributing to the release of radioactivity to the environment, large amounts of contaminated water that accumulated inside the RBs and TBs became a major concern.

By September 2013, the underground trenches and shafts were flooded with approximately 11 000 m^3 of water contaminated to ~10^9 Bq/L [148][149]. That water is gradually seeping into the ground through the layer of crushed stones, contaminating the clean groundwater that bypassed the basements of the buildings, and the whole amount is flowing to the ocean.

[149] Here activity concentrations for ^{137}Cs are given, since it is the main contributing radionuclide.

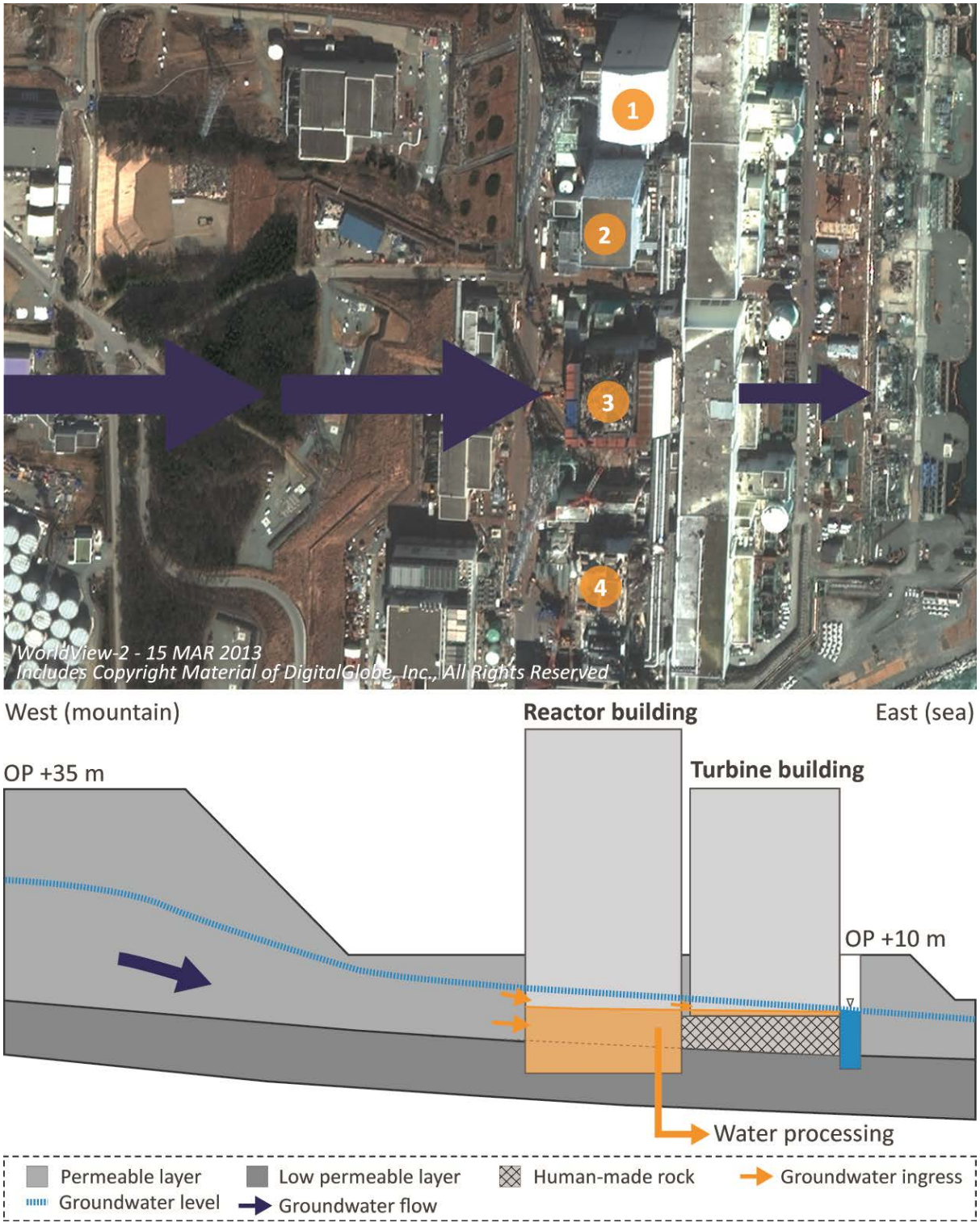


FIG. 1.4–7. Layout of groundwater flow trend at the Fukushima Daiichi site.

In order to reduce the infiltration of radioactivity into the groundwater and ocean, TEPCO installed a treatment and storage system coupled with a water injection system. It allows the radioactively contaminated water stored in the basements of the TB to be treated and reused for injection into the RPV. However, because of additional basement flooding with groundwater, the total amount of water accumulating in the basements (~800 m^3) exceeds the amount needed to cool the corium (~400 m^3), and so each day a surplus of ~400 m^3 is accumulating at the site. That excess of low activity salted

water is collected in cylindrical storage tanks and stored at the NPP site. By the end of March 2014, the total volume of these tanks reached about 350 000 m^3.

Since the accident, several major events have occurred in which contaminated water has been released to the ground or ocean:

— On 2 April 2011, TEPCO found that highly contaminated water, with readings over 1000 mSv/h, was leaking directly into the sea from a 20 cm crack in a pit wall storing electric cables near the intake channel of Unit 2. Several measures were taken and the water discharge was stopped on 6 April. Based on ambient dose rates measured on 1–2 April 2011 near the sea surface around the Unit 2 screen, TEPCO estimated that the contaminated water had been flowing out between 1 and 6 April. The outflow rate was calculated to be 4.3 m^3/h. Given the sampling results, the total inventory of radioactive materials released with this water was estimated at 4.7 PBq;
— A planned and approved discharge of low contaminated water to the ocean occurred in April 2011. Then, TEPCO decided to discharge the low level radioactively contaminated water accumulated in the Radioactive Waste Treatment Facilities and subdrains of Units 5 and 6 in order to create space for the highly concentrated radioactive wastewater accumulated in the basement floor of the turbine building of Unit 2, which they feared might escape. About 10 000 m^3 of water was discharged to the ocean from 4 to 10 April, containing a total activity of about 1.5 × 1011 Bq [1].
— Another outflow of contaminated water into the sea occurred from a pit near the Intake Channel of Unit 3 on 11 May 2011. The leakage lasted for 41 hours and the volume of water released was estimated at 250 m^3. The total amount of radioactive material released to the sea was estimated at 0.02 PBq.

TEPCO disclosed on 21 August 2013 [149] that a leakage of approximately 300 m^3 of β and low level caesium contaminated water had occurred on 19 August from a storage tank, which was categorized as an INES 3 event by the Nuclear Regulation Authority (NRA). The causes of the leakage were loose flanges and a drain valve left in the open position. The radioactivity in the leaked water was deemed to have been released into the ground. However, most of the seawater samples taken later near the Fukushima Daiichi NPP remained below the detection limits, and no change was observed before and after the leakage from the cylindrical storage tank.

In order to investigate and mitigate the consequences of the leak, multiple wells were dug around the location and between the tank and the seashore (Fig. 1.4–8). The sampling results as of 22 April 2014 are shown in Tables 1.4–10 and 1.4–11. The maximum values from the sampling in the ground bypass pump wells were observed regularly at No. 7 and No. 12 and did not exceed 1600 Bq/L of ^{3}H. As of 22 April 2014, the maximum value of gross β activity concentration (710 000 Bq/L) around the tank area was found on 10 November 2013, while the highest activity concentration of ^{3}H (790 000 Bq/L) was measured on 17 October 2013.

Besides these events, several other minor leaks of contaminated water from the storage tanks have occurred since April 2011 in different areas. For instance, the discovery of two leaks of contaminated water from cylindrical storage tanks was announced by TEPCO on 21–22 December 2013. The total amount of water that could have escaped into the ground was estimated to be 1.8 t. The level of radioactivity was measured to be 1000 Bq/L for β and 190 Bq/L for ^{90}Sr in the first leak location, and 25 Bq/L for β and 2.7 Bq/L for ^{90}Sr in the second leak location.

Another leak coming from the upper part of a tank containing reverse osmosis concentrated salt water was discovered on 19 February 2014 [150]. The flow of water was stopped on 20 February 2014. Inspection of the area showed that contaminated water had not escaped into the sea, since there were no drainage channels in the surrounding areas. According to TEPCO's estimates, the volume of the leakage was approximately 100 m^3.

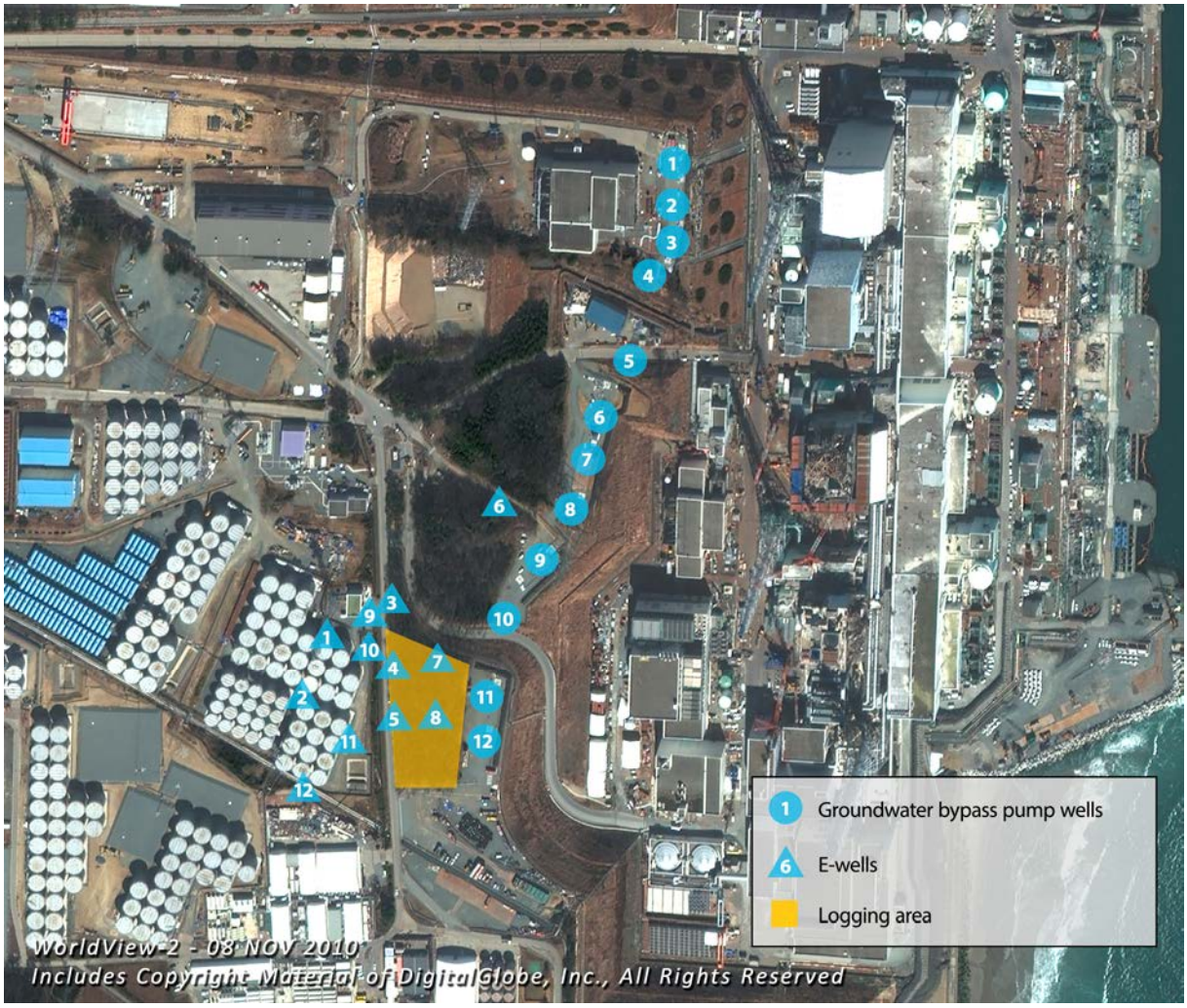


FIG. 1.4–8. Map of wells around the leaking tank location [151].

TABLE 1.4–10. RESULTS OF GROUNDWATER SAMPLING FROM E-WELLS, IN Bq/L (19 APRIL 2014) [151]

Measured parameter	E-Well				
	E-1	E-2	E-3	E-4	E-5
Gross β	29 000	28	18	37	26
^{3}H	23 000	430	5500	1800	1000

TABLE 1.4–11. RESULTS OF GROUNDWATER SAMPLING FROM GROUND BYPASS PUMP WELLS, IN Bq/L (15 APRIL 2014) [152]

Measured parameter	Well											
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	No. 10	No. 11	No. 12
Gross β	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(13)	nd(4.4)
^{3}H	nd(5.2)	25	40	63	19	170	330	90	77	190	310	1600

Note: 'nd' indicates that the measurement result is below the detection limit, and the detection limit of each nuclide is provided in parentheses.

High concentrations of caesium were found in groundwater samples taken in 2013–2014 in the wells approximately 50 m from the coast. The highest radioactivity level (93 000 Bq/L of ^{137}Cs and 37 000 Bq/L of ^{134}Cs) was measured on 13 February 2014 near Unit 2. This demonstrates that contaminated water may still be seeping from underground trenches connected to the basements of the turbine buildings.

TEPCO considers that up to 10 TBq of strontium and up to 20 TBq of caesium have leaked into the port from the trenches and similar locations. At the same time the concentrations of tritium and all beta radiation inside the port and in the vicinity of the entrances to the port (port entrance, north intake, near the south intake) are below detectable limits (in the range of several tens of Bq/L). According to measurements, the fluctuations in radiation concentrations are limited to inside the Unit 1–4 open culvert and have no impact offshore or inside the port [147].

1.5. ACTIONS BY ORGANIZATIONS OTHER THAN TEPCO

This section describes actions during the accident by organizations other than TEPCO. Such off-site organizations supported the accident management and emergency response and recovery processes, mainly to protect the environment and general public near the accident, in Japan and internationally. Some off-site organizations also participated in directing actions taken by on-site organizations.

Technical Volume 2, Safety Assessment, and Technical Volume 3, Emergency Response, provide further information and analyses of the emergency preparedness and response issues described in this section.

Section 1.5.1 summarizes how the off-site organizations were structured and interacted with each other. It also describes how they were activated as the accident progressed. Sections 1.5.2–1.5.5 present the actions of national off-site organizations in response to the accident in chronological order. Section 1.5.6 presents the actions of international organizations.

1.5.1. Structure and interactions of on-site and off-site organizations

Immediately following the earthquake, a number of local, regional and national emergency response organizations were activated. Their main point of on-site contact was the on-site ERC that TEPCO had immediately established at the seismically isolated building at the Fukushima Daiichi NPP site. The Site Superintendent was the designated emergency preparedness manager responsible for directing the site response and for coordinating with on-site and off-site organizations.

Within 20 minutes of the earthquake, at 15:06, an off-site ERC was also established at TEPCO Headquarters in Tokyo. It was responsible for managing both the response to earthquake damage at all of TEPCO's facilities and the recovery from electric outages in its service area. The off-site ERC was headed by TEPCO's Vice President, on behalf of TEPCO's President, and staffed by internal duty personnel. One of TEPCO's directors was designated as the off-site ERC's Manager for oversight and response management. TEPCO's on-site ERC was responsible for communicating with off-site emergency organizations, principally TEPCO's off-site ERC. As the accident progressed into a nuclear emergency, the Fukushima Daiichi and Daini sites became the main focus of TEPCO's off-site ERC, which was linked to both sites' on-site ERCs by real-time videoconferencing. The communication system between TEPCO's on-site and off-site ERCs was not connected with other off-site organizations, which inhibited real-time information sharing among all relevant parties.

As off-site non-TEPCO organizations, such as the national Government and local governments, activated their emergency response and recovery processes, TEPCO's off-site ERC served as the interface between TEPCO's on-site ERC and the national Government in Tokyo. TEPCO's on-site

ERC meanwhile, communicated directly with local emergency response organizations, including the national Government's local emergency organization (Fig. 1.5–1).

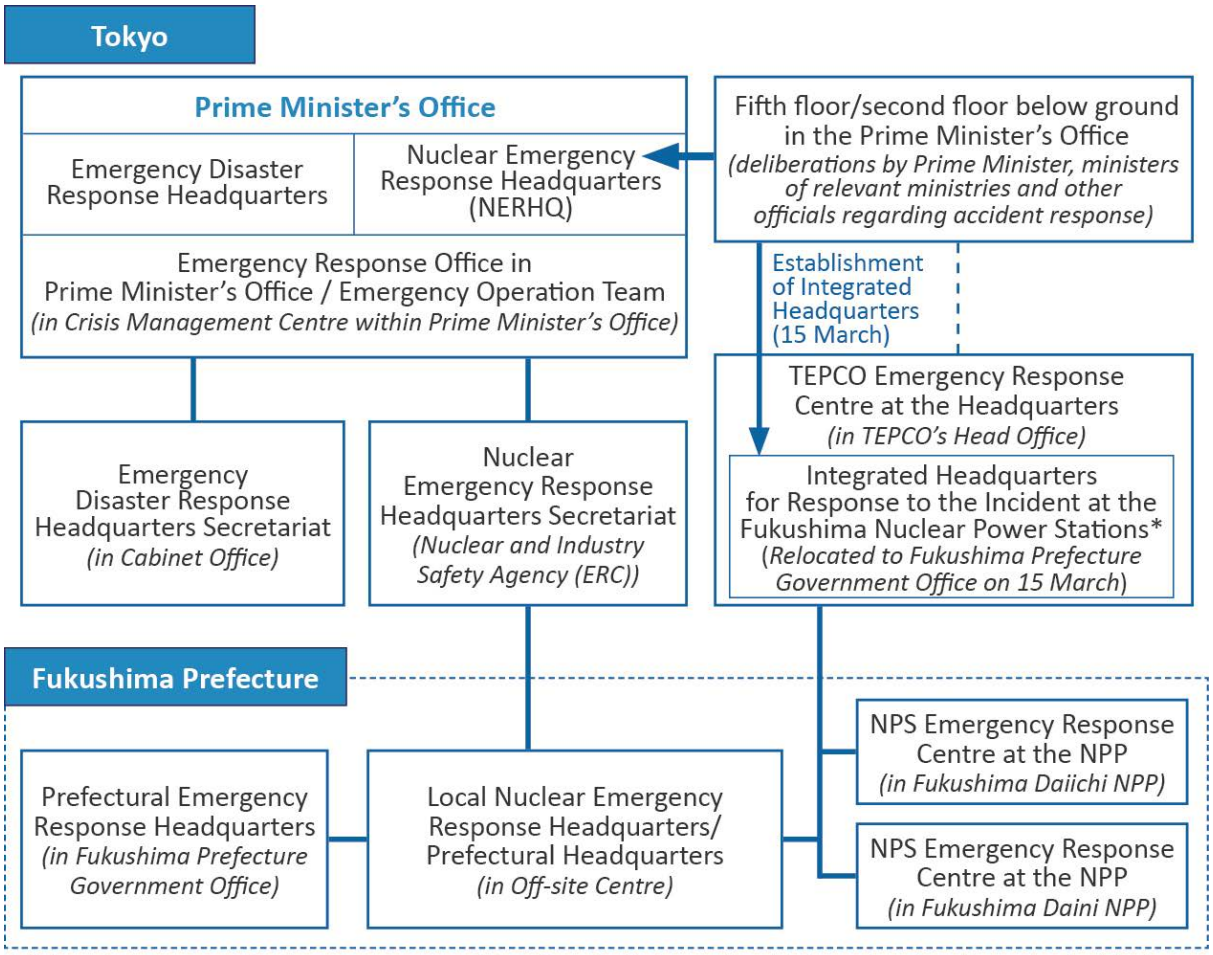


FIG. 1.5–1. Organizational structure and interfaces for initial accident response at the Fukushima Daiichi and Daini nuclear power plants [1].

The Basic Act for Emergency Preparedness governs the structure of governmental organizations during a national disaster. It includes the Prime Minister's Office and other government entities in Tokyo, as well as regional and local entities near the disaster location. As summarized in Fig. 1.5–2 and described below, the roles of these organizations varied from monitoring and advising to commanding and controlling countermeasures.

In response to the earthquake, national and local governments initially established emergency response organizations for a 'general earthquake disaster emergency' (not a nuclear emergency), including the following:

— The Emergency Response Headquarters of the Ministry of Economy, Trade and Industry (METI) was established in the ERC of METI, in Tokyo at 14:46. As a general earthquake response organization under the ministry which is responsible for nuclear infrastructure, it started collecting information on the state of the reactors at all nuclear power stations in the affected areas. Its response initially was not specific to a nuclear emergency at a specific nuclear power plant.

— The Emergency Response Office Headquarters for the earthquake at the Prime Minister's Office was established in Tokyo at 14:50, headed by the Deputy Chief Cabinet Secretary for Crisis Management. The Emergency Operations Team (EOT) members were called in to the Crisis Management Centre (CMC), located inside the Prime Minister's Office as the Emergency Response Office in the Prime Minister's Office. The EOT's responsibility was for the general emergency due to the earthquake, not the nuclear emergency.
— In accordance with the Disaster Countermeasures Basic Act, the Emergency Disaster Response Headquarters Secretariat in the Cabinet Office was established in Tokyo at 15:14 to coordinate the response to the earthquake at the Cabinet level.

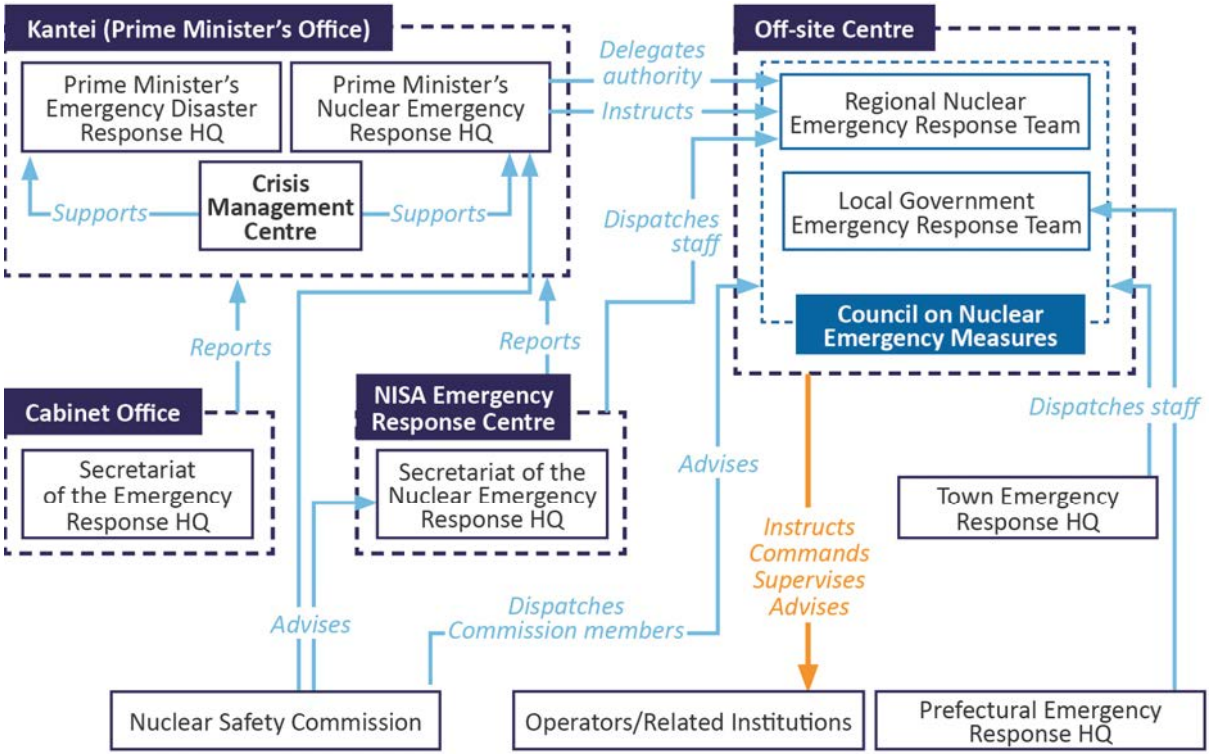


FIG. 1.5–2. Japanese governmental emergency organizations and interfaces [5].

At 15:42, about one hour after the earthquake and seven minutes after the tsunami (the first wave hit at 15:27 and the second wave at 15:35), TEPCO's Fukushima Daiichi NPP Site Superintendent declared emergency in accordance with Article 10. Through TEPCO Headquarters, he notified the Government at 16:00, through the Nuclear and Industrial Safety Agency (NISA) of METI, that the tsunami had rendered the facility's on-site AC power supply inoperable, resulting in the loss of all AC power (an SBO) for Units 1–5. Pursuant to Article 10, Paragraph 1 of the Nuclear Emergency Act [19], this served as the notification to the Government by the nuclear operator of a nuclear emergency. This notification was provided via fax and telephone to the relevant government institutions. Further requirements of the Act included the issuance of relevant information on the plant's status to the public.

Upon this notification, pursuant to Article 10, the national and local government organizations immediately established off-site response centres for 'the nuclear event'. These included:

— A Nuclear Emergency Preparedness Headquarters in the Emergency Response Centre (ERC) of the Ministry of Economy, Trade and Industry (METI), in Tokyo at around 16:00.

— A Local Nuclear Emergency Preparedness Headquarters at the designated Off-site Centre (OFC), by METI, in Okuma Town in the Fukushima Prefecture at around 16:00 (the building initially designated for the OFC was inoperable due to insufficient provisions for an emergency situation caused by the earthquake, and the OFC was subsequently relocated due to the worsening radiological conditions).
— An Emergency Technical Advisory Body established by the Nuclear Safety Commission in Tokyo at 15:59 upon being notified by NISA about the Article 10 notification from TEPCO.

As the accident progressed, TEPCO determined, at 16:36, the situation as a 'nuclear emergency' under Article 15 of the Act [19], because the reactor water level in Fukushima Daiichi Unit 1 could no longer be determined and there was evidence that core cooling had been lost.

Nine minutes after making this determination, at 16:45, TEPCO communicated an 'Article 15 notification' to the Government. At about the same time, TEPCO's on-site ERC cancelled the Article 15 declaration in Unit 1 upon recovering the ability to determine the reactor water level. However, once this ability was again lost, Article 15 was re-declared, at 17:07, and the Government was notified at 17:12.

Upon receiving the Article 15 notification, the Government, through the Prime Minister's Office, declared a nuclear emergency, and the national and local government organizations' off-site response centres for a nuclear emergency were established, all at about 19:03. These included:

— An NERHQ at the Prime Minister's Office in Tokyo, with the Prime Minister as Director General.
— The expansion of the Crisis Management Centre (CMC) team, which supported the Prime Minister's Office Emergency Response Headquarters, to cover the nuclear emergency and coordinate tasks required for disaster response.
— The Local Nuclear Emergency Response Headquarters (Local NERHQ) at the OFC, with the Senior Vice Minister of METI serving as chief at the OFC. The building originally designated for the OFC was inoperable, as noted above was relocated to the Fukushima Prefecture Government office on March 15).
— The NERHQ Secretariat in METI's ERC in Tokyo.

1.5.2. Actions by the Prime Minister's Office and METI

This section summarizes the actions of the Prime Minister's Office (Kantei) and METI in chronological order. All times are JST.

Important interactions with other organizations are indicated in brackets.

11 March 2011

At 14:50, the Kantei Emergency Response Headquarters (for the earthquake), headed by the Deputy Chief Cabinet Secretary for Crisis Management, was established. The Emergency Operations Team (EOT) members were called to staff the CMC for the earthquake emergency. The task of the EOT was to support the Kantei Emergency Response Headquarters by gathering information on the situations in the disaster stricken areas, reviewing potential evacuation measures, procuring supplies and equipment, identifying additional ways to help victims, and issuing instructions and requests to other government departments.

At 15:14, the Secretariat of the Emergency Disaster Response Headquarters was established and began reporting to the Kantei Emergency Response Headquarters.

At 16:00, the Kantei was notified by NISA, pursuant to Article 10, that the TEPCO's Fukushima Daiichi NPP's on-site AC power supply was inoperable due to the tsunami and that Units 1–5 had lost all AC power. As mentioned earlier, the Nuclear Emergency Preparedness Headquarters in the ERC of METI was established by METI, in Tokyo, in addition to the Local Nuclear Emergency Preparedness Headquarters at the designated Off-site Centre (OFC) in Okuma Town in the Fukushima Prefecture.

At 16:36, TEPCO notified the Government, in accordance with Article 15 of the Nuclear Emergency Act, that it could no longer determine the reactor water level in Units 1 and 2.

At 16:36, a Nuclear Emergency Preparedness Office was established in the Kantei and the Emergency Operations Team was expanded to respond to the nuclear emergency.

At 16:45, TEPCO reported to NISA that it might have already become impossible to inject water into Units 1 and 2 using the emergency core cooling systems.

At 16:45, the Article 15 notification, sent by TEPCO at 16:36, was received by the Government. [At about the same time, TEPCO's on-site ERC cancelled the Article 15 declaration upon recovering the ability to determine Unit 1's reactor water level.]

Shortly before 17:00, the Prime Minister summoned the NISA Director General to his office to find out about the conditions at the Fukushima Daiichi NPP. At that time, the NISA Director General had been provided general information about the situation. Details of the plant's condition were not available.

At around 17:00, the Prime Minister also summoned TEPCO staff to explain the conditions at the plant. TEPCO sent four staff to the Prime Minister's Office, but they also had only preliminary information and could offer only general explanations of possible consequences.

At about this time, the NISA Deputy Director General notified METI's Minister of the situation at the Fukushima Daiichi NPP.

At 17:12, the Government was notified about the re-declaration of Article 15 by TEPCO at 17.07.

At 17:35, after NISA had conducted its own technical verifications, the NISA Deputy Director General obtained the approval of METI's Minister's for the declaration of a nuclear emergency.

At 17:42, METI's Minister and NISA officials went to the Prime Minister's Office to notify the Prime Minister of the nuclear emergency and obtain his approval for formally declaring a nuclear emergency. The NISA officials had only preliminary information on the accident, especially on its predicted progress and the potential for hydrogen explosions and core melting.

The Prime Minister also requested information on the provisions of the Nuclear Emergency Preparedness Act as well as related laws and regulations. These were subsequently provided by METI and NISA officials.

By 18:30, the Prime Minister gave his approval for declaring a nuclear emergency.

At 19:03:

— A nuclear emergency was declared by the Japanese Government.
— The Prime Minister's Office established the NERHQ and the Local NERHQ.

— The Deputy Chief Cabinet Secretary for Crisis Management expanded the CMC's scope from the earthquake emergency to include the nuclear emergency, and officials at the Director General level from relevant ministries and agencies began assembling at the CMC; the Emergency Operations Team was formed in the CMC and included the nuclear disaster response staff.
— The first meetings of the NERHQ and the Cabinet Office Emergency Response Headquarters were held. Following these meetings, the Prime Minister discussed possible responses to the accident with METI's Minister, the Deputy Chief Cabinet Secretary and his Special Advisors.

Later, at a press conference around 19:45, the Chief Cabinet Secretary announced that a nuclear emergency had been declared.

At around 20:30, the Prime Minister went to the CMC in order to personally assume the duties of crisis manager and direct the Government's response to the earthquake/tsunami/nuclear emergency. Until then, the Deputy Chief Cabinet Secretary for Crisis Management had been managing the response with the government officials from relevant ministries.

The Prime Minister later left the CMC and continued to direct the response from his office in the same building, together with the Minister of METI, Chief Cabinet Secretary, Deputy Chief Cabinet Secretary and the Prime Minister's Special Advisors. The Chair of the Nuclear Safety Commission, the NISA Deputy Director General, a TEPCO consultant and others were also assembled in the Prime Minister's office, at a more remote location than the CMC. Topics discussed in the Prime Minister's Office included evacuation and sheltering areas, measures to be taken at the plant (e.g. pressure venting and water injection to the reactors) and logistical support such as the procurement of supplies and equipment. The discussions were based on the information made available from the CMC and the information gathered from the TEPCO staff over mobile phones. Although TEPCO sent staff to the Prime Minister's Office only to provide briefings on conditions at the plant, the staff stayed to serve as liaison staff to the Prime Minister's Office. Thus, the arrangement for communicating information about conditions at the plant between the Prime Minister's Office and the site initially depended on TEPCO's liaison staff using their mobile phones to talk to people at the site.

Between 20:00 and 21:00, the Cabinet Members of relevant ministries met with the NSC Chair, the NISA Deputy Director General, and TEPCO staff and decided to establish an evacuation area with a radius of 3 km from the Fukushima Daiichi NPP, and an in-house sheltering area between 3 km and 10 km from the NPP.

At 21:23, the Prime Minister issued the evacuation order for the 3 km zone and the instruction to stay indoors between 3 km and 10 km from the plant.

12 March 2011

At 01:30, the Prime Minister, together with the Minister of METI, and the Deputy Director General of NISA were informed about TEPCO's plans to vent the containments at Units 1 and 2.

[TEPCO's off-site ERC then told its on-site ERC that the venting should proceed after 03:00, when the Minister of METI announced the venting.]

At around 02:00, the Prime Minister became concerned that the Local NERHQ was not functioning as it should, and hence, the Prime Minister's Office had to make decisions without complete and timely information on conditions at the plant. The Prime Minister therefore planned to travel to the site to talk directly with the Site Superintendent and to see the extent of the damage.

At 05:44, the Government ordered the evacuation of residents living within 10 km of the Fukushima Daiichi NPP.

At 06:15, the Prime Minister left his office with his Special Advisor and the NSC Chair to travel to the accident site.

At 06:50, METI issued the order for containment venting.

At 07:11, the Prime Minister arrived at the Fukushima Daiichi site.

At the site, the Prime Minister and his team met with the Site Superintendent inside the seismically isolated building. Also at the meeting were the Senior Vice Minister of METI, who headed the local NERHQ, a TEPCO Vice-President who was from the TEPCO off-site ERC, and the NCS Chair.

At 8:04, the Prime Minister left the Fukushima Daiichi site.

[At 9:04, containment venting began.]

At 15:36, the Prime Minister's Office first learned about the hydrogen explosion at Unit 1's reactor building (RB) from a television report but was unable to obtain further information about the explosion directly from TEPCO.

At 18:25, the Government ordered the evacuation of residents within 10 km of the Fukushima Daini nuclear power plant and within 20 km of the Fukushima Daiichi NPP.

[When TEPCO staff returned from the NERHQ to TEPCO Headquarters on the night of 12 March, they pointed out the need to improve communication between TEPCO Headquarters and the Prime Minister's Office.]

13 March 2011

On the morning of 13 March, TEPCO Headquarters sent three staff as liaison to the Prime Minister's Office, together with fax machines and personal computers. This improved communication between TEPCO's headquarters and the Prime Minister's Office.

Throughout the day, management and engineering staff participated in meetings at the Prime Minister's Office, including the NSC Deputy Chair, the NISA Deputy Director General in charge of nuclear power plant safety and fuel cycles, engineers representing relevant plant vendors and staff from JNES.

There were frequent telephone calls between the CMC, TEPCO Headquarters, the Prime Minister, the Chief Cabinet Secretary and the Fukushima Daiichi Site Superintendent. Personnel at the Prime Minister's Office advised TEPCO Headquarters and the Fukushima Daiichi Site Superintendent by telephone on whether sea water should be injected into the reactor and on which unit should be given priority for water injection.

Members of the Emergency Operations Team at the CMC in the Kantei began communicating directly with TEPCO Headquarters through the several TEPCO personnel who had been dispatched to the CMC.

14 March 2011

On the morning of 14 March, NISA and TEPCO executives moved to a different room where TEPCO's telephones and fax machines were installed. From then on, this room functioned as a liaison information point between TEPCO and the Prime Minister's Office.

15 March 2011

The Prime Minister proposed that the Government and TEPCO should establish an integrated ERC inside TEPCO Headquarters to ensure rapid information sharing and promote comprehensive measures to deal with the Fukushima Daiichi accident. The order for the sheltering of residents living within a radius of 20–30 km area around the Fukushima Daiichi NPP was given on 15 March and remained in force until 25 March.

16 March 2011

On 16 March, the Prime Minister appointed a special advisor to the Cabinet. The Special Advisor joined with a member of the House of Representatives and others to form a private initiative Advisory Team at offices in the Secretariat of the Atomic Energy Commission (AEC). This Advisory Team served as technical consultants. It obtained documentation (primarily nuclear power plant information and monitoring data) mainly from the NERHQ via the AEC and used it to examine responses to the accident both inside and outside the plant.

17 March 2011

The Prime Minister met with the Director General of the IAEA, who visited Tokyo for this purpose. The Prime Minister committed himself to transparent information sharing with the IAEA and making every effort to provide accurate and objective information to the international community.

20 March 2011

[Senior TEPCO executives joined the core staff of the Emergency Operations Team.]

21 March 2011

The Prime Minister, as the Director General of the NERHQ, directed the Governors of Fukushima, Ibaraki, Tochigi and Gunma Prefectures to impose restrictions on the distribution of spinach and kakina harvested in these prefectures, and fresh raw milk produced in the Fukushima Prefecture. Further food restrictions in these and other prefectures were announced in subsequent days and months.

23 March 2011

[Concentrations of ^{131}I exceeded established limits in raw milk samples in the Fukushima Prefecture and in spinach samples in the Ibaraki Prefecture].

In response, the Prime Minister, as the Director General of the NERHQ, instructed the Governor of Fukushima Prefecture to restrict the distribution (and restrict the consumption) of certain leafy vegetables (spinach, komatsuna, cabbages, etc.) and flower-head brassicas (broccoli, cauliflower, etc.) produced in the Fukushima Prefecture until further notice. He also instructed the Governor of the Ibaraki Prefecture to restrict the distribution of fresh raw milk and parsley produced in the Ibaraki Prefecture until further notice.

25 March 2011

On 25 March 2011, a recommendation for voluntary evacuation was issued by the national government to residents within the 20–30 km zone.

29 March 2011

The Government of Japan founded 'The Support Team for Residents Affected by Nuclear Incidents' headed by NERHQ.

4 April 2011

The Government of Japan gave TEPCO permission to discharge 10 000 t of low level contaminated water into the sea.

11 April 2011

The Government of Japan announced the establishment of 'Deliberate Evacuation Areas' and 'Evacuation Prepared Areas' located further than 20 km from the Fukushima Daiichi NPP.

The Support Team for Residents Affected by Nuclear Incidents established a Headquarters for Measures against the Economic Impact Caused by the Nuclear Power Station Incident.

21 April 2011

The Government established restricted areas (Technical Volume 3 details the restricted areas further).

22 April 2011

The Chief Cabinet Secretary announced instructions from the Prime Minister about protective actions to be taken by the Government of Fukushima Prefecture and the governments of affected municipalities in connection with the 'Planned Evacuation Areas' and 'Evacuation Prepared Areas'. These instructions included:

— Designating 'planned evacuation zones' more than 20 km from the Fukushima Daiichi NPP in Iitate Village, parts of Katsurao Village, parts of Namie Town and Kawamata Town, and part of Minamisoma City, where planned evacuations were expected to be implemented within approximately one month.
— Designating as an 'emergency evacuation prepared area' the area between 20 and 30 km from the plant, excluding those areas designated as 'deliberate evacuation zones', i.e. Hirono Town, part of Kawauchi Village, part of Naraha Town, and parts of Tamura City, Minamisoma City and Iitate Village. In the emergency evacuation prepared area, preparations were to be made so that residents could take shelter indoors or evacuate by their own means in the event of a further emergency. The instructions simultaneously lifted the advisory for sheltering indoors that had been in effect in the areas between 20 and 30 km from the plant.

1.5.3. Actions by NISA and the NSC

The chronology in this section highlights the immediate efforts made pertinent to NISA and the Nuclear Safety Commission (NSC) relevant to the accident. Although these entities are part of (or connected to) the Government of Japan, their actions are reiterated in this section due to their specific roles and responsibilities.

11 March 2011

Following the earthquake, NISA summoned the essential personnel from the ERC of NISA and formed six teams, each with a specific function for general affairs, radiation, plant, medical, resident safety, and public relations. It also made preparations to gather information and respond as necessary.

At 15:42, the TEPCO's Fukushima Daiichi NPP Site Superintendent notified NISA via TEPCO Headquarters that the facility's on-site AC power supply had been rendered inoperable by the tsunami resulting in the loss of all AC power for Units 1–5. NISA then notified the Prime Minister's Office and other relevant organizations on the declaration pursuant Article 10 of the Nuclear Emergency Act at the Fukushima Daiichi NPP.

At 15:59, NISA notified the Nuclear Safety Commission (NSC) on the declaration pursuant Article 10 of the Nuclear Emergency Act at the TEPCO's Fukushima Daiichi NPP.

At 16:00, the NSC held an extraordinary meeting, formed the Emergency Technical Advisory Body, sent emails to the members of the Emergency Technical Advisory Body asking them to remain on standby, and dispatched one member of the NSC Secretariat to the ERC to serve as a liaison staff member. The Emergency Technical Advisory Body formed by NSC met on a regular basis, thereafter.

At around 17:00, NISA's Director General joined the CMC in the Prime Minister's Office as a member of the Emergency Operations Team. The NISA officials, who were accompanying METI's Minister, had preliminary information on the details of the accident sequence, especially on predicted progress of the accident conditions at that time, including the potential core melt and hydrogen explosion.

At around 18:00, the NSC Chair and the Secretary General of the NSC headed to the Prime Minister's Office to attend the first NERHQ meeting. After the meeting, upon return to the NSC Secretariat, they were called back to the Prime Minister's Office.

Also at around 19:03, NISA dispatched the Director General and a number of liaison personnel to the CMC at the Prime Minister's Office. Later, the Deputy Director General and other executives joined the CMC's Emergency Operations Team, alternating periodically with each other.

At 19:03, the Government issued the emergency declaration and established the NERHQ and the Local NERHQ (OFC). At the same time, NISA also established the Secretariat of the NERHQ in the NISA-ERC. Members of the NISA-ERC received information about the Fukushima Daiichi NPP through several TEPCO personnel who were dispatched earlier, soon after the accident, from TEPCO Headquarters.

At TEPCO Headquarters, updated information on the Fukushima Daiichi NPP was received via an in-house videoconferencing system, beginning immediately after the accident. However, the NISA-ERC did not utilize TEPCO's videoconferencing devices for their information gathering purposes. NISA did not send staff to TEPCO Headquarters or arrange for the same system to be expanded to the ERC. Arrangements were made, before dawn on 12 March, for the system to be used by NISA personnel dispatched to the OFC.

Between 20:00 and 21:00, the NSC Chair, the NISA Deputy Director General and TEPCO management met with the cabinet members of relevant ministries and decided to establish an evacuation area with a radius of 3 km around the Fukushima Daiichi NPP, and an sheltering area in the zone from 3 km to 10 km from the NPP. Later, some of these people met to discuss changes to the evacuation areas, measures to be taken at the Fukushima Daiichi NPP such as water injections into the reactors and pressure venting, and logistical support for the procurement of supplies and equipment.

12 March 2011

At 06:15, the NSC Chair accompanied the Prime Minister visiting the Fukushima Daiichi NPP site.

13 March 2011

Throughout the day, the Deputy Chair of the NSC, the NISA Deputy Director General in charge of NPP safety, engineers representing the plant manufacturers, and personnel from the Japan Nuclear Energy Safety (JNES) organization joined the deliberations in the Prime Minister's Office from time to time.

14 March 2011

NISA reported to the IAEA that about 185 000 residents have been evacuated from the towns near Fukushima Daiichi NPP.

12 April 2011

NISA issued a new provisional rating for the accident at the TEPCO's Fukushima Daiichi NPP, rating it as a 'Major Accident', or Level 7 on the INES scale.

14 April 2011

NISA reported that among the approximately 300 workers at the Fukushima Daiichi site, 28 had received accumulated doses in excess of 100 mSv in the period related to this emergency.

16 April 2011

NISA directed TEPCO to increase the number of sea sampling points (from 10 to 16).

1.5.4. Actions by the local governments

11 March 2011

The Fukushima Prefecture Government building became unusable due to the earthquake. Essential equipment and supplies were moved to the third floor of the adjacent Fukushima Prefecture Local Government Hall, where the Fukushima Prefectural Emergency Response Headquarters (HQ) was established with the Fukushima Prefecture Governor as the director.

The Prefectural Emergency Response HQ began efforts to verify the safety of personnel, while gathering information on the Fukushima Daiichi and Daini NPPs.

At around 15:50, staff from TEPCO's Fukushima City office went to the Local Government Hall, and reported to emergency response staff that the TEPCO's Fukushima Daiichi NPP had issued a notification that an emergency situation existed due to loss of all AC power. This information was conveyed to the Governor of Fukushima Prefecture and other prefecture officials. The Government of Fukushima Prefecture initiated preparations for a nuclear emergency response by retrieving documents, such as nuclear emergency response manuals and supplies and equipment from the damaged prefecture government building.

The Prefectural Emergency Response Headquarters continued to obtain information regarding the Fukushima Daiichi and Daini NPPs, mainly from the TEPCO Fukushima City office. Contact between these two locations was maintained primarily through the use of satellite phones and by TEPCO staff carrying documentation and information, in person, to the Local Government Hall.

At around 16:48, the Prefectural Emergency Response Headquarters received a report from the Fukushima Daiichi NPP, stating that a nuclear emergency had been declared because the capability to

determine the reactor water level and the status of cooling water injection into the core had been lost at 16:36.

After the press conference at 19.45 announcing the declaration by the national Government (at 19:03) of a nuclear emergency, Fukushima Prefecture Government officials began examining the need to issue an evacuation directive to residents near the Fukushima Daiichi NPP.

At 20:50, the Governor of Fukushima Prefecture issued an evacuation order for the residents of Okuma Town and Futaba Town to evacuate the area within a 2 km radius of the Fukushima Daiichi NPP. This order was announced to the public by a press conference, which was the first press conference by the Fukushima Prefecture Government after the accident.

Following the issuance of the evacuation order, the Deputy Governor of Fukushima Prefecture joined the Local Nuclear Emergency Preparedness Headquarters at the designated OFC, in Okuma Town in the Fukushima Prefecture. Thereafter, he participated in coordination of the national and local efforts at the OFC in accordance with provisions in the Fukushima Prefecture Local Disaster Response Plan.

1.5.5. Actions by international entities

In response to the accident at the Fukushima Daiichi NPP, the IAEA and the international community immediately offered both technical and humanitarian assistance to the Government of Japan and TEPCO. The Japanese Government and TEPCO also actively requested foreign countries and international organizations, including the IAEA, to provide their knowledge, experience and technologies to be utilized in response to the accident.[150] Over 25 countries and international organizations immediately offered and supplied equipment and materials for stabilizing the power plant, as well as supporting the evacuation efforts. This section summarizes the activities provided by the international entities. Further information on international actions are provided in Technical Volume 3.

1.5.5.1. Actions by the IAEA

The responsibility for responding to a nuclear or radiological emergency and for the protection of workers, the public and the environment, rests with the operating organization at the level of the facility concerned, and with the affected State at the local, regional and national levels.

The IAEA has a central role in the international framework for emergency preparedness and response.[151] This role includes: (1) notification and official information exchange through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision

[150] Government of Japan did not request assistance under the Convention on Assistance in the Case of a Nuclear Accident and Radiological Emergency [72].

[151] The international emergency preparedness and response framework at the time of the accident consisted of: (a) international legal instruments and agreements, in particular the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention); (b) IAEA safety standards and technical guidance in the area of emergency preparedness and response; and (c) international operational arrangements and tools, in particular the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET) and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN).

and facilitation of international assistance upon request; and (4) coordination of the inter-agency response.[152]

The IAEA discharges this role through its Incident and Emergency System (IES). This system includes a 24-hour contact point and an operational focal point, the Incident and Emergency Centre (IEC).

As the initial response to the emergency, the IAEA's IES was activated, at 15:42 JST on 11 March 2011, following notification from the IAEA's International Seismic Safety Centre (ISSC) of the earthquake and of the potential for damage at four nuclear power plants on the north-east coast of Japan as well as the potential for a tsunami. At 16:21 JST, the IEC established initial communication with the official contact point designated by Japan, METI and NISA, and the IEC was activated to Full Response Mode [153]. The information about the accident was communicated to the Member States via the Early Notification and Assistance Conventions (ENAC) web site and periodic press briefings as well as updates on the IAEA web site (www.iaea.org) provided accident information to general public.[153]

An offer of assistance by the IAEA (referred to formally as 'the Agency's good offices') was sent to METI–NISA and the Permanent Mission of Japan in Vienna at 16:48 JST. On 12 March 2011 the Agency again sent an offer of good offices to Japan. Three days after the accident, on 14 March, the Government of Japan requested the IAEA to provide expertise. On 15 March, the Japanese Government requested assistance from the IAEA in the areas of environmental monitoring and assessing the effects of radiation on human health, in the form of an IAEA team of experts in Japan to assist local experts.

Within the IAEA, the Director General established the Fukushima Accident Coordination Team (FACT) to ensure effective interdepartmental coordination. Through FACT, the IAEA provided information on radioactive releases to the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization and the World Meteorological Organization's Regional Specialized Meteorological Centre.

On 16 March, Japan asked the IAEA to provide an inventory of items that might be potentially needed to help deal with the emergency, such as remote controlled monitoring robots, aerial survey systems, unmanned trucks and unmanned helicopters. In response to this request, the IAEA collected information from Member States about available materials and equipment, some of which were later provided to Japan.

From 17 to 19 March, the IAEA Director General visited Japan and held high level consultations with Japanese organizations, including the Japanese Prime Minister and the Ministers of the Ministry of Foreign Affairs (MOFA) and METI. He also met with senior TEPCO and NISA officials. At the time of this visit, IAEA initiated support to Japan, comprising the following:

— A senior IAEA official was deployed to Japan to coordinate the IAEA's assistance and activities, and the offers of assistance from Member States to the Japanese authorities;

---

[152] The primary coordinating body for nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). This body was established following the Chernobyl accident in 1986 and currently includes 18 international organizations. One of the primary roles of IACRNE is the development and maintenance of the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN 2010 at the time of the accident).

[153] The first message for Member States and international organizations was published on the ENAC web site at 17:06 JST and the first press statement was published on the IAEA web site at 17:30 UTC on 11 March 2011.

— IAEA liaison officers were deployed to Tokyo to facilitate and improve communication between IAEA and NISA;
— The IAEA's radiation monitoring team was deployed, which began transmitting measurements to Vienna from various locations in Japan, including locations near to the Fukushima site.

Starting from 18 March, the IAEA sent several expert teams to Japan, including experts in radiation measurement, marine, food monitoring and BWRs:

— Between 18 March and 18 April 2011, the IAEA sent four teams to Japan for radiological monitoring. The teams assisted in validation of the radiological measurements being made by the Japanese authorities. The four teams also took measurements at a number of locations inside and outside the 20 km evacuation zone around the Fukushima Daiichi NPP site. Another team was deployed in the general vicinity of Tokyo for radiological measurement assistance.
— A Joint FAO/IAEA Food Safety Assessment Team (FSAT) visited Japan from 26 to 31 March 2011. The team provided technical advice and assistance to the Japanese organizations, including local governments, on issues related to food safety and agricultural countermeasures. The issues supported by the team included sampling and analytical strategies and validation and assessment of monitoring data to ensure that reliable information could be provided to the public and the international community on the extent of food contamination in the affected areas.
— At the Government of Japan's request, the IAEA sent an expert team from the IAEA Marine Environment Laboratories in Monaco, from 31 March to 7 April 2011 to assist marine monitoring programmes. From 2–4 April, the team joined Japanese experts on a research vessel to observe and to provide technical advice on the collection of seawater samples in the ocean monitoring activities. The team also reviewed and provided advice on the marine monitoring process that was coordinated by MEXT.
— A BWR expert team was sent to Japan by the IAEA from 3 to 12 April, 2011. The team mission held meetings with TEPCO and NISA staff to discuss technical issues in detail, focusing on the reactors and spent fuel pools. The team visited the Fukushima Daiichi and Daini NPP sites in order to communicate directly with those working on the ground to mitigate the conditions and, hence, to gain a first-hand understanding of the accident. The team exchanged views with officials of the Japanese Government and TEPCO technical teams.
— From 27 to 30 April, the FAO/IAEA FSAT visited the areas neighbouring the Fukushima Daiichi site to exchange views with relevant local authorities and to provide technical advice on food monitoring.

On 12 April 2011, industry guidelines for the transportation of people who may have been contaminated (internally or externally) with radioactive material and for aircraft decontamination were adopted. These guidelines were developed by the IAEA, the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO). They were subsequently incorporated into the technical instructions[154] and put into force internationally for air transport. Additionally, the IAEA and the IMO reviewed maritime safety issues and prepared guidance and distributed internationally.

The IAEA Director General presented a report [153] to the IAEA Board of Governors on the IAEA's activities in response to the Fukushima Daiichi accident which provided details of all activities, including the ones listed above.

[154] As an addendum to the 2011–2012 edition of ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air.

1.5.5.2. IAEA Ministerial Conference on Nuclear Safety

In June 2011, a Ministerial Conference on Nuclear Safety was convened by the Director General at IAEA Headquarters with the objective of strengthening nuclear safety by drawing on the lessons from the accident. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a preliminary assessment of the accident. The conference also considered actions for safety improvements, issues regarding emergency preparedness and response, and implications for the global nuclear safety framework.

The outcome was a Ministerial Declaration on Nuclear Safety [154], which outlined a number of measures to further improve nuclear safety, emergency preparedness and radiation protection of people and the environment worldwide. It also expressed the firm commitment of IAEA Member States to ensure that these measures were taken. The key measures were to: strengthen the IAEA safety standards; systematically review the safety of all NPPs, including by expanding the IAEA's programme of expert peer reviews; enhance the effectiveness of national nuclear regulatory bodies and ensure their independence; strengthen the global emergency preparedness and response system; and expand the IAEA's role in receiving and disseminating information. The Ministerial Declaration also requested the Director General to prepare a draft IAEA Action Plan on Nuclear Safety in consultation with Member States.[155]

1.5.5.3. Actions by other international organizations

International organizations such as the World Health Organization (WHO), the International Civil Aviation Organization (ICAO), the International Air Transport Association (IATA) and the International Maritime Organization (IMO), as well as the International Commission on Radiological Protection (ICRP), evaluated radiological impacts on human health and transportation infrastructure. They provided technical information to the global community which, for example, showed that radiation levels at and around airports and seaports in Japan did not pose health or transportation risks, and provided appropriate advice for travellers to Japan. The World Meteorological Organization (WMO) also provided essential information on meteorological situations and weather patterns.

1.5.5.4. Actions by Member States and other organizations

The Japanese Government received assistance offers from foreign countries through MOFA. The delivery and distribution of material and expert assistance was coordinated by NISA. Initially, there were difficulties in the receiving procedure because such procedure had not been defined in the basic emergency preparedness plan or other documents. It was difficult to ascertain the needs and to obtain such information as names, specifications, numbers and delivery timing of necessary equipment and materials. It took some time to secure storage places and to mobilize the necessary number of officials to handle the process. However, the situation improved in April and the work went more smoothly from then onwards.

The equipment and materials provided included, among others:

— **USA:** Fire engines, large capacity water pump set, feedwater pumps, water carrying barges, boron, remote control robots, equipment for aircraft monitoring, gamma cameras, germanium

[155] The Action Plan, unanimously endorsed by the 55th IAEA General Conference in 2011, defined a programme of work to strengthen the global nuclear safety framework. It consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For a detailed discussion of the Action Plan, see the Report by the Director General.

radiation detectors, personal protective equipment and materials, personal dosimeters, and survey meters.
— **France:** Environment monitoring cars, pumper trucks, generators, compressors, survey meters, personal protective equipment and materials, and personal dosimeters.
— **United Kingdom:** Personal protective equipment and materials, survey meters, and personal dosimeters.
— **Canada:** Survey meters and personal dosimeters.
— **China:** Concrete pumping vehicle.
— **Republic of Korea:** Survey meters and boron.
— **Germany:** Robots for site restoration and debris removal.
— **Russian Federation:** Personal dosimeters, personal protective equipment and materials.
— **Finland:** Survey meters.
— **Ukraine:** Survey meters, personal protective equipment and materials.

The pumps, fire engines and mobile concrete pumps were used by TEPCO for cooling the nuclear reactors and other facilities. The barges were used for transferring fresh water to be injected into the nuclear reactors and spent fuel pools in the early stages of the accident. The remote controlled robots were used for inspection inside the plant where worker access was difficult due to high levels of radiation. The survey meters, personal dosimeters and personal protective materials such as protective clothing, masks, and gloves were used for the inspection/restoration work at the plants as well as the evacuation of local inhabitants. Supplies of protective clothing, rubber gloves and boots became short after the middle of March and several countries supplied those materials at the request of Japan.

Some offers for material and equipment were specifically declined by the Government of Japan on the basis that either they would require specific training in their use or the equipment/material was abundant in Japan. For example, an offer to supply stable iodine was declined since Japan already had large stocks (and/or the storage and transportation of the stable iodine, in liquid form, was expensive). The supply of unmanned robots or monitoring vehicles was also rejected, since operation of those would have required training for operators in non-feasible conditions, e.g. training to be performed in the donor country or requiring a long period of time.

In addition to material and equipment, many states provided expert support. After the accident occurred, many experts visited Japan from China, France, the Republic of Korea, the Russian Federation, the United Kingdom and the USA to discuss the relevant issues and potential assistance with Japanese Government agencies and TEPCO. Japan received much advice, especially on the stabilization of the reactors and spent fuel pools, prevention of dispersion of radioactive materials and measures to cope with accumulations of radioactively contaminated water.

Organizations with expertise and capabilities in nuclear energy mobilized quickly and offered critical help. The United States Nuclear Regulatory Commission (NRC) interfaced early on with its Japanese regulatory counterparts and sent two experts to Tokyo to support immediate Japanese efforts. By 14 March, it had dispatched a total of 11 NRC staff to provide technical support in Tokyo. The US military stationed in or around Japan was also mobilized to help deliver food, water, blankets, clothing, and medical supplies to the people affected by the earthquake and tsunami.

In addition to governmental assistance, the nuclear industry and research organizations immediately offered assistance by sending supplies, technology and industry support teams, comprised of nuclear engineers and other experts, to lend technical expertise. Among others, these included:

— Radiation specialists from the US Argonne National Laboratory Radiological Assistance Program (RAP) who supported the collection of radiation readings and soil samples in the region around the Fukushima Daiichi site.

— The Korea Atomic Energy Research Institute (KAERI) and the Korea Institute of Nuclear Safety (KINS), in the Republic of Korea, both of which provided technical support.
— Experts from the member countries of the OECD/NEA visited and advised Japan.

Teams put together by multinational, private nuclear industry organizations, composed of representatives from vendors and electric utilities also provided technical assistance for assessment and issue resolution at the accident site. These included the World Association of Nuclear Operators (WANO), the Institute of Nuclear Power Operations (INPO), the Electric Power Research Institute (EPRI), as well as a number of individual companies, e.g. Exelon Corporation, AREVA, Bechtel Corporation, GE-Hitachi Nuclear Energy, The Shaw Group, Westinghouse Energy Company, and STP Nuclear Operating Company.

1.6. ACTIONS TAKEN IN THE AFTERMATH OF THE ACCIDENT

This section describes actions taken between May 2011 and December 2014.[156] It also provides an update on the status of the Fukushima Daiichi reactors and the Japanese nuclear industry as a whole. The actions taken have included short term countermeasures to deal with the day to day situation at the Fukushima Daiichi site, as well as mid-term and long term measures by TEPCO and the Japanese Government aimed at decommissioning of the NPP and remediation of the off-site contaminated areas.

The following sections provide the details of those actions and the results observed from those actions and will be discussed further in Technical Volume 5 and, as relevant, in Technical Volumes 2, 3 and 4.

1.6.1. Actions taken towards stabilization and restoration of the Fukushima Daiichi units

On 17 April 2011, TEPCO issued the Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station [23] in order to bring the reactors and spent fuel pools to a stable cooling condition and mitigate the release of radioactive material. The immediate actions for achieving stability were focused on the areas of cooling, mitigation, monitoring and decontamination. The Government of Japan and TEPCO agreed to work together to implement the roadmap in order to steadily reduce radiation levels and to undertake to control and to minimize releases of radioactive material, when necessary [155].

1.6.1.1. Establishment of recirculation cooling of fuel debris

Following the initial seawater injection during the accident and subsequent transition to freshwater coolant by fire engines, starting in May 2011 cooling of the reactors in Fukushima Daiichi Units 1–3 was temporarily provided by fresh water injected through the feed water system piping utilizing temporary electric pumps. On 30 April, TEPCO started building a water treatment and reprocessing system, which became operable on 17 June. Recirculation cooling for all three reactors was established on 27 June 2011, using the new system (Fig. 1.6–1). TEPCO also started operation of the second caesium adsorption system on 19 August 2011 to improve the recirculation cooling loop while controlling radioactivity (water reprocessing is discussed further below).

After recirculation cooling was established, the RPV and PCV temperature monitors showed continuous cooling of the reactors.

[156] In some cases, additional information is available up until March 2015 and this information is provided where possible.

Until early September 2011, cooling was controlled by adjusting the amount of circulation water injected via the feedwater line through the downcomer and lower plenum into the core region. In September 2011, an additional injection path through the core spray system was established which allowed water to be sprayed over the core region from the top.

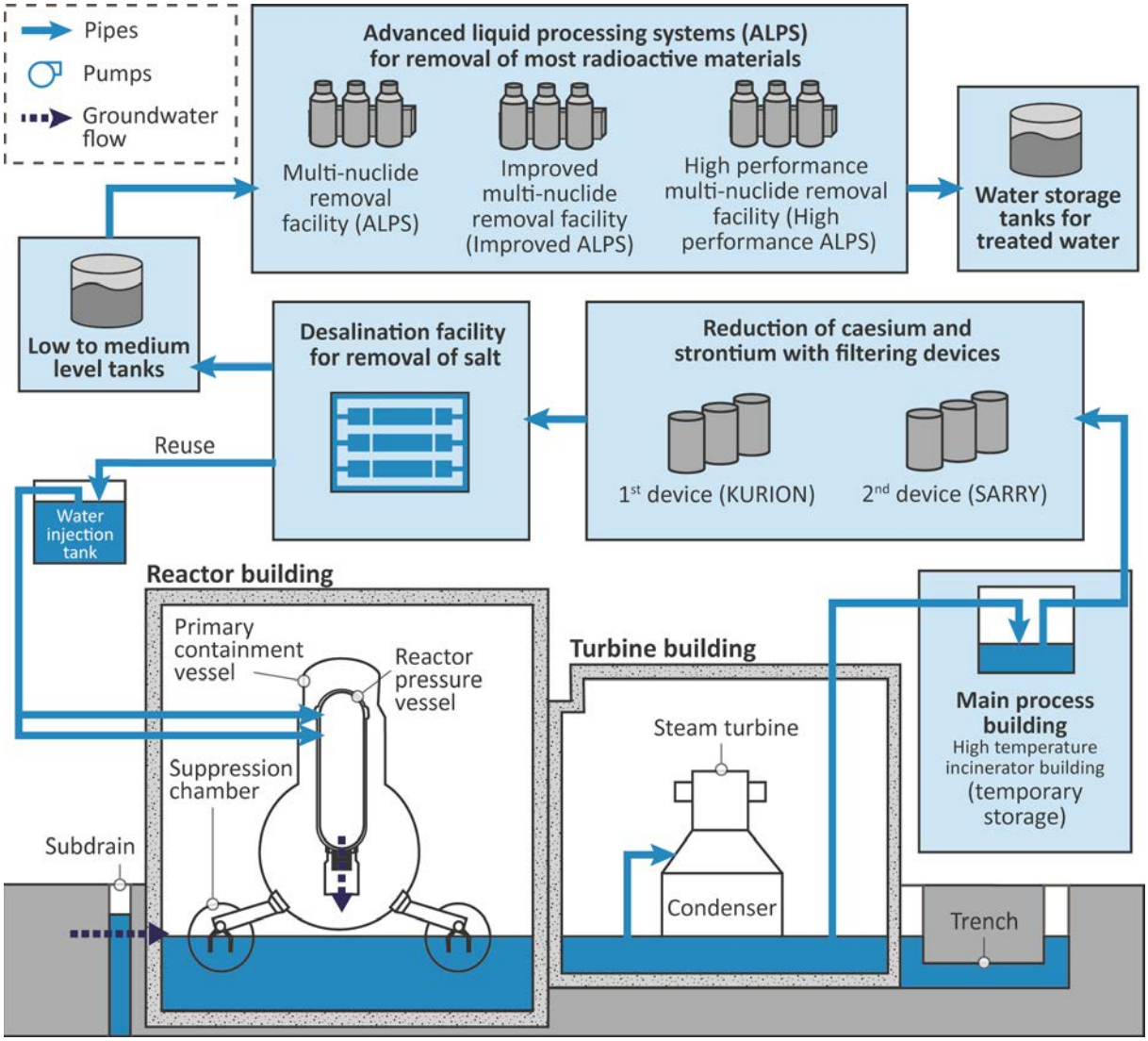


FIG. 1.6–1. Diagram of the circulating water cooling system for Units 1–3 [156].

1.6.1.2. Construction of water cleanup facilities

As the priority action following the accident was to establish circulating water cooling of fuel debris in Units 1–3, and the water became contaminated after flowing through the fuel debris, the installation of a water cleanup system became a key issue. On 30 April 2011, TEPCO started building the water treatment facilities incorporating oil separation, caesium adsorption, decontamination and water desalination with a reverse osmosis membrane. The facilities started operation on 17 June 2011 [157]. Further, TEPCO started installation of the second caesium adsorption system, SARRY (Simplified Active Water Retrieve and Recovery System), on 26 July, and it started operation on 19 August 2011. TEPCO implemented the distillation apparatus for desalination in series with the RO membrane apparatus and started operating the KURION-AREVA and SARRY systems in parallel. The levels of

accumulated water in the basements of turbine buildings started to decrease following start of operation of the SARRY water processing facility on 19 August 2011, as shown in Fig. 1.6–2.

After mid-September 2011, TEPCO focused its efforts on controlling the water level to prevent the outflow of contaminated water and minimizing penetration of groundwater from outside into the turbine buildings, as will be discussed in Section 1.6.2.

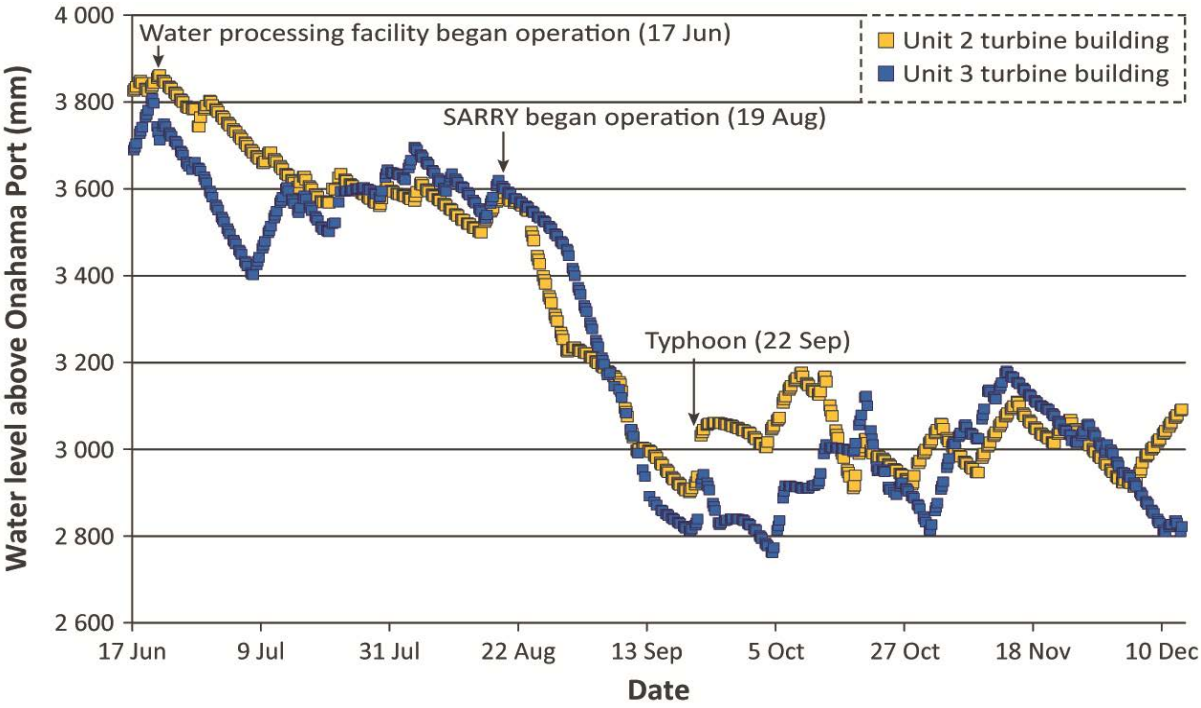


FIG. 1.6–2. Water levels in the turbine buildings in Units 2 and 3 [157].

1.6.1.3. Cooling of spent fuel in the spent fuel pools

In order to remove heat from the spent fuel stored in the SFPs of Fukushima Units 1–4, alternative circulating cooling systems were installed and started operation first in Unit 2 (31 May 2011), and later in Unit 3 (30 June), Unit 4 (31 July) and Unit 1 (10 August). A quasi-stable condition with temperatures of 30–40°C in SFPs was achieved by 27 August, 5 June, 7 July and 3 August 2011 at Units 1, 2, 3 and 4, respectively.

In Units 5 and 6, stable cooling has been maintained since the operating mode was changed to the shutdown cooling mode on 25 June and 6 May 2011 at Units 5 and 6, respectively.

In the common SFP, the water temperature had increased continuously until 24 March 2011 before the temporary cooling system started operation. Since then, stable cooling has been maintained.

During the accident, seawater was injected into the SFPs of Units 1–4. In order to mitigate the adverse effects of salt such as corrosion of structural components, TEPCO started desalination of Unit 2 SFP water with the reverse osmosis membrane method on 19 January 2012, and finished on 19 July 2012 by confirming that the salt concentration decreased from about 1350 ppm to 11 ppm. Similarly, desalination started on 11 April 2012 and finished on 18 March 2013 at Unit 3, and started on 29 November 2011 and finished on 12 October 2012 at Unit 4.

In order to prevent corrosion of structural components, hydrazine injection was started in Unit 1 SFP in August 2012, and later in the Unit 2–4 SFPs.

1.6.1.4. Assessment and stabilization of the Unit 4 SFP

After the inspections of the facility on 7 May 2011, TEPCO decided that due to the potential structural impact of the accident, the Unit 4 SFP needed reinforcements to enhance seismic safety margin. On 30 July 2011, TEPCO completed installation of the necessary reinforcements, although the preliminary assessments had shown sufficient seismic margin still remain. A detailed analytical assessment of Unit 4 SFP integrity and stability was performed by TEPCO in May 2012, which showed that the structural integrity is adequate.

1.6.1.5. Measures to reduce releases of radioactive materials to the atmosphere

After the initial releases of radioactive material in the early stages of the accident, TEPCO undertook a number of actions to contain the material that had already been released and to limit further releases to the atmosphere. The result of these measures was a dramatic reduction in atmospheric releases between July and August 2011, followed by a more gradual reduction between August 2011 and February 2012, when the release was essentially zero (see Fig. 1.6–3).

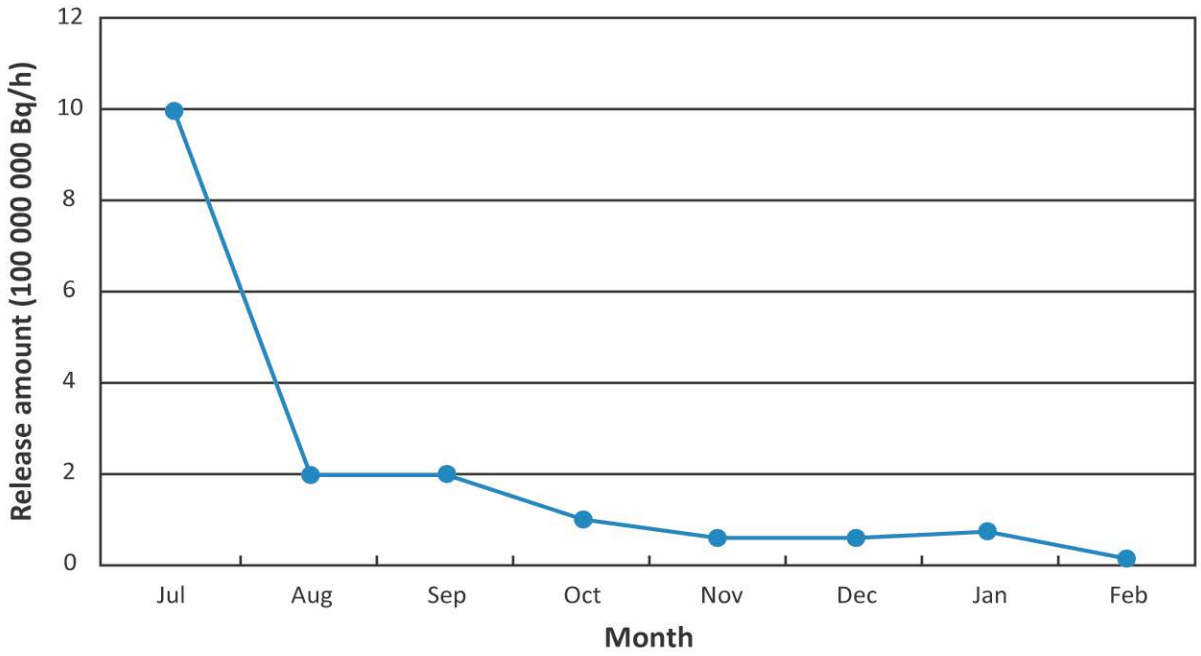


FIG. 1.6–3. Atmospheric release from the Fukushima Daiichi units between July 2011 and February 2012 [158].

The following actions were taken by TEPCO to reduce the release of radioactive material to the atmosphere:

— Following the accident, TEPCO sprayed dust inhibitor on the buildings and site ground to prevent the dispersal of dust in order to reduce radioactive material emissions to the atmosphere. In the early stages, the dust inhibitor was sprayed manually and then by a mobile pump was used for spraying. After May 2011, a concrete pumper and a bendable spray tower vehicle were used. By the end of June 2011, the work had been completed covering the target area of approximately 560 000 m^2 [158].

— On 28 October 2011, TEPCO completed the construction of a structure covering the RB of Unit 1 to suppress the dispersal of radioactive materials [158]. The cover consisted of a steel frame structure with roof and wall panels made of polyester fibre fabric. It is equipped with an exhaust system with filters which remove 99% of the radioactive materials before they can reach the outside atmosphere.
— TEPCO also installed gas control systems to reduce the radioactive releases from the primary containment vessels of Units 1–3, with a target filtering efficiency of 99%. The systems started operation first in Unit 2 in October 2011, and then Unit 1 in December 2011 and in Unit 3 in February 2012. As well as reducing the radioactive releases to less than 1%, the systems also analyse the radioactive nuclide content of the release and measures its hydrogen concentration, as discussed in Section 1.6–5.

1.6.1.6. Measures to reduce releases of radioactive material to the ocean

According to TEPCO [158], it was found that highly contaminated water had been leaking to the site harbour near the Unit 2 intake on 2 April 2011.[157] The leakage was stopped on 6 April [159]. Later, on 11 May 2011, a similar leakage took place near the Unit 3 intake [78]. TEPCO assumed that the highly contaminated water that had accumulated in the basement of the turbine building had leaked through the trench located between the turbine building and the intake. The trench had been damaged by the earthquake and/or tsunami.

TEPCO injected coagulator into the soil around the points where leaks had been found and also applied cement grout to the cracks. According to TEPCO, all the possible leakage paths were plugged by June 2011.

In April 2011, TEPCO closed off the entrances to the intake of Units 1–4 with silt fences and closed off the water intake of Units 1–4 with concrete block walls in June 2011.

From July to September 2011, in order to prevent radioactive materials from flowing into the ocean, TEPCO placed piles of steel pipe sheets at the permeation prevention structure located near the open conduit of southern water intake at Units 1–4. In addition, on 26 October 2011, TEPCO started construction of a water shielding wall in front of the existing seawall of Units 1–4.

TEPCO had also covered the seabed of the site harbour with a mixture of cement and clay in order to prevent radioactive materials deposited in the seabed from being stirred by bad weather conditions or turbulence caused by marine traffic.

In April 2013, the Council for the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Plant, chaired by the minister of METI, established a Committee on Measures related to Contaminated Water Treatment to cope with this issue. On 30 May 2013, the committee issued a report [160] and proposed to implement a 'frozen soil wall' enclosing Units 1–4.

At a press conference on 19 June 2013, TEPCO said it identified high concentrations of tritium and strontium in the groundwater samples from the No. 1 observation well located at the sea side of the turbine building of Units 1 and 2. On 22 July, TEPCO acknowledged that the groundwater containing radioactive materials was leaking to the site harbour. By then, TEPCO had started cleanup of the contaminated water in the trenches. The R&D activities associated with using 'ice plugging' technology, in order to stop the leaks between the TB and the trenches, was also started by TEPCO.

[157] Start time of the leak is unknown.

On 8 July 2013, TEPCO started injecting coagulator (water glass) into the soil of the surrounding area. This was called 'ground improvement'. TEPCO also started pumping up groundwater by using the 'well point' method.

On 3 September 2013, the NERHQ issued Basic Policy for the Contaminated Water Issue at the TEPCO's Fukushima Daiichi Nuclear Power Station [161] stating that the Government of Japan would take a more proactive role in the contaminated water issue, and establishing the roles, responsibilities and interfaces of government branches and TEPCO. The policy also described the activities to control contaminated water issues.

1.6.1.7. Hydrogen control

As mentioned above, TEPCO installed gas control systems to reduce radioactive releases from the primary containment vessels between October 2011 and February 2012. These systems have also been utilized to monitor hydrogen concentrations. Control measures to maintain hydrogen levels below flammable concentrations have been provided by nitrogen injection and purge of hydrogen, when necessary. Nitrogen gas injection to control hydrogen concentration below flammable limits started on April 2011 at Unit 1 PCV in order to purge the hydrogen gas produced by radiolysis [1, 2]. Nitrogen gas injection started at Units 2 and 3 as well on 28 June and 14 July 2011, respectively.

1.6.1.8. Recriticality control

After the initial boron injection as boric acid mixed with sea or fresh water to prevent recriticality during the accident, TEPCO installed a Boric Acid Injection Facility connected to the recirculation water system in June 2011 to guard against possible return to criticality in Units 1–3 and to reduce the potential for criticality in the SFPs of Units 1–4.

The potential return to criticality has been monitored by looking for increases in the ^{135}Xe concentration and/or abnormal temperature/pressure increases in the containment and reactor vessels. On 1 November 2011, TEPCO detected the possible presence of ^{133}Xe and ^{135}Xe gases in samples from inside the PCV of Fukushima Daiichi Unit 2. It responded to this development by injecting 10 t of boric acid solution (water containing 480 kg of boric acid) into Unit 2 on 2 November 2011 [162]. Again, on 7 February 2012, a temperature increase in the Unit 2 RPV bottom also triggered boric acid injection. To prevent criticality in the SFPs, TEPCO also injected boric acid solution into the SFP of Unit 3 on 27 June 2011.

1.6.1.9. Post-accident radiation monitoring

Radiation levels have been monitored continuously by TEPCO at the site boundaries of Fukushima Daiichi NPP site. There was a significant amount of debris and rubble on the site, some of which had high radiation dose rates. These were removed using heavy machinery. TEPCO compiled an on-site dose survey map and used it to help reduce the exposures of on-site workers. In addition, monitoring has been carried out at the north and south water discharge channels to the sea.

Marine monitoring has been conducted since March 2011 and a systematic plan was established in October 2011. The Monitoring Coordination Meeting, which was established under the NERHQ and chaired by the Minister of the Environment, developed a Comprehensive Radiation Monitoring Plan [163] on 1 April 2013. Also, a revised version of the 2013 Implementation Guides on Sea Area Monitoring was enclosed in the plan.

1.6.2. Actions towards a mid-term and long term roadmap for decommissioning

On 6 May 2011, the Integrated Countermeasure Headquarters for the Fukushima Nuclear Power Plant Accident, which was established on 15 March 2011 by the Prime Minister's Office, was reorganized into the Government–TEPCO Integrated Response Office under the NERHQ of the Japanese Government.

On 19 July 2011, the Government–TEPCO Integrated Response Office released its first announcement, stating that the first condition of 'cold shutdown state' defined in the Roadmap towards Restoration as "[r]adiation dose is in steady decline", had been achieved. This achievement was based on the data taken at the on-site and off-site monitoring posts, which showed that the release of radioactive materials had steadily decreased [156, 164].

On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the second condition of 'cold shutdown state' had been achieved in Units 1–3 by stating that: (1) the temperatures measured at the RPV bottom and those of the gaseous phase inside the PCV were maintained below approximately 100°C; and (2) as a result, the radiation doses at the site boundary due to the additional release of radioactive materials from the PCVs was evaluated to be 0.1 mSv/a, well below the target of 1 mSv/a.

Upon declaration of the achievement of 'cold shutdown state' on 16 December 2011, the Government–TEPCO Integrated Response Office was abolished and a new organization, the Government–TEPCO Mid-to-Long Term Response Council[158], was created in TEPCO Headquarters. On 21 December 2011, the Council issued the Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, TEPCO (hereafter the Roadmap) [165]. Its basic concept is shown in Fig. 1.6–4.

On 27 June 2013, the Council revised the roadmap. In the revised version, for example, multiple plans are provided for fuel debris removal and the target for commencement is accelerated [166]. The Japanese Government and TEPCO have conducted various activities according to the roadmap under the management of the Council. Those activities are described in the following sections.

[158] Later, on 8 February 2013, the name of the Council was changed to the Council for the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Plant by adding members from research organizations.

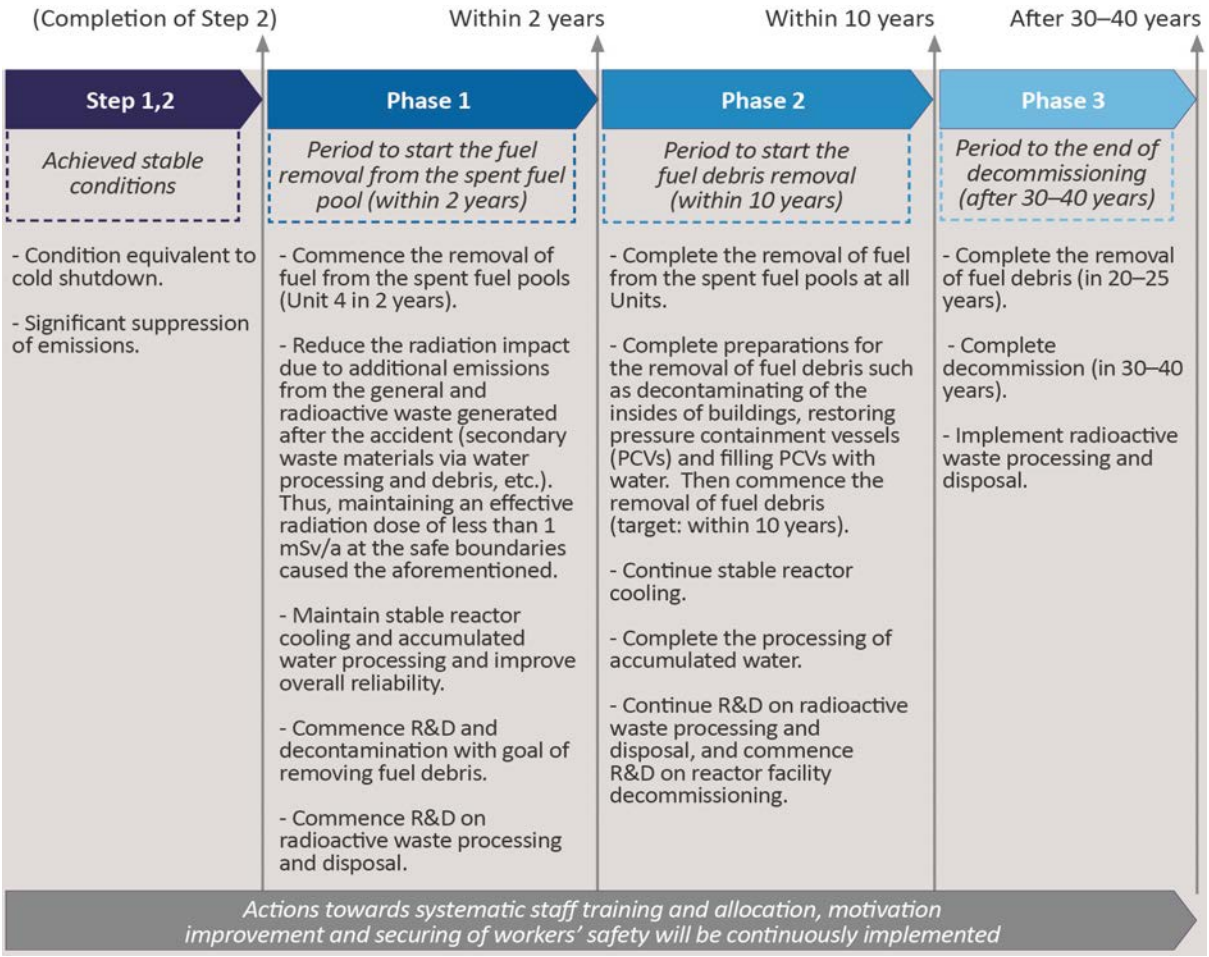


FIG. 1.6–4. *Basic concept of the Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima* Daiichi *Nuclear Power Station Units 1–4, TEPCO [165].*

1.6.2.1. Construction of a multi-nuclide removal facility

The decontamination facilities which were constructed just after the accident mainly remove caesium. A multi-nuclide removal facility, namely the Advanced Liquid Processing System (ALPS), was constructed to further reduce the radioactivity of the processed water by removing a larger number of radioactive nuclides (excluding tritium) down to levels less than the detection limit. TEPCO started its construction in June 2011 and completed it in October 2012 [167]. The test operation of ALPS started in November 2013. The operation of expanded ALPS started in September 2014. The operation of High-performance ALPS (HERO) started in October 2014.

1.6.2.2. Groundwater bypass

TEPCO has estimated that approximately 400 m^3/d of groundwater is penetrating into the reactor buildings and turbine buildings of Units 1–4 from the hill side. Approximately the same amount of water is circulating for debris cooling in the reactor vessels. Since the penetrating groundwater is mixed with the circulating water, a total of approximately 800 m^3/d of water is being processed [168]. Nearly 400 m^3/d of this processed water is injected back to the reactor vessels for debris cooling and the remaining 400 m^3/d has to be stored in the contaminated water storage tanks.

TEPCO is conducting 'groundwater bypass' to reduce the amount of groundwater penetrating into the buildings by pumping up groundwater from upstream of the buildings. Figure 1.6–5 shows its

concept. For this purpose, TEPCO constructed a total of 12 pump wells and water transfer systems by February 2012. Since 21 May 2014, pumped-up groundwater has been transferred to the temporary water storage tanks and, after the water contamination has been measured, discharged to the sea.

1.6.2.3. Removal of fuel from the Unit 4 SFP

In March 2012, in accordance with the Roadmap towards Decommissioning, TEPCO started preparatory activities for this fuel removal operation and in April 2012, started the construction of the cover structure for this purpose. The cover structure was completed in September 2013 and it was reviewed and approved by the regulatory body in November 2013 for use in fuel movement.

The fuel removal operation started on 18 November 2013 and the removal of all spent fuel was completed on 22 December 2014. The fuel assemblies stored in the fuel rack inside the Unit 4 SFP were taken out and transferred to the common pool for centralized storage located within the station site. The fuel assemblies already in the common pool were transferred to the temporary cask custody area in order to make space for the fuel assemblies from Unit 4.[159]

1.6.2.4. Measures taken against external hazards

Taking into account the damage to the reactor buildings of Units 1, 3 and 4 as a result of hydrogen explosions, TEPCO conducted seismic structural assessments of the reactor buildings to ensure structural integrity against further earthquakes with the design basis earthquake ground motion. TEPCO also conducted analyses demonstrating that the impact of the design basis earthquake is "fairly lower than the evaluation criterion" [169].

As discussed earlier, on 30 July 2011, TEPCO completed installation of the necessary supporting structures at the Unit 4 SFP. On 22 January 2012, TEPCO also conducted a survey and inspection of the fifth floor of the reactor building and confirmed that the water surface of the reactor well was parallel with the floor level. This indicated that the building had not tilted. On 9 February 2012, a visual inspection of SFP using an underwater camera was conducted to confirm that the fuel rods stored in the racks had not been dislodged. This was done by comparing with an earlier visual inspection conducted on 7 May 2011 [171]. On 20 March 2012, similar measurements were repeated, confirming that the structure had not been changed since 9 February 2012.

In June 2011, TEPCO analysed potential measures that could be taken with the existing configuration of the facility against a postulated tsunami with a maximum height of 7 m to 8 m [170]. As a result of this study, all the pumps for water injection into the RPVs of Units 1–3 were moved to higher locations by July 2011. The mobile emergency power sources, fire engines and other equipment were also moved to higher locations. TEPCO also constructed a temporary seawall using sandbags of height varying from 2.4 m to 4.2 m at the 10 m level to protect the major buildings.

[159] The fresh fuel assemblies were transferred to the Unit 6 SFP.

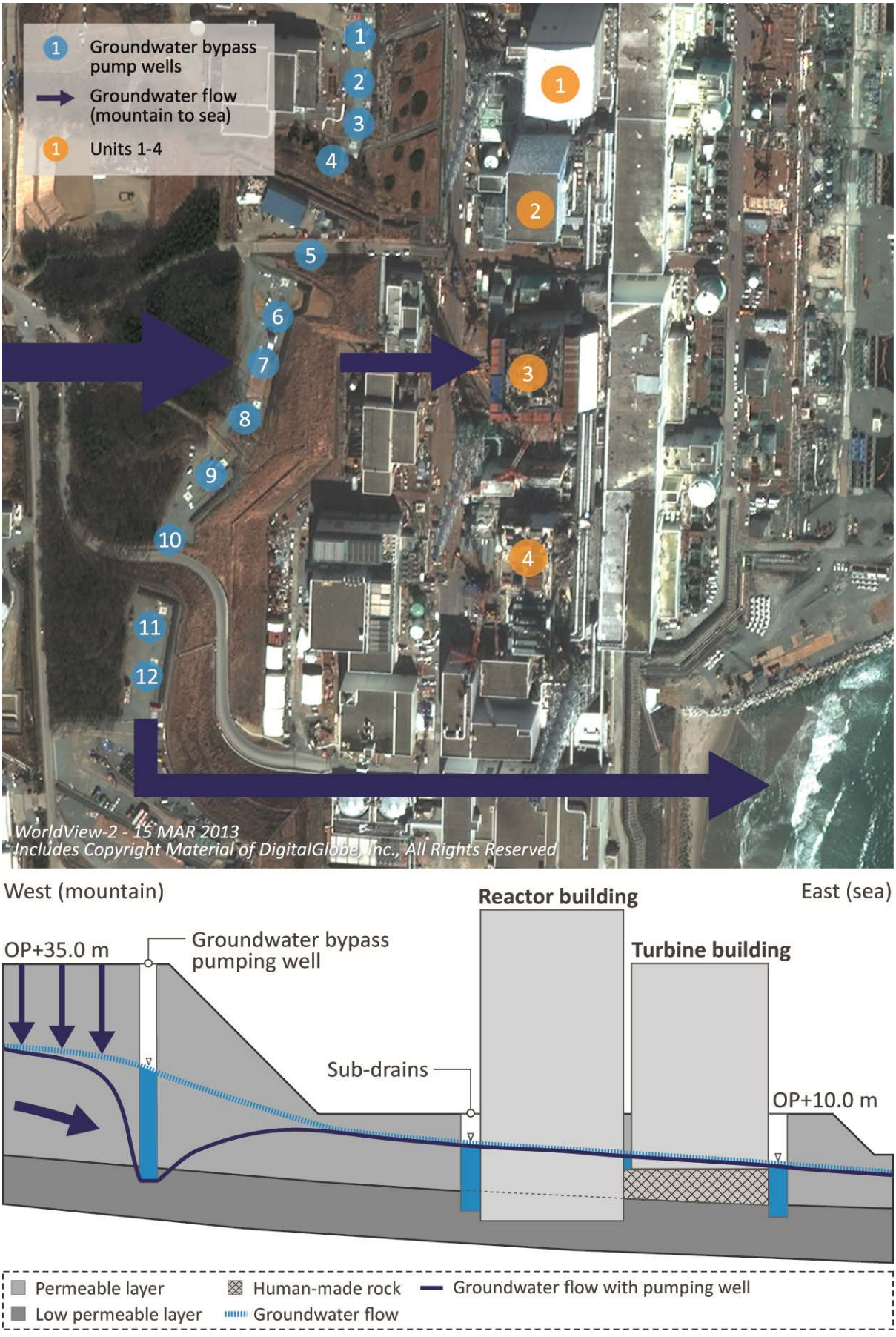


FIG. 1.6–5. Concept of groundwater bypass [170].

1.6.2.5. Enhancement of reliability

TEPCO established an organization for reliability enhancement, referred to as the Immediate Response Headquarters for Reliability Improvements, in April 2013 following frequent failures of equipment and associated events. Since the organization has been put in place, it has performed reviews of plant documents to identify vulnerabilities and common cause failures. Its teams have also conducted targeted facility walkdowns to confirm the assurance of reliability and to identify any potential issue that would affect essential functions of the equipment, to keep safe and stable conditions. TEPCO has reported that the primary functions targeted for this effort were: controlling radioactive material release, cooling the reactors and spent fuel pools, preventing hydrogen explosions, and preventing criticality [172].

In order to enhance reliability of water injection to the RPVs, redundancy and diversity of water and power sources were implemented with multiple pumps, tanks, and redundant off-site and on-site power sources. In addition, water can be retrieved from a nearby hydro dam. Seawater injection by fire engines is available as a final option.

Water injection for SFP cooling was also enhanced with redundant equipment. TEPCO installed two redundant trains of fuel pool cooling systems, each of which has a heat exchanger with a secondary system with an air-fin cooler. It also installed an emergency water injection system. Water from the filtrated water tanks and raw water underground tanks can be injected by the electric pumps, fire engines, or alternatively by concrete pumper. Two lines of the off-site power supply are available and, in case of loss of off-site power, on-site emergency power supply and mobile power sources are available.

1.6.3. Government/regulatory actions

1.6.3.1. Reorganization of the regulatory body

On 19 September 2012, the Nuclear Regulation Authority (NRA) was established [173]. Taking into account the lessons learned from the Fukushima Daiichi accident, the NRA was set up as an independent commission body affiliated to the Ministry of the Environment (MOE) and its chairman and commissioners were appointed by the Prime Minister, as approved by the National Diet of Japan. In addition, the roles and responsibilities that had been assigned to different governmental organizations were integrated into the NRA.

Regarding the technical support organizations, the NRA holds jurisdiction over part of the affairs of the National Institute of Radiological Sciences (NIRS) and the Japan Atomic Energy Agency (JAEA) and Japan Nuclear Energy Safety Organization (JNES), which was merged with NRA on 1 March 2014 [174]. New structure of the regulatory body is further discussed in Technical Volume 2.

1.6.3.2. Amendments to the Atomic Energy Basic Act and the Reactor Regulation Act

The amendments of the Basic Act and the Reactor Regulation Act, which were promulgated in June 2012, came into force on 19 September 2012. The amended Reactor Regulation Act also clarified the objectives of safety regulation and established new requirements, as further discussed in Technical Volumes 2 and 5, including [174]:

— Mandatory severe accident measures;
— Mandatory backfitting;
— Forty year lifetime limit for NPPs (with the possibility of up to a 20 year extension).

Based on this new legal framework, the NRA developed the new regulatory requirements which came into force on 8 July 2013. Immediately after this, four utilities applied for a review of 12 units at six sites.

1.6.3.3. New regulatory framework for the Fukushima Daiichi NPP facility

To cope with the Fukushima Daiichi accident, the former regulatory bodies NISA and NRA had taken 'emergency measures' stipulated in Article 64 of the Reactor Regulation Act.

When the Reactor Regulation Act was amended in September, 2012, a new regulatory framework was introduced for the regulation of 'Disaster-Experienced Facilities', such as the Fukushima Daiichi NPP. In this framework, the NRA designates such facilities as 'Specified Nuclear Facilities' by detailing the 'items for which the measures shall be taken for operational safety', based on Article 64–2, Paragraph (1) of the amended Act. In such a case, the licensee is required to submit a plan, referred as the 'Implementation Plan'. Then, the NRA reviews and approves it, and then conducts the regulatory oversight and control according to the Plan.

On 7 November 2012, the NRA designated Fukushima Daiichi NPP as specified nuclear facilities and required TEPCO to submit the Implementation Plan, while detailing the items for which the measures should be taken and the applicable time limit. The major points of the items are as follows: (1) with the goal of completing fuel removal as promptly as possible and reducing risks of the specified nuclear facilities as a whole, thereby ensuring safety on-site and offsite, measures shall be taken promptly and efficiently; (2) regarding Units 1–4, decommissioning measures, including removal and storage of fuel debris from molten cores, shall be completed as early as possible, while ensuring safety in the process; (3) regarding Units 5 and 6, stable cold shutdown conditions shall be maintained; and (4) Workers' exposure doses shall be ascertained and managed.

On 7 December 2012, TEPCO submitted the Implementation Plan to the NRA for review and approval [175]. The plan consisted of seven specific sections corresponding to the measures to be taken, as specified by the NRA, on: the overall process towards decommissioning and risk assessment of the 'specified nuclear facilities'; design and operation of structures, systems and components (SSCs) of the specified nuclear facilities; safety management of the specified nuclear facilities; protective measures for specified nuclear fuel materials; removal of fuel debris and decommissioning; promotion of public understanding of the Implementation Plan; and regulatory inspections based on the Implementation Plan. Upon receipt of the Implementation Plan, the NRA established the Commission on Supervision and Evaluation of the Specified Nuclear Facilities, for oversight of the plan implementation as well as site inspection.

1.6.3.4. New framework for emergency preparedness and response

In conjunction with the establishment of the NRA in September 2012, the Basic Act, the Nuclear Emergency Act and other related laws and regulations were amended. As a result of the revisions of laws and regulations, a new governmental framework for nuclear emergency preparedness was developed on the basis of the experience and lessons learned from the accident at the Fukushima Daiichi NPP [174]. The new framework included:

— Nuclear emergency preparedness has to be addressed and promoted by the entire Government in a consistent manner. In this context, the Nuclear Emergency Preparedness Council, chaired by the Prime Minister, was established within the Cabinet as a standing organization to promote the implementation and coordination of the emergency preparedness actions during normal times [176]. The chairperson of the NRA serves as one of the vice chairpersons of the Council, and the secretariat of the Council is headed by the Minister of Environment.

— The allotment of roles within the NERHQ was clearly defined [174]. The NRA takes responsibility for technical and professional matters concerning the safety of the affected nuclear facility. Arrangements for equipment and materials necessary for coping with the situations at the site and off-site response activities are carried out by other relevant ministries and agencies under the supervision of the head of the NERHQ.
— In line with the enhancement of nuclear emergency response systems, the nuclear emergency preparedness part of the Basic Plan for Emergency Preparedness was revised, incorporating the changed division of responsibilities which resulted from the establishment of the NRA, the crisis management system involving the NRA at the Prime Minister's Office, and clarification of on-site and off-site response activities [174].
— The Nuclear Emergency Preparedness Council approved the Nuclear Emergency Response Manual, which specifies such items as staff deployment and response procedures of the relevant ministries and agencies, including the NRA during an emergency.
— In conjunction with the enforcement of the amended Nuclear Emergency Act, the Cabinet Office revised related ministerial ordinance for the off-site centres and issued complementary guidelines specifying the technical standards for the off-site centres.
— In accordance with the provisions of the amended Nuclear Emergency Act and the newly established Guide for Nuclear Emergency Preparedness and Response, the relevant municipalities revised their regional emergency preparedness plans, which include evacuation plans in case of a nuclear accident.
— Recognizing the need for more realistic emergency response actions as soon as possible in the areas surrounding NPPs, a subcommittee of the former Nuclear Safety Commission started to study the revision of the Guide for Nuclear Emergency Preparedness and Response with the aim of incorporating the lessons learned from the Fukushima Daiichi accident into the Guide. A draft document showing the basic principles of the revision was issued on 1 November 2011 [177]. In the Guide, principles regarding the areas in which emergency preparedness should be concentrated were defined, and new zones, the Precautionary Action Zone and Urgent Protective Action Planning Zone, were proposed to replace the previous Emergency Planning Zone. These arrangements were implemented in the completely revised Guide by the NRA on 31 October 2012. The Guide entered into force on 27 February 2013 [178].

1.6.3.5. Plan for remediation of off-site areas

The Special Act for Decontamination[160] entered into force in August 2011, except for some parts [179].

Decontamination has been conducted according to the basic policy [180] developed from the Special Act for Decontamination, with the goal of reducing, in a phased manner, the areas where the additional annual exposure dose (in addition to natural and medical exposure dose) is higher than 20 mSv. For the Special Decontamination Areas, the Japanese Government prepared the decontamination plan and proceeded with the work according to the Decontamination Roadmap [181].

1.6.3.6. Actions on the health management of residents living nearby

Following the accident, surveys on the health conditions of residents in response to the accident were conducted by Fukushima Prefecture and other relevant organizations. Their respective roles in implementing health management surveys are specified in the Act on Special Measures for

[160] Titled 'The Act on Special Measures concerning the Handling of Environment Contamination by Radioactive Materials Discharged by the NPS Accident Associated with the Tohoku District off the Pacific Ocean Earthquake that Occurred on March 11, 2011', 30 August 2011.

Fukushima Reconstruction and Revitalization and other related laws and regulations. A team was put together and, after study and deliberations compiled a summary on 19 February 2013. Based on the results of the study by an advisory team, the NRA issued, on 6 March 2013, a set of recommendations on the health management of the residents living nearby.

1.6.3.7. Return of residents

The Government of Japan issued a policy statement on 26 December 2011 to review and rearrange the evacuated areas by the end of March 2012. The policy statement defined basic principles for determining to which zones in the evacuated areas residents would be allowed to return.

Rearrangement of areas to which evacuation was ordered pursuant to the policies mentioned above was completed in August 2013 for Kawauchi Village, Tamura City, Minamisoma City, Iitate Village, Naraha Town, Okuma Town, Katsurao Village, Tomioka Town, Namie Town, Futaba Town and Kawamata Town [182]. The evacuation order was lifted for the Miyakoji district of Tamura City on 1 April 2014 for the first time after the accident. On 1 October 2014, the Government also partially lifted the evacuation in Kawauchi Village which enabled the residents to return.

1.6.3.8. Guidance for the management of decontamination and disposal of waste

The Ministry of the Environment issued guidelines for handling, decontamination, and disposal of contaminated material on 14 December 2011. The guidelines provided a structure for the processing of decontamination wastes [183].

1.6.3.9. Interim storage facilities for decontamination wastes

The interim storage facilities were proposed to be built in the Fukushima Prefecture by the Japanese Government.[161] Borehole drilling investigation has started in some of the candidate areas. The interim storage facilities were planned to include a volume reduction facility, atmospheric and groundwater radiation monitoring facility, information service centre, and an R&D facility for the development and evaluation of effective volume reduction technology [184].

1.6.3.10. Revision of energy policy (Basic Energy Plan) in Japan and the status of NPPs

The Fukushima Daiichi accident resulted in changes in energy policy in Japan as a consequence of widespread and serious concerns over the safety of nuclear power. This necessitated a reconsideration of the feasibility of the large scale nuclear expansion, included in the 2010 Basic Energy Plan [185]. Therefore, the Japanese Government embarked on a comprehensive review of the Basic Energy Plan. Special government advisory committees were established to discuss the revision of the Plan. Then the Energy and Environment Council, a central body in charge of energy policy review in the Government, decided to adopt the Innovative Energy and Environment Strategy, on 14 September 2012, in which it was stated that Japan should seek to end its reliance on nuclear power as soon as possible [186]. However, following the formation of a new Japanese Government and further discussion, the Strategic Policy Committee released a draft recommendation in late 2013 on the Basic Energy Plan, positioning nuclear power as a key energy source while giving top priority to safety based on the lessons learned from the Fukushima Daiichi accident. The Government of Japan published a draft version of the Basic Energy Plan (based on the recommendations of the Committee) on 25 February 2014, which was subsequently submitted for Cabinet Decision [187].

[161] Consultations with local people in the candidate areas and negotiation with relevant municipalities are currently continuing to obtain acceptance.

In May 2012, the last remaining nuclear plant stopped operation for maintenance, and Japan experienced a 'zero nuclear' situation for the first time since nuclear power was introduced in 1966. Although two units of the Ohi NPP, operated by the Kansai Electric Power Company, restarted operation in July 2012, the plants were shut down for regular maintenance in September 2013. The NRA is responsible for conducting safety reviews for permitting the restart of the shutdown NPPs requesting permission. These reviews are based on the new regulatory requirements which include a wide range of safety measures for large scale earthquakes, tsunamis and severe accidents. As of August 2014, power companies had submitted applications to restart 19 nuclear power plants at 12 sites.

1.6.3.11. Investigation and analysis of the accident by the regulatory body

The NRA conducts technical reviews, taking into account the results from both medium and long term investigations of the inside of the damaged units. TEPCO investigated the inside of the Unit 1 containment in October 2012 and investigated the high dose areas within the Unit 3 reactor building by using a robotic camera in November 2012. Investigations by NRA mainly focus on:

— Technical issues identified by the National Diet commission and government committee that need further verification;
— Consequences of the accident and subsequent actions taken for the systems and components, including the reactors;
— Technical issues that need clarification in order to incorporate the lessons into future safety regulations.

TEPCO also continues to conduct further investigations into the inside of the containments and reactor buildings and informs the NRA of the results of these investigations in support of NRA's efforts.

1.6.4. Other events at the Fukushima Daiichi site following the accident

Following the initial stage of the accident, the situation at the site remained very complex and required the implementation of special controls and monitoring activities in order to maintain stability. The complexity and specialty of the situation at site were underlined by emerging issues and events. Pursuant to Paragraph 1 of Article 25 of the Act on Special Measures for Nuclear Emergency Preparedness, TEPCO is required to report the events at Fukushima Daiichi NPP site that adversely affect the stability of the facilities, such as those which led to the leakage of water containing radioactive materials, to the NRA.

As discussed earlier, the Reactor Regulation Act was amended in September 2012 and a new regulatory framework was introduced for the Fukushima Daiichi NPP site. Based on this new framework, the NRA approved TEPCO's Implementation Plan on 14 August 2013 [173]. Since then, TEPCO has reported events to the NRA pursuant to the amended Reactor Regulation Act. The following sections outline significant ones of those reported events.

1.6.4.1. Leakage of water containing radioactive material in the Unit 3 turbine building on 14 August 2012

Water containing radioactive material leaked from the line used to transfer water from the turbine building in Unit 4 to the water cleanup systems [188]. A second water leakage occurred in the same transfer line in the Unit 3 turbine building on 15 October, prior to implementation of corrective actions from the 14 August incident.

TEPCO started replacing the original pressure hoses by polyethylene pipes, which were more reliable, and completed all the replacements by June 2013 [189].

1.6.4.2. Fall of a steel beam into the SFP in Unit 3 on 22 September 2012

During debris removal from the upper part of the Unit 3 reactor building, a steel beam (approximately 300 mm × 200 mm × 7 m, and weighing 470 kg) fell into the SFP as workers were trying to clear the debris using a crane [190].

1.6.4.3. Water leakage from the vent line of the SARRY on 20 November 2012

Water leaked from the Simplified Active Water Retrieve and Recovery System (SARRY) vent line running from the high temperature incinerator building to the outside [191]. TEPCO shut down the operation and confirmed that the leakage had stopped. TEPCO evaluated the amount of leaked water from the size of the puddle on the ground (16 m × 11 m × 1 mm) to be approximately 176 L. Chemical analysis of the water showed the following radioactive nuclide concentrations: ^{134}Cs: 3.7×10^2 Bq/cm^3, ^{137}Cs: 6.5×10^2 Bq/cm^3, ^{60}Co: 3.5 Bq/cm^3.

1.6.4.4. Suspension of facility operation due to blackout on 18 March 2013

On 18 March 2013, a blackout occurred in part of the power supply system. As a result, the alternative cooling system for the SFP, the cooling system for the common SFP, part of the gas control system for the Unit 3 containment vessel, the caesium adsorption equipment, and part of the nitrogen gas transfer unit stopped operation.

Investigation discovered charred parts in the makeshift switchboard and the body of a small animal was found on the floor nearby. TEPCO concluded that the animal may have touched the conduction system, causing a short circuit and subsequent blackout.

1.6.4.5. Leakage of contaminated water from the storage tank on 19 August 2013

On 19 August 2013, it was found that water that had accumulated inside the dyke around the contaminated water storage tanks (so-called ‘flange type’ tanks in the H4 tank area) and had leaked outside the dyke through the drain valve [192]. High radiation doses were detected in the leaked puddle of water outside the dyke.

On 28 August 2013, the NRA categorized the leakage of contaminated water as a ‘serious incident’, i.e. Level 3 on the International Nuclear and Radiological Event Scale.

On 6 December 2013, TEPCO submitted a preliminary report to the NRA [193]. According to the report, TEPCO estimated the total amount of the leak to be approximately 300 m^3 since the water level of the tank was about 3 m lower than the presumed initial level (there was no water level measurement device in this tank). The concentrations of radioactive nuclides in the water were ^{134}Cs: 44 Bq/cm^3, ^{137}Cs: 92 Bq/cm^3, ^{125}Sb: 53 Bq/cm^3, total β: 2.0×10^5 Bq/cm^3. Since the amount of collected water from the tank area surrounded by the dyke was approximately 4 m^3 and that of the puddle outside the area was approximately 8 m^3, TEPCO presumed that most of the leaked water had escaped outside and permeated the soil.

Water sampling continued to be carried out not only at the existing ground water bypass and observation wells, but also at ones drilled specifically for the purpose of understanding how the leaked water affected the groundwater and sea water [193].

1.6.4.6. Water leakage from the contaminated water storage tank on 2 October 2013

On 2 October 2013, TEPCO was pumping up the water accumulated inside the dyke at B South Tank area to prepare for the rainfall expected from an approaching typhoon [194, 195]. The pumping was conducted by setting the limit for the maximum water level without quantitatively considering the ground slope.

After completing the pumping operation, the water level of B-A1 tank was 98.6%, but it decreased finally to 98.1% after the leak stopped. The reverse osmosis treated water (desalinated water) inside the tank had leaked from the flange part between the top plate and side plate, which was not leaktight. The estimated amount of the leak was approximately 17 m^3 inside the dyke and approximately 430 L outside the dyke.

1.6.4.7. Leakage of contaminated water from the desalination system on 9 October 2013

On 9 October 2013, water leaked from a pipe joint of the desalination system inside the temporary warehouse [196, 197]. TEPCO confirmed that the water was retained inside the dyke installed in the warehouse, but six out of the eleven workers involved received some internal exposure. The amount of the leak was approximately 11 m^3.

1.6.4.8. Inappropriate transfer of contaminated water on 13 April 2014

On 11 April 2014, TEPCO found that the level of contaminated water in the central waste building had decreased although the contaminated water was not transferred to other places. On 13 April, it was found by TEPCO that some contaminated water in the central waste building was transferred to the incineration building, which had been prepared as an emergency storage facility for contaminated water. TEPCO stopped the transfer of contaminated water [198]. The total amount of inappropriately transferred water was estimated by TEPCO to be approximately 203 m^3.

1.6.4.9. Leakage of contaminated water from the storage tanks on 9 June 2014

On 9 June 2014, the NRA's resident inspectors identified a small leakage of contaminated water near the bolt on the side of each of the two 'notch-tanks' [199]. On the same day, TEPCO transferred the water to the other tanks and then the leakages were stopped. Based on the fact that no anomaly was identified during the last surveillance in February 2014, TEPCO estimated that the total amount of the contaminated water leaked to the outside of the area surrounded by the weir was approximately 3.4 m^3 and its radioactivity was approximately 2.5×10^8 Bq (sum of all β nuclides). Since TEPCO treated the tanks in that area in a similar manner to those for storing the rain water temporarily, the drain valve from the area surrounded by the weir was left open. Actually, however, the radioactivity level of the water was high due to the influence of past leakages.

1.6.5. International actions

Numerous actions were undertaken in response to the Fukushima Daiichi accident by the nuclear international community with the aim of supporting the efforts of TEPCO and the Japanese authorities in the recovery efforts and learning the lessons from the accident to strengthen the safety of nuclear power plants worldwide.

The most relevant of these actions to this report are listed in the following sections.

1.6.5.1. Meetings of the Contracting Parties to the Convention on Nuclear Safety

At the Fifth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, held from 4 to 14 April 2011, the Parties adopted a statement in which they, inter alia, reaffirmed their commitment to the objectives of the Convention. The Contracting Parties agreed to hold an extraordinary meeting to review and discuss initial analyses of the accident and the effectiveness of the Convention.

Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Extraordinary Meeting was convened at IAEA Headquarters in Vienna from 27 to 31 August 2012. The Contracting Parties discussed: external events; design issues; severe accident management and recovery (on-site); national organizations; emergency preparedness and response; post-accident management (off-site); and international cooperation.

The Contracting Parties also agreed by consensus on a number of concrete actions to enhance the effectiveness of the peer review process. The three underlying guidance documents of the Convention were amended in order to enhance the transparency of the review process, encourage Contracting Parties to refer to the IAEA safety standards in their National Reports; and reinforce efforts for continuous improvement by performing periodic reassessments of safety through periodic safety reviews or alternative methods.[162]

A Working Group on Effectiveness and Transparency was established to report to the Sixth Review Meeting of the Contracting Parties on further actions to strengthen the Convention on Nuclear Safety and on proposals to amend it, where necessary. The Contracting Parties also considered a list of action-oriented objectives for strengthening nuclear safety, which was attached to the Summary Report of the Extraordinary Meeting [203].

Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety

The Sixth Review Meeting of the Contracting Parties to the Convention on Nuclear Safety was held from 24 March to 4 April 2014. During a special session of the meeting, Contracting Parties reported on the actions carried out in light of the Fukushima Daiichi accident. It was noted that, while nuclear safety and arrangements for emergency preparedness and response had improved, more remained to be done. National safety frameworks were being further enhanced, with steps taken to establish the effective independence of regulatory bodies and to update regulations. International cooperation had also increased, with greater participation in peer reviews and exchange of information [204].

The Contracting Parties to the Convention on Nuclear Safety reported the implementation of safety upgrades, including: the introduction of additional means to withstand prolonged loss of power and cooling; enhancement of power systems to improve reliability; re-evaluation of site-specific external natural hazards and multi-unit events; improvements of on-site and off-site emergency control centres to ensure protection from extreme external events and radiation hazards; the strengthening of measures to preserve containment integrity; and improvement of severe accident management provisions and guidelines.

[162] The Rules of Procedure and Financial Rules [200], the Guidelines regarding the Review Process [201] and the Guidelines regarding the National Reports [202].

The Contracting Parties also adopted proposals to further amend the underlying guidance documents of the Convention and made recommendations for action by the IAEA Secretariat, the Contracting Parties and other organizations.

Finally, the Contracting Parties decided by vote to convene a Diplomatic Conference within one year to consider a proposal by Switzerland to amend Article 18 of the Convention, on the design and construction of both new and existing NPPs.

Diplomatic Conference and the Vienna Declaration on Nuclear Safety

The Diplomatic Conference was convened by the Director General at IAEA Headquarters on 9 February 2015 and attended by 71 Contracting Parties. The Parties unanimously adopted the Vienna Declaration on Nuclear Safety. This Declaration included the following principles for the implementation of the third objective of the Convention, which is to prevent accidents with radiological consequences and to mitigate such consequences should they occur:

> "1. New nuclear power plants are to be designed, sited, and constructed, consistent with the objective of preventing accidents in the commissioning and operation and, should an accident occur, mitigating possible releases of radionuclides causing long-term off site contamination and avoiding early radioactive releases or radioactive releases large enough to require long-term protective measures and actions.
>
> 2. Comprehensive and systematic safety assessments are to be carried out periodically and regularly for existing installations throughout their lifetime in order to identify safety improvements that are oriented to meet the above objective. Reasonably practicable or achievable safety improvements are to be implemented in a timely manner.
>
> 3. National requirements and regulations for addressing this objective throughout the lifetime of nuclear power plants are to take into account the relevant IAEA safety standards and, as appropriate, other good practices as identified *inter alia* in the Review Meetings of the [Convention on Nuclear Safety]" [205].

The Vienna Declaration took into account the significant number of efforts and initiatives at the international, national and regional levels that had taken place since the accident at the Fukushima Daiichi NPP to enhance nuclear safety worldwide.

1.6.5.2. The IAEA Action Plan on Nuclear Safety

The IAEA Ministerial Conference on Nuclear Safety, convened in June 2011 to direct the process of learning and to act upon the lessons learned following the accident at the Fukushima Daiichi NPP, requested the IAEA Director General to prepare a draft Action Plan covering all the relevant aspects relating to nuclear safety, emergency preparedness and response, and radiation protection of people and the environment, as well as the relevant international legal framework. The draft IAEA Action Plan on Nuclear Safety was approved by the Board of Governors in September 2011. The Action Plan was then presented at the regular session of the 2011 IAEA General Conference, where it was unanimously endorsed by Member States [206]. The General Conference subsequently called upon the IAEA Secretariat and Member States to implement the actions as an overarching priority in a comprehensive and coordinated manner [207].

Activities under the Action Plan started immediately after its adoption. The full and effective implementation of the activities in this plan required joint efforts and full commitment by the IAEA Secretariat, Member States and other stakeholders.

Since the adoption of the Action Plan, significant progress has been made in several key areas, such as: assessments of the safety vulnerabilities of NPPs; strengthening of the IAEA's peer review services; review and revision, as necessary, of the relevant IAEA safety standards; improvements in emergency preparedness and response capabilities; capacity building; and enhancing communication and information sharing with Member States, international organizations and the public. Regular progress reports were presented to the IAEA Board of Governors and the IAEA General Conference [208-210].

In the resolution adopting the Action Plan, the IAEA's role in responding to a nuclear emergency was expanded to include providing Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information on its potential consequences. This is to include an analysis of available information and a prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

A number of international experts meetings (IEMs) were organized in different areas of safety to analyse the technical aspects and to learn the lessons from the Fukushima Daiichi accident. Reports on these key safety areas, including the results of the IEMs, were published by the IAEA (see Table 1.6–1).

Additional reports were prepared in 2013 on the following subjects:

— Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on a series of technical meetings held in 2012–2013 [211].
— Strengthening Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, based on the results of the International Conference on Effective Nuclear Regulatory Systems, Ottawa, Canada, 2013 [212].

TABLE 1.6–1. INTERNATIONAL EXPERTS MEETINGS (IEMS)

Date	Title	Focus
19–22 Mar. 2012	IEM I: Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [213]	Analyse technical aspects; understand root causes; share lessons from the accident.
18–20 Jun. 2012	IEM II: Enhancing Transparency and Communication Effectiveness in the Event of a Nuclear or Radiological Emergency [214]	Identify and analyse lessons from the accident and discuss best practices for improving the dissemination of information.
4–7 Sep. 2012	IEM III: Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [215]	Share lessons; exchange information and identify issues to be further investigated on: seismic and tsunami hazard assessment; special flooding issues; uncertainties associated with hazard assessments; approaches to establishing design values; addressing beyond design basis events; safety against earthquakes and tsunamis.
28 Jan. – 1 Feb. 2013	IEM IV: Decommissioning and Remediation after a Nuclear Accident [216]	Examine short term and long term issues for decommissioning of accident damaged facilities; management of radioactive waste arising from a nuclear accident; and remediation of the off-site environment.
21–24 May 2013	IEM V: Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant [217]	Explore ways to improve nuclear safety culture across a range of key institutions, including operating organizations and regulatory bodies.
17–21 Feb. 2014	IEM VI: Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding [218]	Focus on radiation protection issues highlighted by the Fukushima Daiichi accident and how these could be addressed at both the national and international levels.

TABLE 1.6–1. INTERNATIONAL EXPERTS MEETINGS (IEMS) (cont.)

Date	Title	Focus
17–20 Mar. 2014	IEM VII: Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant	Gather and share knowledge and experience gained in the light of the Fukushima Daiichi accident concerning severe accident management (SAM); identify lessons and best practices.
16–20 Feb. 2015	IEM VIII: Strengthening the Effectiveness of Research and Development in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant.	Facilitate the exchange of information arising from new R&D activities undertaken by IAEA Member States, as well as by the OECD Nuclear Energy Agency (OECD/NEA) and other international organizations dealing with severe accidents at NPPs, including those affecting spent fuel pools; further strengthen international collaboration among Member States and international organizations.
20–24 Apr. 2015	IEM IX: Assessment and Prognosis in Response to a Nuclear or Radiological Emergency	Facilitate the exchange of timely, clear, factually correct information during a nuclear or radiological emergency and its potential consequences, including analysis of available information and prognosis of possible scenarios based on the evidence, scientific knowledge and the capabilities of Member States.

1.6.5.3. IAEA peer review and assistance missions

Fact finding expert mission

Based upon an agreement with the Government of Japan, an International Fact Finding Expert Mission was undertaken by experts from the IAEA and Member States from 24 May to 2 June 2011. The mission gathered information for a preliminary assessment of the accident at the Fukushima Daiichi NPP and on events at other sites (Fukushima Daini and Tokai Daini). In addition, generic safety issues associated with natural events were identified that needed further exploration or assessment on the basis of the IAEA safety standards. It aimed to identify initial lessons to be learned from the accident at Fukushima Daiichi and share this information with the worldwide nuclear community. The Mission visited three affected NPPs — Tokai Daini, Fukushima Daini and Fukushima Daiichi to gain an appreciation of the status of the plants and the scale of the damage. The preliminary conclusions and lessons were shared and discussed with Japanese experts and officials and fell into three main areas: external hazards, severe accident management and emergency preparedness [62]. The specific scope of the mission included: external events of natural origin; plant safety assessment and the application of defence in depth; plant response after an earthquake and tsunami; management of a severe accident; management of spent fuel in a severely degraded facility; emergency preparedness and response; and radiological consequences. The mission findings [62] included 15 conclusions and 16 lessons, which were reported to the IAEA Ministerial Conference on Nuclear Safety in June 2011 [62].

Mission on remediation of large contaminated areas off-site the Fukushima Daiichi NPP

An IAEA mission to assist the Japanese Government in remediation of the large contaminated areas around the Fukushima Daiichi NPP took place in Japan with FAO and other international experts on 7–15 October 2011. Its main focus was on the remediation of the affected areas outside the 20 km restricted area [219]. The mission objectives were to: provide assistance to Japan in the plans to manage the remediation of large contaminated areas resulting from the accident at the Fukushima Daiichi NPP; and review remediation related strategies, plans and works, including contamination mapping, undertaken by Japan.

Mission to review NISA's approach to comprehensive assessments for safety of existing power reactor facilities

The IAEA organized a mission from 23 to 31 January, 2012 to review NISA's approach to the comprehensive assessment of the safety of existing power reactor facilities [220]. The scope of the IAEA mission covered NISA's comprehensive safety assessment process in order to identify how it is addresses external hazards, evaluation of safety margins, plant vulnerabilities, and severe accident management. The mission consisted of meetings at NISA's offices in Tokyo and a visit to the Ohi NPP to observe an example of how the comprehensive safety assessment was being implemented by the licensee.

Mission to Onagawa NPP to examine the performance of SSCs following the Great East Japan Earthquake and tsunami

The IAEA conducted a mission between 30 July and 11 August 2012 to the Onagawa NPP to examine the performance of the structures, systems and components (SSCs) of the Onagawa units which were subject to high level of ground motion during and following the earthquake and tsunami [221]. The information gathered was intended to be used to populate a database designed to capture the experience and performance of SSCs during strong earthquakes worldwide.

Peer review mission on the Mid-Term and Long-Term Roadmap

An IAEA Peer Review Mission on the Mid-Term and Long-Term Roadmap towards the Decommissioning Fukushima Daiichi NPP was conducted in Tokyo and in the Fukushima Prefecture from 15 to 22 April 2013 as part one of two consecutive missions on the Roadmap [222]. The objective of the first mission was to undertake an initial review of the Roadmap, including assessments of decommissioning strategy, planning and timing of decommissioning phases, and a review of several specific short term issues and recent challenges. The incidents recently experienced at the site, relating to failures of the power supply and leakages of water from the underground reservoirs, were also included in the review of the specific short term issues.

Mission (follow-up) on remediation of large contaminated areas off-site the Fukushima Daiichi NPP

A follow-up to the October 2011 IAEA mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi NPP took place again in Tokyo and in the Fukushima Prefecture between 14 and 21 October 2013 at the request of the Government of Japan [223]. The follow-up mission was to evaluate the progress of the ongoing remediation works achieved since the previous mission, as well as to review remediation strategies, plans and works, in view of the advice given in the first mission. Its scope also included the provision of assistance to Japan in assessing the progress made with the remediation of the Special Decontamination Area, which was not included in the first mission in 2011, and the Intensive Contamination Survey Areas. The Mission Team, which included FAO and other international experts, visited the affected areas, including several sites where remediation activities were being conducted.

Expert visits for seawater sampling and analysis

An expert visit was held between 6–12 November 2013. The objectives of the visit were to observe seawater sampling and data analysis in Fukushima (7 and 8 November 2013) and to meet the relevant Japanese authorities in Tokyo to collect information on marine monitoring conducted by Japan under its Sea Area Monitoring Plan.

Expert missions on marine monitoring confidence building and data quality assurance were held between 10–16 September 2014 and 4–14 November 2014. The missions focused on availability of marine monitoring results.

Peer review mission (follow-up) on the Mid-Term and Long-Term Roadmap

A second IAEA mission on the Mid-Term and Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi NPP Units 1–4 took place in Tokyo and at the Fukushima NPP from 25 November to 4 December 2013 [224]. The focus of this second IAEA mission was to provide a more detailed and holistic review of the revised Roadmap and mid-term challenges, including a review of specific topics agreed and defined in the first IAEA mission, such as removal of spent fuel from storage pools, removal of fuel debris from the reactors, management of contaminated water, monitoring of marine water, management of radioactive waste, maintenance and enhancement of stability and reliability of structures, systems and components, and R&D relevant to pre-decommissioning and decommissioning activities. The IAEA team also met with the NRA to discuss issues concerning marine monitoring.

Following the recommendation of the second decommissioning mission, projects were started to enhance transparency and to provide independent assessments of monitoring of the marine environment by Japan. Proficiency tests were conducted at the IAEA Environment Laboratories in Monaco to monitor the performance and analytical capabilities of participating laboratories. The results of the marine monitoring programme are regularly updated on the IAEA web site.

Fukushima Ministerial Conference on Nuclear Safety

In December 2012, the Government of Japan organized a Ministerial Conference in the Fukushima Prefecture, co-sponsored by the IAEA, with the principal objective of contributing to strengthening nuclear safety worldwide [225]. The conference provided an opportunity to share with the international community further knowledge and lessons learned from the accident and to discuss the progress of international efforts aimed at strengthening nuclear safety, including progress in the implementation of the Action Plan.

Discussions included: levels of radiation at Fukushima Daiichi; post-accident challenges for decommissioning and remediation; and the status of damage and recovery in the areas around the plant. The conference highlighted the importance of taking actions on the basis of scientific and factual information in the event of a nuclear or radiological emergency, and of enhancing international cooperation.

Memorandum of cooperation with Fukushima Prefecture

A memorandum of cooperation between the IAEA and Fukushima Prefecture was signed in December 2012 [226]. On the basis of this memorandum, practical arrangements on cooperation in the areas of radiation monitoring and remediation [227], human health [228], and emergency preparedness and response [229] were signed, with Fukushima Prefecture, the Fukushima Medical University and the Ministry of Foreign Affairs of Japan, respectively.

An IAEA Response and Assistance Network (RANET) Capacity Building Centre was designated in the city of Fukushima in May 2013. The Centre is used for a range of IAEA activities aimed at enhancing capacity for emergency preparedness and response, both in Japan and worldwide. A number of training workshops were held at the Centre dealing with monitoring during a nuclear and radiological emergency, notification, reporting and requesting assistance, and emergency preparedness and response.

1.6.5.4. Assistance from other international organizations

The OECD/NEA organized a mission to Tokyo from 16 to 18 November 2011 to discuss the complementary safety analyses to be performed for the Japanese NPPs. The OECD/NEA team of international experts met with NISA and JNES to foster a better understanding of post-Fukushima national safety reviews (or 'stress tests') conducted by other OECD/NEA member countries [230].

The Institute of Nuclear Power Operations (INPO) and the World Association of Nuclear Operators (WANO) jointly conducted an independent review of the accident in April 2012, at the request of TEPCO, to identify and share operational and organizational lessons with other nuclear operating organizations/companies. The review also included an investigation and analysis of the response to the earthquake and tsunami at the Fukushima Daini NPP as a source for learning additional lessons. INPO published a Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Plant in 2011 and a document called Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station in 2012 [231, 232]. WANO also conducted a shutdown safety review for the Fukushima Daiichi NPP and a corporate peer review for TEPCO in October 2013.

Following the Fukushima Daiichi accident, the OECD/NEA initiated a benchmark study to investigate and reconstruct the accident sequence in order to identify improvements for severe accident management. The Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant (BSAF), led by the Japan Atomic Energy Agency (JAEA), has two main objectives: to analyse and evaluate the accident progression and current status within the RPV and PCV of Fukushima Daiichi Units 1–3 to assist with future investigation and ultimately with fuel removal at those units; and to improve the methods and models of computer codes to reduce uncertainties in severe accidents analysis and to validate them using actual data from Fukushima Daiichi NPP Units 1–3 [230]. The participants include several organizations from France, Germany, Japan, the Republic of Korea, the Russian Federation, Spain, Switzerland and the USA.

REFERENCES

[1] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety — The Accident at TEPCO's Fukushima Nuclear Power Stations, Tokyo (2011), http://www.iaea.org/newscenter/focus/fukushima/japan-report

[2] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA — The Accident at TEPCO's Fukushima Nuclear Power Stations — Second Report, Tokyo (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html

[3] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Final Report, Cabinet Secretariat of the Government of Japan, Tokyo (2012), http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html

[4] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Interim Report, Cabinet Secretariat of the Government of Japan, Tokyo (2011), http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html

[5] THE NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of The Fukushima Nuclear Accident Independent Investigation Commission, The National Diet of Japan, Tokyo (2012).

[6] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report, TEPCO, Tokyo (2012).

[7] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression — Progress Report No. 1, TEPCO, Tokyo (2013).

[8] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression, Progress Report No. 2, Press Release, TEPCO (6 August 2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1240140_5892.html

[9] NUCLEAR REGULATION AUTHORITY, Analysis of the TEPCO Fukushima Daiichi NPS Accident, Interim Rep., NRA (2014), https://www.iaea.org/sites/default/files/anaylysis_nra1014.pdf

[10] JAPAN METEOROLOGICAL AGENCY, Information on the 2011 off the Pacific Coast of Tohoku Earthquake (2015), http://www.jma.go.jp/jma/en/2011_Earthquake/Information_on_2011_Earthquake.html

[11] NATIONAL POLICE AGENCY, Damage Situation and Police Countermeasures Associated with the 2011 Tohoku District–Off the Pacific Ocean Earthquake, Press Release (11 March 2015), https://www.npa.go.jp/archive/keibi/biki/higaijokyo_e.pdf

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Power Reactor Information System (PRIS) (2015), http://www.iaea.org/pris/

[13] COASTAL ENGINEERING COMMITTEE OF JAPAN SOCIETY OF CIVIL ENGINEERS, The 2011 off the Pacific coast of Tohoku Earthquake Information (30 March 2012), Coastal Engineering Committee, JSCE http://www.coastal.jp/tsunami2011/index.php?Field%20survey%20results

[14] JAPAN METEOROLOGICAL AGENCY, Tsunami Information (Estimated Tsunami Arrival Time and Height) (2011), http://www.jma.go.jp/en/tsunami/info_04_20110311145026.html

[15] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Fukushima Daiichi Unit 1 Establishment Permit, NISA (1966) (in Japanese).

[16] TOKYO ELECTRIC POWER COMPANY, Building Diagrams for 1F Ground Level and Cross Section of Unit 4 and the Common Spent Fuel Pool, official communication (2014).

[17] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Dry Storage Cask Leak Test Results Reported to METI, METI (2013) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/20130530_03.html
[18] CABINET OFFICE, Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness, No. 195 (2000) (in Japanese), http://law.e-gov.go.jp/htmldata/H12/H12SE195.html
[19] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156, 17 December 1999, http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf
[20] TOKYO ELECTRIC POWER COMPANY, Operation Manuals of TEPCO Fukushima Daiichi NPP in Case of Accident, TEPCO (2011) (in Japanese), http://www.nsr.go.jp/archive/nisa/earthquake/manual/manual_index.html
[21] NUCLEAR SAFETY COMMISSION, Accident Management: Measures against Severe Accidents at Light Water Nuclear Power Reactor Facilities, NSC (1992) (in Japanese), http://www.mext.go.jp/b_menu/hakusho/nc/t19920528001/t19920528001.html
[22] NUCLEAR SAFETY COMMISSION, Accident Management for Severe Accidents at Light Water Power Reactor Installations, NSCRG: L-AM-II.01, NSC (1992).
[23] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (17 April 2011), http://www.meti.go.jp/english/speeches/pdf/20110417_a.pdf
[24] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Power Profile for Japan, IAEA, Vienna, (2004, partially updated in 2009) http://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2004/CNPP_Webpage/countryprofiles/Japan/Japan2004.htm
[25] TOKYO ELECTRIC POWER COMPANY, Nuclear Safety Reform Plan: Progress Report (4th Quarter, FY2014), TEPCO, Tokyo (2015).
[26] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Summary and Nuclear Safety Reform Plan, TEPCO, Tokyo (2013).
[27] WORLD ASSOCIATION OF NUCLEAR OPERATORS, Traits of a Healthy Nuclear Safety Culture, WANO Guideline No. GL2013-1, WANO (2013).
[28] KAWAMURA, S., Integration of Knowledge Management in Plant Support Engineering Processes at TEPCO, Knowledge Management in Nuclear Facilities, IAEA-CN-153/2/P/04, IAEA, Vienna (2007).
[29] HIDEAKI, S., Regulatory Failures of Nuclear Safety and Complex Risk Governance: The Case of the Fukushima Accident, Annual Meeting of the The Law and Society Association, The Law and Society Association, Hilton Hawaiian Village Resort, 3 June 2012 (2012).
[30] OECD NUCLEAR ENERGY AGENCY, Nuclear Law Bulletin **22** 1 (1978) 1–68.
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, The International Nuclear and Radiological Event Scale (INES) User's Manual, IAEA, Vienna (2013).
[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on the Preliminary Fact Finding Mission Following the Accident at the Nuclear Fuel Processing Facility in Tokaimura, Japan, IAEA, Vienna (1999).
[33] OECD NUCLEAR ENERGY AGENCY, Regulatory and Institutional Framework in Japan against the Background of Fukushima, Nuclear Law Bulletin **87** 1 (2011) 27–44.
[34] OECD NUCLEAR ENERGY AGENCY, Reorganisation of the Japanese Government in the Nuclear Sector (2001), Nuclear Law Bulletin **66** (2000) 42.
[35] OECD NUCLEAR ENERGY AGENCY, Nuclear Law Bulletin **68** 2 (2001).
[36] GOVERNMENT OF JAPAN, National Report to the 4th Review Meeting on the Convention on Nuclear Safety, Tokyo (2007), http://www.nsr.go.jp/archive/nsc/anzen/shidai/genan2007/genan064/siryo64-3_t2.pdf
[37] GOVERNMENT OF JAPAN, National Report to the 5th Review Meeting on the Convention on Nuclear Safety, Tokyo (2010).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Regulatory Review Service (IRRS) to Japan, IAEA-NSNI-IRRS-2007/01, IAEA, Vienna (2007).
[39] OECD NUCLEAR ENERGY AGENCY, Nuclear Law Bulletin **65** 1 (2000) 44–46.
[40] GOVERNMENT OF JAPAN, National Report to the 3rd Review Meeting on the Convention on Nuclear Safety, Tokyo (2004).

[41] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from the JCO Nuclear Criticality Accident in Japan in 1999, IAEA, Vienna (2009).
[42] KATO, S., "Recent Development in Safety Regulation of Nuclear Fuel Cycle Activities", Topical Issues in Nuclear Safety (Proc. Int. Conf. Vienna, 2001), IAEA, Vienna (2001).
[43] MINISTRY OF FOREIGN AFFAIRS OF JAPAN, Central Government Reform (2001), MOFA, http://www.mofa.go.jp/about/hq/central_gov/index.html
[44] Law for Establishment of the Ministry of Economy, Trade and Industry, Law No. 120, 2000, of November 17.
[45] WORLD NUCLEAR ASSOCIATION, Nuclear Power in Japan, WNA (25 November 2014), http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan/
[46] NUCLEAR REGULATORY COMMISSION, A Comparison of US and Japanese Regulatory Requirements in Effect at the Time of The Fukushima Accident, NRC, Washington, DC (2013).
[47] NUCLEAR STANDARDS COMMITTEE OF JAPAN ELECTRIC ASSOCIATION, Regulations for Decision-Making Operators, JEAC4804-2014, JEA (2014) (in Japanese), http://www.denki.or.jp/committee/nuc/jeac/4804/jeac4804.html
[48] JAPAN NUCLEAR TECHNOLOGY INSTITUTE, Description of the Division's activities, Technical Skill Development Division, JANTI (2014), http://www.gengikyo.jp/english/katsudo/GiryoIkseiTop.html
[49] BWR OPERATOR TRAINING CENTER CORPORATION, Responsible Operator Certification, BTC (2014) http://www.btc.co.jp/e_coursecertificate.html
[50] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, The Standard for Responsible Operators, METI Bulletin No. 589, METI (2001) (in Japanese).
[51] ALDRICH, D.P., Site Fights: Divisive Facilities and Civil Society in Japan and the West, 1st edn, Cornell University Press, New York (2008).
[52] MUTSU RADIOACTIVITY LEAK INVESTIGATION COMMISSION, Mutsu Radioactivity Leak Investigation Report, Atomic Energy Commission Monthly Rep. **20** 5, Atomic Energy Commission (1975).
[53] NUCLEAR SAFETY COMMISSION, A Summary of the Report of the Criticality Accident Investigation Committee, NSC (1999) (provisional translation), http://www2.ans.org/pi/docs/doe-japan-final.pdf
[54] JAPAN ATOMIC INDUSTRIAL FORUM, Toward Reform of Japan's Private-sector Nuclear Industry, JAIF (8 October 1999), http://www.jaif.or.jp/english/news/1999/1008-1.html
[55] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation into Inspection and Maintenance Problems at TEPCO's Nuclear Power Plants, Pointed out by General Electric, Press Release, TEPCO (17 September 2002), http://www.tepco.co.jp/en/press/corp-com/release/02091701-e.html
[56] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Measures of the Nuclear and Industrial Safety Agency Concerning the Kashiwazaki-Kariwa Nuclear Power Station, Affected by the Niigataken Chuetsu-oki Earthquake, Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry, Tokyo (2009).
[57] INTERNATIONAL ATOMIC ENERGY AGENCY, 2nd Follow-Up IAEA Mission in Relation to the Findings and Lessons Learned from the 16 July 2007 Earthquake at Kashiwazaki-Kariwa NPP (1–5 December 2008), Tokyo and Kashiwazaki-Kariwa NPP, Japan, IAEA, Vienna (2009).
[58] NUCLEAR SAFETY COMMISSION, Actions to Take Concerning the Malicious Conduct of Unreported Alteration and Concealment at Nuclear Facilities, NSC, Tokyo (2007).
[59] ISHII, N., (Ed.), Hokuriku Electric Rocked by Scandal: Criticality Accident Cover-up, JAIF (2007), http://www.jaif.or.jp/english/aij/member/2007/2007-03-19.pdf
[60] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Simulation Techniques for Accident Management Training in Nuclear Power Plants, IAEA-TECDOC-1352, IAEA, Vienna (2003).
[61] NUCLEAR STANDARDS COMMITTEE OF JAPAN ELECTRIC ASSOCIATION, Nuclear Power Plant Contingency Planning Guidelines, JEAG4102-2010, JEA (2010) (in Japanese), http://www.denki.or.jp/committee/nuc/jeac/4102/jeag4102.html

[62] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Fact Finding Expert Mission Report of the Fukushima Daiichi NPP Accident Following the Great East Japan Earthquake and Tsunami, Tokyo, Fukushima, IAEA, Vienna (24 May–2 June 2011), IAEA, Vienna (2011).
[63] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report (Interim Report), TEPCO, Tokyo (2011).
[64] TOKYO ELECTRIC POWER COMPANY, Data of Abnormal Events Including Alarm Records — Unit 1 (23 June 2011) (in Japanese), http://www.tepco.co.jp/en/nu/fukushima-np/plant-data/f1_3_Keihou1.pdf
[65] TOKYO ELECTRIC POWER COMPANY, Data of Abnormal Events Including Alarm Records — Unit 3 (23 June 2011) (in Japanese), http://www.tepco.co.jp/en/nu/fukushima-np/plant-data/f1_3_Keihou3.pdf
[66] NUCLEAR REGULATORY COMMISSION, Boiling Water Reactor (BWR) Systems, Reactor Concepts Manual, USNRC Technical Training Center, http://www.nrc.gov/reading-rm/basic-ref/teachers/03.pdf
[67] GENERAL ELECTRIC, BWR Owners' Group Emergency Procedure Guidelines, Revision 4, BWROG-TP-80S-082 (NEDO-31331) (1987).
[68] INTERNATIONAL ATOMIC ENERGY AGENCY, Implementation of Accident Management Programmes in Nuclear Power Plants, Safety Reports Series No. 32, IAEA, Vienna (2004).
[69] TOKYO ELECTRIC POWER COMPANY, Severe Accident Operation Manual, Press Release, METI (2011), http://www.meti.go.jp/press/2011/10/20111024003/20111024003-4.pdf
[70] FUJIWARA, T., et al., The 2011 Tohoku-Oki Earthquake: Displacement Reaching the Trench Axis, Science **334** 6060 (2011) 1240.
[71] FUJII, Y., SATAKE, K., SAKAI, S., SHINOHARA, M., KANAZAWA, T., Tsunami source of the 2011 off the Pacific Coast of Tohoku earthquake, Earth Planets Space **63** 7 (2011) 815–820.
[72] INTERNATIONAL ATOMIC ENERGY AGENCY, Convention on Early Notification of A Nuclear Accident and Convention on Assistance in the Case of A Nuclear Accident or Radiological Emergency, Legal Series No. 14, IAEA, Vienna (1987).
[73] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Interim Report: Effects of the Earthquake and Tsunami on the Fukushima Daiichi and Daini Nuclear Power Stations, Especially on Electric and I&C Systems and Equipments, IEEE Nuclear Power Engineering Committee, TEPCO (2011).
[74] TOKYO ELECTRIC POWER COMPANY, Status of TEPCO's Facilities and its services after the Tohoku-Chihou-Taiheiyou-Oki Earthquake — Past Progress, Press Release, TEPCO (19 August 2011), http://www.tepco.co.jp/en/press/corp-com/release/11081909-e.html
[75] NUCLEAR REGULATORY COMMISSION, Digest Email Series — Kazuhito Takeda, official communication, NRC (2011), http://pbadupws.nrc.gov/docs/ML1129/ML11297A091.pdf
[76] JAPAN ATOMIC ENERGY AGENCY, Results of Analysis of Accumulated Water in the Turbine Buildings and Results of Nuclide Analysis, TEPCO (22 March 2011), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_110522_04-e.pdf
[77] TOKYO ELECTRIC POWER COMPANY, Present Status of Fukushima Daiichi NPS and Implemented Countermeasures — 2.3 Countermeasures to Protect the Ocean, TEPCO (2014), http://www.tepco.co.jp/en/nu/fukushima-np/review/review2_3-e.html
[78] TOKYO ELECTRIC POWER COMPANY, Measures Against Leakage of Water Containing Radioactive Materials near the Intake at Unit 2 of Fukushima Daiichi Nuclear Power Station, Press Release, TEPCO (21 May 2011) (in Japanese), http://www.tepco.co.jp/cc/press/11052102-j.html
[79] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Seismic Damage Information (the 26th Release), Press Release, Ministry of Economy, Trade and Industry (16 March 2011), http://www.nsr.go.jp/archive/nisa/english/files/en20110317-1.pdf
[80] TOKYO ELECTRIC POWER COMPANY, Data of Abnormal Events Including Alarm Records — Unit 2 (23 June 2011) (in Japanese), http://www.tepco.co.jp/en/nu/fukushima-np/plant-data/f1_3_Keihou2.pdf

[81] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Operational Status of Nuclear Facilities in Japan, 2011 edn, JNES, Tokyo (2011).
[82] NISHIHARA, K., IWAMOTO, H., SUYAMA, K., Estimation of fuel compositions in Fukushima-Daiichi Nuclear Power Plant, JAEA-Data/Code 2012-018, Japan Atomic Energy Agency, Tokaimura (2012) (in Japanese), http://jolissrch-inter.tokai-sc.jaea.go.jp/search/servlet/search?5036485&language=1
[83] SCHWANTES, J.M., ORTON, C.R., CLARK, R.A., Analysis of a nuclear accident: Fission and activation product releases from the Fukushima Daiichi Nuclear Facility as remote indicators of source identification, extent of release, and state of damaged spent nuclear fuel, Environ. Sci. Technol. **46** 16 (2012) 8621–8627.
[84] KIRCHNER, G., BOSSEW, P., DE CORT, M., Radioactivity from Fukushima Dai-ichi in air over Europe; Part 2: What can it tell us about the accident? J. Environ. Radioact. **114** (2012) 35–40.
[85] AVVAKUMOV, A.V., et al., Verification of the BONUS module integrated into the SOCRAT code, Atomic Energy **106** 5 (2009) 316–325.
[86] KISELEV, A.E., TARASOV, V.I., TSAUN, S.V., Verification of an improved module for calculating fission products production in the industry code SOKRAT, Atomic Energy **113** 6 (2013) 435–438.
[87] DOLGANOV, K.S., et al., Real-time calculation of the accident at the Fukushima-1 NPP (Japan) using the SOKRAT code, Atomic Energy **114** 3 (2013) 161–168.
[88] INTERNATIONAL ATOMIC ENERGY AGENCY, Fission Gas Release and Fuel Rod Chemistry Related to Extended Burnup (Proc. Tech. Comm. Mtg, Pembroke, Ontario, 1992), IAEA-TECDOC-697, IAEA, Vienna (1993).
[89] SERNA, J.J., et al., Experimental observations on fuel pellet performance at high burnup, J. Nucl. Sci. Technol. **43** 9 (2006) 1045–1053.
[90] TOKYO ELECTRIC POWER COMPANY, Analysis and Evaluation of the Operation Record and Accident Record of Fukushima Daiichi Nuclear Power Station at the Time of Tohoku-Chihou-Taiheiyou-Oki-Earthquake, Press Release, TEPCO (23 May 2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110524e16.pdf
[91] FUSHIMI, K., NAKAYAMA, S., SAKAMA, M., SAKAGUCHI, Y., Measurement of airborne radioactivity from the Fukushima reactor accident in Tokushima, Japan, Cornell University Library (2011), http://arxiv.org/pdf/1104.3611v5.pdf
[92] SAEGUSA, J., KIKUTA, Y., AKINO, H., Observation of gamma-rays from fallout collected at Ibaraki, Japan, during the Fukushima nuclear accident, Applied Radiation and Isotopes **77** (2013) 56–60.
[93] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience — Report of the Chernobyl Forum Expert Group 'Environment', Radiological Assessment Reports Series, IAEA, Vienna (2006).
[94] NAKAMURA, T., Radiation and Radioactivity Monitoring in the Surrounding Environment after the Fukushima Daiichi Nuclear Power Plant Accident: Overview, The 1st NIRS symposium on reconstruction of early internal dose in the TEPCO Fukushima Daiichi Nuclear Power Station accident, NIRS-M-252 (KURIHARA, O., AKAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., (Eds)), National Institute of Radiological Sciences, Chiba (2012) 113–120.
[95] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Monitoring Air Dose Rates from a Series of Aircraft Surveys 30 Months after the Fukushima Daiichi NPS Accident (25 December 2013), https://www.nsr.go.jp/data/000067233.pdf
[96] HARDY, E., Depth Distribution of Global Fallout Sr^{90}, Cs^{137} and $Pu^{239, 240}$ in Sandy Loam Soil, Health and Safety Laboratory Fallout Program Quarterly Summary Report, 1 June – 1 September 1974, HASL-286, United States Atomic Energy Commission, New York (1974).
[97] ZHENG, J., et al., Isotopic Evidence of Plutonium Release into the Environment from the Fukushima DNPP Accident, Scientific Reports **2** (2012).
[98] SHOZUGAWA, K., NOGAWA, N., MATSUO, M., Deposition of fission and activation products after the Fukushima Dai-ichi nuclear power plant accident, Environ. Pollut. **163** (2012) 243–247.
[99] SCHNEIDER, S., et al., Plutonium release from Fukushima Daiichi fosters the need for more detailed investigations, Sci. Rep. **3** (2013) Artno. 2988.

[100] TOKYO ELECTRIC POWER COMPANY, Estimation of Radioactive Material Released to the Atmosphere during the Fukushima Daiichi NPS Accident, Press Release, TEPCO (May 2012), http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120524e0205.pdf
[101] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Fukushima, One Year Later: Initial Analyses of the Accident and its Consequences, Rep. IRSN/DG/2012-003, IRSN, Fontenay-aux-Roses (2012).
[102] MATHIEU, A., KORSAKISSOK, I., QUELO, D., Atmospheric dispersion and deposition of radionuclides from the Fukushima Daiichi nuclear power plant accident, Elements **8** 3 (2012) 195–200.
[103] MATHIEU, A., et al., État de la modélisation pour simuler l'accident nucléaire de la centrale Fukushima Daiichi, Pollution Atmosphérique, **2013** 217 (2013).
[104] SAUNIER, O., et al., An inverse modeling method to assess the source term of the Fukushima nuclear power plant accident using gamma dose rate observations, Atmos. Chem. Phys. **13** 22 (2013) 11403–11421.
[105] WINIAREK, V., BOCQUET, M., SAUNIER, O., MATHIEU, A., Estimation of errors in the inverse modeling of accidental release of atmospheric pollutant: Application to the reconstruction of the Cesium-137 and Iodine-131 source terms from the Fukushima Daiichi power plant, J. Geophys. Res. **117** D5 (2012) 1–16.
[106] WINIAREK, V., et al., Estimation of the Caesium-137 source term from the Fukushima Daiichi nuclear power plant ssing a consistent joint assimilation of air concentration and deposition observations, Atmospheric Environment **82** (2014) 268–279.
[107] CHINO, M., et al., Preliminary estimation of release amounts of ^{131}I and ^{137}Cs accidentally discharged from the Fukushima Daiichi nuclear power plant into the atmosphere, J. Nucl. Sci. Technol. **48** 7 (2011) 1129–1134.
[108] KATATA, G., OTA, M., TERADA, H., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part I: Source term estimation and local-scale atmospheric dispersion in early phase of the accident, J. Environ. Radioact. **109** (2012) 103–113.
[109] SAKURAI, H.E., NSC Recalculates Total Amount of Radioactive Materials Released, Japan Atomic Industrial Forum, D. o. I. C., Tokyo (2011).
[110] TERADA, H., KATATA, G., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioact. **112** (2012) 141–154.
[111] KOBAYASHI, T., NAGAI, H., CHINO, M., KAWAMURA, H., Source term estimation of atmospheric release due to the Fukushima Dai-ichi nuclear power plant accident by atmospheric and oceanic dispersion simulations, J. Nucl. Sci. Technol. **50** 3 (2013) 255–264.
[112] STOHL, A., et al., Xenon-133 and Caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: Determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. **12** 5 (2012) 2313–2343.
[113] RUBINSHTEIN, K.G., et al., Software package of atmospheric radionuclide distribution models and its use for assessing the radiation conditions after the Fukushima Dai-ichi nuclear power plant accident, Russian Meteorology and Hydrology **37** 9 (2012) 586–597.
[114] ARUTYUNYAN, R.V., et al., Estimation of radionuclide emission during the March 15, 2011 accident at the Fukushima-1 NPP (Japan), Atomic Energy **112** 3 (2012) 188–193.
[115] INTERNATIONAL ATOMIC ENERGY AGENCY, The IAEA Questionnaire on Radiological Release Evaluation Input, Assumptions, Methods and Results, IAEA, Vienna (2014).
[116] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Regarding the Evaluation of the Conditions on Reactor Cores of Unit 1, 2 and 3 Related to the Accident at Fukushima Dai-ichi Nuclear Power Station, Tokyo Electric Power Co. Inc., Nuclear and Industrial Safety Agency, Ministry of Economy, Trade and Industry (2011), http://www.nsr.go.jp/archive/nisa/english/press/2011/06/en20110615-5.pdf
[117] HOSHI, H., HIRANO, M., Severe Accident Analyses of Fukushima-Daiichi Units 1 to 3, Side event by Government of Japan at 56th IAEA General Conference, Vienna, 2012, Japan Nuclear Energy Safety Organization (2012), http://www.nsr.go.jp/archive/nisa/english/files/P-4.pdf

[118] ZENTRALANSTALT FÜR METEOROLOGIE UND GEODYNAMIK, Accident in the Japanese NPP Fukushima: Large Emissions of Cesium-137 and Iodine-131/Spread of Radioactivity/Weather Currently Favourable/Low Level Radioactivity Observed in Iceland (Update: 24 March 2011 16:00), ZAMG, Vienna (2011).
[119] MORINO, Y., OHARA, T., NISHIZAWA, M., Atmospheric behavior, deposition, and budget of radioactive materials from the Fukushima Daiichi nuclear power plant in March 2011, Geophys. Res. Lett. **38** 7 L00G11 (2011) 1–7.
[120] ACHIM, P., et al., Analysis of radionuclide releases from the Fukushima Dai-ichi nuclear power plant accident part II, Pure Appl. Geophys. **171** 3–5 (2012) 645–667.
[121] GUGLIELMELLI, A., ROCCHI F., FAST-1: Evaluation of the Fukushima Accident Source Term through the fast running code RASCAL 4.2: Methods & Results, ENEA Rep. UTFISSM-P000-017, ENEA, Bologne (2014).
[122] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).
[123] UNITED NATIONS, Sources and Effects of Ionizing Radiation, UNSCEAR 2008 Report, Vol. II, Annexes C, D and E, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2011).
[124] BUESSELER, K.O., et al., Fukushima-derived radionuclides in the ocean and biota off Japan, Proc. Natl. Acad. Sci. **109** 16 (2012) 5984–5988.
[125] BAILLY DU BOIS, P., et al., Estimation of marine source-term following Fukushima Dai-ichi accident, J. Environ. Radioact. **114** (2012) 2–9.
[126] POVINEC, P.P., et al., Dispersion of Fukushima radionuclides in the global atmosphere and the ocean, Applied Radiation and Isotopes **81** (2013) 383–392.
[127] KAWAMURA, H., et al., Preliminary numerical experiments on oceanic dispersion of ^{131}I and ^{137}Cs discharged into the ocean because of the Fukushima Daiichi nuclear power plant disaster, J. Nucl. Sci. Tech. **48** 11 (2011) 1349–1356.
[128] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Regarding the Report on the Impact of the Outflow of Contaminated Water from Fukushima Dai-ichi Nuclear Power Station, Tokyo Electric Power Co. Inc., to the Sea and Other Report, etc., Press Release (24 May 2011), http://www.nsr.go.jp/archive/nisa/english/files/en20110525-1.pdf
[129] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Impact on the Marine Environment of Radioactive Releases following the Nuclear Accident at Fukushima Daiichi, IRSN, Fontenay-aux-Roses (2011), http://www.irsn.fr/EN/newsroom/News/Documents/IRSN_Fukushima-Accident_Impact-on-marine-environment-EN_20110513.pdf
[130] JAPAN ATOMIC ENERGY AGENCY, Simulation of Radioactivity Concentrations in the Pacific Ocean, Press Release, JAEA (17 June 2011), http://www.jaea.go.jp/english/jishin/kaisetsu04.pdf
[131] BUESSELER, K., AOYAMA, M., FUKASAWA, M., Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Technol. **45** 23 (2011) 9931–9935.
[132] NAKANO, M., POVINEC, P.P., Long-term simulations of the ^{137}Cs dispersion from the Fukushima accident in the world ocean, J. Environmental Radioactivity **111** (2012) 109–115.
[133] TSUMUNE, D., TSUBONO, T., AOYAMA, M., HIROSE, K., Distribution of oceanic ^{137}Cs from the Fukushima Dai-ichi nuclear power plant simulated numerically by a regional ocean model, J. Environmental Radioactivity **111** (2012) 100–108.
[134] ESTOURNEL, C., et al., Assessment of the amount of Cesium-137 released into the Pacific Ocean after the Fukushima accident and analysis of its dispersion in Japanese coastal waters, J. Geophys. Res. **117** (2012) C11014.
[135] HONDA, M.C., AONO, T., AOYAMA, M., Dispersion of artificial Caesium-134 and -137 in the Western North Pacific one month after the Fukushima accident, Geochem. J. **46** 6 (2012) e1–9.
[136] DIETZE, H., KRIEST, I., Cs-137 off Fukushima Dai-ichi, Japan – model based estimates of dilution and fate, Ocean Sci. **8** 3 (2012) 319–332.

[137] MIN, B.I., PERIANEZ, R., KIM, I.G., SUH, K.S., Marine dispersion assessment of ^{137}Cs released from the Fukushima nuclear accident, Mar. Pollut. Bull. **72** 1 (2013) 22–33.
[138] ROSSI, V., VAN SEBILLE, E., SEN GUPTA, A., GARÇON, V., ENGLAND, M.H., Multi-decadal projections of surface and interior pathways of the Fukushima Cesium-137 radioactive plume, Deep Sea Research Part I: Oceanographic Research Papers **80** (2013) 37–46.
[139] MASUMOTO, Y., et al., Oceanic dispersion simulations of ^{137}Cs released from the Fukushima Daiichi nuclear power plant, Elements **8** 3 (2012) 207–212.
[140] CHARETTE, M.A., et al., Radium-based estimates of Cesium isotope transport and total direct ocean discharges from the Fukushima nuclear power plant accident, Biogeosciences **10** 3 (2013) 2159–2167.
[141] RYPINA, I.I., et al., Short-term dispersal of Fukushima-derived radionuclides off Japan: Modeling efforts and model-data intercomparison, Biogeosci. Discuss. **10** 1 (2013) 4973–4990.
[142] MIYAZAWA, Y., et al., Inverse estimation of source parameters of oceanic radioactivity dispersion models associated with the Fukushima accident, Biogeosciences **10** 4 (2013) 2349–2363.
[143] KANDA, J., "Long-term Sources: To What Extent Are Marine Sediments, Coastal Groundwater, and Rivers a Source of Ongoing Contamination?", Fukushima Ocean Impacts Symposium, Tokyo University of Marine Science and Technology, Sanjo Conference Hall, University of Tokyo, 12–13 November (2012), http://www.whoi.edu/fileserver.do?id=138570&pt=2&p=141589
[144] RYPINA, I.I., et al., Short-term dispersal of Fukushima-derived radionuclides off Japan: Modeling efforts and model-data intercomparison, Biogeosci. Discuss. **10** 1 (2013) 1517–1550.
[145] YAMASHIKI, Y., et al., Estimation of Radioactive Contaminant Load from Abukuma River, Fukushima Ocean Impacts Symposium, Tokyo (2012).
[146] NAGAO, S., et al., Export of ^{134}Cs and ^{137}Cs in the Fukushima river systems at heavy rains by Typhoon Roke in September 2011, Biogeosciences **10** 10 (2013) 6215–6223.
[147] TOKYO ELECTRIC POWER COMPANY, Increases in the Concentration of Radioactive Materials in Seawater and Groundwater on the Ocean Side of the Site: Current Situation and Countermeasures (2013), http://www.tepco.co.jp/en/decommision/planaction/images/handouts_130722_07-e.pdf
[148] YAMAGATA, H., Updated Status of Fukushima Daiichi Nuclear Power Station, 57th IAEA General Conference, Nuclear Regulation Authority, Vienna (2013), http://www.nsr.go.jp/english/data/20130917_presentation.pdf
[149] TOKYO ELECTRIC POWER COMPANY, Contaminated Water Leakage from the Tank in the H4 Area, Press Release, TEPCO (21 August 2013), http://www.tepco.co.jp/en/nu/fukushima-np/water/13082101-e.html
[150] TOKYO ELECTRIC POWER COMPANY, Fukushima Daiichi NPS Prompt Report 2014. Immediately Release: TEPCO Workers Discover and Halt Water Overflow from Tank; No Impact Expected on Seawater, Press Release, TEPCO (20 February 2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1234394_5892.html
[151] TOKYO ELECTRIC POWER COMPANY, Analysis Results of Groundwater Obtained around the H4 Area at Fukushima Daiichi Nuclear Power Station, Press Release, TEPCO (5 December 2014), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2014/images/around_h4_map-e.pdf
[152] TOKYO ELECTRIC POWER COMPANY, Sampling Results of Pump Wells of the Groundwater Bypass at Fukushima Daiichi Nuclear Power Station, Press Release, TEPCO (3 December 2014), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2014/images/pump_well_14120301-e.pdf
[153] IAEA Activities in Response to the Fukushima Accident, GOV/INF/2011/8, IAEA, Vienna (2011).
[154] Declaration by the IAEA Ministerial Conference on Nuclear Safety in Vienna on 20 June 2011, INFCIRC/821, IAEA, Vienna (2011).
[155] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station, Press Release, TEPCO (17 April 2011), http://www.tepco.co.jp/en/press/corp-com/release/11041707-e.html
[156] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Roadmap towards Settlement of the Accident at Fukushima Daiichi Nuclear Power Station, TEPCO — Step 2 Completion Report, Government of Japan–TEPCO Integrated Response Office, Press Release (16 December 2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/111216e4.pdf

[157] TOKYO ELECTRIC POWER COMPANY, Recovery and Processing of Radioactive Accumulated Water at Fukushima Daiichi Nuclear Power Station — Water Processing Facility (Removal of Radioactivity), TEPCO (29 October 2011), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_111029_03-e.pdf
[158] TOKYO ELECTRIC POWER COMPANY, Present Status of Fukushima Daiichi NPS and Implemented Countermeasures — 2.2 Countermeasures to Protect the Atmosphere, TEPCO (2014), http://www.tepco.co.jp/en/nu/fukushima-np/review/review2_2-e.html
[159] TOKYO ELECTRIC POWER COMPANY, Measure and Amount of Contaminated Water Released to Sea at Unit 2 of Fukushima Daiichi NPS, Press Release, TEPCO (21 April 2011) (in Japanese), http://www.tepco.co.jp/cc/press/11042102-j.html
[160] SECRETARIAT OF THE COUNCIL FOR THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER PLANT, Progress Status and Future Challenges of Mid-and-Long-Term Roadmap towards the Decommissioning of Units 1–4 of TEPCO's Fukushima Daiichi Nuclear Power Station (Outline) (2013), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/d130530_01-e.pdf
[161] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Basic Policy for the Contaminated Water Issue at the TEPCO's Fukushima Daiichi Nuclear Power Station, Ministry of Foreign Affaires, Press Release (3 September 2013), http://www.mofa.go.jp/files/000013034.pdf
[162] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Fukushima Daiichi Status Report — Updates: 27 October – 10 November 2011, IAEA (2011), http://www.iaea.org/newscenter/news/iaea-fukushima-daiichi-status-report-2
[163] NUCLEAR REGULATION AUTHORITY, FISHERIES AGENCY, MINISTRY OF LAND, INFRASTRUCTURE, TRANSPORT AND TOURISM, JAPAN COAST GUARD, JAPAN METEOROLOGICAL AGENCY, MINISTRY OF THE ENVIRONMENT, FUKUSHIMA PREFECTURAL GOVERNMENT, TOKYO ELECTRIC POWER COMPANY, Comprehensive Radiation Monitoring Plan, NRA, Tokyo (2014).
[164] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Points of Progress Status of "Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station, TEPCO" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_nps_02.pdf
[165] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, TEPCO (2011), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/111221_02.pdf
[166] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, COUNCIL FOR THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER STATION, Revised Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, Ministry of Economy, Trade and Industry, Tokyo (2013), http://josen.env.go.jp/en/documents/pdf/workshop_july_17-18_2013_02.pdf
[167] TOKYO ELECTRIC POWER COMPANY, Multi-nuclide Removal Equipment (ALPS), Confirmatory Testing, Installation and Characteristics of Radioactive Waste, TEPCO (25 June 2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m120625_01-e.pdf
[168] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Progress Report on Mid-to-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 and Future Challenges, METI (2012) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/pdf/121203/121203_02ss.pdf
[169] TOKYO ELECTRIC POWER COMPANY, Present Status of Fukushima Daiichi NPS and Implemented Countermeasures — 2.4 Future Large-scale Earthquake and Tsunami Countermeasures, TEPCO (2014), http://www.tepco.co.jp/en/nu/fukushima-np/review/review2_4-e.html
[170] TOKYO ELECTRIC POWER COMPANY, Commencement of Installation Work for Water Shielding Wall at the Seaside and the Study Result on Water Shielding Wall at Groundside, Press Release, TEPCO (26 October 2011), http://www.tepco.co.jp/en/press/corp-com/release/11102608-e.html
[171] TOKYO ELECTRIC POWER COMPANY, 1. Accident Overview at Fukushima Daiichi NPS — 1.2 Urgent Response Measures, TEPCO (2014), http://www.tepco.co.jp/en/nu/fukushima-np/review/review1_2-e.html

[172] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report — IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, Japan, IAEA, Vienna (25 November–4 December 2013), IAEA, Vienna (2014).
[173] NUCLEAR REGULATION AUTHORITY, FY2012 Annual Report, NRA, Tokyo (2012) (provisional translation).
[174] NUCLEAR REGULATION AUTHORITY, National Report to the 6th Review Meeting of the Convention on Nuclear Safety, NRA, Tokyo (2013).
[175] NUCLEAR REGULATION AUTHORITY, The NRA Has Received an Implementation Plan on Specified Nuclear Power Facilities of Tokyo Electric Power Co., Inc. including Measures for Security and Protection of Specified Nuclear Fuel Material, Press Release (7 December 2012), http://www.nsr.go.jp/data/000067172.pdf
[176] SECRETARIAT OF THE NUCLEAR EMERGENCY PREPAREDNESS COUNCIL, Outline of the Nuclear Emergency Preparedness Council, Prime Minister of Japan and His Cabinet (2012) (in Japanese), http://www.kantei.go.jp/jp/singi/genshiryoku_bousai/dai01/sankou03.pdf
[177] EXPERT SUBCOMMITTEE FOR NUCLEAR EMERGENCY OF NUCLEAR FACILITIES, Principles for Areas where Disaster Countermeasures Should Be Intensively Improved, Nuclear Regulation Authority, Tokyo (2011) (in Japanese), http://www.nsr.go.jp/archive/nsc/senmon/shidai/bousin/bousin2011_07/siryo3-2.pdf
[178] NUCLEAR REGULATION AUTHORITY, Nuclear Emergency Response Guidelines (revised draft), 31st Nuclear Regulatory Commission Meeting, Document No. 6-2, NRA, Tokyo (2012) (in Japanese), http://www.nsr.go.jp/committee/kisei/h24fy/data/0031_08.pdf
[179] MINISTRY OF THE ENVIRONMENT, Act on Special Measures concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District – Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110 (2011), http://josen.env.go.jp/en/framework/pdf/special_act.pdf?20130118
[180] MINISTRY OF THE ENVIRONMENT, Basic Principles of the Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged from the Nuclear Power Station Accident Associated with the Tohoku District–Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 (2011), http://josen.env.go.jp/en/framework/pdf/basic_principles.pdf
[181] MINISTRY OF THE ENVIRONMENT, "Decontamination Roadmap" for the Special Decontamination Areas, Tokyo (2012), http://josen.env.go.jp/en/roadmap/pdf/outline_of_the_roadmap.pdf
[182] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Update of Areas to which Evacuation Was Ordered and Alert Zones in Futaba-Machi, Prime Minister of Japan and His Cabinet, Tokyo (7 May 2013) (in Japanese), http://www.kantei.go.jp/jp/singi/genshiryoku/dai30/siryou.pdf
[183] MINISTRY OF THE ENVIRONMENT, Decontamination Guidelines, First Edition, MOE (2011), http://josen.env.go.jp/en/framework/pdf/decontamination_guidelines_2nd.pdf
[184] MINISTRY OF THE ENVIRONMENT, Basic Policy on Interim Storage and Other Facilities Required for the Handling of the Environmental Pollution from Radioactive Materials Associated with the Accident at Tokyo Electric Power Co.'s Fukushima Daiichi Nuclear Power Stations (2011), http://josen.env.go.jp/en/roadmap/pdf/basic_policy.pdf
[185] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Strategic Energy Plan of Japan, Press Release, METI (June 2010), http://www.meti.go.jp/english/press/data/pdf/20100618_08a.pdf
[186] THE ENERGY AND ENVIRONMENT COUNCIL, Innovative Energy and Environment Strategy, Government of Japan, Tokyo (2012), http://www.un.org/esa/socdev/egms/docs/2012/greenjobs/enablingenvironment.pdf
[187] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Strategic Energy Plan, METI, Tokyo (2014), http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf

[188] TOKYO ELECTRIC POWER COMPANY, Measures against Radioactive Water Leakage in Unit 3 Turbine Building of Fukushima Daiichi Nuclear Power Station, Press Release, TEPCO (31 October 2012), http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/121031e0201.pdf
[189] TOKYO ELECTRIC POWER COMPANY, Completion of Reliability Improvement Work for Accumulated Water Transfer Pipeline between the On-site Bunker Building and the Process Main Building at Fukushima Daiichi Nuclear Power Station, TEPCO (7 June 2013), http://www.tepco.co.jp/en/nu/fukushima-np/handouts/2013/images/handouts_130607_07-e.pdf
[190] TOKYO ELECTRIC POWER COMPANY, Report on the Steel Beam Falling into Unit 3 Spent Fuel Pool at Fukushima Daiichi Nuclear Power Station to the Nuclear Regulatory Authority, Press Release, TEPCO (3 October 2012), http://www.tepco.co.jp/en/press/corp-com/release/2012/1221393_1870.html
[191] TOKYO ELECTRIC POWER COMPANY, Results of investigation on water leakage from the vent line of the 2nd cesium adsorption equipment (Sally), TEPCO (22 November 2012) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/images/handouts_121122_01-j.pdf
[192] TOKYO ELECTRIC POWER COMPANY, Current Status of Fukushima Daiichi Nuclear Power Station Unit 1, TEPCO (17 December 2013) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/f1/genkyo/fp_reactor/fp_no01/index.html
[193] NUCLEAR REGULATION AUTHORITY, Report on the Leakage from Tanks for Contaminated Water within the Controlled area of TEPCO's Fukushima Daiichi NPS, NRA, Press Release (19 August 2013) (in Japanese), https://www.nsr.go.jp/activity/bousai/trouble/20130819-1.html
[194] TOKYO ELECTRIC POWER COMPANY, On the Leak of RO Condensed Radioactive Water from the Storage Tank (Preliminary Report), TEPCO (2013) (in Japanese), http://www.tepco.co.jp/cc/press/betu13_j/images/131206j0301.pdf
[195] NUCLEAR REGULATORY AUTHORITY, Press Release, NRA (3 October 2013) (in Japanese), http://www.nsr.go.jp/activity/bousai/trouble/20131003-1.html
[196] TOKYO ELECTRIC POWER COMPANY, Cause for the Water Leak from a Top Plate of a Tank at B South Area in Fukushima Daiichi NPS and the Leak Prevention Measures, TEPCO (2013), http://www.tepco.co.jp/en/nu/fukushima-np/handouts/2013/images/handouts_131206_08-e.pdf
[197] NUCLEAR REGULATORY AUTHORITY, Press Release, NRA (9 October 2013) (in Japanese), http://www.nsr.go.jp/activity/bousai/trouble/20131009-1.html
[198] MORITANI, N., Current Issue on Management of Off-site Waste Contaminated with Radioactive Materials due to the Accident at Fukushima Nuclear Power Stations, official communication (2013).
[199] NUCLEAR REGULATION AUTHORITY, Inappropriate Transfer of Contaminated Water at Fukushima Daiichi Nuclear Power Station, Press Release, NRA (15 April 2014), http://www.nsr.go.jp/english/newsrelease/data/20140415.pdf
[200] Convention on Nuclear Safety, Rules of Procedure and Financial Rules, INFCIRC/573/Rev.6, IAEA, Vienna (2015).
[201] Guidelines regarding the Review Process under the Convention on Nuclear Safety, INFCIRC/571/Rev.7, IAEA, Vienna (2015).
[202] Guidelines regarding National Reports under the Convention on Nuclear Safety, INFCIRC/572/Rev.5, IAEA, Vienna (2015).
[203] 2nd Extraordinary Meeting of the Contracting Parties to the Convention on Nuclear Safety: Final Summary Report, CNS/ExM/2012/04/Rev.2 (2012), http://www.iaea.org/sites/default/files/cns-summaryreport310812.pdf
[204] 6th Review Meeting of the Contracting Parties to the Convention on Nuclear Safety, Summary Report, CNS/6RM/2014/11_Final (2014), http://www-ns.iaea.org/downloads/ni/safety_convention/2014-cns-summary-report-w-annexes-signed.pdf
[205] Summary Report and Vienna Declaration on Nuclear Safety, CNS/DC/2015/3/Rev.2 (2015), https://www.iaea.org/sites/default/files/cns_summary090215.pdf
[206] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Action Plan on Nuclear Safety, IAEA, Vienna (2011), http://www.iaea.org/sites/default/files/actionplanns.pdf

[207] Measures to Strengthen International Cooperation in Nuclear, Radiation, Transport and Waste Safety, Resolution GC(57)/RES/9, IAEA, Vienna (2013).
[208] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GC(56)/INF/5, IAEA, Vienna (2012).
[209] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GC(57)/INF/5, IAEA, Vienna (2013).
[210] Progress in the Implementation of the IAEA Action Plan on Nuclear Safety, GC(58)/INF/7, IAEA, Vienna (2014).
[211] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[212] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Strengthening Nuclear Regulatory Effectiveness in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[213] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, International Experts Meeting Vienna, 19–22 March 2012, IAEA, Vienna (2012).
[214] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Enhancing Transparency and Communication Effectiveness the Event of a Nuclear or Radiological Emergency, International Experts Meeting, Vienna, 18–22 June 2012, IAEA, Vienna (2012).
[215] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Protection against Extreme Earthquakes and Tsunamis in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, International Experts Meeting Vienna, 4–7 September 2012, IAEA, Vienna (2012).
[216] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, International Experts Meeting Vienna, 28 January–1 February 2013, IAEA, Vienna (2013).
[217] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Human and Organizational Factors in Nuclear Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, International Experts Meeting Vienna, 21–24 May 2013, IAEA, Vienna (2014).
[218] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Radiation Protection After the Fukushima Daiichi Accident: Promoting Confidence and Understanding, International Experts Meeting Vienna, 17–21 February 2014, IAEA, Vienna (2014).
[219] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of the International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP, Japan 7–15 October 2011, IAEA, Vienna (2011).
[220] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission Report — IAEA Mission to Review NISA's Approach to Comprehensive Assessments for Safety of Existing Power Reactor Facilities, Tokyo and Ohi, Japan 23–31 January 2012, IAEA, Vienna (2012).
[221] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Mission Report — IAEA Mission to Onagawa Nuclear Power Station to Examine the Performance of Systems, Structures and Components Following the Great East Japanese Earthquake and Tsunami, Onagawa and Tokyo, Japan (30 July–11 August 2012), IAEA, Vienna (2012).
[222] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report — IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (First Mission), Tokyo and Fukushima Prefecture, Japan, 15–22 April 2013, IAEA, Vienna (2013).
[223] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of the Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site of the Fukushima Daiichi Nuclear Power Plant Tokyo and Fukushima Prefecture, Japan (14–21 October 2013), IAEA, Vienna (2013).
[224] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, COUNCIL FOR THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER STATION, Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4, Ministry of Economy, Trade and Industry, Tokyo (2013).

[225] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA and Japan Host Fukushima Ministerial Conference on Nuclear Safety, Press Release (15 December 2012), https://www.iaea.org/newscenter/news/iaea-and-japan-host-fukushima-ministerial-conference-nuclear-safety
[226] Memorandum of Cooperation between Fukushima Prefecture and the International Atomic Energy Agency Following the Accident at TEPCO's Fukushima Daiichi Nuclear Power Station (15 December 2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_04.pdf
[227] Practical Arrangements between Fukushima Prefecture and the International Atomic Energy Agency on Cooperation in the Area of Radiation Monitoring and Remediation (15 December 2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_05.pdf
[228] Practical Arrangements between Fukushima Medical University and the International Atomic Energy Agency on Cooperation in the Area of Human Health (15 December 2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_06.pdf
[229] Practical Arrangements between the Ministry of Foreign Affairs of Japan and the International Atomic Energy Agency on Cooperation in the Area of Emergency Preparedness and Response (15 December 2012), http://www.mofa.go.jp/policy/energy/fukushima_2012/pdfs/fukushima_iaea_en_07.pdf
[230] OECD NUCLEAR ENERGY AGENCY, The Fukushima Daiichi Nuclear Power Plant Accident, OECD, Paris (2013)
[231] INSTITUTE OF NUCLEAR POWER OPERATIONS, Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005, INPO, Atlanta (2011).
[232] INSTITUTE OF NUCLEAR POWER OPERATIONS, Special Report: Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005 Addendum, INPO, Atlanta (2012).

CONTENTS OF CD-ROM

The following annexes to Technical Volume 1 are included on the attached CD-ROM:

Annex I: Unit 1 sequence of events

Annex II: Unit 2 sequence of events

Annex III: Unit 3 sequence of events

ABBREVIATIONS

ABWR	advanced boiling water reactor
ADS	automatic depressurization system
AEC	Atomic Energy Commission
AESJ	Atomic Energy Society of Japan
ALPS	Advanced Liquid Processing System
AM	accident management
AMG	accident management guideline
AMTA	Ageing Management Technical Assessment
ANRE	Agency for Natural Resources and Energy
AO	auxiliary operator
AOP	abnormal operating procedure
AOV	air operated valve
APD	alarm pocket dosimeter
APWR	advanced pressurized water reactor
ATWS	anticipated transient without scram
BDBA	beyond design basis accident
Bq	becquerel
BSAF	Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Plant
BTC	BWR Operator's Training Centre Corporation
BWR	boiling water reactor
BWROG	BWR Owners' Group
CAMS	containment atmospheric monitoring system
CCS	containment cooling system
CMC	Crisis Management Centre
CR	control rod
CRD	control rod drive
CRIEPI	Central Research Institute of the Electric Power Industry
CS	core spray
CSC	Convention on Supplementary Compensation for Nuclear Damage
CST	condensate storage tank
DBA	design basis accident
DC	direct current
DDFP	diesel driven fire pump
DG	diesel generator
DGSW	diesel generator seawater
DSS	Deputy Shift Supervisor
DW	dry well
ECCS	emergency core cooling system
EDG	emergency diesel generator
EECW	emergency equipment cooling water
ENAC	Early Notification and Assistance Conventions
ENATOM	Emergency Notification and Assistance Technical Operations Manual
EOP	emergency operating procedure
EOT	Emergency Operations Team
EP	Establishment Permit
EPRI	Electric Power Research Institute
ERC	Emergency Response Centre
ETS	education and training system
FACT	Fukushima Accident Coordination Team
FAO	Food and Agriculture Organization of the United Nations
FBR	fast breeder reactor
FCS	flammability control system

FEPC	Federation of Electric Power Companies
FNEP	Framework for Nuclear Energy Policy
FP	fire protection
FPC	fuel pool cooling
FSAR	Final Safety Analysis Report
FSAT	Food Safety Assessment Team
FW	fresh water
GCR	gas cooled reactor
GE	General Electric
HERO	High-performance ALPS
HO	hydraulic operated
HPCI	high pressure coolant injection
HPCS	high pressure core spray
HQ	headquarters
HVAC	heating, ventilating and air-conditioning
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
IATA	International Air Transport Association
IC	isolation condenser
ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
IEM	International Experts Meeting
IES	Incident and Emergency System
IMO	International Maritime Organization
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Group
IRRS	Integrated Regulatory Review Service
IRS	International Reporting System
ISO	International Organization for Standardization
ISSC	International Seismic Safety Centre
JAEA	Japan Atomic Energy Agency
JAERI	Japan Atomic Energy Research Institute
JAIF	Japan Atomic Industrial Forum
JANSI	Japan Nuclear Safety Institute
JANTI	Japan Nuclear Technology Institute
JAPC	Japan Atomic Power Company
JBOG	Japanese BWR Owners' Group
JCO	Japan Nuclear Fuels Conversion Company
JEA	Japan Electric Association
JMA	Japan Meteorological Agency
JNES	Japan Nuclear Energy Safety Organization
JPLAN	Joint Radiation Emergency Management Plan of the International Organizations
JSCE	Japan Society of Civil Engineers
JSME	Japan Society of Mechanical Engineers
JST	Japan Standard Time
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
LBLOCA	large break loss of coolant accident
LOCA	loss of coolant accident
LOOP	loss of off-site power
LPCI	low pressure coolant injection
LPCS	low pressure core spray
LTMP	long term maintenance programme
LUHS	loss of ultimate heat sink
LWR	light water reactor

M/C	metal clad switch gear
MCC	motor control centre
MCR	main control room
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MITI	Ministry of International Trade and Industry
MO	motor operated
MOE	Ministry of the Environment
MOFA	Ministry of Foreign Affairs
MOV	motor operated valve
MOX	mixed oxide
MP	measuring point
MP	monitoring post
MSIV	main steam isolation valve
MUWC	make-up water condensate
NERHQ	Nuclear Emergency Response Headquarters
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPS	nuclear power station
NRA	Nuclear Regulation Authority
NRC	United States Nuclear Regulatory Commission
NSC	Nuclear Safety Commission
NS-net	Nuclear Safety Network
NTC	Nuclear Power Training Centre Ltd
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OFC	Off-site Centre
OLCs	operational limits and conditions
OP	Onahama Port
OSART	Operational Safety Review Team
P/C	power centre
PA	public address
PARV	power-actuated relief valve
PBq	peta becquerel
PCIS	primary containment isolation signal
PCV	primary containment vessel
PSA	probabilistic safety assessment
PSR	periodic safety review
PWR	pressurized water reactor
QMS	quality management system
R&D	research and development
RANET	Response and Assistance Network
RAP	Radiological Assistance Program
RB	reactor building
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
RHRC	residual heat removal and cooling system
RHRS	residual heat removal and cooling seawater
RO	reactor operator
RPS	reactor protection system
RPV	reactor pressure vessel
S/S	site simulator
SAM	severe accident management

SAR	safety analysis report
SARRY	Simplified Active Water Retrieve and Recovery System
SB	service building
SBO	station blackout
SC	suppression chamber
SDF	Self-Defense Force
SFP	spent fuel pool
SGTS	standby gas treatment system
SHC	shutdown cooling
SLC	standby liquid control
SO	senior operator
SOP	Severe Accident Operating Procedure
SRO	senior reactor operator
SRV	safety relief valve
SS	shift superintendent
SS	shift supervisor
SSCs	structures, systems and components
SSO	system senior operator
STA	Science and Technology Agency
SV	safety valve
SW	sea water
TAF	top of active fuel
TB	turbine building
TENPES	Thermal and Nuclear Power Engineering Society
TEPCO	Tokyo Electric Power Company
TSC	technical support centre
UHS	ultimate heat sink
WANO	World Association of Nuclear Operators
WHO	World Health Organization
WMO	World Meteorological Organization
WR	wide range
ZPGA	zero period ground acceleration

CONTRIBUTORS TO DRAFTING AND REVIEW

WORKING GROUP 1 (WG1): DESCRIPTION AND CONTEXT OF THE ACCIDENT

Co-Chairs

Jammal, R.
Canadian Nuclear Safety Commission
Canada

Vincze, P.
Department of Nuclear Energy
IAEA

Scientific Secretary

Heitsch, M. (until August 2014)
Department of Nuclear Safety and Security
IAEA

Members

Dobrzyński, L.
National Centre for Nuclear Research
Poland

Dolganov, K.
Nuclear Safety Institute of the Russian Academy of Sciences
Russian Federation

Duspiva, J.
UJV Řež, a.s.
Czech Republic

Grant, I.
Federal Authority for Nuclear Regulation
United Arab Emirates

Guerpinar, A.
Senior Consultant
Turkey

Hirano, M.
Nuclear Regulation Authority
Japan

Khouaja, H.
Canadian Nuclear Safety Commission
Canada

Kim, H.T.
KHNP — Central Research Institute
Republic of Korea

Krijger, H.
N.V. Electriciteits-Productiemaatschappij Zuid-Nederland
Netherlands

Lequerica, I.
ENDESA
Spain

Noel, M.
European Commission Joint Research Centre

Orders, W.
Nuclear Regulatory Commission
USA

Urzua, G.
AREVA
France

Volkholz, P.
AREVA
France

Weidenbrück, K.
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
Germany

Weiss, S.
Global Research for Safety (Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH)
Germany

Zheng, M.G.
Shanghai Nuclear Engineering Research and Design Institute
China

Invited experts

Dodo, T.
Japan Nuclear Safety Institute
Japan

Ihara, T.
Tokyo Electric Power Company
Japan

Kanno, M.
Nuclear Regulation Authority
Japan

Kawano, A. (until August 2013)
Tokyo Electric Power Company
Japan

Muftuoglu, K.
GE Hitachi Nuclear Energy
USA

Taira, J.
Tokyo Electric Power Company
Japan

Yamamoto, M. (August 2013 onwards)
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG1

Kang, K.-S.
Kilic, N.
Pagannone, B.
Yamada, K.
Yoshimoto, Y.

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group (INSAG)

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Mohammad Jais, A.
International Nuclear Safety Group

Niu, S.
International Labour Organization

Sharma, S.K.[†]
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

[†] Deceased.

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

12–13 September 2013
3rd meeting of WGs 1 and 2, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

6–7 August 2013
CS on Source Term, Vienna

Bilateral meetings in Japan

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

23 January 2014
Meetings with Reconstruction Agency and Team in Charge of Assisting the Lives of Disaster Victims — Cabinet Office

24 January 2014
Meetings with the Institute of Energy Economics of Japan



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)

The Fukushima Daiichi Accident



Technical Volume 2/5
Safety Assessment



IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 2
SAFETY ASSESSMENT

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 2
SAFETY ASSESSMENT

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.
STI/PUB/1710
ISBN 978–92–0–107015–9 (set)
Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This publication has been prepared from contributions submitted by many international experts to the five Working Groups for the preparation of the technical volumes. The content does not necessarily reflect the views of IAEA Member States, or the organizations nominating experts.

Great care has been taken to maintain the accuracy of information contained in this publication. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with this publication.

This publication is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from this publication may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this publication indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continued existence of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from this report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

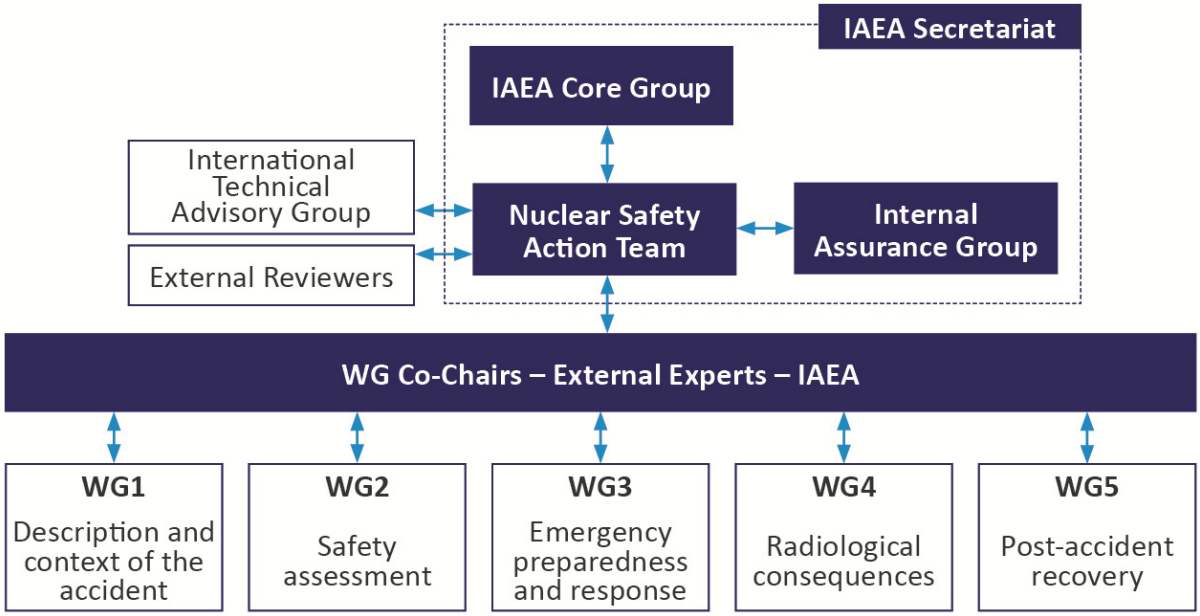


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

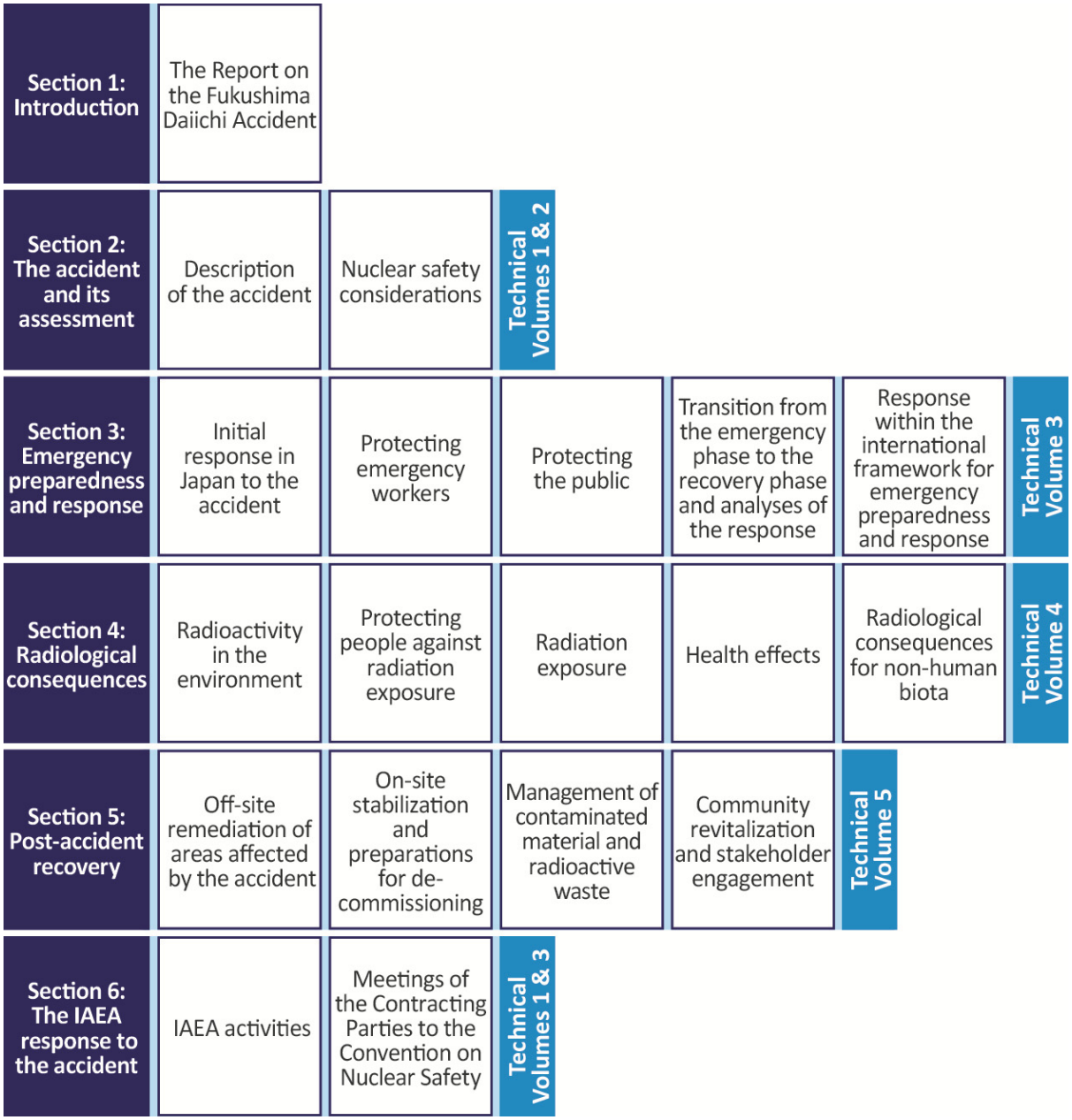


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

SAFETY ASSESSMENT 1

2. INTRODUCTION 1

2.1. ASSESSMENT OF THE PLANT IN RELATION TO EXTERNAL EVENTS 3
2.1.1. Site characteristics: Reassessment of the design bases for the Fukushima site and selection of the main plant grade level 3
2.1.2. International safety standards in relation to earthquake and tsunami hazard assessments and design aspects 7
2.1.3. Japanese regulatory practices in relation to earthquake and tsunami hazards and design aspects 10
2.1.4. Design basis and reassessments of the earthquake hazards and remedial actions taken during the operational life of the Fukushima Daiichi NPP 15
2.1.5. Design basis and reassessments of tsunami hazards and remedial actions taken during the operational life of the Fukushima Daiichi plant 24
2.1.6. Extreme external events in a multi-unit site and multiple sites in the same region 45
2.1.7. Summary 46
2.1.8. Observations and lessons 49
2.2. ASSESSMENT OF THE FAILURE TO MAINTAIN FUNDAMENTAL SAFETY FUNCTIONS 52
2.2.1. Introduction 52
2.2.2. Electrical power supply systems 53
2.2.3. Ultimate heat sink (emergency seawater system) 59
2.2.4. Main control room and instrumentation and control 60
2.2.5. Design features of Units 1–3 for maintaining fundamental safety functions 61
2.2.6. Reactivity control 61
2.2.7. Maintenance of core cooling 62
2.2.8. Maintenance of containment integrity 69
2.2.9. Design features of Unit 4 72
2.2.10. Design features of Units 5 and 6 72
2.2.11. Spent fuel storage facilities at the Fukushima Daiichi NPP 73
2.2.12. Application of defence in depth 75
2.2.13. Summary 79
2.2.14. Observations and lessons 81
2.3. ASSESSMENT OF THE TREATMENT OF BEYOND DESIGN BASIS EVENTS 81
2.3.1. Introduction 81
2.3.2. Review of deterministic safety assessment 83
2.3.3. Review of the probabilistic safety assessment 85
2.3.4. Summary 89
2.3.5. Observations and lessons 89
2.4. ACCIDENT MANAGEMENT PROVISIONS AND THEIR IMPLEMENTATION 90
2.4.1. Introduction 90
2.4.2. Accident management provisions available at the Fukushima Daiichi NPP 90
2.4.3. Comparison of accident management provisions at Fukushima Daiichi Units 1–4 with IAEA safety standards 95
2.4.4. Evaluation of accident management actions at the Fukushima Daiichi NPP and identification of key factors leading to severe consequences of the accident 102
2.4.5. Summary 104
2.4.6. Observations and lessons 106
2.5. ASSESSMENT OF THE EFFECTIVENESS OF REGULATORY PROGRAMMES 106
2.5.1. Introduction 106
2.5.2. Governmental, legal and regulatory framework for nuclear safety in Japan 106

2.5.3. Organization and staffing of the regulatory body 110
2.5.4. Regulatory management systems and safety culture 111
2.5.5. Authorization of facilities and activities by the regulatory body 111
2.5.6. Severe accident assumptions and countermeasures 112
2.5.7. Authorization of long term operation: Requirements for periodic safety review and backfit 113
2.5.8. Inspections of facilities and activities 114
2.5.9. Regulatory requirements and guidance 116
2.5.10. International cooperation 117
2.5.11. Current status of regulatory requirements in Japan 118
2.5.12. Summary 120
2.5.13. Observations and lessons 121
2.6. HUMAN AND ORGANIZATIONAL FACTORS 121
2.6.1. Introduction 121
2.6.2. Methodology 122
2.6.3. Basic assumptions of the main stakeholders regarding nuclear safety and their impact on the conditions for the Fukushima Daiichi accident 124
2.6.4. The impact of basic assumptions on the accident response 136
2.6.5. Human and organizational assessment 141
2.6.6. The implications for the nuclear community 142
2.6.7. Summary 145
2.6.8. Observations and lessons 146
2.7. APPLICATION OF OPERATING EXPERIENCE TO IMPROVE PLANT DESIGN AND OPERATION 147
2.7.1. Significant operating experience events relevant to the accident at the Fukushima Daiichi NPP 148
2.7.2. Effectiveness of application of TEPCO's operating experience programme 150
2.7.3. Regulatory oversight of TEPCO's operating experience programme 156
2.7.4. Summary 157
2.7.5. Observations and lessons 158

REFERENCES 159
CONTENTS OF CD-ROM 166
ABBREVIATIONS 167
CONTRIBUTORS TO DRAFTING AND REVIEW 170
INTERNATIONAL TECHNICAL ADVISORY GROUP 173
MEETINGS 174

SAFETY ASSESSMENT

2. INTRODUCTION

Technical Volume 1 of this report has described what happened during the accident at the Fukushima Daiichi nuclear power plant (NPP). The accident exceeded the design basis of the Fukushima Daiichi units in several respects. It was a severe accident, it affected multiple units and it was an accident which left the operators with little indication of what was happening, rendering them unable to control the situation. This volume describes why the accident occurred the way it did. To do so, multiple assessments have been performed to answer the following questions:

— Why did the site suffer from an extended station blackout?
— Why was site staff unable to cool the reactors and maintain the containment function?

The methodology used in this assessment is based on the IAEA safety standards in force at the time of the accident. The IAEA Safety Standards Series provides a system of Fundamental Safety Principles, Safety Requirements and Safety Guides. As the primary publication in the IAEA Safety Standards Series, the Fundamental Safety Principles No. SF-1 [1] establishes the basic safety objectives and principles of protection and safety for ensuring the protection of the public and the environment, now and in the future, from the harmful effects of ionizing radiation. Safety Requirements publications establish the requirements that must be met to ensure the protection of people and the environment, both now and in the future, in accordance with the objective and principles of the Safety Fundamentals. Safety Guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus on the measures recommended. The IAEA Statute makes the safety standards binding on the IAEA in relation to its own activities. They are not by default binding on Member States, but any State entering into an agreement with the IAEA concerning any form of IAEA assistance is required to comply with the requirements of the safety standards that pertain to the activities covered by the agreement. Many States elect to use IAEA safety standards as templates for their own legislation and regulations. Many other States, including Japan, use legislation and regulations adapted to their own situation and traditions.

All nuclear accidents result from a failure to maintain one or more of three fundamental safety functions, as described in IAEA Safety Standards Series No. NS-R-1, Safety of Nuclear Power Plants: Design, [2]:

— Control of reactivity;
— Removal of heat from the core;
— Confinement of radioactive material and control of operational discharges, as well as limitation of accidental releases.

The accident at the Three Mile Island NPP occurred owing to the loss of the second safety function, but releases were minimized because the containment successfully prevented any significant radioactive release to the environment. The Chernobyl accident occurred owing to the loss of the first safety function, and in this case no containment was available, resulting in the core being exposed to the environment and a very large release of radioactive material. The accident at the Fukushima Daiichi NPP occurred owing to the loss of the second and third safety functions as a result of an unanticipated severe external event — an earthquake followed by a resultant tsunami of extreme height. In this volume, the reasons behind the failure to maintain the second and third safety functions at the Fukushima Daiichi reactors are assessed in detail.

The volume begins (Section 2.1) with a review of how the design basis of the site for external events was assessed initially and then reassessed over the life of the NPP. The section also describes the physical changes that were made to the units as a result. The remainder of the volume describes the

treatment of beyond design basis events in the safety assessment of the site, the accident management provisions, the effectiveness of regulatory programmes, human and organizational factors and the safety culture, and the role of operating experience. Further background information is contained in three annexes included on the CD-ROM of this Technical Volume which describe analytical investigations of the accident along with information on topics such as system performance, defence in depth and severe accident phenomena.

Section 2.2 provides an assessment of the systems that failed, resulting in a failure to maintain the fundamental safety functions in Units 1–3, which were in operation at the time of the tsunami and in which the reactor pressure vessels (RPV) and containment vessels failed. The section also describes Units 4-6, which were shut down at the time of the tsunami, and the site's central spent fuel storage facility.

Section 2.3 discusses the probabilistic and deterministic safety assessments of beyond design basis accidents (BDBAs) that had been performed for the plant and the insights from these assessments that had led to changes in the plant's design. The section pays particular attention to the assessment of extreme natural hazards, such as the one which led to the total loss of AC power supply on the site. The additional loss of DC power supply in Units 1 and 2 played a key role in the progression of the accident because it impeded the diagnosis of plant conditions and made the operators unaware of the status of safety systems.

Section 2.4 describes the accident management provisions and their implementation. All components of accident management are discussed, both preventive (before core melt) and mitigative (after core melt or severe accident). The section covers hardware provisions, emergency operating procedures, severe accident operating procedures, human resources and organizational arrangements, including training and drills. Interface with the off-site emergency arrangements is also discussed.

Section 2.5 deals with the governmental, legal and regulatory framework for nuclear safety in Japan up to the time of the Fukushima Daiichi accident. It evaluates this framework and its contribution to the accident, and identifies lessons learned.

Section 2.6 analyses the human and organizational aspects of the accident. It examines the main stakeholders of nuclear safety in Japan and shows how their actions were interrelated and interconnected, thereby reinforcing basic assumptions about nuclear safety that prevented them from adequately preparing for such an accident. The section analyses why the accident happened despite advancements in nuclear safety in areas such as solid design, peer reviews, regulatory frameworks, safety assessment methodologies, years of successful operating experience, defence in depth, emergency preparedness, severe accident management guidelines (SAMGs) and a strong international commitment to nuclear safety.

Finally, Section 2.7 addresses the role of operating experience in improving plant design and operation in order to continuously improve nuclear safety and support defence in depth. The section assesses the TEPCO operating experience programme and the extent to which lessons were learned from events both in Japan and internationally, and the design changes made.

2.1. ASSESSMENT OF THE PLANT IN RELATION TO EXTERNAL EVENTS

2.1.1. Site characteristics: Reassessment of the design bases for the Fukushima site and selection of the main plant grade level

2.1.1.1. Reassessment of the design bases of the site

The Fukushima Daiichi NPP site was selected for the location of six reactor units at the beginning of the 1960s. The site permissions were issued for Unit 1 in 1966, Unit 2 in 1968, Unit 3 in 1970, Unit 5 in 1971 and for Units 4 and 6 in 1972. With the exception of Unit 1, which was connected to the grid in November 1970, all of the other units were constructed and put into operation during the 1970s.

The process of site selection and site evaluation followed the practice and regulations at the time. Detailed information on this aspect as well as on the site characteristics is given in Technical Volume 1 in accordance with the information obtained from the Establishment Permit document [3, 4] drawn up for all six units. It can be considered as being equivalent to the section on site characteristics in a safety analysis report (SAR) for NPPs, as outlined, for example, in IAEA Safety Standards Series No. GS-G-4.1, Format and Content of the Safety Analysis Report for Nuclear Power Plants [5]. However, attention should be paid to the age of the data provided in the Establishment Permit, checking, in particular, that they have been updated regularly, as needed (see, for example, Ref. [4]). In this case, the population data originate from the end of the 1960s, the meteorological data are more recent, and the data and studies on seismic matters for some structures, systems and components (SSCs) date from the beginning of the 2000s.

During the operational life of the units, a comprehensive reassessment of the site characteristics and all its aspects was not required by the regulatory authority, regardless of evidence on new hazards or new hazard levels, updated regulatory requirements on periodic safety reviews or the availability of new scientific and technical findings or experiences [6]. However, the Tokyo Electric Power Company (TEPCO) performed the reassessment of specific subjects related to seismic and tsunami hazards, as described later in this volume.

Before March 2011, safety reviews in Japan resulting from a regulatory request were mainly conducted in relation to specific hazards or issues — called ‘backchecking’ in Japanese practice — rather than as a comprehensive reassessment and implementation of physical plant upgrading or ‘backfitting’.[1] Thus, the backchecking of seismic hazards had been requested since 2006, while tsunami hazards were not given the same priority. This was confirmed by the newly established Nuclear Regulation Authority (NRA) during the IAEA Consultancy Meeting on Regulatory Activities and Operating Experience held in Tokyo from 20 to 24 January 2014. The implementation of physical upgrades to enhance safety were carried out only for specific aspects, with a grace period of five years being granted for executing the relevant plant upgrading [7]. This situation changed after March 2011 and the current regulatory system requires the mandatory implementation of safety backfits.

Thus, prior to the Fukushima Daiichi NPP accident, no formal legal or regulatory requirements existed in Japan that required the comprehensive reassessment of the original site related design basis and site characteristics, either periodically or in response to new knowledge that might have been gained. This situation precluded periodic safety reassessment of the full range of external hazards that may affect plant safety under new conditions. On the other hand, since the beginning of the 1990s, periodic safety reviews have been an established practice in several Member States, where comprehensive

[1] Assessment is a process aimed at providing information that forms the basis of a decision on whether or not something is satisfactory. Reassessment is a new assessment, performed after the original assessment and triggered by any of the reasons described above. The final decision on whether or not something is satisfactory may lead to the launch of a plan for determining effective corrective measures, including implementation of physical plant upgrading.

reassessments of site related aspects have been implemented on a regular basis. Furthermore, relevant guidance has been provided in IAEA safety standards [8], including technical and scientific support services. In this regard, the IAEA site and design Safety Requirements and related Safety Guides have been updated to take account of developments in the methodology, new requirements from regulatory authorities and new data. Such safety review and reassessment programmes must include consideration of the site related aspects of existing operating nuclear installations in a systematic and comprehensive manner. All topics and potential hazards are to be considered in this process, and the subsequent execution of safety upgrades has to enhance significantly the safety of those installations. A comprehensive reassessment of site related aspects would generally include the following aspects:

— Geological and geotechnical hazards (e.g. surface faulting, soil liquefaction, cavities);
— Earthquake hazards;
— Volcanic hazards, which are of particular importance in Japan due to its high volcanic risk;
— Hydrological hazards, such as external flooding hazards, from several potential sources (e.g. tsunamis, storm surges, downbursts with heavy precipitation);
— Extreme and rare meteorological phenomena (e.g. hurricanes, cyclones, typhoons, tornadoes);
— Human induced events of accidental origin (e.g. aircraft crash, explosion pressure waves).

Many of the safety reassessment programmes of existing nuclear installations have had the support and guidance of the IAEA and have resulted in modern and updated safety standards [8]. An important example of such measures to assess and enhance safety is the re-evaluation of site related safety aspects (mainly seismic) that was carried out for most of the water cooled water moderated energy reactor (WWER) type reactors in Eastern European countries mainly during the 1990s.

Before the accident, due to the lack of a regulatory framework for updating and upgrading plant safety in relation to the characteristics of the site, the Fukushima Daiichi NPP's site related characteristics were not reassessed in a systematic and comprehensive manner. Such a reassessment would have considered all site related aspects and external events (i.e. seismic and geological, meteorological and hydrological, volcanic, and human induced hazards) as well as environmental issues. Regarding the specific regulatory framework for assessing tsunami hazards, at the time of the issuance of the Establishment Permit and during the entire operational period, the regulatory authorities did not issue any requirements or guidance concerning the need to reassess the tsunami hazards and, correspondingly, the plant safety with regard to these extreme natural events. The new guidance developed and released by the Nuclear Safety Commission (NSC) of Japan in 2006 [9] as part of the seismic safety guidelines does not contain any requirements, criteria or methodology that could be used in the reassessment of tsunami hazards in view of new and updated methodologies, data, evidence or concerns, except for a generic statement on the need to take into account concurrent events, in addition to the seismic hazards.

The situation described above led to an underestimation of the tsunami hazards that affected the site and the plant. It also resulted in a lack of appropriate measures to cope with higher than design basis tsunami hazards. It was characterized, in addition, by the absence of systematic reviews, as well as by the lack of interim measures before confirmation of emerging information from trial calculations.

2.1.1.2. Selection of the main grade level of the plant units

The decision on the finished top level of the ground at the location of the main plant buildings — at an elevation defined with respect to a reference level as, for example, the mean sea level — is an important aspect of the site that affects plant safety owing to its significance in relation to flooding hazards. This aspect refers to the adoption of the main plant grade level[2] at the time of the design and

[2] The main plant grade level is the top level of the ground, as finished, after plant construction.

construction of the plant with respect to the natural topographical situation prevailing on land and offshore.

The reference marker for all plant elevations in the region corresponds to the Onahama Port datum line (Onahama Port, or OP)[3], located about 50 km south of the Fukushima Daiichi NPP. TEPCO selected a main plant grade level of OP +10.00 m for the nuclear island and main buildings of Units 1–4 when the 'natural' ground level, i.e. the terrain topography, was approximately +30–35 m, well above such a level. For Units 5 and 6, this main plant grade level was defined as OP +13.00 m. The selection of such main plant grade levels implied the removal of a significant portion of natural soil/rock to reach that grade level.

Some general considerations about the main plant grade level are worth noting. Many factors are usually taken into consideration for a decision on that grade level, in view of the requirement of maintaining, throughout the operational life of the plant, a 'dry site' concept. The dry site concept implies that all items important to safety will be constructed above the level of the design basis flood, taking into account wind wave effects and any accompanying event(s) that may affect the reference level of the water at the time of the design basis flood (such as storm surge, sea level rise, tectonic movement, accumulation of debris, sediment transportation and ice). This can be accomplished by locating the plant at a sufficiently high elevation or, if necessary, by means of construction arrangements that raise the ground level at the site above the estimated maximum flood level. The site boundary should be monitored and maintained to keep such dry conditions during the operational life of the plant. In particular, if any filling is necessary to raise the plant above the level of the flood conditions for the design basis flood, this engineered plant item should be considered as an item important to safety and should therefore be adequately designed and maintained.

The dry site concept is considered a key measure against site flooding hazards that may affect safety. The original plant layout is to be defined on such bases, and it should be reassessed during the operational life of the plant to confirm these conditions. If the reassessment yields negative results, adequate protective measures and mitigation actions should be implemented in a timely manner.

If the above conditions are not met, the site is considered a 'wet site', where the level of the design basis flood is determined to be above the plant main grade level. Consequently, permanent site protective measures must be taken during the construction and operational stages, and, as mentioned above, these engineered plant protective measures are to be considered as items important to safety and should therefore be appropriately designed and maintained. Thus, the factors that are usually taken into account for the decision on the main plant grade level include the following:

— Specific plant design aspects (e.g. the plant and building layout, particularly the layout of the reactor building and reactor room level);
— Maximum and minimum levels of the estimated flooding caused by storm surges, rare meteorological phenomena (e.g. typhoons, hurricanes) or tsunamis (generated by, for example, earthquakes, landslides or volcanoes), i.e. as a result of the evaluation of all hydrological hazards;
— Geotechnical aspects related to foundation soil properties, the competent soil layers for the foundation of the buildings and, accordingly, the type (shallow or deep) of the selected foundation system;
— Hydrogeological aspects related to the presence of the groundwater table (aquifers), with its influence during the construction and operation stages;
— Construction methods and costs for digging, excavation and backfill, as well as considerations regarding the transport and assembly of heavy components;

[3] Onahama Port datum lines are 0.727 m below Tokyo Bay standard mean sea level as indicated in section 2.2.2 of the Establishment Permit [3].

— Operational aspects, e.g. those related to pumping water in and out to the main condensers, with its impact on in-house energy consumption;
— Embedment effects of the main buildings in the site response to seismic loads and the soil–structure interaction effects in the dynamic response of the SSC.

In the civil construction of the plant, TEPCO considered these factors, as indicated in the TEPCO Fukushima Nuclear Accident Analysis Report [10], through interviews with former employees who were involved in this work [10]. Although the topography provided a natural ground level of OP +30–35 m, TEPCO decided to build the plant at OP +10.00 m, i.e. much closer to the sea water level. This decision entailed the removal of soil and rock layers with a thickness of more than 20 m over a large area.

Figure 2.1–1 shows a cross-section of the construction site, including soil characteristics, based on the figure included in the Establishment Permit [3], to illustrate this discussion.

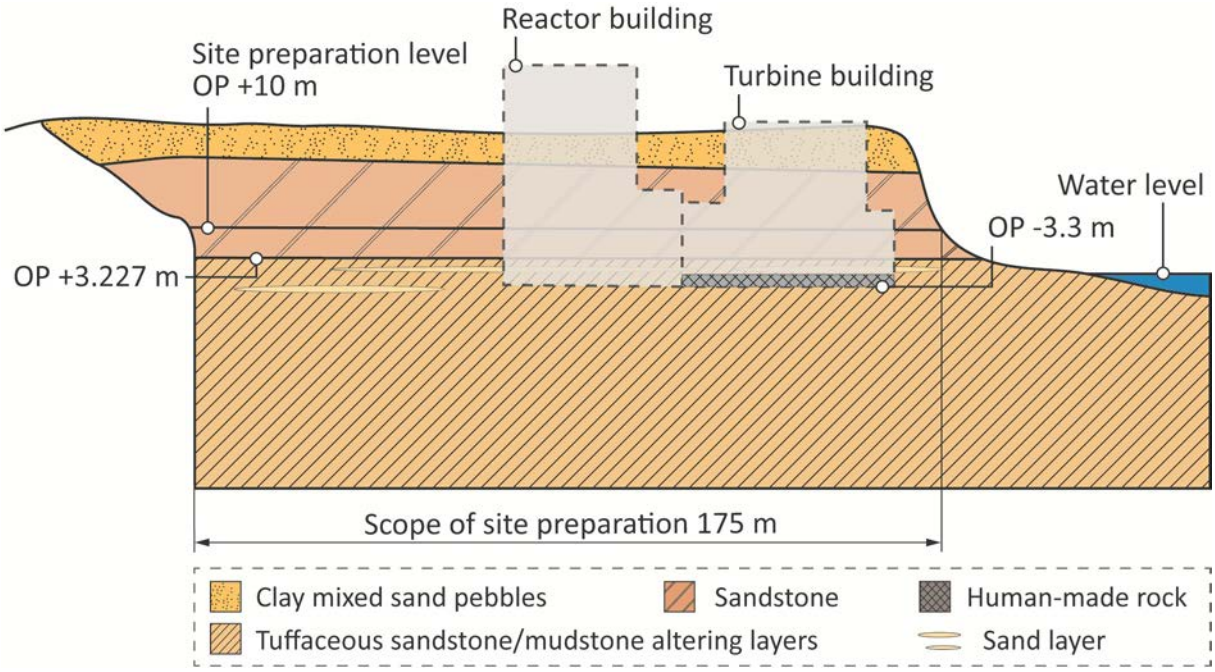


FIG. 2.1–1. Cross-section of the Fukushima Daiichi construction site showing soil characteristics (all levels are above mean sea level) [3].

Figure 2.1–2 shows a typical cross-section of the main buildings of Unit 1, illustrating the location of the grade level at OP +10.00 m and the relationship with the layout of the buildings.

The TEPCO report on the accident [10] indicated that the main plant grade level was defined in accordance with the information available from the historical records on tsunamis in the Fukushima Daiichi region and the topographical and bathymetric conditions of the shoreline in the area. In terms of construction costs, it would have been preferable not to excavate to a low level, though on the other hand, the lower level provided access advantages for water intakes and loading wharfs as well as significantly lower installation (i.e. required pump power) and operating costs for pumping cooling water. The report [10] also listed economic factors. These included the total excavation cost to develop the power station site area, including road access and the work area required, as well as the need to remove the clay and sandstone upper layers to reach the stable strata to obtain firm foundation soil where the major buildings were founded.

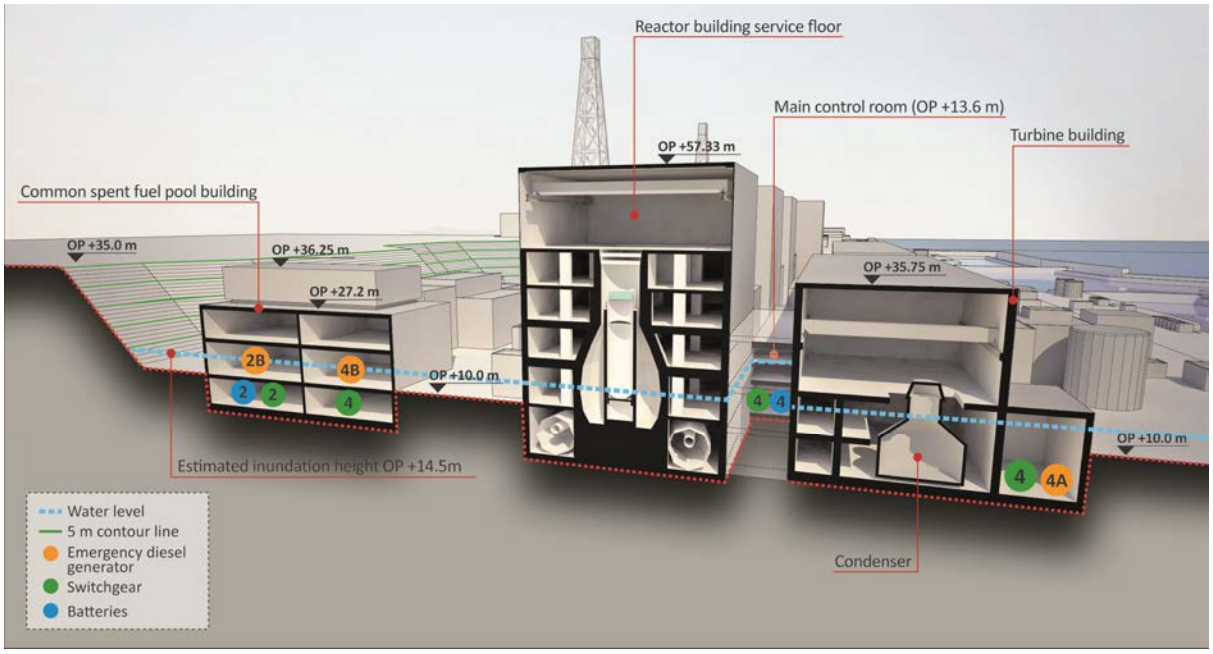


FIG. 2.1–2. Cross-section of the main buildings at Unit 1 of the Fukushima Daiichi NPP [3].

Thus, the main reason for the decision on the main plant grade level would have been the economics of water cooling supply (i.e. installation cost during the construction stage and transport energy cost during the operational life of the installation) based on the assumption that the external flooding levels would not impose a risk according to recent historical records in this area [10].

These plant grade elevations, particularly those at OP +10.00 m and +4.00 m, played a key role in the runup to the flooding from the tsunami in March 2011. Thus, a site that was considered as a dry site in the original design basis became a wet site during its operational period as result of the analyses of the flood levels performed before March 2011. These analyses were under review in March 2011.

2.1.2. International safety standards in relation to earthquake and tsunami hazard assessments and design aspects

2.1.2.1. Earthquakes: Hazards and design considerations

The IAEA has issued a number of publications focusing on earthquake and flood hazards since the 1970s through its Nuclear Safety Standards (NUSS) programme. These publications include Safety Requirements and Safety Guides, which were developed on the basis of consensus among Member States and recognized engineering practices. The safety standards in these areas, of generic and specific nature, have been periodically updated in accordance with scientific and practice developments, and considering also the lessons learned from occurred external events in the world.

IAEA safety standards require that, before the construction of an NPP, site specific external hazards, such as earthquakes and tsunamis, need to be identified, and the impacts of these hazards on the NPP need to be evaluated as part of a comprehensive and full characterization of the site. Adequate design bases are required to be established to provide sufficient safety margins over the life of the NPP. These margins need to be sufficiently large to address the high level of uncertainty associated with the evaluation of external events. Site related hazards need to be periodically reassessed in order to identify any need for change as a result of new information and knowledge during the life of the plant.

The guidance provided in the IAEA safety standards on seismic hazards (fault displacement and ground motion hazard) has been revised three times.

The first Safety Guide on this topic was published in 1979 as Safety Series No. 50-SG-S1, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting [11]. At that time, the concept of capable fault was first introduced to differentiate those active faults which may have the potential for relative displacement at or near the ground surface.

In the 1960s and 1970s, it was common international practice to use historical records when applying methods for estimating seismic and concomitant (e.g. tsunami) hazards. This common practice included increasing safety margins by increasing the maximum recorded historical seismic intensity or magnitude in the site region, and assuming that such an event would occur at the closest distance to the site [11]. This was done to account for the uncertainties in the observations of intensities or magnitudes, as well as to compensate for the fact that the maximum potential values might not be attained in a relatively short period of observation when, typically, the observation period needs to include pre-historical data in order to provide robust estimates for the hazard assessment. However, the seismic hazard assessment for the design of Units 1 and 2 at the Fukushima Daiichi NPP was conducted mainly on the basis of regional historical seismic data without increasing the safety margins as described above. During the process of obtaining construction permits for the later units, a new methodology was applied using a combination of historical earthquake information and the geomorphological fault dimensions [3, 4]. At that time, the regulations on deterministic seismic hazard assessment in many countries did not require a given frequency of occurrence for this extreme event. However, later, in the 1990s, studies demonstrated that the mean period of recurrence of those design bases spanned from 1000 to 100 000 years, with the median being 10 000 years [12]. These studies were performed in support of the revision of siting regulations in some countries based on a comparison of the original design basis for earthquakes with the available probabilistic hazard results.

The first version of the Safety Guide on seismic hazard assessment [11] was substantially revised in 1991 and published as Safety Series No. 50-SG-S1, Rev. 1 [13]. At this time the concept of seismic hazard analysis based on a seismotectonic model using a reliable geological, geophysical, geotechnical and seismological data set was established. This meant that the seismic hazard at an NPP site would be controlled not only by seismicity (i.e. the historical record of occurred earthquakes), but also by tectonics, which gives an indication of the long term potential for geological structures to generate earthquakes. This concept has been retained in the subsequent revisions of this Safety Guide, first in 2002 [14] and, finally, in 2010 with the current Specific Safety Guide, IAEA Safety Standards Series No. SSG-9, Seismic Hazards in Site Evaluation for Nuclear Installations [15].

In the Safety Requirements publication IAEA Safety Standards Series No. NS-R-3, Site Evaluation for Nuclear Installations [16], a preference was indicated for probabilistic hazard analyses for external events in order to take into consideration the potential for hazards beyond the design basis and, as a consequence, the need to avoid cliff edge effects affecting safety. Following this requirement, IAEA Safety Standards Series No. SSG-9 [15] provides detailed recommendations for a probabilistic seismic hazard analysis (PSHA).

Although the probabilistic approach is recognized as an efficient tool to evaluate hazards beyond the design basis, there are examples of deterministic approaches for beyond design basis seismic evaluation. The European Utility Requirements (1998) provide a factor of 1.4 beyond design for checking the adequacy of the plant, while the United States Nuclear Regulatory Commission (NRC) requires a plant to demonstrate a high confidence of low probability of failure (HCLPF) of 1.67.

2.1.2.2. Tsunami: Hazards and design considerations

Tsunami waves and associated phenomena may produce severe damage to installations located in coastal areas. With regard to nuclear installations, IAEA safety standards require that the potential for tsunamis that can affect safety and the determination of its characteristics should be assessed, taking into consideration pre-historical and historical data as well as associated hazards, with account taken of any amplification due to the coastal configuration at the site (see paras 3.24–3.28 of Ref. [16]).

If such a potential exists and detailed hazard characterization is done, the facility, installation or plant should be designed to withstand the event according to adequate design bases, including specific performance criteria determined as a result of a tsunami hazard assessment, as indicated in IAEA Safety Standards Series No. NS-R-1, Safety of Nuclear Power Plants: Design [2] (see paras 5.16 and 5.17). These aspects have also been considered in the current revision of NS-R-1, IAEA Safety Standards Series No. SSR-2/1 [17], in Requirement 17.

To comply with these requirements, IAEA Safety Standards Series No. NS-G-3.5, Flood Hazard for Nuclear Power Plants on Coastal and River Sites (2003) [18], and IAEA Safety Standards Series No. NS-G-1.5, External Events Excluding Earthquakes in the Design of Nuclear Power Plants [19], provided detailed recommendations based on recognized practice and consensus among Member States at that time. Characterization of runup, drawdown and associated phenomena (i.e. hydrodynamic forces, debris and sedimentation) was recommended in NS-G-3.5 [18]. This version of the Safety Guide on flood hazards reflected the operating experience from the flooding affecting the Le Blayais NPP site in France in 1998.

As stated in the IAEA safety standards [18], the dry site concept needs to be applied (as defined in the previous section) particularly in relation to flood events. Thus, all items important to safety should be constructed above the level of the design basis flood, with account taken of wind wave effects and any accompanying event(s) that may affect the reference level of the water at the time of the design basis flood (such as storm surges, sea level rise, tectonic movement, accumulation of debris and ice). In many Member States, this concept is preferred to the alternative solution of permanent external protective barriers such as levees, sea walls and bulkheads, which require being classified as safety related SSCs with strict design and construction engineering, periodic inspections, maintenance and monitoring features, among other aspects important to safety. In both cases, redundant and conservative measures should be implemented owing to the intrinsic cliff edge characteristics involved in surmounting the protective barriers in place. These measures include ensuring waterproofing and the suitable design of items necessary to provide the capability to properly perform the fundamental safety functions of shutting down the reactor and maintaining it in safe shutdown condition [18].

A revision of NS-G-3.5 was recently undertaken to consider new data, information and lessons learned, mainly from the December 2004 Indian Ocean tsunami. The result was IAEA Safety Standards Series No. SSG-18, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations [20], which was published in 2012. This new version maintains the concepts and recommendations from the previous Safety Guides and provides more detailed recommendations related to the protection of NPPs against the hazardous effects of tsunamis. An annex in this safety standard — which is not considered as part of the safety standard — refers to current practices in some Member States, with Japan and the United States of America being the examples.

2.1.3. Japanese regulatory practices in relation to earthquake and tsunami hazards and design aspects

2.1.3.1. Earthquakes

At the time the construction permit for Units 1–6 of the Fukushima Daiichi NPP was issued, between 1966 and 1972, the applicable criteria in Japan for defining the site related design bases including the review guidance were, in general, those established in the:

— Regulatory Guide for Reviewing Nuclear Reactor Site Evaluation and Application Criteria, issued by the Japan Atomic Energy Commission (JAEC) in 1964 [21] (revised in 1989).
— Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities, issued by JAEC in 1970. This guidance document was revised in 1977 and 1990 [22] and provides very general requirements on the need for safety functions not to be affected by this type of natural hazard.

Regarding the seismic hazard assessment, a document entitled Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities was issued by the NSC in 2006 [9] [4] which was valid at the time of the Fukushima Daiichi accident.

Active and capable faults — Japan

Until very recently, the Japanese nuclear regulatory guides and Japanese practice did not make a clear distinction between active faults and capable faults as established by the IAEA. In other words, seismic hazard analyses involved only vibratory ground motion and not fault displacement. Starting with the 16 July 2007 Niigata-Chuetsu-Oki earthquake that affected the Kashiwazaki-Kariwa NPP, and following several IAEA missions that recommended that fault displacement hazard issues be specifically addressed, more attention was given to this topic by TEPCO. In fact, TEPCO agreed to conduct a research study, including performing specific and detailed site investigations in relation to the fault displacement issue at the Kashiwazaki-Kariwa site and to initiate probabilistic fault displacement hazard analysis. This was also identified as a task within the framework of the IAEA Extrabudgetary Programme on Seismic Safety. TEPCO presented their results during a seminar on fault displacement hazards in January 2014 at the IAEA, which was organized as part of the annual Donors' Meeting of the Extrabudgetary Programme of the IAEA's International Seismic Safety Centre (ISSC).

The NSC Regulatory Guidelines of 2006[9] increased the definition of an active fault from 50 000 to 120 000–130 000 years. The latter period refers to the late Pleistocene. This change was significant since the faults near the NPPs, which may have been previously considered not active during the original site selection and design process, had to be considered active after 2006 and the seismic hazard values, consequently, were increased. Even though the older faults were considered to be active by the NSC Regulatory Guidelines of 2006 [9], the Japanese regulatory authority at that time, the Nuclear and Industrial Safety Agency (NISA), did not have in place specific requirements or regulations regarding fault displacement issues and only required that the vibratory ground motion be re-evaluated.

The regulatory outlook on the fault displacement issue has changed significantly in Japan since the Fukushima Daiichi accident. Fault displacement hazard has now become a subject that is raised frequently by the current Nuclear Regulation Authority (NRA). However, even though regulatory requirements were not in place, NISA had already asked several utilities to investigate the fault displacement hazard at their NPPs. After the 2007 Niigata Chuetsu-Oki earthquake and the

[4] Hereafter referred to as the NSC Regulatory Guidelines of 2006

identification of the potential fault displacement issue at the Kashiwazaki-Kariwa site by the IAEA, NISA became more proactive in its oversight of the problem. The issue was formally raised by NISA only after the Fukushima Daiichi accident and in the context of the backcheck programme at the Expert Hearing on Earthquakes and Tsunamis [23].

NISA/NRA have asked for reviews of the following NPPs regarding the potential for fault displacement hazard at the site according to information provided by the official NRA web site:

— On 29 August 2012, NISA directed the Kansai Electric Power Company (KEPCO) to develop an additional plan on the fracture zones at the site of the Mihama NPP.
— In November 2012, the NRA conducted investigations and held evaluation meetings relating to the fracture zones at the site of KEPCO's Ohi NPP. Additional investigations are planned, including a feature called the F-6 fracture zone.
— NISA received additional investigation plans from the Japan Atomic Power Company (JAPC) in May and August 2012 regarding the fracture zones at the site of the Tsuruga NPP. The NRA conducted field investigations related to on-site capable faults at Tsuruga in December 2012.
— NISA directed the Hokuriku Electric Power Company to conduct additional investigations of the fracture zone at the site of the Shika NPP on 18 July 2012.
— NISA received a report on the evaluation results of the fracture zones at the site of the Higashidori NPP from Tohoku Electric Power Company in March 2012.

A new regulation prepared by the NRA in July 2013 defines fault activity. The document puts the new limit for fault capability to 400 000 years in cases where the late Pleistocene dating cannot be established due to the absence of these horizons [24]. This may have some major consequences for Japanese NPPs, as follows:

— Faults in the vicinity of the site, previously not identified as active (or 'capable' in IAEA terminology) under old regulations, may now become a seismogenic source which would be able to generate seismic ground motion and/or be a source for fault displacement hazards.
— In the case of seismic ground motion, there will yet be another increase in the vibratory ground motion hazard with respect to the level for which the SSCs were designed or previously re-evaluated.
— In the case of fault displacement hazards, there would now be a serious issue if they were found at or near an NPP site.

The M 6.5 default earthquake that most of the NPPs in Japan were designed against may have concealed some small faults (or folds) in the site vicinity (i.e. about a 5 km radius around the NPP site) as they contributed much less to the ground motion hazard than the M 6.5 default earthquake. Because fault displacement was not explicitly considered a separate hazard, this did not cause an issue before the new NRA regulations. It is likely that small capable faults may exist in the vicinity of some Japanese NPPs. Without resorting to probabilistic fault displacement hazard analysis, it is difficult to resolve issues related to these faults. The NRA will make deterministic decisions regarding these faults because Japanese regulations do not support probabilistic fault displacement hazard analysis.

Vibratory ground motion

The underestimation of the seismic hazards for the Fukushima Daiichi and Daini NPPs is shown in Tables 2.2–1 and 2.2–2, provided by TEPCO. At these sites, the original design basis as well as the values obtained from recently conducted seismic hazard reassessments were exceeded with respect to the maximum acceleration values recorded in March 2011.

The underestimation of the seismic hazard is related to the reliance of past Japanese practice on basing the seismic hazard assessment mainly on observed earthquakes (recent historical data) and not on the

tectonic potential of the faults (including the subduction zone), coupled with the lack of conservative assumptions for taking into account the uncertainties that exist in the assessment of pre-historical extreme events. In this regard, consideration of an active fault survey for assessing vibratory ground motion has been strengthened after the issue of the NSC Regulatory Guidelines of 2006.

It is important to point out the difference in the Japanese approach with respect to the international practice. As indicated in the previous section, in the 1960s and 1970s, it was common international practice to use historical records when applying methods for estimating seismic and concomitant (e.g. tsunami) hazards. This approach was basically deterministic. The international practice [11] was to add a safety margin to supplement the lack of information on non-observed extreme events of very low annual frequency of occurrence by increasing the maximum historically recorded seismic intensity or magnitude and by assuming that such an event may occur at the closest distance to the site, as explained in detail in Safety Series No. 50-SG-S1 [11]. This was not done in Japan in order to compensate for the fact that the maximum values might not be attained in a relatively short period of observation. The pre-historical data are to be included in order to consider extreme events and provide robust estimates for the hazard assessment of very low annual probability of occurrence events. In addition to the criterion to use pre-historical and historical data commensurate with the low annual frequency of occurrence of these extreme external events, the internationally recognized practice also recommended the use of global analogues in order to cope with the lack of such pre-historical data. This is another important tool, particularly as an earthquake with M 9.5 (the largest in history) had occurred previously in the same tectonic environment of the Pacific tectonic plate.

When the IAEA Fact Finding Expert Mission of 24 May–2 June 2011 [6] said in its report that the "tsunami hazard was underestimated", it meant that the magnitude associated with the subduction zone was underestimated because of the emphasis on the use of historical data only (see the detailed description in Section 2.1.4.2).

At the beginning of the 1960s, when the first unit of Fukushima Daiichi was designed, there were two major subduction earthquakes (in Chile in 1960 at M 9.5 and in Alaska in 1964 at M 9.2) in the Circum-Pacific Belt, on which Japan is also located. At that time, an integrated approach to large scale seismotectonic modelling was not adopted in Japan. The tectonic potential of faults was not considered because at that time the earthquake occurrence model relied heavily on seismicity data and a belief that a mega earthquake like the M 9.5 earthquake in Chile in 1960 would not occur in this area which proved to be incorrect.

Due to the conservative approach of the Japanese regulatory guides for seismic design of NPPs — e.g. using the static approach with three times the static equivalent seismic loads established for conventional building codes — the site specific seismic hazard may not be the actual design basis. The difference between S1 and S2 earthquake levels[5], as they were defined by the Japanese regulations, is related to the time frame for which the faults that may generate significant earthquakes are considered to be active. Until the publication of the NSC Regulatory Guidelines of 2006 [9] for calculating S1, it was required to postulate that faults that had moved within the past 10 000 years were to be considered as being active. For the calculation of S2 this time frame was 50 000 years. This meant that many more faults had to be considered active in the calculation of S2. This increased the estimated value of the seismic ground motions hazard.

[5] S1 and S2 are the two levels of severity of design basis ground motions that should be taken into account. IAEA Safety Series No. 50-SG-S2 defined the application of these two levels in design as follows: (1) ground motion level 1 (S1), which is the maximum that reasonably can be expected to be experienced at the site area once during the operating life of the nuclear power plant; (2) ground motion level 2 (S2), which is considered to be the maximum earthquake potential at the site area [11, 25].

With the publication of the NSC Regulatory Guidelines in September 2006 [9], the 50 000 year period was increased to 120 000–130 000 years, as was described in the previous section. This meant that every NPP in Japan was required to perform a backcheck in order to understand the impact of the additional faults that needed to be considered to be active for assessing the vibratory ground motion.

Since September 2006, the derivation of the seismic design basis using the seismic hazard approach has stipulated the following approaches:

— Following a methodology similar to the deterministic seismic hazard analysis outlined in IAEA Safety Standards Series No. SSG-9 [15], using the ground motion prediction equations (GMPEs) approach for the identified seismic sources as formulated, for example, by the Japan Electric Association (JEA) Response Spectrum;
— Using the Green's Function approach for numerical simulation of the ground motion generated by the identified seismic sources;
— Considering diffuse seismicity, formulating the ground motion by collecting and analysing relevant strong motion records that cannot be assigned to an identified seismic source with account taken of site characteristics.

During the preparation of IAEA Safety Standards Series No. SSG-9 [15], the following paragraph was added in order to represent the Japanese approach regarding the second item in the list above:

> "5.14. In seismically active regions for which data from ground motion caused by identifiable faults are available in sufficient quantity and detail, simulation of the fault rupture as well as of the wave propagation path is another procedure that should be followed. In cases where nearby faults contribute significantly to the hazard, this procedure may be especially effective. The parameters needed include:
>
> (a) Fault geometry parameters (location, length, width, depth, dip, strike);
> (b) Macroparameters (seismic moment, average dislocation, rupture velocity, average stress drop);
> (c) Microparameters (rise time, dislocation, stress parameters for finite fault elements);
> (d) Crustal structure parameters, such as shear wave velocity, density and damping of wave propagation (i.e. the wave attenuation Q value).
>
> "For complex seismotectonic environments such as plate boundaries, thrust zones and subduction zones, and in particular for offshore areas, the specific seismotectonic setting of the earthquake that affects those seismic source parameters mentioned in (a)–(d) should be considered in the characterization of the ground motion."

Minimum magnitude (M 6.5) event

Historically, postulating an M 6.5 default earthquake at the site may have had favourable and unfavourable consequences. The favourable consequence is that a certain level of robustness is ensured for every NPP in Japan as a minimum. However, this assumption also had an unfavourable consequence because it led plant operators to ignore nearby faults if they produced lower ground motions that were less than the enveloping response spectrum due to the M 6.5 postulated earthquake. While this had no implication in the evaluation of the vibratory ground motion hazard, it led to the potential for the fault displacement hazard being ignored. As expressed in the previous subsection, this topic was recognized as a regulatory issue in Japan after the 2007 Niigata Chuetsu-Oki earthquake, at the Kashiwazaki-Kariwa site. It has been formally recognized as a regulatory issue in Japan since the Fukushima Daiichi NPP accident, and the corresponding reassessments of several Japanese NPPs to verify safety against earthquake related hazards are ongoing.

Ground motion prediction equations for the Niigata-Chuetsu-Oki and Great East Japan earthquakes

For approximately the same epicentral distance and distance from fault rupture (about 200 km), the base mat motions recorded at the two plants, Fukushima Daiichi and Daini (only 10 km apart), are significantly different (see Tables 2.1–1 and 2.1–2). The soil properties are similar (at ~50 m, a layer with shear wave velocity of V_s = 700 m/s). The plant structures are also similar, as is the embedment depth of ~10–12 m for all units.

The two earthquakes (Niigata-Chuetsu-Oki in 2007 and the Great East Japan in 2011) which were recorded in the basement levels of the reactor buildings of the seven units of the Kashiwazaki-Kariwa NPP and all the units of the Fukushima Daiichi and Daini NPPs show that when the location of the earthquake focus with respect to the NPP is of the same order of magnitude as the causative fault dimensions, the values obtained using the conventional GMPE and site response (considering only soil amplification) will not be accurate in terms of predicting ground motion.

The variability between the records obtained at Units 1–4 and Units 5–7 of the Kashiwazaki-Kariwa NPP during the Niigata-Chuetsu-Oki earthquake is significant and cannot be predicted using conventional tools. As shown in Tables 2.1–1 and 2.1–2, the same is true for the records obtained at the Fukushima Daiichi and Daini units during the Great East Japan Earthquake. This may explain the emphasis given to the fault rupture simulation approach by Japanese scientists.

2.1.3.2. Tsunamis and external flooding

At the time the construction permit for the Fukushima Daiichi NPP was issued, from 1966 to 1972 for Units 1–6, the applicable criteria in Japan for defining the site related design bases including the review guidance, were those established in the:

— Regulatory Guide for Reviewing Nuclear Reactor Site Evaluation and Application Criteria, issued by the JAEC in 1964, (revised in 1989) [21].
— Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities, issued by JAEC in 1970. This guidance document was revised in 1977 and 1990 and provides very general requirements on the need that safety functions must not be affected by natural hazards [22].

Specifically regarding the tsunami hazard assessment, the 1990 version of the Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities [22] provided very generic requirements and only stated that the effect of the tsunami should be considered in the design, but it did not prescribe an approach or methodologies to be used or performance criteria to be fulfilled in that regard. It also stated that the design tsunami should be determined, for example, by numerical simulation.

Later, in 2002, reflecting the advances and progress in the area of numerical simulations for tsunami hazard evaluation, a standard assessment methodology was developed by the Japan Society of Civil Engineers (JSCE) through its Tsunami Evaluation Subcommittee of the Nuclear Civil Engineering Committee. Thus, the Tsunami Assessment Method for Nuclear Power Plants in Japan [26] was published and its main elements are described in Section 2.1.5.4. It is based on a deterministic approach, and the uncertainties in the tsunamigenic source data are considered by processing a number of studies with a variation of the significantly involved parameters.

However, the most important characteristic of the JSCE methodology, from the point of view of its incidence in the calculations performed before March 2011 by TEPCO and which led to an underestimation of the tsunami wave heights at Fukushima Daiichi, is the fact that the tsunamigenic

sources are fixed or deterministically established by the guidelines, and the applicant should apply only those sources as indicated by the procedure. It should also be highlighted that this standard provides a method for calculating the maximum and minimum tsunami heights, but does not include specific guidance on how to deal with the associated effects such as, for example, hydrodynamical loads, sand drift, or missiles from transported debris (see chapter 2, point 2 of Ref. [26]). Moreover, the JSCE methodology indicates that "it is assumed that the effects of the other phenomena are less important than that of the water level". These associated effects are only referred to as future challenges in the last sentence of the final chapter.

The JSCE methodology had been applied by TEPCO and all other utilities in Japan since 2002, as described in detail in Section 2.1.5.4 of this volume. It is also included in an annex of IAEA Safety Standards Series No. SSG-18 [20] as an example of practice of a Member State (Japan). Practice in the USA is also included in that annex.

In relation to regulatory requirements and guidance, the new NSC Regulatory Guidelines of 2006 address tsunami safety in chapter 8 as an accompanying event of an earthquake, stating that "safety functions of Facilities shall not be significantly affected by the tsunami which could be postulated appropriately to attack but very scarcely in the operational period of Facilities". No detailed or specific requirements or guidance is provided on the way to comply with this statement, in particular regarding the meaning of "very scarcely" [9].

Regarding the combination with other flooding hazards, it was indicated that in practice only the high tide is added to the calculated tsunami water levels. In the meeting with NSC authorities at the time of the IAEA Fact Finding Expert Mission, it was clarified that the NSC Regulatory Guidelines of 2006 were not legally binding and they were not regulations, although in practice they were considered as such. It was also expressed that these guidelines would be revised in view of recent experience and lessons learned [6].

No regulatory guidelines existed, also, regarding the consideration of external flooding as a hazard that may result from a combination of meteorological and hydrological phenomena.

2.1.4. Design basis and reassessments of the earthquake hazards and remedial actions taken during the operational life of the Fukushima Daiichi NPP

2.1.4.1. Background information on seismic hazards

IAEA safety standards require that the site of a nuclear installation be adequately investigated with regard to all characteristics that could be significant to safety and possible external natural and human induced hazardous phenomena. IAEA Safety Standards Series No. NS-R-3, Site Evaluation for Nuclear Installations [16] states the key requirements to be complied with, as follows:

> "3.2. Information on prehistorical, historical and instrumentally recorded earthquakes in the region shall be collected and documented.
>
> "3.3. The hazards associated with earthquakes shall be determined by means of seismotectonic evaluation of the region with the use to the greatest possible extent of the information collected.
>
> "3.4. Hazards due to earthquake induced ground motion shall be assessed for the site with account taken of the seismotectonic characteristics of the region and specific site conditions. A thorough uncertainty analysis shall be performed as part of the evaluation of seismic hazards.

"3.5. The potential for surface faulting (i.e. the fault capability) shall be assessed for the site. The methods to be used and the investigations to be made shall be sufficiently detailed that a reasonable decision can be reached using the definition of fault capability given in para. 3.6."

The IAEA Safety Requirements mentioned above, which updated similar safety requirements established in Safety Series No. 50-C-S (Rev. 1), Code on the Safety of Nuclear Power Plants: Siting [27], published in 1998, are supported by the detailed recommendations provided in the newly revised IAEA Safety Standards Series No. SSG-9 [15], in which methodologies and criteria for assessing seismic hazards and, particularly, seismic ground motions and the potential for fault capability are provided.

As indicated in IAEA Safety Standards Series No. SSG-9 [15], the general approach to seismic hazard evaluation should be directed towards reducing uncertainties at various stages of the evaluation process in order to obtain reliable results driven by data. Experience shows that the most effective way of achieving this is to collect a sufficient amount of reliable and relevant data. There is generally a trade-off between the time and effort necessary to compile a detailed, reliable and relevant database and the degree of uncertainty that the analyst should take into consideration at each step of the process. All pre-instrumental data on historical earthquakes (that is, events for which no instrumental recording was possible), extending as far back in time as possible, should be collected. Palaeoseismic and archaeological information on historical and pre-historical earthquakes should also be taken into account.

Since its first revision in 1991, Safety Series No. 50-SG-S1 (Rev. 1), Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting [13, 27] recommends the application of a seismotectonic approach which is established on the basis of a database comprising geological, geophysical, geotechnical and seismological information. The integration of the geological data (physical capability of tectonic structures to generate earthquakes) with historical and pre-historical seismicity (empirical data) is the cornerstone of the seismotectonic approach regardless of the method used for the calculation of the seismic hazard specific to the site (deterministic or probabilistic).

After detailed hazard characterization is done, the plant should be designed to withstand the seismic events according to specific design bases determined as a result of this hazard assessment, as indicated in paras 5.16 and 5.17 of IAEA Safety Standards Series No. NS-R-1, Safety of Nuclear Power Plants: Design [2]. Moreover, para. 5.22 of NS-R-1 [2] states that: "The seismic design of the plant shall provide for a sufficient safety margin to protect against seismic events."

To comply with such design requirements, mainly applicable to the design of new installations, IAEA Safety Standards Series No. NS-G-1.6, Seismic Design and Qualification for Nuclear Power Plants [8], provides detailed recommendations for the design of SSCs according to their safety significance and following recognized international engineering practice and consensus at the time.

Finally, and more applicable to the situation at the Fukushima Daiichi NPP, for existing operating power plants the evaluation of seismic safety should be conducted as required by the following factors, as prescribed by para. 2.10 of IAEA Safety Standards Series No. NS-G-2.13, Seismic Safety Evaluation for Existing Installations [28]:

"(a) Evidence of a seismic hazard at the site that is greater than the design basis earthquake arising from new or additional data (e.g. newly discovered seismogenic structures, newly installed seismological networks or new palaeoseismological evidence), new methods of seismic hazard assessment, and/or the occurrence of actual earthquakes that affect the installation;
(b) Regulatory requirements, such as the requirement for periodic safety reviews, that take into account the 'state of knowledge' and the actual condition of the installation;

(c) Inadequate seismic design, generally due to the vintage of the facility;
(d) New technical findings, such as vulnerability of selected structures and/or non-structural elements (e.g. masonry walls), and/or of systems or components (e.g. relays);
(e) New experience from the occurrence of actual earthquakes (e.g. better recorded ground motion data and the observed performance of SSCs);
(f) The need to address the performance of the installation for beyond design basis earthquake ground motions in order to provide confidence that there is no 'cliff edge effect'; that is, to demonstrate that no significant failures would occur in the installation if an earthquake were to occur that was slightly greater than the design basis earthquake...;
(g) A programme of long term operation of which such an evaluation is a part."

2.1.4.2. Design basis in relation to earthquake hazards

The following is based on the Establishment Permit Report of the Fukushima Daiichi NPP [3] and Nuclear Reactor Establishment Change Permit Application (Nuclear Industry Report to the Government No. 5–11) submitted on 13 April 1993 [4]. The site description parts of the original Establishment Permit Report [3] have been included in Technical Volume 1. Those parts that relate directly to the derivation of the seismic design basis are treated in this section.

The contents of the section on earthquakes in Ref. [4] are as follows:

— Seismic motion earthquakes and earthquake damage that have occurred in Fukushima Prefecture and surrounding areas;
— History of earthquake damage in areas near the Fukushima Daiichi site;
— Ground conditions of the Fukushima Daiichi site;
— Seismic past earthquakes;
— Recent seismic activity;
— Active faults;
— Seismic geotectonics;
— Site ground vibration characteristics;
— Standard seismic motion;
— Reference documents.

Earthquakes and earthquake damage that has occurred in Fukushima Prefecture and surrounding areas

As indicated in Refs [3] and [4], records of earthquake damage in Japan date back as far as A.D. 599 and have been used to create chronological tables which provide information on the magnitude, hypocentre and degree of damage from each earthquake. Earthquakes around Fukushima Prefecture can be classified into two groups, those with hypocentres in the ocean off the coast of Iwaki and Sanriku, and those occurring inland around Lake Inawashiro.

According to isolines that indicate the number of years between recurrences in the region around Fukushima Prefecture, earthquakes with intensities greater than severe earthquakes and those greater than disastrous earthquakes occur only once every approximately 150 years and once every approximately 400 years, respectively. Furthermore, a very severe earthquake is not known to have occurred in the vicinity of Fukushima Prefecture, making it one of the least earthquake prone areas in Japan.

According to historical research, other than Aizuwakamatsu, in the vicinity of Lake Inawashiro, no other areas in the vicinity of Fukushima Prefecture have suffered damage in the past, and areas around the site of the Fukushima Daiichi and Daini NPPs have never been damaged by an earthquake.

History of earthquake damage in areas near the Fukushima Daiichi NPP

Of all the earthquakes that have occurred in Fukushima Prefecture and its surrounding areas, those that are thought to have caused some damage near the site of the Fukushima Daiichi NPP and for which records of damage still exist have been extracted as follows:

— Aizu earthquake in 1611 (27 September 1611) M 6.9;
— Sendai earthquake in 1646 (9 June 1646), M 7.6;
— Iwashiro-no-kuni Koori earthquake in 1731 (7 October 1731) M 6.6;
— Earthquake off the coast of Shioyazaki to the southeast in 1938 (23 May 1938) with M 7.5 and intensity V in Onahama, Fukushima, Aizu;
— Earthquake off the coast of Fukushima Prefecture to the east in 1938 (5 November 1938), with M 6.5 and intensity V in Onahama, Fukushima, Aizu.

Reference [3] provides a description of the effects of the above mentioned earthquakes and concludes that the area in the vicinity of the Fukushima Daiichi NPP site is a region of Fukushima Prefecture with little seismic activity.

One important point to note is related to the offshore earthquakes that occurred on the subduction zone to the east, the Sendai earthquake in 1646 to the north-east and the earthquake off the coast of Shioyazaki in 1938 to the south-east of the site have been estimated at M 7.6 and M 7.5, respectively. They are both within a distance of 70 km from the Fukushima Daiichi NPP site.

The basic data that have been used in checking the seismic hazard of the site are the historical seismicity starting with an earthquake from the year 1611. This means that the data are constrained to about 400 years.

Ground conditions at the Fukushima Daiichi NPP site

As mentioned in Section 2.1.1, the construction site of the power plant was prepared to an elevation of approximately OP +10.00 m. The main nuclear island structures, such as the reactor buildings of the six units, were built directly on mudstone bedrock that lies near an elevation of OP −4.00 m. This mudstone bedrock belongs to the Sendai Group from the Pliocene Epoch of the Neogene Period and is approximately 400 m thick.

On the basis of the results of the bearing capacity tests and on the values obtained of the compression (P) and shear (S) soil wave velocities, the ground conditions were deemed to be good.

Original seismic design basis

Applying the above described methodology and data available at the time of the licensing of the Fukushima Daiichi NPP units — based more on historical seismicity than on tectonics — the original design basis values for the seismic hazard, expressed in terms of zero period ground acceleration (ZPGA), are quite modest, with values ranging from 245 Gals (~0.25g) to 294 Gals (~0.29g) for the north–south and east–west horizontal components, respectively, for Units 1–5. For Unit 6, higher values of ~0.50g were evaluated as the original design basis.

In addition, and in compliance with the seismic design criteria in Japanese practice, a static horizontal acceleration of 470 Gals (~0.47g) is used for designing the buildings and structures. ZPGA values, measured in Gals, for each unit are included in Tables 2.1–1 and 2.1–2 [6].

2.1.4.3. Reassessment of the earthquake hazards

Information on the evolution of the assessment of seismic hazards was obtained mainly from the chapter on Seismic Motion of the Nuclear Reactor Establishment Change Permit Application (Nuclear Industry Report to the Government No. 5–11) [3, 4].

New investigations were performed in order to obtain a change permit for the construction of structures as described below. The importance of these investigations is that they are based on much more recent earthquake catalogues as well as information on tectonics, i.e. active faults in the region of investigation. A new set of ground motion parameters were derived for these new structures. However, it is not clear whether or not the new parameters were applied to the existing structures, i.e. whether or not backcheck evaluations were performed.

The following explains the methodology used in the determination of the design basis seismic motion as it should be applied to "common facilities used to assist operation, as well as concrete ducts and internal equipment connected to these facilities" mentioned as part of changes made to the Nuclear Reactor Establishment Change Permit Application (Nuclear Industry Report to the Government No. 5–11) [3, 4]. Specifically, these include the establishment of the spent fuel pool and dry storage facility, the establishment of the spent fuel transport vessel storage area and specialization and extra installation of emergency diesel generators.

The change permit application states that the USAMI Catalog (1979), Utsu Catalog (1982) and Meteorological Agency Earthquake Catalog were the most reliable at that time. A figure provided in the change permit application shows the distribution of recent damaging earthquakes having epicentres within 200 km of the site from all of the damaging earthquakes mentioned in the USAMI Catalog and the Meteorological Agency Earthquake Catalog. With regard to the magnitude and epicentre locations of the earthquakes, the USAMI Catalog was used for earthquakes that occurred prior to 1884, the Utsu Catalog was used for earthquakes occurring between 1885 and 1980, and the Meteorological Agency Earthquake Catalog was used for earthquakes that occurred after 1981. This decision was likely made on the basis of the confidence that was placed in the three catalogues for the respective time periods mentioned above.

While there are some differences between the information available earlier and the new earthquake catalogues, the impact of the new seismicity information on the design does not seem to be very significant. Nevertheless, the following important conclusions were made after the review of the recent earthquakes from the Meteorological Agency Earthquake Catalog:

— According to the hypocentre distribution, earthquakes frequently occur around the site in ocean areas offshore of Miyagi, Fukushima and Ibaraki Prefectures.
— According to the vertical distribution, earthquakes that occur on the Pacific Ocean side are generated in conjunction with subduction of the Pacific plate, and the hypocentres get deeper as they near land.
— Earthquakes that occur in conjunction with the subduction of the Pacific plate as mentioned above occur at a depth of between 60 and 90 km near the site.

Active faults

The latest comprehensive survey on active faults at the time was Active Faults in Japan (New Edition) [29]. The report shows active faults within 100 km of the Fukushima Daiichi NPP site. According to this publication, the main faults having late Quaternary activity in areas around the site are the Futaba fault and the western marginal fault zone of the Fukushima Basin:

(1) Futaba fault:
The length of the Futaba fault (on land) is 18 km, from the vicinity of south-western Kayakura in Soma City to the vicinity of Ogai in Haramachi City. Its activity extends to the late Quaternary.

No connection was considered to have existed between this fault and observed past earthquakes or microearthquakes. As Active Faults in Japan (New Edition) [29] puts the activity level of this fault at Class B, earthquakes occurring on the Futaba fault (M 6.9, $\Delta = 35$ km) are considered to be extreme design basis earthquakes. This means that deterministically, a design basis earthquake of M 6.9 has been considered to have occurred at a distance of 35 km from the Fukushima Daiichi NPP.

(2) Western marginal fault zone of the Fukushima Basin:
According to Active Faults in Japan (New Edition) [29], there are a number of faults, from the vicinity of Shiroishi City in Miyagi Prefecture to the vicinity of Tsuchiyu in Fukushima Prefecture along the western marginal fault zone of the Fukushima Basin. The longest of these extends 15 km, and all are of Class B in terms of activity level. Earthquakes occurring near this fault zone were the Iwashiro earthquake of 1731 (M 6.6) and one in southern Miyazaki Prefecture in 1956 (M 6.0). Neither of these extended along the full length of the fault zone; the impact on the NPP site is described in section 3.2.1 (Past Earthquakes) of Active Faults in Japan (New Edition) [29]. No connection was found between this fault zone and the observed microearthquakes.

Further consideration of this issue was based on the connection between this fault zone and the seismic geological structure described below. With regard to other faults, their size and distance from the site were considered to have a minimal impact at the site.

Seismotectonic structures

Seismically active tectonic structures near the Fukushima Daiichi NPP site can be classified as follows:

— Earthquakes occurring in north-eastern Japan:
(1) Near the Japan Trench at shallow depth;
(2) At plate boundaries;
(3) In the Earth's crust, mainly onshore;
(4) Within the sinking Pacific Plate.
The analysis of destructive earthquakes that have occurred in these areas reveals the following:
- The M 8 class earthquakes occurring near the Japan Trench and further eastward have little impact on the NPP site, given the distance.
- Earthquakes of around M 7.5 are occurring off the coast of Miyagi, Fukushima and Ibaraki Prefectures, at the plate boundaries.
- Earthquakes around M 7.0–M 7.5 are thought to be occurring in the Earth's crust west of the Ou Mountains, the Kitakami River Basin and near Nikko.
- No large earthquakes that would impact the NPP site are occurring in the intra-Pacific Plate slab.

While M~8 earthquakes occurring near the Japan Trench would not have much of an impact on the site due to their distance, M~9 earthquakes would likely have an impact on both the seismic hazard as well as the tsunami hazard. The underestimation of the tsunami hazard seems to be based on the assumption of M~8 earthquakes instead of using M~9 for the Japan Trench earthquakes.

— Earthquakes that may occur on seismotectonic structures:
The following earthquakes may occur in seismically active tectonic structures near the Fukushima Daiichi NPP site:
(1) Earthquakes near the plate boundary: The largest earthquakes occurring in the ocean near the Fukushima Daiichi NPP site were one in Rikuzen in 1646 and an M 7.6 earthquake in Sendai in 1835. The potential magnitude of earthquakes in this area is a maximum of M 7.75. Due to the potential for earthquakes of this maximum magnitude

to occur anywhere near the plate boundary from off the coast of Fukushima Prefecture to the Japan Trench, it is assumed that an M 7.8 earthquake will occur near the plate boundary off the coast of Fukushima Prefecture (Δ = 50 km, focal depth (H) = 40 km). This means that deterministically, a design basis earthquake of M 7.8 has been considered to have occurred at a distance of 50 km (and at a depth of 40 km) from the site.

(2) Crustal earthquakes: The largest earthquake occurring on land near the NPP site was one in Nikko in 1683 with a likely magnitude of between M 7.3 and M 7.5. Due to the connection with active faults in the area, an M 7.5 earthquake is expected to occur in the western marginal fault zone of Fukushima Basin (Δ = 65 km).

Regarding the seismic hazard assessment, there are several aspects of the applied methodology that would be important to understand, as they may have a bearing on the underestimation of the seismic hazards and, consequently, on the eventual underestimation of earthquake concomitant events as the tsunami hazard.

— The estimation of the maximum magnitude was made using a combination of historical earthquake information and the geomorphological fault dimensions. The latter is specifically for 'on-land' events and not for those generated at the Japanese Trench in the Pacific subduction zone.
— The information regarding the on-land faults was taken from official sources, but conservative parameters are assumed for the analysis.
— For the Japan Trench, it is assumed that the magnitude would be about M 8. Furthermore, because of the distance from the site, it was assumed that these events would not impact the site, because closer sources would dominate the seismic hazard.

A point that has not been considered here is the fact that the maximum magnitude associated with the Japan Trench was estimated without much tectonic based justification and was based mostly on observed historical data. An approach similar to the on-land faults (deriving maximum magnitudes in relation to physical fault dimensions) was followed for the maximum magnitude estimation (M 8) of the Japanese Trench, but the number of segments to be mobilized during a single event was underestimated.

2.1.4.4. Actions taken to cope with reassessed earthquake hazards

At the time of the Fukushima Daiichi accident in March 2011, TEPCO was in the process of backchecking or reassessing the seismic safety of the plants in compliance with the requirements from NISA following the issue of the new NSC Regulatory Guidelines of 2006 [9] and as a result of the 2007 Niigata-Chuetsu-Oki earthquake that affected the Kashiwazaki-Kariwa NPP.

Tables 2.1–1 and 2.1–2 [6] present information for all units of the Fukushima Daiichi and Daini NPPs on:

— The original design basis for the seismic horizontal ground motion, including the static horizontal acceleration;
— The revised seismic design bases as part and as a result of the backcheck reassessment process started in 2006;
— The observed maximum acceleration values during the Great East Japan Earthquake. The figures in boxes indicate exceedance with respect to the original design basis values.

As can be seen in Table 2.1–1, for the first two units of the Fukushima Daiichi NPP, the original design basis values are quite modest, with about 0.25g for the ZPGA and with 0.47g for the static horizontal acceleration. The latter is applied for specific design purposes of the building and structures as part of the seismic design process of Japanese NPPs, which is quite conservative, follows three

distinct paths and chooses the most conservative result. This point is illustrated in a recent IAEA publication on the results of a benchmark project conducted for the Kashiwazaki-Kariwa NPP (the KARISMA benchmark project) [30].

Another interesting point to be noted is that, for Unit 6, the original design values of the peak ground acceleration are higher than the reassessed values, in line with the application of the new NSC Regulatory Guidelines of 2006 and also higher than the ZPGA values recorded from the March 2011 event.

Regarding Units 1–5, a significant increase can be observed in the reassessed ground motion (obtained after 2006–2007) as compared with the original design ground motions. This may be attributed to two factors: the use of a more seismotectonic based approach to seismic hazard analysis (less dependence on historical seismicity), as described previously for the new seismic guidelines; and a more conservative estimation of the ground motion for a given set of magnitude/distance pairs due to the availability of a much richer ground motion database feeding into more robust ground motion prediction equations (GMPEs).

The reassessed ground motion parameters for the Fukushima Daiichi NPP were exceeded at Units 2, 3 and 5 in the east–west (E–W) direction. It should be noted that similar exceedance is not observed in the north–south (N–S) and vertical (U–D) components, where a comfortable margin still remains between the reassessed design ground motions and the observed accelerations.

Furthermore, the observed accelerations at the Fukushima Daini units (at least those in the two horizontal directions) are significantly less than those for the Fukushima Daiichi units, although the distance from the causative fault may differ only slightly (about 10%). It can be concluded that some directivity effect (E–W component) or local soil response at the Fukushima Daiichi NPP site may be responsible for this difference in the exceedances observed at the two sites.

It is possible to perform a brief comparison of the consequences of the exceedance of the seismic accelerations and the tsunami heights observed in March 2011 with respect to the re-evaluated seismic and tsunami hazard values. The reassessed seismic hazard was exceeded at three units and only in one direction. While the seismic source parameters of the 11 March 2011 earthquake (e.g. the magnitude of the subduction earthquake) may have been underestimated, the consideration in the seismotectonic model of other seismogenic sources (as part of the regional seismotectonic model which may be located onshore) and the use of new GMPEs for calculating the reassessed hazards may have compensated for part of this underestimation in the maximum magnitude of one of the sources (i.e. in the offshore subduction zone).

Regardless of the underestimation of the seismic hazard, TEPCO's Progress Report No. 2 [31] confirmed that the earthquake did not have a serious impact on plant safety. It did not cause a loss of coolant accident (LOCA) or the loss of emergency diesel generator (EDG) functions in Unit 1, as speculated after the accident and indicated in the Report of the National Diet of Japan [32]. Thus, it has been concluded that pipe breaks causing leakage on a scale that would have affected the development of the accident did not occur. Concerning the loss of EDG functions, it has been shown that this was not caused by the earthquake, since the recorded data clarified that the EDG function loss followed immediately after the loss of function of the seawater pumps, which is considered to have been caused by the tsunami.

Tsunami hazards are caused by tsunami waves generated by fault dislocation at the seabed produced by earthquakes as the root cause. The tsunamitectonic model for calculating the tsunami wave height differs greatly from the seismotectonic model for calculating the seismic hazard expressed in terms of ground accelerations. Only subduction earthquakes which can generate out of plane components of fault displacement are the cause of the generated tsunami water waves. Therefore, the underestimation

of the source parameters (e.g. the magnitude) would be more difficult to compensate. Nevertheless, the tsunami hazard as re-evaluated in the trial calculations shows little difference from the one that actually occurred.

TABLE 2.1–1. MAXIMUM ACCELERATION VALUES OBSERVED AT UNITS 1–6 OF THE FUKUSHIMA DAIICHI NPP, AND COMPARISON WITH ORIGINAL DESIGN BASIS VALUES AND RE-EVALUATION VALUES [6]

Fukushima Daiichi NPP unit	Maximum measured acceleration value (Gal)			Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
				Revised design basis (2008)			Original design basis (1966)		
	N–S	E–W	U–D	N–S	E–W	U–D	N–S	E–W	
Unit 1	460	447	258	487	489	412	245		470
Unit 2	348	550	302	441	438	420	250		
Unit 3	322	507	231	449	441	429	291	275	
Unit 4	281	319	200	447	445	422	291	283	
Unit 5	311	548	256	452	452	427	294	255	
Unit 6	298	444	244	445	448	415	495	500	

Note: Values in boxes indicate that the maximum recorded value was beyond the original design basis.

TABLE 2.1–2. MAXIMUM ACCELERATION VALUES OBSERVED AT UNITS 1–4 OF THE FUKUSHIMA DAINI NPP, AND COMPARISON WITH THE ORIGINAL DESIGN BASIS VALUES AND RE-EVALUATION VALUES [6]

Fukushima Daini NPP unit	Maximum measured acceleration value (Gal)			Maximum response acceleration value (Gal)					Static horizontal acceleration (Gal)
				Revised design basis (2008)			Original design basis (1966)		
	N–S	E–W	U–D	N–S	E–W	U–D	N–S	E–W	
Unit 1	254	230	305	434	434	512	372	372	470
Unit 2	243	196	232	428	429	504	317	309	
Unit 3	277	216	208	428	430	504	196	192	
Unit 4	210	205	288	415	415	504	199	196	

Note: Values in boxes indicate that the maximum recorded value was beyond the original design basis.

A final point to be highlighted is related to the design practice to cope with seismic and tsunami hazards. As mentioned before, the Japanese practice of seismic design incorporates several approaches, adopting the one that is most conservative. This results in a robust design of SSCs in NPPs. In the case of the Fukushima Daiichi accident, this design clearly prevented significant consequences from the exceedance of ground motion parameters, which would have been the result if other design criteria, like the application of more than three times the static acceleration of the conventional building codes, had been applied for the design of the buildings at the Fukushima Daiichi site. This was also observed and documented by the IAEA after the Niigata-Chuetsu-Oki earthquake in 2007 at another TEPCO plant, the Kashiwazaki-Kariwa NPP.

However, the design against tsunami hazards is quite sensitive to cliff edge effects, and this leads to less robust solutions than those that can be implemented for seismic events. A minor exceedance of

flood levels may lead to severe consequences by causing internal flooding. This difference was highlighted in the report of the IAEA International Fact Finding Expert Mission of the Fukushima Daiichi NPP [6].

Figure 2.1–3 illustrates the location of the measurement points for the measurements shown in Table 2.1–1 for Fukushima Daiichi NPP units [6].

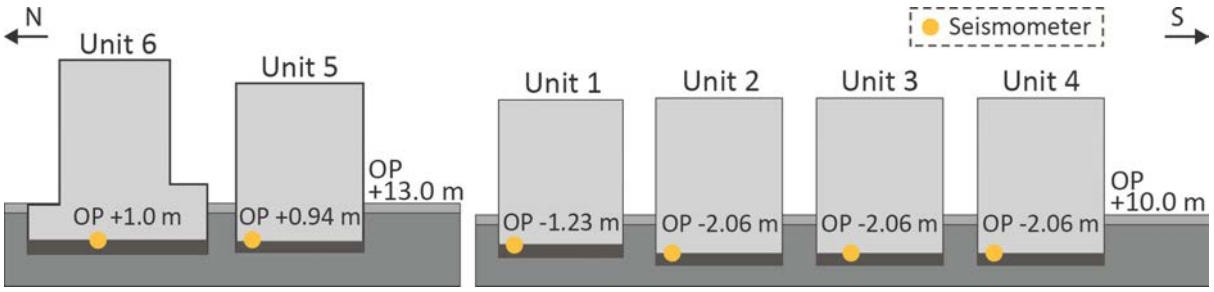


FIG. 2.1–3. Maximum acceleration values observed at Units 1–6 of the Fukushima Daiichi NPP, and comparison with the original design basis values and re-evaluation values [6].

2.1.5. Design basis and reassessments of tsunami hazards and remedial actions taken during the operational life of the Fukushima Daiichi plant

2.1.5.1. Characteristics of tsunami hazards

A tsunami — in Japanese meaning a wave (‘nami’) in a harbour (‘tsu’) — is a series of travelling waves of long wave length (e.g. from kilometres to hundreds of kilometres) and period (e.g. several minutes to tens of minutes, and, exceptionally, hours), generated by deformation or disturbances of the sea floor (or, in generic terms, underwater floor). Earthquakes, volcanic phenomena, underwater and coastal landslides, rock falls or cliff failures can generate a tsunami. Large meteorites impacting the ocean can also generate a tsunami. All oceanic regions and sea basins of the world, and even fjords and large lakes, can be affected by tsunamis.

Tsunami waves and associated phenomena may produce severe damage to installations located in coastal areas. With regard to nuclear installations, IAEA safety standards require that the characteristics of potential tsunamis that can affect safety be assessed, taking into consideration pre-historical and historical data and other types of associated hazards, with account taken of any amplification due to the coastal configuration at the site, (see paras 3.24–3.28 of Ref. [16]).

Consequently, if the potential of a tsunami exists and detailed hazard characterization is carried out, the facility, installation or plant should be designed to withstand the event according to design bases, including specific performance criteria which are to be determined as a result of a tsunami hazard assessment and the intensity or magnitude of the postulated event.

In addition to the effects produced by a variation in water levels (maximum and minimum), the hazardous effects of tsunami waves include strong currents in harbours and bays, bores in rivers, estuaries and lagoons, and huge hydrodynamic forces. Sedimentation phenomena, including deposition and erosion, may also be generated owing to large forces at the sea floor.

Two important issues should be considered in the process of assessing tsunami hazards when estimating the flooding design basis for a nuclear installation:

— The minimum water level produced by the receding wave of the tsunami plays a key role in safety, since, for a period of time, the cooling water may be disrupted or interrupted.
— Tsunami waves are strongly dependent on the configuration of the coast (bathymetry and topography). Therefore, the hazard assessment (e.g. the runup and water level at the shoreline) not only needs to consider the coastal configuration at the site evaluation stage before the plant has been built, but also — and significantly — it needs to consider the final layout of the installation with all modifications to the ground elevation, slopes, grade levels, etc.

Finally, as shown in Fig. 2.1-4, tsunamis are one of the factors to consider in the assessment of the final flood level (maximum and minimum levels). Thus, the tide height, wave heights produced by other meteorological and hydrological phenomena, tectonic subsidence or uplift have to be considered in combination with the occurrence of the tsunami waves. The final flooding level reaching the site is the combination and result of all those factors at the time of the occurrence of the event.

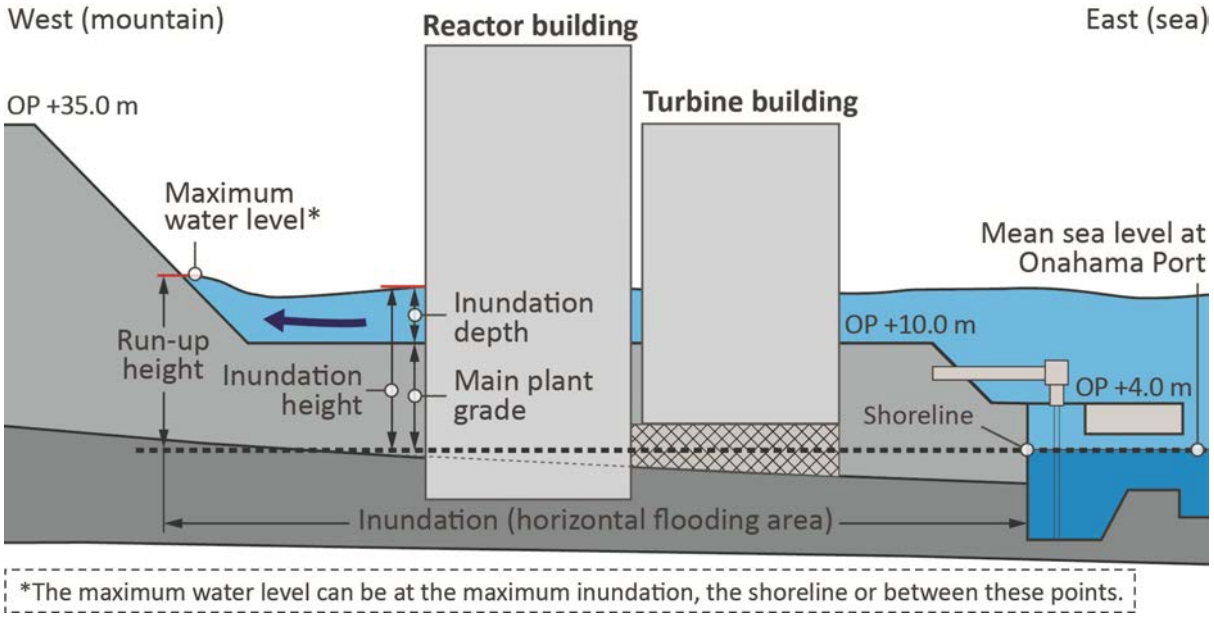


FIG. 2.1–4. Tsunami parameters at the shoreline [20].

2.1.5.2. Design basis in relation to tsunami hazards

As indicated in Section 2.1.2, according to the approach applicable in the 1960s, when the application for the Establishment Permit for the Fukushima Daiichi NPP was submitted, it was common international practice to use historical records for assessing the design basis tsunami height for designing the installation but adding conservative assumptions and using deterministic approaches to count for the potential occurrence of extreme events with very low annual frequency of occurrence. Later, during the 1970s, the methods for assessing the tsunami levels evolved and numerical simulations based on source models of the tectonic mechanisms for characterizing the tsunamigenic sources that generate the sea floor deformations were developed and used. In line with that approach, the design basis tsunami was determined for each site on the basis of the available information on the maximum historical observed tsunamis and the greatest tsunamis induced by submarine active faults (Fig. 2.1–5).

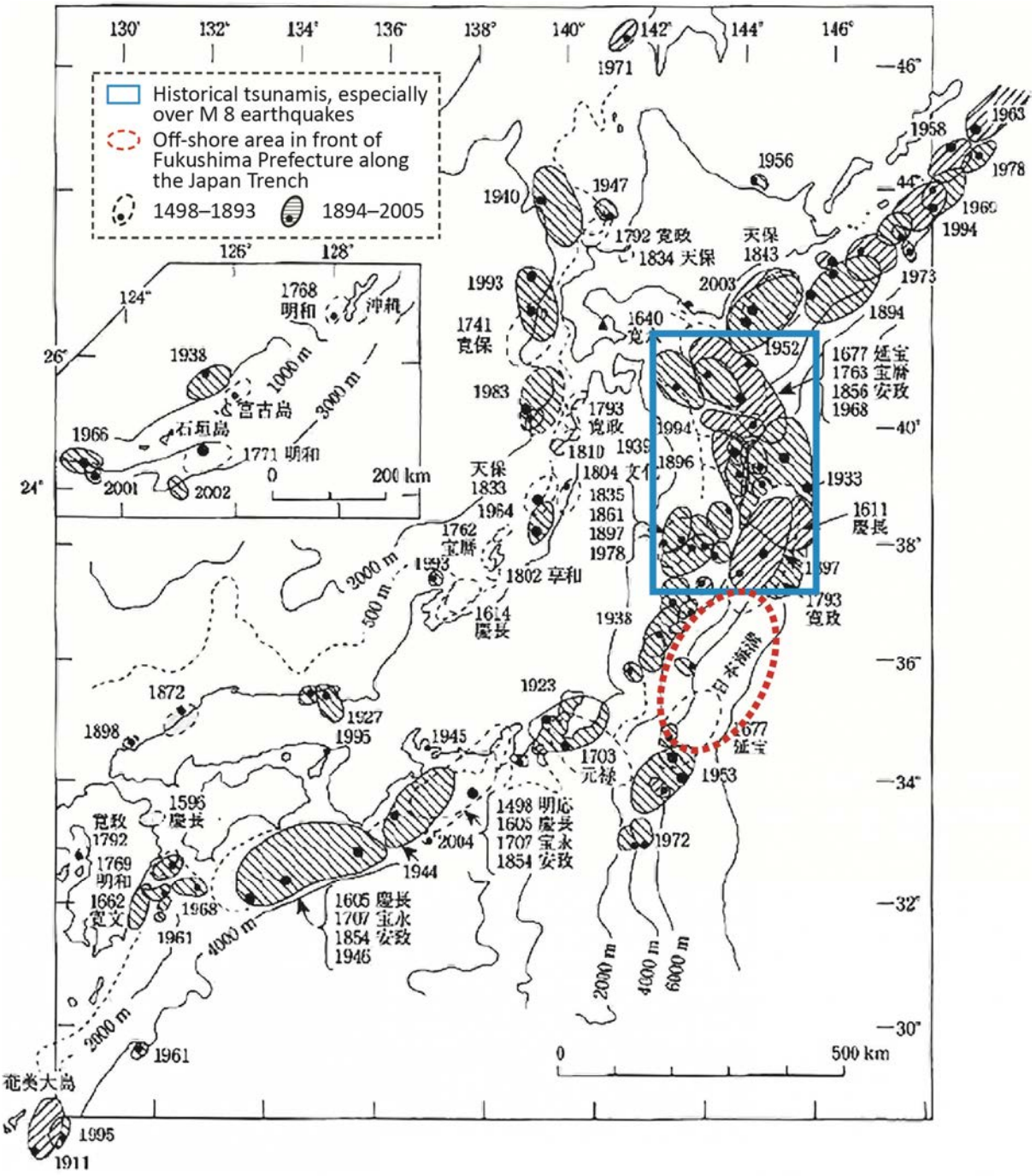


FIG. 2.1–5. Historical earthquakes in the Japan subduction trench [33].

Following these criteria, the tsunami hazard at the Fukushima Daiichi NPP site was initially estimated based on the data and observations from the tsunami generated by the M 9.5 earthquake in Chile in 1960 that reached Japan's east coast. Thus, the design maximum height was defined at OP +3.122 m in accordance with the tide level records observed during that event at Onahama Port, in Fukushima Prefecture, located 50 km south of the site (see also Section 1.2 of Technical Volume 1).

As reported by NISA to the 2011 IAEA Fact Finding Expert Mission [6], this value still represented the licensing design basis for flooding generated by tsunamis at the time of the accident in March 2011. Based on that practice, according to the Japanese reports prior to the accident in

March 2011, the regulatory body had no authority to impose new requirements on the licensee or to change the design bases.

Consequently, the OP +4.00 m of the plant grade level for locating the safety related SSCs at the water intake area corresponding to the location of the seawater cooling pumps would have been considered sufficient by TEPCO to cope with the maximum flood level evaluated as was indicated above. Moreover, the main plant grade levels (i.e. the elevation of the buildings and structures of the nuclear island and balance of plant) that were established at OP +10.00 m for Units 1–4 and at OP +13.00 m for Units 5 and 6 would have been considered enough margin.

Table 2.1–3 summarizes the values of the maximum and minimum tsunami flood levels adopted for the Fukushima Daiichi and Daini NPP sites and for the different units.

TABLE 2.1–3. ORIGINAL DESIGN BASIS: MAXIMUM AND MINIMUM FLOOD LEVELS FOR TSUNAMI HAZARDS AT THE FUKUSHIMA DAIICHI AND DAINI NPP SITES [33]

Site	Unit	Year of Establishment Permit	Rise	Drawdown
Fukushima Daiichi NPP	1	1966	OP +3.122 m	OP −1.918 m
	2	1968		
	3	1970		
	4	1972		
	5	1971		
	6	1972		
Fukushima Daini NPP	1	1974	OP +3.690 m	
	2	1978		
	3	1980	OP +3.705 m	
	4	1980		

OP −1.918 m	Historical low water level
OP +3.122 m	Height of the tide from the Chilean tsunami at Onahama Port on 24 May 1960
OP +3.690 m	= OP +1.490 m + 2.2 m
OP +1.490 m	Mean of high tides at Onahama Port
2.2 m	Height of the tsunami component from the Chilean tsunami at Onahama Port on 24 May 1960
OP +3.705 m	= OP +1.505 m + 2.2 m
OP +1.505 m	Mean of high tides

At this point, it should be noted that the approach applied used only known historical data, leading to the determination of the plant design basis, as shown in Figs 2.1–5 and 2.1–6:

— Figure 2.1–5 shows the location and rupture areas of the earthquakes that generated those tsunamis at the subduction offshore zone (Japan Trench) of the Eurasian and Pacific tectonic plates. The figure shows that no records were available of earthquakes occurring along the Japan Trench in the offshore area in front of Fukushima Prefecture.
— Figure 2.1–6 shows that at the Fukushima Daiichi site the tsunami flood levels were low (of the order of a few metres) compared with the levels in locations to the north of the site — as in Iwate and Miyagi Prefectures — that had recorded maximum levels of around +38 m for tsunamis that occurred in 1611, 1677, 1896, 1933, 1938 and 1960.

The following points should be highlighted in this approach:

— The use of historical records dating from a very recent period of a few hundred years only. No conservative assumptions were made regarding the need to take account of the potential occurrence of extreme events (i.e. a typical period of recurrence of the order of 10 000 years).
— The correspondence between the lack of historical records of tsunami flood levels at the specific location of the Fukushima Daiichi and Daini sites and the lack of data on the occurrence of earthquakes in the offshore area in front of the sites, i.e. a seismic gap for that seismogenic source which coincides with the lack of a high level of tsunami flooding phenomena.

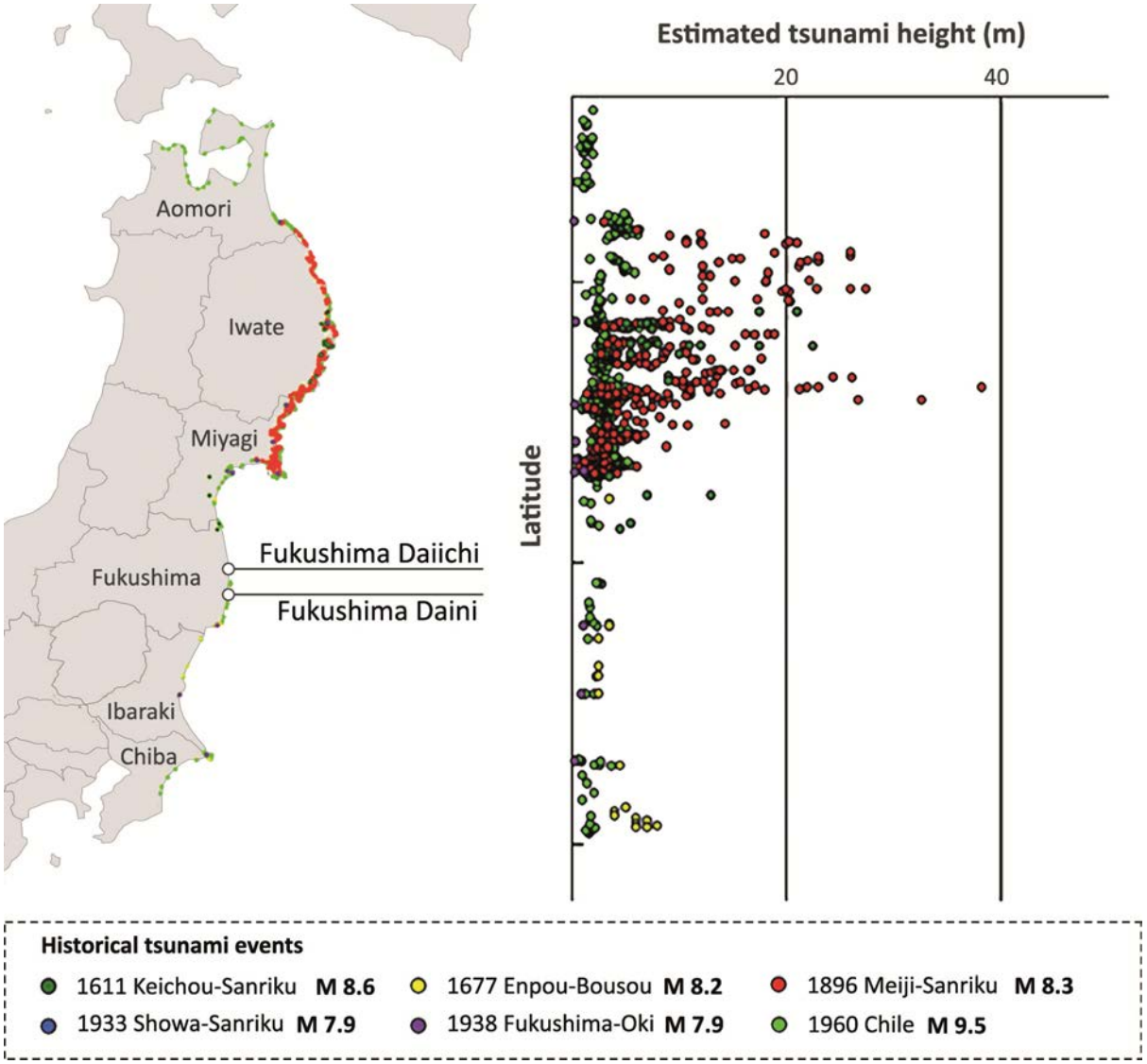
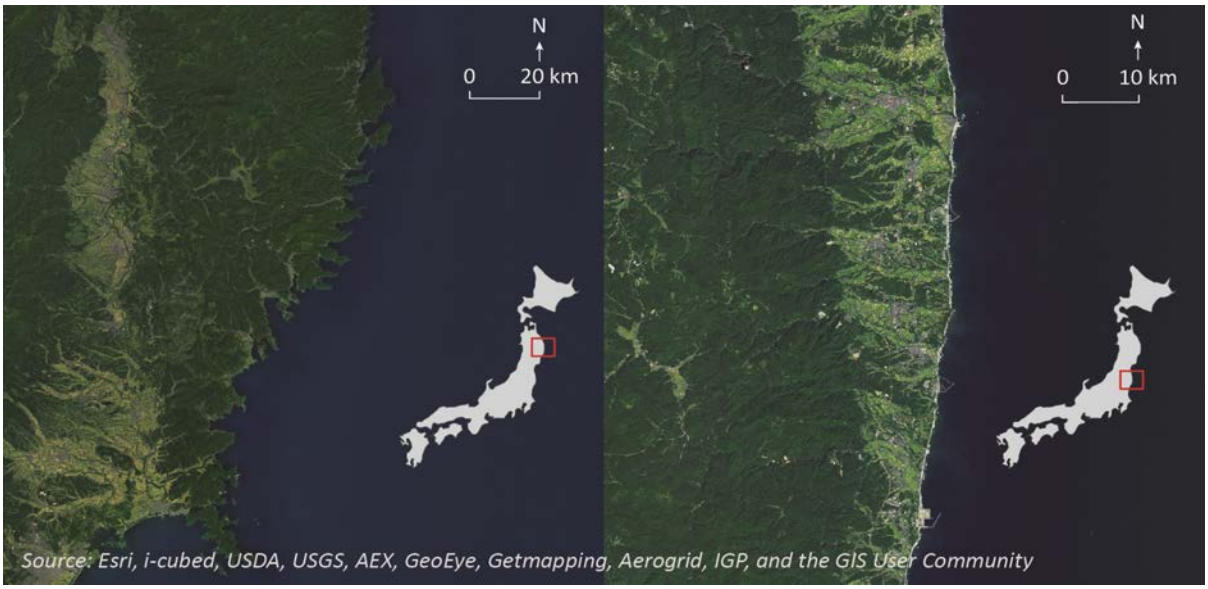


FIG. 2.1–6. Historical tsunami records [33].

The practice in the 1960s, as described above, was not unique to TEPCO. Other utilities in Japan also used the same approach, for example, at the Onagawa NPP operated by the Tohoku Electric Power Company, located about 120 km to the north of the Fukushima Daiichi NPP site in Miyagi Prefecture. In this region, most of the larger earthquakes occurred in historically recorded times in the Japan subduction trench located off the eastern coast, as shown in Fig. 2.1–5, in comparison with the ones recorded at Fukushima Prefecture.

Using the same approach as in the Fukushima Daiichi NPP design basis, the maximum level adopted for the flood design event for Unit 1 of the Onagawa NPP site in 1970 was OP +2.00–3.00 m, as indicated in its Establishment Permit. This level corresponds to values obtained from the literature survey. Later, for Unit 2, in 1987, the highest flood level was determined at OP +9.10 m using numerical simulation techniques. However, the main plant grade level of the Onagawa NPP site is OP +14.80 m. Another reason for the increased level of tsunami runup historically recorded at the north of the Fukushima Daiichi NPP site, in the region of Miyagi and Iwate Prefectures, is the influence of the coastal topography and bathymetry. The Fukushima Daiichi site is located along a rectilinear coastline, while at the Onagawa NPP site, the coastline is a ria (a coastal inlet) with a V shape that would significantly amplify the wave heights of tsunamis. Figures 2.1–7 and 2.1–8, illustrate these issues [33].



(a) (b)

FIG. 2.1–7. (a) Aerial view of Iwate and Miyagi Prefectures; and (b) Fukushima Prefecture.

Finally, there is the issue of floods other than tsunamis. The Establishment Permit [3] document indicates the following in Section 2.2.3:

> "2.2.3 Wave Height
>
> "Large waves occurring near the site are produced by mainly typhoons or low pressure systems and according to observational records after February 1965 the largest wave was produced by Typhoon #28 (1965) and had a significant wave height at a water depth of 10 m of 6.51 m and a maximum wave height of 7.94m.
>
> "Waves usually hit perpendicular to the coast flowing in an easterly direction and the majority of waves fall between the directions of ESE and ENE."

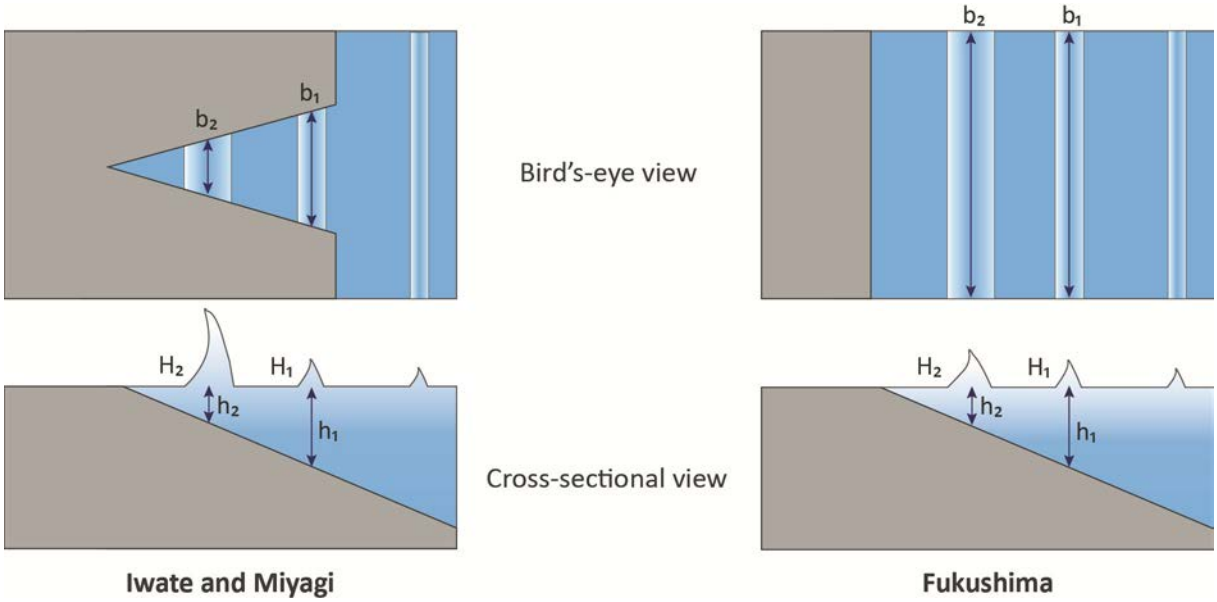


FIG. 2.1–8. Influence of topography and bathymetry in Iwate and Miyagi Prefectures in comparison with Fukushima Prefecture [33].

This would mean that flood levels significantly higher than the estimated value of OP +3.122 m for a tsunami would be considered for other natural phenomena such as the rare meteorological phenomena of powerful typhoons. In this regard, TEPCO has clarified that site protective design countermeasures adopted for coping with the high waves from typhoons include breakwater structures which have the function of damping the waves, and thus the heights of waves in the harbour would stay below the adopted level of OP +4.00 m.

2.1.5.3. Re-evaluation of tsunami hazards

The numerical simulation of earthquake induced tsunamis based on a tectonic mechanism and source modelling was carried out only after the mid-1970s. These simulation techniques involve the characterization of tectonic sources of earthquakes that occur at the bottom of the ocean and which cause the uplift and subsidence of the seabed and, subsequently, lead to the generation of tsunami waves at the sea surface, which propagates in the sea to reach shorelines far away. These relative displacements between both sides of the colliding tectonic plates are the tsunami source. Table 2.1–4 summarizes the evaluations performed by TEPCO after the Establishment Permit, including the remedial measures taken at each time.

As can be seen from the table, from 1966 to 2002, there were no developments and tsunami hazard levels were not reassessed. After 2002, following new guidance from the JSCE in 2002 and 2009 and to strengthen safety according to the disaster prevention plans of the local governments (Ibaraki and Fukushima Prefectures in 2007), the original maximum flood level due to tsunamis was revised upwards from the design basis of OP +3.122 m to the higher level of OP +5.70 m in 2002, and to OP +6.10 m in 2009 using latest bathymetry and tidal data. In addition to those re-evaluations, TEPCO conducted a number of trial calculations using approaches and assumptions different than those proposed by the JSCE. They are described in the following sections.

TABLE 2.1–4 SUMMARY OF TSUNAMI EVALUATIONS PERFORMED BY TEPCO BETWEEN 1966 AND 2009 [33]

Year	Tsunami height	Evaluation method	Countermeasures
1966	OP +3.122 m	Establishment Permit (observed height as result of Chilean tsunami in 1960)	—
2002	OP +5.7 m	Japan Society of Civil Engineers (JSCE) assessment method	To raise elevation of the pumps To make buildings watertight, etc.
2007	OP +4.7 m	Disaster prevention plan by Ibaraki Prefecture	Unnecessary
2007	Approx. OP +5 m	Disaster prevention plan by Fukushima Prefecture	Unnecessary
2009	OP +6.1 m	Latest bathymetric and tidal data on the basis of the JSCE assessment method	To raise pumps' elevation, etc.

2.1.5.4. The JSCE methodology

Using the JSCE methodology, the Fukushima Daini, Tokai and Onagawa NPPs also revised their tsunami flood levels upwards as follows:

— Fukushima Daini NPP: OP +5.20 m (increasing 2.078 m from the original design basis of OP +3.122 m);
— Tokai NPP: OP +4.88 m (with no provisions in this regard in the original design basis);
— Onagawa NPP: OP +13.60 m (increasing 4.5 m from the value of OP +9.10 m estimated in 1987).

Specific aspects of the JSCE methodology included the following:

— It deals only with earthquake generated tsunamis.
— It deals mainly with local or near field tsunamis, i.e. tsunamis generated close to the Japanese shorelines, since the effects of near field tsunamis are greater and more destructive than those of far field tsunamis. It recognizes the occurrence of far field, distant tsunamis (e.g. tsunamis originating in the Alaska/Cascadia subduction zone in North America or in the Nazca plate subduction zone in South America), but it uses them for validating the historical data. The simulation models assume that in those regions of the world the largest historical earthquakes have already been experienced.
— It provides specific guidance only on maximum–minimum wave heights, i.e. on the variation of water levels; it does not provide specific recommendations on how to address the issue of other tsunami related hazards (hydrodynamic forces of the waves, debris impact, sedimentation, etc.) as indicated in chapter 2, point 2 of the JSCE document [26].
— It defines the 'design tsunami' as the one that causes the maximum and minimum water waves at the site among all the various possible scenario tsunamis. The scenario tsunamis are a large number of postulated tsunamis for which numerical simulations are performed, each with different characterizations of the source model. Accordingly, a parametric study is conducted, varying some of the source parameters (e.g. fault position, depth of upper edge, strike direction, dip angle, dip direction), with the uncertainties taken into account. The design tsunami should exceed all recorded and calculated historical tsunamis at the target site. The historical tsunami records are used to validate the numerical simulations.
— It specifies standard tsunamigenic sources, i.e. those common to any target sites. This is one of the most critical aspects of this guidance, since the tectonic sources that can generate tsunamis are modelled with all their characteristics provided by the established guidance, which corresponds to historical tsunamis. The scenario tsunamis corresponding to the different tectonic regions around Japan are defined in Table 2.1–5.

TABLE 2.1–5. TSUNAMIGENIC SOURCES FOR JAPAN AS DEFINED IN TABLE 4-1 OF REF. [26]

Classification	Sea area	Types of earthquakes
Tsunamis due to earthquakes along the plate boundaries	Sea areas related to the subduction of the Pacific plate	Typical interplate earthquakes Tsunami earthquakes (slow earthquakes) Intraplate earthquakes with a reverse fault Intraplate earthquakes with a normal fault
	Sea areas related to the subduction of the Philippine Sea plate	Typical interplate earthquakes
Tsunamis due to earthquakes in the eastern margin of the Sea of Japan	Eastern margin of the Sea of Japan	Shallow inland earthquake
Tsunamis due to earthquakes in the submarine active faults	Entire area around Japan	Shallow inland earthquake

An important consideration discussed explicitly in the JSCE methodology is tectonic plate displacement — either subsidence or uplift — produced by the tsunami generating seismic event and affecting the onshore area. This issue is not indicated in the methodology for determining the tsunami flood level, since the main plant grade level changes owing to the crustal movement, although TEPCO has considered it in the model simulation using an elastic theory.

During the 11 March 2011 event, the onshore ground level at the Fukushima Daiichi site experienced a subsidence of approximately 0.66 m, meaning that the main plant grade level had subsided by such an extent. Therefore, instead of an OP +10.00 m main grade level, the plant was located about 0.66 m below, i.e. approximately OP +9.34 m, when the tsunami reached the coast and flooded the plant site. In any case, the new main plant grade level should count for this phenomenon.

In summary, the tectonic subsidence is usually considered in estimating the tsunami flood level, but the level of water reaching a plant grade level is not the difference between the tsunami estimated level minus the original plant grade level, but minus the 'subsided new' plant grade level.

Figure 2.1–9 and Table 2.1–6 illustrate the geodetic measurements after the earthquake, at locations P1 to P5 and T1 to T3 of the main plant grade level and the subsidence values that the plant has experienced at those points, with an average of 0.662 m.

TABLE 2.1–6. GEODETIC MEASUREMENTS AND SUBSIDENCE AFTER THE 11 MARCH 2011 EARTHQUAKE (AFTER THE TEPCO REPORT TO NISA IN OCTOBER 2011) (ORIGINAL IN JAPANESE) [34][a]

T1	T2	T3	P1	P2	P3	P4	P5
OP +13 m	OP +10 m	OP +4 m	OP +4 m	OP +4 m	OP +4 m	OP +4 m	OP +10.2 m
OP +12.375 m	OP +9.338 m	OP +3.300 m	OP +3.379 m	OP +3.358 m	OP +3.209 m	OP +3.370 m	OP +9.579 m

[a] Top row: original measurements; bottom row: measurements following the earthquake.



FIG. 2.1–9. Geodetic measurements and subsidence after the 11 March 2011 earthquake (after the TEPCO report to NISA in October 2011) (original in Japanese) [4].

The application of the JSCE methodology in 2002 for re-evaluating the design tsunami at the Fukushima Daiichi NPP is illustrated in Fig. 2.1–10, where the eight zones of potential tsunami sources are indicated. It should be highlighted that the offshore trench fault source in front of the Fukushima Daiichi NPP is not included in that re-evaluation.

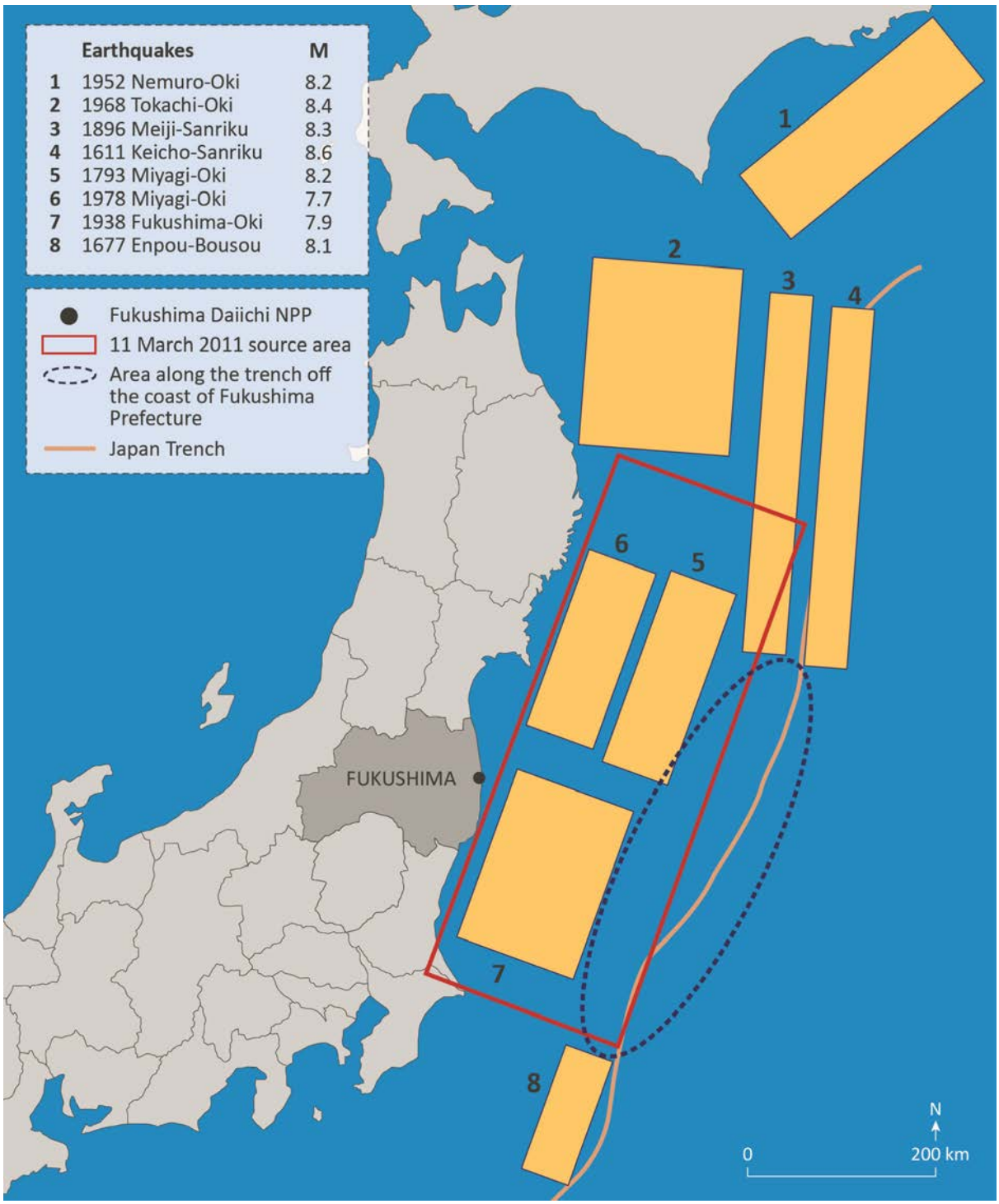


FIG. 2.1–10. Standard source model as defined by JSCE guidance, 2002 [26].

One hundred and forty-five simulations (see Fig. 2.1–11) were performed, with the dominant source being the one identified as No. 7 with M 8, corresponding to the earthquake at Fukushima-Oki (M 7.9) in 1938, which was assumed at M 8 in the calculations.

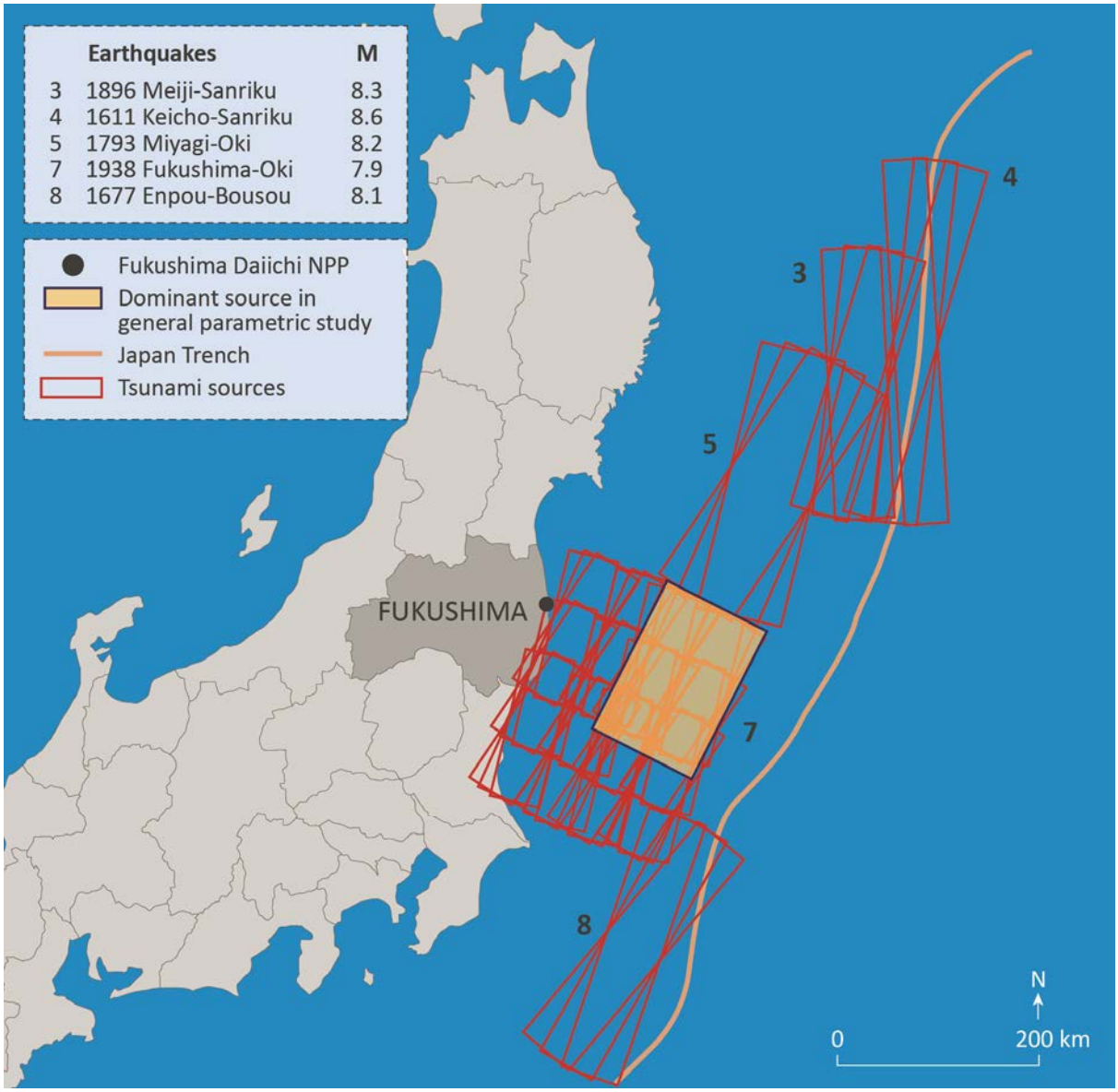


FIG. 2.1–11 Scenario of tsunamis for calculations performed by TEPCO in 2002 [33].

As a result of these calculations by TEPCO, the tsunami hazard water levels (maximum and minimum) were obtained with a maximum high water level of OP +5.7 m, while the minimum water level of OP −3.60 m was calculated on the basis of the 1960 Chile earthquake (M 9.5).

Another important consideration is the runup value, which is the water height, reached at the maximum inundation point, as shown in Fig. 2.1–4. The estimated value corresponds to the tsunami height at the location that can be called the water cooling intake point, which is the point at shoreline at which the water reaches the level of the cooling intake structures. TEPCO indicated [33] that the runup was taken into account and did not significantly increase the calculated value of OP +5.7 m since it did not reach the main grade level of OP +10 m.

In 2007, to confirm the level of nuclear safety in relation to the disaster prevention plans of Ibaraki and Fukushima Prefectures, TEPCO voluntarily performed new evaluations with the source models corresponding to historical tsunamis, which were defined as illustrated in Fig. 2.1–12.

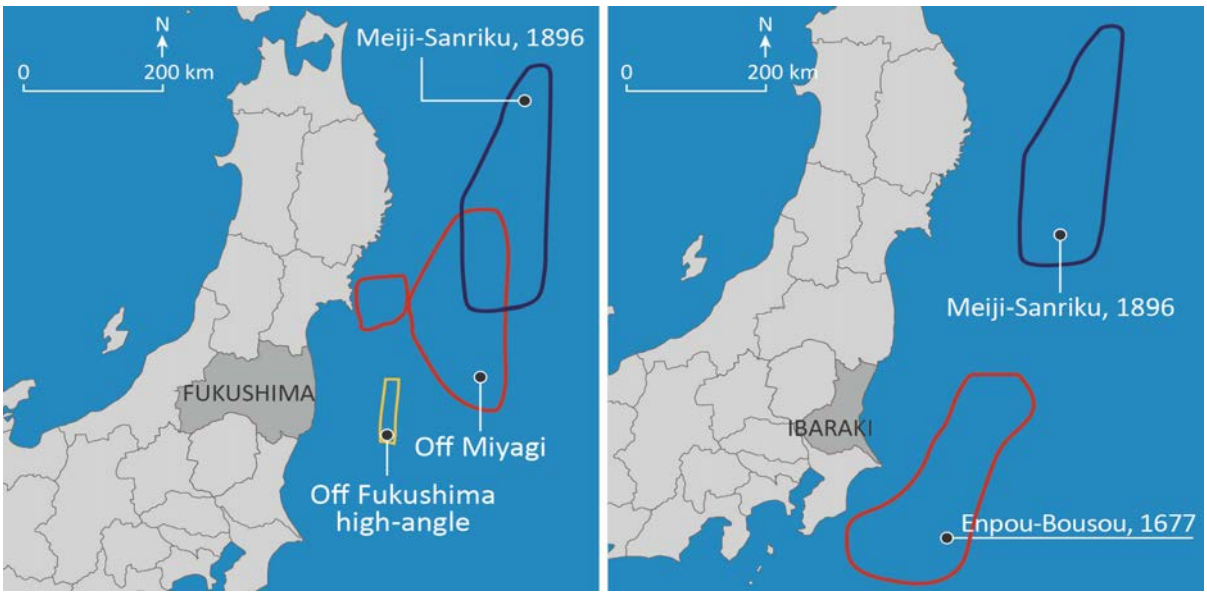


FIG. 2.1–12. Tsunamigenic sources for the evaluations performed in 2007 to ensure safety in relation to the disaster prevention plans of Ibaraki and Fukushima Prefectures [33].

The Japan Atomic Power Company (JAPC), the operator of the Tokai Daini NPP, recalculated the design tsunami heights for its site based on these new wave source models to maintain consistency with the assumptions in the disaster prevention plans. In the case of the Tokai Daini NPP, the results of these evaluations showed maximum water levels of OP +4.70 m and +5.00 m, which were similar to the results obtained in 2002. The design tsunami height had to be revised upwards, and the JAPC decided to construct a 7.0 m high wall at Tokai Daini to protect the emergency seawater pump room [10].

Later, in 2009, with more precise topography (onshore), bathymetry (offshore) and tidal data of the Fukushima Daiichi NPP site, TEPCO again performed this evaluation using the JSCE source models, and obtained the maximum water level of OP +6.10 m. Figures 2.1–13 and 2.1–14 illustrate the results obtained by TEPCO of the tsunami re-evaluations performed between 2002 and 2009 for the Fukushima Daiichi and Daini NPPs.

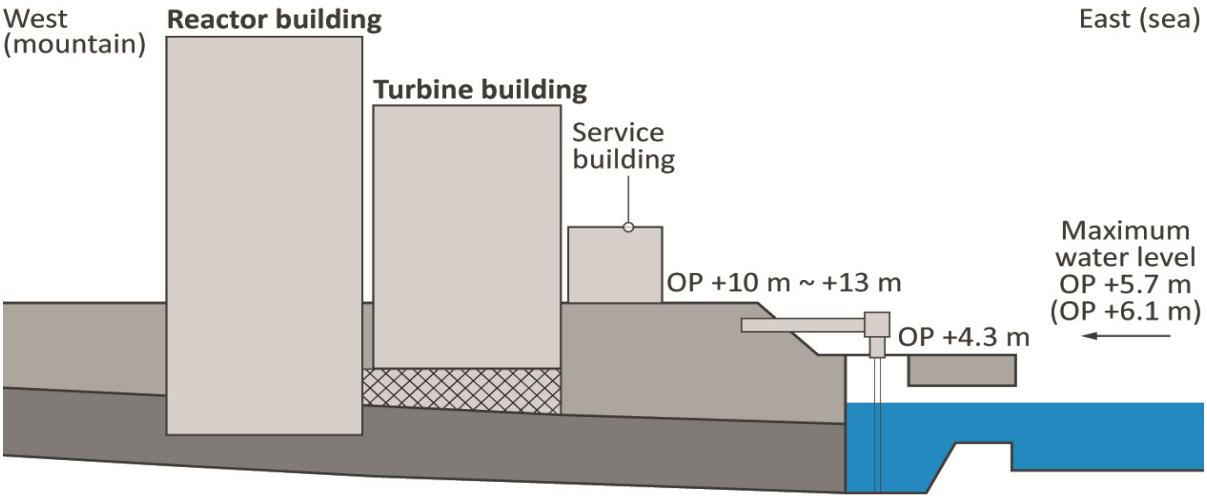


FIG. 2.1–13. Summary of 2002 and 2009 tsunami re-evaluations of the Fukushima Daiichi NPP using the JSCE methodology (topography and tide data were revised in 2009) [33].

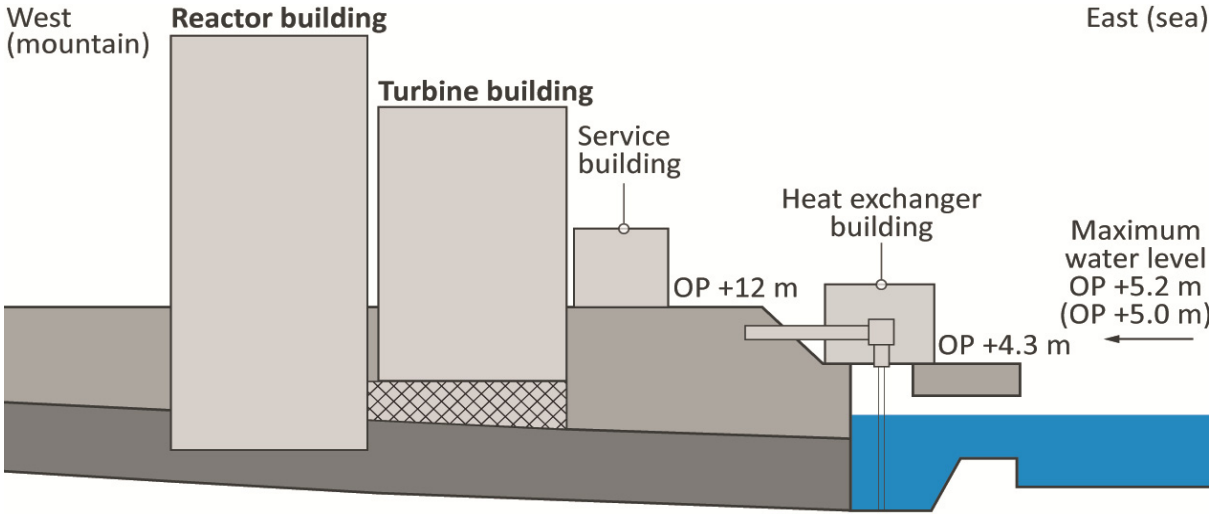


FIG. 2.1–14. Summary of 2002 and 2009 tsunami re-evaluations of the Fukushima Daini NPP using the JSCE methodology (topography and tide data were revised in 2009) [*33*].

In addition to the studies completed by TEPCO between 2002 and 2009 based on the JSCE deterministic methodology and wave source models, as described above, a number of trial calculations were performed using wave source models or methodologies that went beyond the JSCE tsunami assessment method. In the following section, these trial calculations, and the results obtained, are described.

2.1.5.5. First trial analysis using the probabilistic tsunami hazard assessment approach

The first trial analysis was conducted using a probabilistic approach under discussion at the JSCE and identified as a prototype approach. Thus, a probabilistic tsunami hazard assessment was performed by TEPCO to confirm the adaptability and improvement of the JSCE prototype method [33].

This first trial analysis resulted in a mean annual frequency of exceedance of 10^{-5} to 10^{-6} for a tsunami exceeding 10 m at the Fukushima Daiichi NPP site. TEPCO did not interpret this result as the actual frequency of tsunamis that could strike the nuclear power plants at the Fukushima Daiichi NPP site. These results were presented in the International Conference on Nuclear Engineering-14 (ICONE-14) on 17–20 July 2006.

2.1.5.6. Trial analyses using the JSCE methodology with different source models

Two additional trial calculations were performed in 2008–2009 by TEPCO using the JSCE methodology, but with different source models, as described in Fig. 2.1–15:

— Using as a tsunami source the model proposed by the Headquarters for Earthquake Research Promotion (HERP) with an M 8.2 earthquake rupturing an area of 200 km × 50 km located anywhere in the offshore zone, as indicated in the figure on the left in Fig. 2.1–15;
— Using as a tsunami source the Jogan 869 earthquake with M 8.4 and with the assumed location as proposed by Satake et al. [35], as indicated in the graph in the figure in the middle in Fig. 2.1–15.

The comparison of these two models with respect to the rupture and magnitude of the 11 March 2011 earthquake is also illustrated in the figure on the right in Fig. 2.1–15, as well as with respect to the 2002 re-evaluation that strictly applied the JSCE prescribed methodology.

The results obtained from these two trial calculations using different source models are described in the following sections.

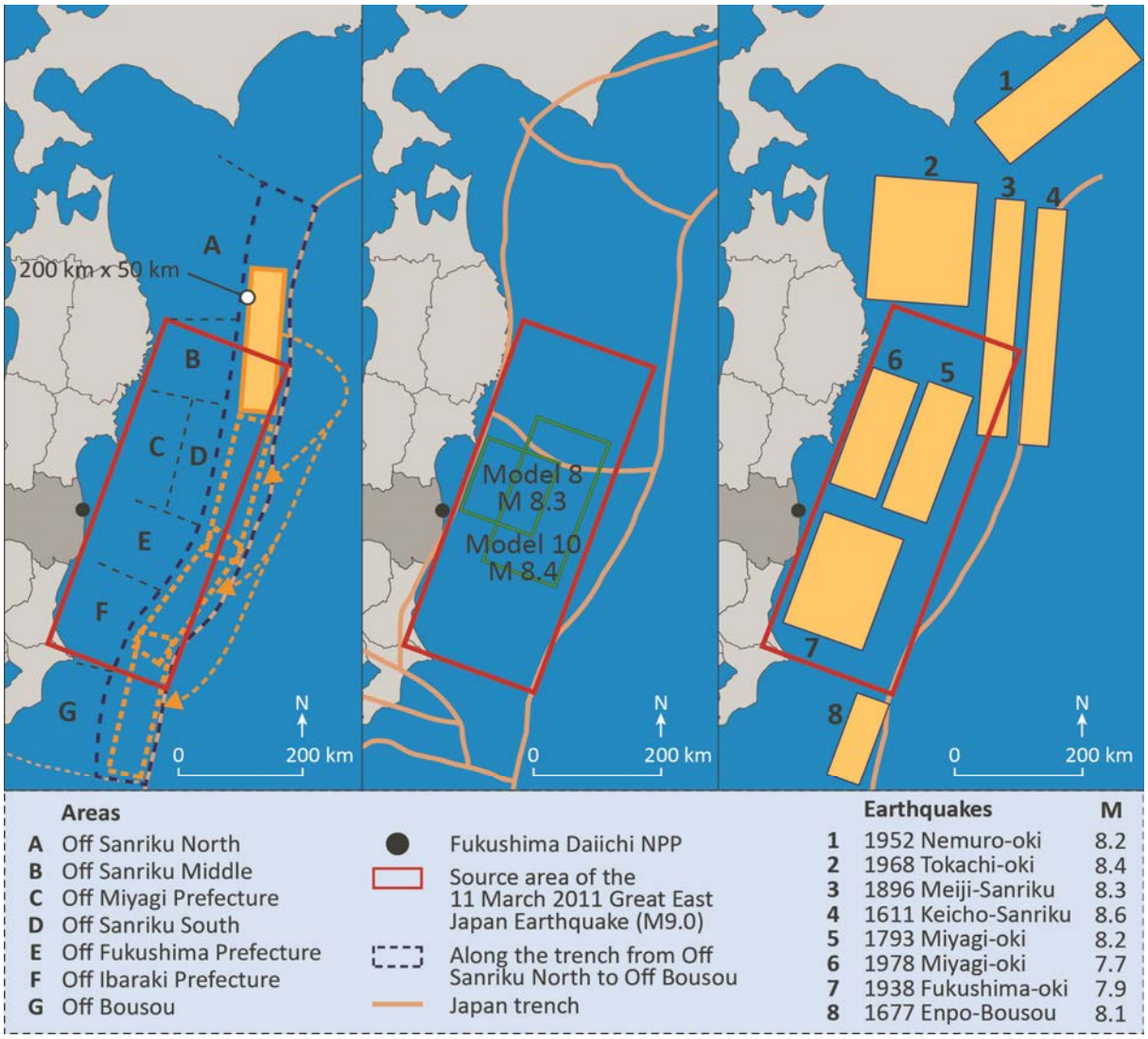


FIG. 2.1–15. Trial calculation performed by TEPCO in 2008. Comparison of source models (see Ref. [36] for the figure on the left, Ref. [35] for the figure in the middle, and Ref. [26] for the figure on the right).

2.1.5.7. Trial analysis based on the JSCE methodology with HERP source models

As stated above, this trial calculation was carried out using the model proposed by the Headquarters for Earthquake Research Promotion (HERP) with an M 8.2 earthquake rupturing an area of 200 km × 50 km, located in the subduction zone. Here, the basic difference with respect to previous re-evaluations by TEPCO applying the JSCE methodology is the assumption that an M 8.2 earthquake may occur in the offshore trench of the Japan subduction fault facing Fukushima Prefecture. This assumption was not considered previously because it was accepted that there was a seismic gap, reflecting that there was no record of a large, M 8 level earthquake off the coast of Fukushima Prefecture.

In 2007, the Central Disaster Management Council (CDMC) of the Cabinet Office discussed the proposal by HERP of the source model and concluded that a large, M 8 level earthquake along the

Japan Trench off the coast of Fukushima Prefecture should not be taken into account because it was unclear whether or not it would be feasible to assume the existence of a wave source in areas where no earthquake had previously occurred. It was decided to use only records available from a given historical time.

Because the HERP proposal did not specify a wave source model, TEPCO conservatively used the wave source model of the M 8.3 Meiji Sanriku earthquake of 1896. This earthquake occurred off the coast of Iwate Prefecture, more than 100 km north of Fukushima, and resulted in a tsunami of 38 m.

The results of this second trial calculation carried out by TEPCO in 2008 for the Fukushima Daiichi and Daini NPPs are shown in Fig. 2.1–16, as presented by TEPCO during the meeting with the IAEA of 10–14 February 2014 [33].

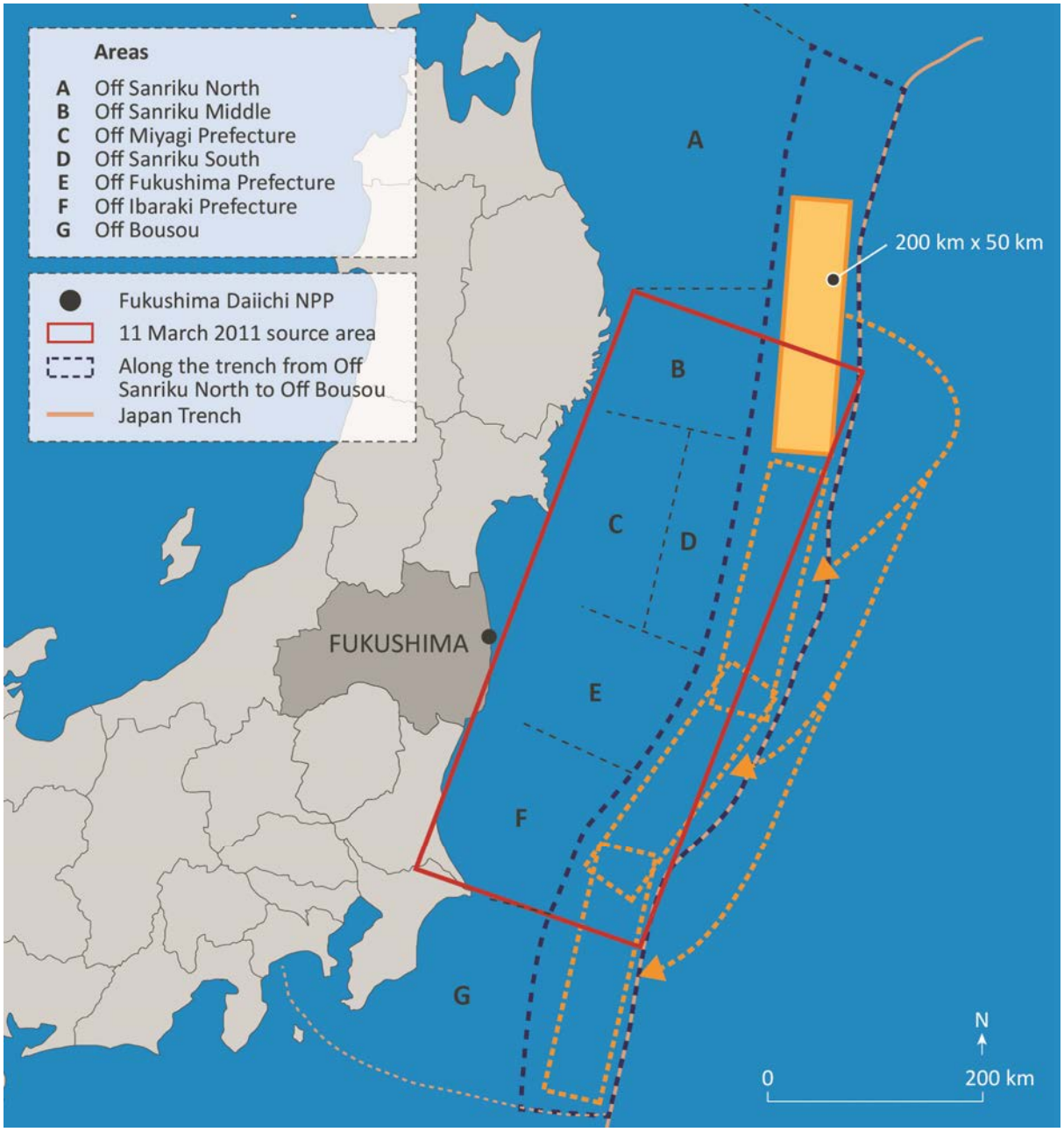


FIG. 2.1–16. Earthquake regions as determined by the Headquarters for Earthquake Research Promotion (HERP) for the Fukushima Daiichi and Daini sites as used by TEPCO in 2008 [36].

TABLE 2.1–7. RESULTS OF THE TRIAL CALCULATIONS FOR THE FUKUSHIMA DAIICHI NPP SITE

	Fukushima Daiichi							
Unit	1	2	3	4	5	6	Northern part (OP +13 m)	Southern part (OP +10 m)
Tsunami height (m)	8.7	9.3	8.4	8.4	10.2	10.2	13.7	15.7

TABLE 2.1–8. RESULTS OF THE TRIAL CALCULATIONS FOR THE FUKUSHIMA DAINI SITE

	Fukushima Daini				
Unit	1	2	3	4	(OP +12 m)
Tsunami height (m)	7.6	7.2	7.8	8.2	15.5 (southern part)

The results of the trial calculation presented in Tables 2.1–7 and 2.1–8 are summarized as follows:

— In front of Units 1–4, at the location of the seawater cooling pumps where a maximum level of OP +5.7 m was calculated in 2002, a maximum tsunami height of OP +9.3 m was estimated.
— In front of Units 5 and 6, the maximum tsunami height was estimated as OP +10.2 m.
— Other locations at the site, at the southern and northern parts, show maximum tsunami heights of OP +13.7 and 15.7 m, significantly higher than the previous re-evaluation values.

2.1.5.8. Trial analysis using Jogan 869 tsunami source models

Regarding the trial calculation with consideration of the Jogan 869 earthquake and tsunami, Fig. 2.1-17 and Table 2.1–9 shows the evolution of the knowledge and hypothesis between 1990 and 2008 about the location of the epicentre in the Japan offshore trench.

TEPCO conducted the trial calculation with magnitude 8.4 and with the assumed location of the tsunami source as proposed by Satake et al. [35]. This model is based on data obtained from soil deposits from the Jogan tsunami through paleo-tsunamigenic investigations. As indicated by TEPCO [33], Satake et al. [35] did not determine the Jogan tsunami source model because of the lack of deposit data of that tsunami and the need to conduct additional tsunami deposit survey investigations in Fukushima and Ibaraki Prefectures.

Five boreholes were dug along the coast in the vicinity of the Fukushima Daiichi and Daini NPPs to investigate the existence of evidence of the Jogan 869 tsunami. Three boreholes, located to the south of the site, yielded no evidence of tsunami deposits, while two boreholes located to the north of the site showed evidence of tsunami deposits at 0.5 m depth in one of them and between 3 m and 4 m depth in the other. TEPCO indicated that the results obtained from the deposit investigations showed some inconsistencies with respect to the trial calculation using the source model proposed by Satake et al. [35]. Therefore, additional investigations were proposed to be carried out.

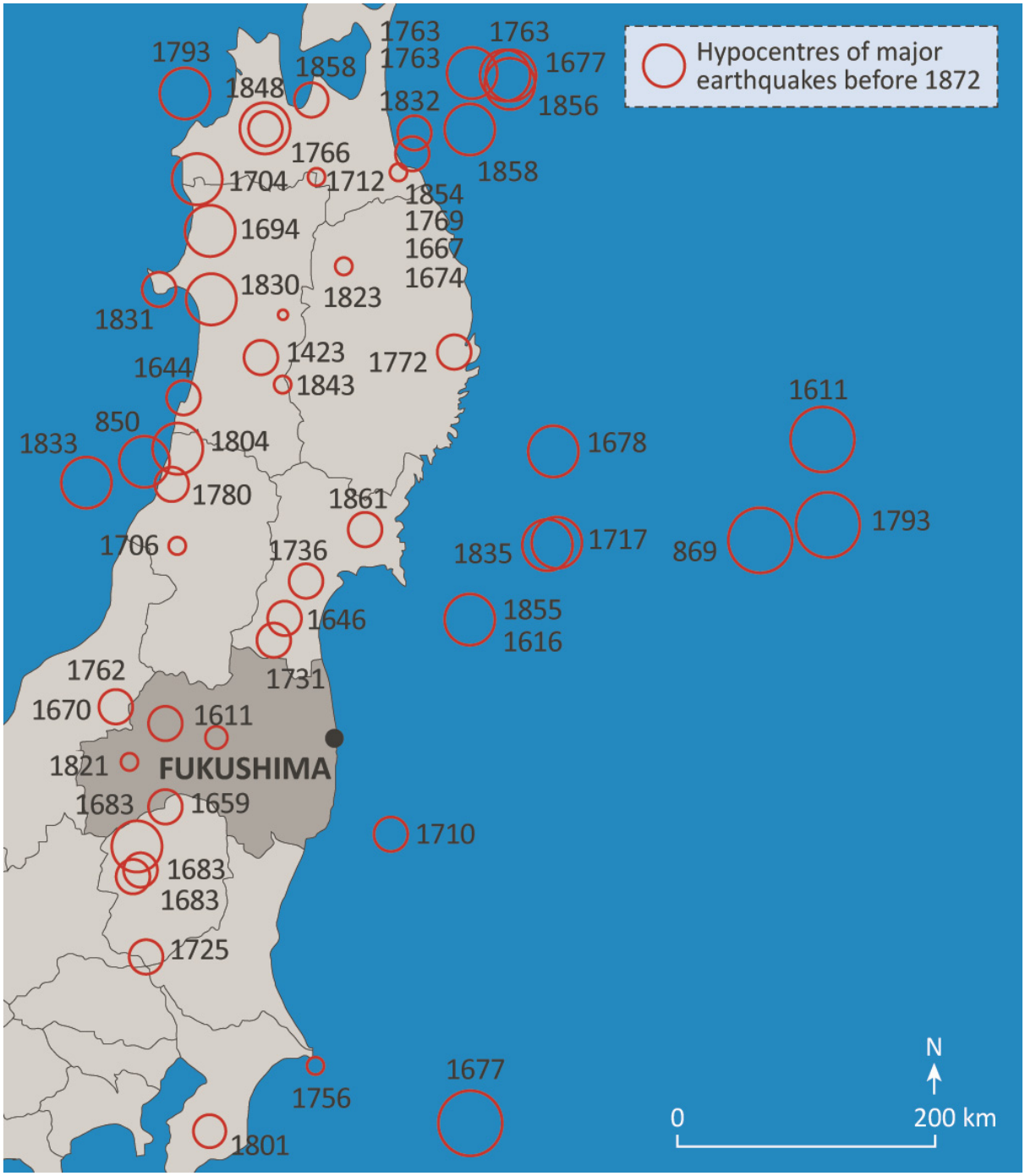


FIG. 2.1–17. Jogan 869 earthquake and tsunami potential locations [33].

TABLE 2.1–9. POTENTIAL LOCATIONS OF THE JOGAN 869 EARTHQUAKE AND TSUNAMI [33]

1990 Abe et al.	Tsunami source was assumed to be located off Sanriku Tsunami height in Sendai plane was smaller than 1611 Keicho Sanriku tsunami
2001 Minoura et al.	Tsunami source was assumed to be located off Miyagi Tsunami height in Fukushima coast was approximately 2–4 m
2006 AIST and Tohoku University	Tsunami deposit survey was carried out in Miyagi Prefecture at first and then in Fukushima Prefecture
2008 Satake et al.	Tsunami source was supposed to be located from off Miyagi Prefecture to off Fukushima Prefecture

Because information about the Jogan tsunami was limited and the source model was uncertain before 2005, the JSCE (2002) [26] did not take the Jogan tsunami into account.

The source model adopted by TEPCO for this calculation assumed an M 8.4 earthquake with a rupture area of 200 km × 100 km for Model 10 and an M 8.3 earthquake with a rupture area of 100 km × 100 km for Model 8 [33]. These were facing Miyagi and Fukushima Prefectures, offshore in the Japan subduction trench.

This trial calculation using the Jogan 869 tsunami resulted in maximum tsunami wave heights of OP +8.7–9.2 m for the six units of Fukushima Daiichi (Table 2.1–10) with no inundation in other northern and southern parts of the site at the grade levels of OP +13.00 m and OP +10.00 m, and tsunami wave heights of OP +7.8–8.00 m for the four units at Fukushima Daini and no inundation for the grade level OP +12.00 m (Table 2.1–11).

TABLE 2.1–10. TRIAL CALCULATION RESULTS FOR THE JOGAN 869 TSUNAMI FOR FUKUSHIMA DAIICHI [33]

	Fukushima Daiichi							
Unit	1	2	3	4	5	6	Northern part (OP +13 m)	Southern part (OP +10 m)
Tsunami height (m)	8.7	8.7	8.7	8.7	9.1	9.2	No inundation	No inundation

TABLE 2.1–11. TRIAL CALCULATION RESULTS FOR THE JOGAN 869 TSUNAMI FOR FUKUSHIMA DAINI [33]

	Fukushima Daini				
Unit	1	2	3	4	(OP +12 m)
Tsunami height (m)	8.0	7.8	7.8	7.9	No inundation

2.1.5.9. Conclusions by TEPCO on the trial calculations

In view of the results obtained from the trial calculations performed, TEPCO management considered that it was necessary to review the appropriateness of the tsunami source models. Thus, electric utilities requested that the JSCE review the suitability of the tsunami sources in 2009. In parallel, in August 2010, TEPCO constituted the Tsunami Measures Working Group as an internal body in the utility to conduct a full scale examination to study measures for reducing the impact of tsunamis.

Each of these trial calculations — performed between 2006 and 2009 — predicted maximum tsunami wave heights considerably greater than either the original design tsunami height of OP +3.122 m or the results of OP +5.7–6.1 m from the re-evaluations performed between 2002 and 2009 using the consensus JSCE methodology. The prediction to be properly considered in this case was for a runup that would reach and flood the main plant grade level at OP +10.00 m and +13.00 m if the HERP data were considered in the source model.

Another issue is the difference between the tsunami heights produced by the Great East Japan Earthquake at the Fukushima Daiichi and Daini NPP sites and for which studies presented by TEPCO show that the rupture that caused the Great East Japan Earthquake was so large that several trains of tsunami waves were generated from different locations along the rupture, as if they had been produced by multiple separate earthquakes. At Fukushima Daiichi, some trains arrived almost in phase, causing them to reinforce each other and produce a much bigger tsunami. The superposition of peaks did not

occur at Fukushima Daini, leading to a lower wave height. The possibility of this phenomenon occurring had not been realized before the Great East Japan Earthquake and was not explicitly considered in the JSCE methodology. As shown by the trial analyses, the JSCE methodology was able to provide conservative predictions of tsunami heights if the correct assumptions were made about the source model and the magnitude of the earthquake in the offshore trench of the Japan fault in front of Fukushima Prefecture (the HERP source model).

2.1.5.10. Actions taken to cope with reassessed tsunami hazards

Actions taken by TEPCO

As a result of the reassessment processes of the flood level caused by a tsunami, which were carried out by TEPCO and other utilities in Japan with NPPs operating on the east coast, and which were triggered mainly by: (i) the issue of the 2002 JSCE methodology; (ii) the issue of the NSC Regulatory Guidelines of 2006 and (iii) the Niigata-Chuetsu-Oki earthquake in 2007 affecting the Kashiwazaki-Kariwa NPP, a number of countermeasures, through plant modifications or safety upgrades, were implemented at four NPPs, as summarized in Table 2.1-12.

In the case of the Fukushima Daiichi NPP, considering the fact that safety related items for removing the reactor decay heat (linked to the ultimate heat sink) and for cooling the emergency diesel generators (EDGs) for emergency power supply are located at the plant area at OP +4.00 m, which would be flooded in case of the newly reassessed tsunami flood level of OP +5.70–6.10 m, TEPCO mentioned during the IAEA Fact Finding mission in 2011 [6] that the motors of the safety related pumps (residual heat removal (RHR) system) were accordingly elevated to avoid disruption of function. However, no additional details were provided about the adequacy of these measures to cope with such an event for the protection of all related mechanical, electrical and instrumentation and control (I&C) components of the RHR system. Table 2.1–12 shows that TEPCO raised the pumps. Whether all the pumps or the pump motors were elevated was not clear.

Until 2009, TEPCO carried out actions in response to the newly calculated values for the tsunami flood level which were obtained using only the JSCE methodology. The results of the trial calculations carried out from 2008 using (i) the HERP assumptions of an M 8.3 earthquake in the Japan Trench offshore, facing the Fukushima Daiichi and Daini sites, and (ii) the model proposed by Satake et al. [32] for the Jogan 869 showed significantly higher values of the tsunami wave heights. This implied the need to cope with several more metres of flood, runup and inundation areas, including the main plant grade where the nuclear buildings are located. TEPCO did not implement interim corrective actions to develop protective measures for the plant to cope with such higher levels of flooding resulting from the trial calculations while conducting further examinations of the assessments, based on the following reasons:

— There was no historical record of a large, M 8 level earthquake off the coast of Fukushima.
— The JSCE methodology was the applicable standard developed with the consensus of all participating institutions in Japan, and it was also accepted and used by other utilities.
— Other institutions, not only the JSCE but also the Central Disaster Management Council (CDMC) and the Prefectural Governments in Ibaraki and Fukushima, did not consider the tsunami source located off the coast of Fukushima Daiichi and Daini NPP sites.
— An earthquake with a magnitude higher than 9 was not considered to be a credible event in the Japan Trench by the Japanese scientific community.
— Historical events such as the Jogan 869 earthquake and tsunami, which caused flood levels similar to the ones reached in March 2011, required additional investigation and collection of data for better knowledge of their causes and effects before applying them to assess those hazards for nuclear installation sites.

TABLE 2.1–12. SUMMARY OF THE RESULTS OF TSUNAMI REASSESSMENTS (2002–2009) AND PLANT MODIFICATIONS BY JAPANESE ELECTRICAL UTILITIES [33]

	TEPCO		JAPC	Tohoku Co.
Event	Fukushima Daiichi	Fukushima Daini	Tokai Daini	Onagawa
Ground level of main building	OP +10 or +13 m	OP +12 m	HP* +8.9 m	OP +14.8 m
Establishment Permit	Unit 1 in 1966 OP +3.122 m	Unit 1 in 1972 OP +3.122 m Units 3 and 4 in 1978 OP +705 m	— in 1971	Unit 1 in 1970 OP + 2–3 m (literature survey) Unit 2 in 1987 OP +9.1 m (numerical simulation)
JSCE method in 2002	OP +5.7 m (tsunami off the coast of Fukushima is dominant)	OP +5.2 m	TP* +4.88 m	OP +13.6 m (tsunami off the coast of Sanriku is dominant)
	Countermeasure such as raising the seawater pumps was completed	Countermeasure such as making the buildings watertight was completed	Countermeasure was unnecessary	Countermeasure was unnecessary
Scenario tsunami for disaster prevention was published by Ibaraki Prefectural Government	OP +4.7 m	OP +4.7 m	TP* +5.72 m	Unexplained
	Countermeasure was unnecessary	Countermeasure was unnecessary	Countermeasure such as raising the wall around seawater pumps was completed	
Scenario tsunami for disaster prevention was published by Fukushima Prefectural Government	Approximately OP +5 m	Approximately OP +5 m	Unexplained	Unexplained
	Countermeasure was unnecessary	Countermeasure was unnecessary		
Latest bathymetric and tidal data in 2009	OP +6.1 m	OP +5.0 m	Unexplained	Unexplained
	Countermeasure such as raising the seawater pumps was completed.	Countermeasure was unnecessary		
Tsunami in 2011	OP +13.1 m (tsunami height) OP +15.5 m (inundation height)	OP +9.1 m (tsunami height) OP +14.5 m (inundation height)	TP* +5.4 m	OP +13.8 m

* See water reference level for Fukushima Daini (HP: Hitachi Port; TP: Tokyo Peil).
Note: JAPC — Japan Atomic Power Company, Tohoku Co. — Tohoku Electric Power Company.

Actions taken by the regulatory authority

The reassessments of the tsunami hazards at the Fukushima Daiichi NPP site conducted by TEPCO during the operational period values were not requested by NISA (the regulatory authority at that time) according to the information collected at the time of the IAEA Fact Finding Expert Mission in May 2011 [6]. This was also confirmed by NRA (the new regulatory authority established in 2012) during the meetings held in Tokyo in January 2014 [7].

Regarding the actions taken by NISA as a response to the newly developed guidelines for tsunami assessment issued by the JSCE in 2002, NISA and TEPCO concurred that JSCE guidance was

adequate for such a purpose. However, NISA did not issue a specific request to conduct a reassessment based on that methodology [6, 7].

The results of tsunami reassessments performed by TEPCO using the JSCE methodology were not formally submitted to NISA. Consequently, the results were not reviewed, commented, approved or rejected by the regulatory authority, although NISA was aware of their existence [10]. The fact that the tsunami estimate increased by a factor of almost two and the main tsunamigenic source shifted from the distant (Pacific subduction tectonic plate in Chile) to the near (Pacific subduction tectonic plate in the offshore Japan subduction trench Shioyazaki) source did not catch the attention of NISA for a long time (from 2002 until March 2011).

As these reassessments and countermeasures were undertaken by TEPCO voluntarily without any instruction from NISA, they did not lead to changes in the licensing documents, and thus the design bases remained as they were before. Regarding the physical measures taken by TEPCO at the Fukushima Daiichi NPP as a consequence of the reassessed higher tsunami wave heights, described in the previous section, and aimed at enhancing safety measures against tsunami flooding, NISA considered them as sufficient according to the Japanese reports [7].

In general, the actions taken by NISA in relation to reassessment of the external hazards were triggered mainly by the issue of the new NSC Regulatory Guidelines in 2006 [9]. NISA requested all NPP licensees by letter to undergo a backcheck on the basis of the new guidelines. This included the need to re-evaluate the tsunami hazards as an accompanying event, although it was not specifically requested in the letter. By the end of 2010, a few months before the accident, NISA received the reports for Units 3, 4 and 5, but they did not include a tsunami safety evaluation, which was planned to be performed by 2016 [7].

2.1.6. Extreme external events in a multi-unit site and multiple sites in the same region

The complexity of the events of the Great East Japan earthquake and tsunami stems from the fact that the natural external hazards impacted multiple units in the Fukushima Daiichi NPP. In addition, the four other NPPs along the coast were also affected to different degrees by the earthquake and the tsunami. However, all operating reactor units at these plants were safely shut down.

This meant that 14 reactor units at 4 sites were simultaneously exposed to high intensity natural external hazards (main shock and aftershocks, and tsunami warnings) during a long period of time in a geographical region that was simultaneously affected by those natural hazards and whose infrastructure was severely damaged.

Although the lessons learned from the Kashiwazaki-Kariwa experience in 2007 were very useful, particularly for on-site emergency measures at the Fukushima Daiichi NPP, and despite a significant number of lessons being properly implemented before 11 March 2011, there was still major regional disruption, which hampered immediate recovery actions at the plant. The nature of the destruction and the damage that occurred at the regional level at multiple units at multiple sites caused significant delays and disruptions in recovery actions for all sites and units.

Although many Member States have multi-unit sites, and in some cases have NPP units in a number of neighbouring sites that may be exposed to a large natural hazard simultaneously, guidance is lacking regarding how to deal with the safety of multi-reactor unit sites when affected by external hazards that occur in a continuous sequence of events.

The established general design criteria require that SSCs important to safety not be shared among nuclear reactor units unless it can be demonstrated that such sharing will not significantly impair the performance of the assigned safety functions, including, in the event of an accident in one unit, the

orderly shutdown and cooldown of the remaining units. It should be questioned how these design criteria have been applied, how safety was assessed and how the successful performance criteria were demonstrated in the case of the numerous existing multiple unit sites when most of them were sharing the external electrical power grids, the switchyards and the ultimate heat sinks, and especially for the occurrence of external hazards as common cause failure events. It is known that most of the safety assessments performed consider shared SSCs to be an extra layer of redundancy because of the assumption that the accident occurs only in one unit while the remaining are kept safe.

The common cause nature of these extreme hazards plays an important role in off-site emergency preparedness and response because they affect the feasibility of implementing local, regional and national emergency plans. The situation described above should be carefully considered at the very beginning of an NPP project, from the stage of selection and evaluation of the site to the design and construction of the installation, to the final stage of its operation when all the response procedures and measures are duly established.

IAEA Safety Standards Series No. NS-R-3 [16] provides the following general requirement in para. 2.29:

> "The external zone for a proposed site shall be established with account taken of the potential for radiological consequences for people and the feasibility of implementing emergency plans, and of any external events or phenomena that may hinder their implementation".

The details of the implementation of the measures to fulfil such a requirement in all stages of the nuclear installation's life cycle is the challenge to be faced and resolved, since one of the lessons of the Fukushima Daiichi NPP accident was the occurrence of this complex scenario of extreme natural events affecting many reactor units in many sites located in the same region. This situation should also be analysed in relation to the need to comply with the concept of defence in depth. The question is how well this concept is being applied in such complex scenarios as those described earlier and in all stages of the nuclear installation life cycle.

2.1.7. Summary

During the pre-accident operational period, the site characteristics of the Fukushima Daiichi NPP were not reassessed in a systematic and comprehensive manner to consider all site related aspects and external events (i.e. seismic and geological hazards, meteorological and hydrological hazards, volcanic hazards and human induced hazards) as well as environmental issues. A regulatory framework for requiring such full reassessment of all site characteristics did not exist. Regarding specific external hazards, only seismic backchecking has been requested in Japan, following the new guidance on seismic safety that was developed and released by the Nuclear Safety Commission in 2006 [9] and as a result of the 2007 Niigata Chuetso-Oki earthquake that affected the Kashiwazaki-Kariwa NPP. But, specifically for tsunami hazards, this new guidance does not contain any concrete requirements, criteria or methodology that could be used for reassessment purposes, and includes only generic statements and no specific request for reassessment was issued.

The lack of a comprehensive regulatory framework for external hazards is one of the reasons that led to an underestimation of the tsunami hazards and to insufficient measures to cope with extreme external events. The Japanese approach was not in line with international and other national safety standards, resulting in significant discrepancies in the level of assessed hazard. No recommendations were expressed at the international level, since no international reviews had been requested. Even though predicting the height of a tsunami is difficult and subject to a variety of scientific and expert opinions, an international review team of independent experts assessing the Fukushima Daiichi NPP's level of protection against flooding would have recommended use of methodologies consistent with international safety standards. This emphasizes the importance of international cooperation on safety.

International independent peer reviews on site characteristics, external events and design are an effective means in assessing and enhancing the safety level of existing facilities.

The definition of the main plant grade level (i.e. at OP +10.00 m) at the time of the Establishment Permit was of great significance. The prevailing reason for the decision on the plant grade was the economics of the water cooling supply (i.e. installation cost during the construction stage and transport energy cost during the operational life of the installation) based on the assumption that the external flooding levels would not impose a risk according to recent historical records in this area. Thus, a site that was considered a dry site in the original design bases later became a wet site, when the resulting maximum flood levels of the reassessment performed showed values higher than the plant grade levels [10].

Regarding the seismic hazard assessment, the original ground motion design bases were evaluated mainly on the basis of historical seismicity data. During the process of obtaining permits for all the units, and particularly after the issuance of new NSC Regulatory Guidelines of 2006 [9], a methodology using also geomorphological fault dimensions was applied. However, this related specifically to on-land events and not to those generated at the Japan Trench, in the Pacific Ocean, which are the ones that generate tsunamis. The information regarding the on-land faults was taken from official sources, but conservative parameters were assumed for the analysis. Regarding the Japan Trench, the associated maximum magnitude was estimated to be about M 8 without much tectonic based justification, largely based on observed historical data and at the locations where they already occurred. Thus, due to the distance from the site, it was assumed that these offshore events would not be relevant for the seismic hazard at the site because closer on-land faults would constitute the main contributors to the seismic hazard. Although an approach similar to the on-land faults (deriving maximum magnitudes in relation to physical fault dimensions) was followed for the maximum magnitude estimation, M 8, of the Japanese Trench, the number of segments to be mobilized during a single event was underestimated.

The assessment of the maximum flooding levels caused by earthquake generated tsunamis, as done for the original design basis at the time of the issuance of the Establishment Permit in the late 1960s as well as in the reassessments carried out during the operational life of the plant, was underestimated in relation to the potential occurrence of extreme flooding events. The tsunami generated by the Great East Japan Earthquake reached values approximately 10 m higher than the originally estimated value (i.e. OP +3.122 m) and 7 m higher than the highest of the accepted re-estimated value (i.e. OP +6.10 m).

The evaluation by TEPCO of the tsunami flood level at the time of the Establishment Permit used the methodology and criteria prevalent in Japan at that time, which were based only on the study and interpretation of historical records of earthquakes and tsunamis. Although those records covered a period of some thousands of years, the distant tsunami that occurred in the Pacific subduction plate of Chile in 1960 was the event used for design purposes, and the OP +3.122 m level reached at Onahama Port was the adopted as the tsunami flood design level. For near sources located in the Japan Trench facing the east coast, a combination of the lack of historical records of tsunami flood levels at the specific location of the Fukushima Daiichi NPP site and the lack of evidence of the occurrence of earthquakes in the offshore area in front of the site were the basis for supporting this decision.

The Japanese approach, at least until 2006, of using mainly historical data of observed events that were available for a very recent period of a few decades or a few hundred years is the main reason for the underestimation of the earthquake magnitudes in assessing the tsunami hazards. The common international practice at the time of the original plant design was to use historical records when applying methods for estimating seismic and concomitant (e.g. tsunami) hazards. To compensate for the lack of pre-historical data commensurate with the low probability required (the usually accepted period of recurrence on the order of 10 000 years), this practice included the following assumptions:

(i) the rule of increasing the maximum historical recorded intensity or magnitude and (ii) to locate the seismic source closest to the site. This internationally recognized conservative and deterministic approach was also reflected in IAEA Safety Series No. 50-SG-S1 [11], in 1979, which was prepared and discussed according to international criteria applied in the 1970s.

In addition to the criterion to use pre-historical and historical data commensurate with the low annual frequency of occurrence of these extreme external events, the internationally recognized practice recommended the use of global analogues in order to cope with the lack of such pre-historical data. This is another important tool, particularly when an earthquake with M 9.5 (the largest in history) had occurred previously in the same tectonic environment of the Pacific tectonic plate. During the same decade as the site characterization of the Fukushima Daiichi NPP, two major earthquakes occurred on the Circum-Pacific Belt (on which the Japan Trench is also located). These were the Chile earthquake of 1960 with M 9.5 and the Alaska earthquake of 1964 with M 9.2.

Considering the above explanation, the maximum seismic magnitude for the Japan Trench could have been postulated to be M 9+ on the grounds of tectonic similarity.

The need to use pre-historical and historical data and the use of global analogues when data are missing in the area under investigation have been included worldwide since the 1970s in requirements, recommendations and practices for dealing with the assessment of extreme natural external events.

In spite of the lack of regulatory requirements for conducting a reassessment of the tsunami hazards, TEPCO had carried out a number of re-evaluations of the tsunami flood level at the Fukushima Daiichi NPP site since 2002, using numerical simulations. In all these reassessments, the tsunami wave heights were revised upwards, with increases from the original OP +3.122 m design flood level to OP +5.70 m in 2002, to OP +6.1 m in 2009 and to approximately OP +15.7 m in the trial calculations conducted in 2009.

Such reassessments were triggered mainly by the issue of the new guidelines for assessing tsunami hazards for NPP sites published by the JSCE in 2002 as a standard practice accepted by all nuclear utilities in Japan. The JSCE methodology used a standard source model for near tsunamis based on historical data in which no tsunamigenic source was assumed to occur offshore facing the Fukushima Daiichi and Daini NPP sites in the Japan Trench. That assumption was key to all evaluations performed using this standard practice.

Other reassessments were called ‘trial calculations’, and they were based on different assumptions, supported by other institutions or experts in Japan. One institution in Japan, HERP, has maintained that an M 8.2 earthquake should be considered elsewhere in the Japan Trench. When this position was applied in the trial calculation performed by TEPCO, the resulting tsunami flood level value was very similar to the flood level which occurred in March 2011, and was much higher than those obtained using the standard practice.

Therefore, if either a conservative approach had been followed in Japan as the one applied at the time of the original design and construction, or if global analogues had been used due to lack of specific pre-historical data, the associated generated tsunami height would have been close to the height calculated in the trial calculations.

In summary, assessments using a conservative approach, based on all relevant, domestically and internationally available data, yielded predictions of tsunamis heights close to the level reached during the March 2011 accident.

The remedial actions adopted by TEPCO to cope with the new situation, derived from higher tsunami water heights resulting from the reassessments performed, were only commensurate with the values

obtained by using the JSCE 2002 methodology. The design and implementation of protective measures to cope with higher values than the ones corresponding to the trial calculations, including all associated hazardous phenomena such as hydrodynamic forces and debris impact, remained pending the outcome of the additional studies, investigations and confirmations that were to be carried out.

As a country known for its high level of awareness of natural disasters, Japan has an excellent system of warning, preparedness and response to cope with these external events. However, the magnitude of the 2011 natural disaster was not anticipated in any of the reassessments performed for the NPPs located in the affected region and, consequently, a scenario of extreme natural events affecting the whole region was not included in the design and operation bases of these installations.

Moreover, contingency plans for the failure of multiple units at multiple sites within a regional disaster context were not available. The effective mitigation of common cause mode failures affecting multi-unit plants simultaneously required a large amount of resources in terms of trained experienced people, equipment, supplies and external support. The timely provision of those resources for carrying out the recovery actions was disturbed by the disruption produced at the site and off-site at the regional level due to the earthquake and tsunami.

2.1.8. Observations and lessons

— **The safety of nuclear installations, in general, and the site related aspects, in particular, needs to be reassessed during their operational life in response to new knowledge, new hazards, new regulations and new practices, as part of periodic safety reviews. In this regard, the role of national and/or international independent peer reviews needs to be emphasized as an important tool to assess and enhance safety.**
The requirement for a reassessment process of site related aspects needs to be included in the regulatory framework, and the responsible organization needs to implement the plant safety improvements in a timely manner based on the results of this process. This needs to cover, in a systematic and comprehensive manner, all natural and human induced hazards which may create or exert potential effects on nuclear installation safety, as well as the impact on the environment.
The reassessment process needs to be performed in accordance with periodic safety reviews and international safety standards and recognized engineering practice. In this regard, international peer review missions are key elements for assessing and enhancing safety with another layer of effective actions which may contribute to cope with the lack of timely actions or responses by the responsible organizations and/or the regulatory bodies.

— **National and international standards to cope with external events in siting, site evaluation and design aspects need to be periodically updated and revised in accordance with scientific and technical developments, recognized engineering practices as well as using information from experience of recently occurred extreme natural external events.**
The experience and data obtained during the 11 March 2011 earthquake and tsunami in Japan will be useful in the revision of national regulations in the effort: (i) to bring them in line with modern criteria and methodologies; and (ii) to be able to cope better with the involved uncertainties in the assessment of these extreme natural hazards. Regulatory documents need to ensure that databases take into account pre-historical and historical events commensurate with the low annual frequency of occurrence of the extreme natural phenomena in line with the relevant IAEA safety standards. It has been demonstrated that one reason for the underestimation of the 11 March 2011 tsunami was that only Japanese historical data were taken into account in the evaluations as well as in the use of methodologies applied on the basis of an incorrect consensus approach. Since: (i) the magnitudes of all historical earthquakes were smaller than 9; (ii) the historical earthquake magnitudes and/or intensities were not increased as conservatively done in international deterministic practice; and (iii) none were located in the offshore region facing Fukushima, the earthquake and subsequent tsunami hazards were underestimated. Evaluations using standard practice underestimated the tsunami height that might occur, as happened in March 2011. At the

same time, some experts and institutions using alternative approaches based on the source model proposed by HERP determined tsunami flood levels comparable to the 2011 ones in the Fukushima area. These discrepancies between different expert opinions need to be properly treated, since all of them might contribute to reducing the uncertainties that exist in assessing extreme natural events. Therefore, the use of mainly national historical data is not sufficient to characterize the risk of extreme natural hazards, as highlighted by IAEA safety standards since 2003. The prediction of extreme natural hazards often remains difficult and controversial. Natural hazards assessment, as well as reassessments, should be performed in a conservative way and be updated according to new knowledge, as soon as available.

— **Assumptions of complex scenarios need to be made and adequate conservative estimations need to be applied at the site evaluation, design and different operational stages in relation to the potential occurrence of extreme external events of very low frequency but with high safety consequences. When operating nuclear installations are faced with revised estimates that exceed previous predictions, it is important to take interim corrective actions in a timely manner by the responsible organization and the regulatory authority.**

The consideration of uncertainties involved in the knowledge and determination of the loads on SSCs during the operational life of the installation requires the assumption of complex scenarios in a comprehensive manner from the beginning of the process.

Correspondingly, an appropriate regulatory framework has to be in force and in line with the identified needs to be able to request, control, regulate and provide guidance on the acceptable level of risk and the performance criteria that the installation has to comply with to safely cope with assumptions of extreme external events during the operational life of the plant.

In the case of the Fukushima Daiichi NPP, it has been demonstrated that interim corrective measures were not taken in a timely manner.

— **The assessment of natural hazards needs to be sufficiently conservative. Particularly in relation to the assessment of tsunami hazards, there is a need to use highly conservative assumptions for estimating the tsunami heights (maximum and minimum), runup and other site associated phenomena. They should be based on pre-historical and historical specific data commensurate with the low annual frequency of their occurrence and, if such specific data are not fully available, using appropriate global analogues.**

The consideration of mainly historical data in the establishment of the design basis is not sufficient to characterize the risks of extreme natural hazards. Even when comprehensive data are available, due to the relatively short observation periods, large uncertainties remain in the prediction of natural hazards.

Regarding the need to apply a more conservative approach for tsunami hazards than those used for other external natural hazards, the main reasons are as follows:

- Large aleatory and epistemic uncertainties in parameters involved in tsunami hazard calculations, particularly in the characterization of the tsunamigenic sources;
- Significant variations in inundation levels at different parts of the site considering the specific and detailed plant layout and the elevations of different plant sectors;
- Difficulties in incorporating effective tsunami protection measures for operating plants after an increase in tsunami height estimation resulting from periodic reassessments;
- Inability of SSCs at nuclear plants to cope with increased flood heights with respect to the design levels, with possible flood related cliff edge effects seriously affecting the safety of the nuclear installation.

— **Regarding uncertainties in tsunami hazard calculations, special attention needs to be paid to the aleatory and epistemic uncertainties associated with the maximum magnitude earthquake related to tsunamigenic sources such as major subduction zones.**

In general, the assessments of the magnitude of historical tsunamigenic earthquakes contain large uncertainties because they are inferred from damage caused on land, sometimes at a distance of more than 100 km, as well as on tsunamis that also heavily depend on bathymetry and coastal topography. For these reasons, a higher degree of conservatism may be necessary in the estimation of maximum magnitudes for tsunamigenic seismic sources at the time of the original design in

order to avoid onerous physical upgrades later on during the design, construction or operational stages, or when such hazards are reassessed.

While the prevailing view among Japanese scientists before the earthquake of 11 March 2011 was that an M 9 earthquake could not be generated by the Japan Trench, as it has been for this Pacific tectonic plate in the past (in Chile and Alaska), it is important that diverse expert opinions from recognized scientific or academic institutions (both nationally and internationally) be considered to account for the epistemic uncertainties for assessing natural hazards.

— **There is a need to use a systemic approach in dealing with the design and layout of SSCs for effective protection against flooding hazards.**

The dry site concept is considered to be a crucial element for coping successfully with flooding hazards, and it has to be formulated from the beginning of the NPP project. It needs to be periodically reassessed and maintained, and, if conditions for a dry site change, adequate protective measures need to be taken in a timely manner.

The selection of the main plant grade level during the first stages of the NPP project is a critical aspect which needs to receive careful consideration due to its importance for the dry site concept. Leaktightness and water resistance also have to be ensured through a comprehensive evaluation of all potential waterways, although this measure can only be used as a redundancy, i.e. in conjunction with a dry site or an effective site protection measure. Thus, the main plant grade level has to be determined with sufficiently large safety margins to avoid flooding hazards due to cliff edge effects.

On the other hand, for those plant design aspects which may be seriously affected by external flooding but for which major uncertainties or insufficient knowledge exist, larger conservatisms have to be applied with respect to other site related aspects and external events for which those issues are better controlled. The same is true for those aspects with more difficulties and complexities in executing effective upgrades, or with higher consequences in case of failure that may affect the defence in depth concept.

— **There is a need to act effectively and promptly in implementing upgrading measures to maintain the defence in depth concept of an installation and to ensure the performance of safety functions when an original dry site becomes a wet site during its operational life as result of a reassessment of the flooding hazards at the site (i.e. having a potential for higher flood levels than the main plant grade level).**

Attention has to be paid to the fact that the upgrading measures to protect an operational installation that is now located on a wet site, and the closing of all possible waterways, may be practically more difficult to implement for an existing facility than for a new site, where such measures would form part of its original design and construction.

In the case of indications of evidence of greater hazards than those originally predicted in the design bases, the responsible organizations have to react effectively and promptly, and ensure safety through the implementation of interim measures while final confirmation of such evidence is obtained.

— **Complex scenarios involving consequential or independent occurrences of multiple external hazards affecting multiple units located on a site and, possibly, multiple NPPs at different sites in the same region need to be considered in accident scenarios and actions to be taken.**

Due to the nature of the Fukushima Daiichi accident, the lessons learned will cover a very wide area, which involves a wide variety of findings. Traditional engineering thinking for verifying the adequacy of a design involves characterizing limit states and comparing the effects of the loads on the installation (the demand) with the strength (the capacity) of the installation.

However, the greatest uncertainties in this process are with the definition of the acting loads, i.e. with the demand imposed on the installation. For this reason, design loads are defined to cover credible, possible and likely situations. In this sense, the design loads need to cover the potential of the occurrence of extreme events in the future. They have to be properly and conservatively estimated by the designer.

The designer, in the final design process, may or may not derive the proper design basis criteria with due account taken of complex scenarios of either extreme or severe natural hazards and with

enough conservatism to comply with the defence in depth concept and to ensure adequate safety margins.

The potential for complex scenarios involving multiple external hazards that affect multiple units at the same site and at the regional scale, and possibly multiple sites in the region, needs to be comprehensively considered in the accident scenarios and measures to be taken. If such scenarios cannot be screened out, provisions need to be made for plant layout, site protection measures, design of shared and non-shared SSCs, accident management and off-site emergency preparedness and response in order to protect the plants from natural disasters in an environment where serious disruptions of normal life and infrastructure may occur affecting communications, transportation and utilities (water, electricity, gas, sewage), and logistics, human resources and supplies.

— **Clear procedures establishing measures to be taken before, during and after a tsunami, in particular, and for any external event, in general, adopted for design bases need to be prepared, implemented and exercised during the operation of the nuclear installation.**

For well defined tsunamigenic (fault controlled) sources, a large earthquake will always precede the tsunami and, consequently, if the source is located near the site, the vibratory ground motion will provide a warning. If the source is located at a large distance from the site, warnings from international and national tsunami notification centres are available. For all types of tsunami that may occur at the site, notification from the national and/or international tsunami warning system needs to be transmitted to the control room for immediate operator actions. In addition, a clear procedure needs to be followed by plant management in preparing for a possible tsunami until the warning is lifted. It is also important to coordinate post-earthquake procedures with those of the tsunami response, as an imminent tsunami would likely affect the possible inspections related to post-earthquake actions.

Moreover, as a consequence of a major natural disaster, a severe disruption to the plant may have occurred, and the plant state (with degraded systems and degraded physical conditions of the SSCs) may have lost robustness and may have degraded the defence in depth conditions with respect to the design condition level. The safety profile of the plant needs to be well understood (i.e. the SSCs required for fulfilling the fundamental safety functions) for different plant states (e.g. shutdown), to ensure consistent protection of the plant in case of the occurrence of consequential and/or independent natural events (e.g. aftershocks following the main extreme earthquake or other natural events, such as strong winds) which may be generated during an extended period when plant recovery and upgrading actions are being taken.

2.2. ASSESSMENT OF THE FAILURE TO MAINTAIN FUNDAMENTAL SAFETY FUNCTIONS

2.2.1. Introduction

This section assesses, on a reactor by reactor basis, what led to the failure to maintain the fundamental safety functions in Units 1–3 of the Fukushima Daiichi NPP. Units 4-6 are also assessed, taking into consideration their shut down at the time of the initiating event. The focus of this section is on a systems based review, leaving the assessment of other factors to subsequent sections in Technical Volume 2. This review was conducted using as a basis the IAEA Safety Requirements publication, IAEA Safety Standards Series No. NS-R-1, Safety of Nuclear Power Plants: Design [2][6], which was in effect at the time of the accident. The review was supplemented by reference to relevant Safety Guides as appropriate. Since IAEA safety standards require that a design basis be established, it was instructive to begin this assessment with a review of the design basis of the boiling water reactors (BWRs) in operation at Fukushima Daiichi NPP because this will help to identify why certain equipment was unavailable.

[6] It has, in the meantime, been superseded by IAEA Safety Standards Series No. SSR-2/1, published in 2012 [17].

Much of the discussion presented in this section provides a review and assessment of the conditions experienced at Fukushima Daiichi NPP during the progression of the accident in the units relative to the capabilities of the plants as set out in the design basis. The BWRs were designed in the USA by the General Electric Corporation based on the General Design Criteria in 10 CFR Part 50 [37]. These design criteria were formulated as NPPs were first developed in order to provide structure and organization to the design process and to ensure essential quality processes were included. The primary purpose of the General Design Criteria is to ensure that essential equipment, referred to as safety related SSCs, remain functional to protect people and the environment from the effects of postulated design basis accidents (DBAs). As BWR technology was introduced into Japan in the 1960s, regulations related to design were developed so that the reactors at the Fukushima Daiichi site complied with Japanese and not US requirements.

Severe accidents involving significant fuel damage are not included in the set of DBAs which, by definition, the plant is designed to handle. This statement is true for both Japanese and IAEA requirements in effect at the time of the accident. Severe accidents were at one time considered hypothetical; it was not until probabilistic studies such as the Reactor Safety Study (WASH-1400, 1975) [38] identified them as potential contributors to public risk that severe accidents came under consideration. The accident at the Fukushima Daiichi NPP was a beyond design basis accident (BDBA), known as a station blackout (SBO), which refers to the complete loss of off-site and on-site AC power. Further complicating the situation was the near complete loss of DC power.

The risk from an SBO was not fully appreciated until it was identified by safety research programmes in the 1970s as a significant contributor to the core damage frequency (CDF). An example of this work is NUREG-1150 [39], completed as a draft in 1987, which identified an SBO as often approaching 50% of the CDF for some plants. Following NUREG-1150 [36], regulatory authorities in Member States began to develop requirements to address this newly identified risk. In general, these regulatory actions did not contemplate the complete loss of both AC and DC power because they adopted a ‘coping time’ approach in which NPPs needed to demonstrate that they could cope with the loss of AC power. Typically, these coping times were based on expected station battery lifetimes of between 4 and 8 hours.

To a large extent, the assessments in this section focus on the performance of the relevant SSCs as compared with the requirements in IAEA Safety Standards Series No. NS-R-1 [2] related to the design basis because the requirements in NS-R-1 are prescriptive in nature and an objective assessment can be performed. However, this approach is governed by the range of postulated initiating events (PIEs) included in the design basis and the assumption that AC and DC power and vital auxiliaries such as high pressure air are available. In contrast, the requirements related to beyond design basis events typically use language such as ‘adequate consideration needs to be given’ to design requirements, leaving what constitutes ‘adequate’ to the implementation by individual Member States [8, 28]. Therefore, in order to properly assess the performance of equipment following a BDBA, one needs to consider more than its design, including requirements such as procedures and guidance to recover equipment (referred to as severe accident management guidelines or SAMGs) or the use of alternative means to restore the safety function. This assessment is conducted in Section 2.4.

2.2.2. Electrical power supply systems

2.2.2.1. Off-site power supply

The Fukushima Daiichi off-site power supply system consisted of seven transmission lines in total. Units 1–4 were connected to the four Okuma lines (275 kV) from the Shin-Fukushima substation, and the TEPCO nuclear power line (66 kV) from the Tomioka substation (normally not used). Units 5 and 6 were connected to the two Yonomori lines (66 kV) from the Shin-Fukushima substation for the off-

site power supply (these lines could not be connected to the generators of these units) (see Fig. 1.2-17 of Technical Volume 1).

Between the Shin-Fukushima substation and Fukushima Daiichi, pylons were shared by Okuma lines 1 and 2 (27 pylons) and by Okuma lines 3 and 4, together with the two Yonomori lines (22 pylons). Within the site premises, Okuma lines 1 and 2 led to the switchyard of Units 1 and 2, Okuma lines 3 and 4 led to the switchyard of Units 3 and 4, and the two Yonomori lines led to the switchyard of Units 5 and 6 (six additional pylons).

All seven lines were connected via transformers to different 6.9 kV busbars which could be interconnected between Units 1–4 and between Units 5 and 6. The switching facility for Okuma line 3 in the switchyard for Units 3 and 4 was under maintenance when the earthquake occurred. Thus, this line was not available for the off-site power supply.

In terms of seismic standards, equipment for receiving and transforming power from the transmission lines was categorized as Class C equipment designed according to the corresponding general industry guide (Seismic Design Guide for Electrical Facilities at Substations and Other Facilities, JEAG 5003-2010 [40]).

System response during the accident

After the earthquake on 11 March 2011, the off-site power supply to Fukushima Daiichi was completely lost. Okuma line 1 became unavailable due to the opening of a breaker in the switchyard for Units 1 and 2 (presumably triggered by earthquake induced damage to another breaker in the same switchyard). Okuma line 2 became unavailable due to the opening of yet another breaker in the Shin-Fukushima substation (presumably triggered by earthquake induced damage to a related breaker in the switchyard of Units 1 and 2). Okuma line 3 became unavailable due to the opening of a breaker in the Shin-Fukushima substation (presumably triggered by earthquake induced arcs at a pylon of the transmission line; in addition, a ground wire at the Shin-Fukushima substation was disconnected). Okuma line 4 became unavailable due to the opening of another breaker in the Shin-Fukushima substation (presumably triggered by earthquake induced arcs at another pylon of the transmission line). In addition, there was a tilting of the steel structures leading the Okuma lines 3 and 4 into the Shin-Fukushima substation. The Yonomori lines 1 and 2 became unavailable due to the opening of two related breakers in the Shin-Fukushima substation. In addition, an on-site pylon of the Yonomori lines collapsed. The TEPCO nuclear power line was also not available because the power transmission from the Tomioka substation was interrupted due to the occurrence of high voltage discharge in the power lines.

Due to the tsunami, the switchyards for Units 3 and 4 and Units 5 and 6, as well as the six startup transformers for Units 1–6 were exposed to water. In addition, the underground cable of the power line between the metal clad switch gear in the on-site auxiliary substation and the turbine hall of Unit 1 became unavailable due to exposure to water.

Assessment

IAEA Safety Standards Series No. NS-R-1 [2] states that:

> "5.67. In the design of the plant, account shall be taken of power grid–plant interactions, including the independence of and number of power supply lines to the plant, in relation to the necessary reliability of the power supply to plant systems important to safety."

This requirement was formally complied with in the design of the Fukushima Daiichi NPP, which featured redundant off-site power supply lines, but with a low degree of independence.

The off-site power supply to the Fukushima Daiichi NPP was designed against possible failures affecting only a single line by having multiple lines from two different substations (in the case of Units 1–4), leading to three different switchyards as well as options for power transfer between Units 1–4 and between Units 5 and 6. However, the resilience against common cause failures of more than one line was lower due to six lines leading to the same substation, shared pylons for up to four lines, and shared switchyards for pairs of lines. For example, the collapse of a single pylon due to the earthquake on 11 March caused the loss of both Yonomori lines, resulting in the complete loss of off-site power for Units 5 and 6.

The off-site power supply of NPPs can be strengthened not only by sufficient redundancy (e.g. multiple lines), but also by sufficient diversity, for example by being able to connect each unit to different lines which use different pylons or underground cables, leading to different substations of different subgrids. In addition, the overall vulnerability against external events can be reduced, for example by strengthening the seismic design of the transmission lines and the associated switching devices.

A potential loss of off-site power was taken into account in the plant design — as is common practice — by the provision of emergency diesel generators (EDGs) to provide backup power supply, as discussed in Section 2.2.2.2. However, it is desirable to keep the probability for such an event reasonably low.

2.2.2.2. Emergency diesel generators

In total, 13 EDGs were installed at the Fukushima Daiichi NPP. Each unit was equipped with two redundant EDGs; Unit 6 had an extra EDG dedicated to the high pressure core spray (HPCS) system.

All six EDGs of Units 1, 3 and 5 were located in the basement of the respective turbine buildings. This was also the case for EDG 2A of Unit 2 and EDG 4A of Unit 4. The other two EDGs of Units 2 and 4 (EDG 2B and EDG 4B) were placed in the ground floor of a common auxiliary building. In Unit 6, two EDGs (EDG 6A and EDG HPCS) were located in the basement of the reactor building annex and one (EDG 6B) on the ground floor of a separate EDG building.

Most of the EDGs were water cooled, using the sea as ultimate heat sink, whereas three EDGs (EDG 2B, EDG 4B and EDG 6B), installed in the 1990s as part of severe accident management (SAM) modifications, were cooled by air (all being located on the ground floor, rather than the basement of the respective buildings). Air cooling was selected for EDG 2B, 4B and 6B, as the seawater cooling system used for the water cooled EDGs was at its rated capacity. The EDGs were designed to withstand design basis seismic ground motion (Class S equipment) [10].

System response during the accident

When the earthquake occurred, EDG 4A (Unit 4) was not available due to periodic inspection. As designed, all 12 available EDGs started automatically after the complete loss of off-site power following the earthquake and provided AC power to the emergency busbars.

Due to the subsequent tsunami and flooding, the functions of all but one of the EDGs were lost (EDG 6B). The six EDGs of Units 1 to 4, which were located on the basement level of the turbine buildings, were inundated and became inoperable. The two EDGs located at higher elevation in the common auxiliary building were not flooded, but became unavailable for emergency power supply due to the flooding of the associated switchboards in the basement of the building.

Assessment

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.89. The combined means to provide emergency power (such as by means of water, steam or gas turbine, diesel engines or batteries) shall have a reliability and form that are consistent with all the requirements of the safety systems to be supplied, and shall perform their functions on the assumption of a single failure. It shall be possible to test the functional capability of the emergency power supply.
>
> .....
>
> "2.7. …The safety analysis examines: (1) all planned normal operational modes of the plant; (2) plant performance in anticipated operational occurrences; (3) design basis accidents; and (4) event sequences that may lead to a severe accident. On the basis of this analysis, the robustness of the engineering design in withstanding postulated initiating events and accidents can be established, the effectiveness of the safety systems and safety related items or systems can be demonstrated, and requirements for emergency response can be established."

The earthquake apparently did not affect the functionality of the EDGs. Hence, there is no indication of any weakness in their seismic design. However, as manifested by the failures after the tsunami, the design was not robust against a flooding of the site. Although there was some difference in the locations and cooling mechanisms with the effect that several EDGs were not directly affected by the tsunami, the emergency power supply as a whole was not consistently designed against flooding, as the switchboards for the two air cooled EDGs of Units 2 and 4 (at higher elevation) were located in the basement, where they were subject to flooding damage.

The design of the emergency power supply had taken into account a possible single failure by including two redundant EDGs for each unit. Redundancy criteria were supplemented with some of the elements needed for diversity (e.g. different cooling systems and different equipment elevations). However, this was not done in a systematic way and not supported by a comprehensive common cause failure evaluation, which could have identified the vulnerability in case of a flooding of the site.

As a conclusion of the assessment, it could be deduced that the IAEA safety requirements in effect at the time of the accident were formally complied with in the design of these systems, but the protection against common cause failures was not adequately evaluated. It is observed that it is important to consider, in the plant design, phenomena with a low probability of occurrence but with the potential to produce severe consequences for plant safety, even for situations beyond the design basis.

2.2.2.3. DC power systems

The DC power supply is vital for plant safety, as it is needed for instrumentation and control and provides AC power from inverters to a small number of essential components. Each Fukushima Daiichi unit featured 125 V DC busbars backed by batteries. DC panels and the batteries of Units 1, 2 and 4 were located on the basement floor of the turbine building. For Unit 3, DC panels and batteries were located on the mezzanine basement floor of the turbine building. For Units 5 and 6, the DC panels were located on the mezzanine basement floor of the turbine building and the batteries were located on the basement floor. The batteries were designed to cope for at least 8–10 hours with a total loss of AC power [41].

System response during the accident

No earthquake related effects on the battery backed DC power supply were reported. However, in Units 1, 2 and 4, the DC power installations were flooded by the tsunami, leading to the loss of the battery backed DC power supply. The DC power supplies in Units 3, 5 and 6 were not affected by the tsunami due to their location at higher elevations, i.e. the mezzanine area. In Unit 3, the batteries were not flooded and supplied power until they were completely depleted.

Assessment

With regard to postulated initiating events (PIEs), IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.88 After certain PIEs, various systems and components important to safety will need emergency power. It shall be ensured that the emergency power supply is able to supply the necessary power in any operational state or in a design basis accident, on the assumption of the coincidental loss of off-site power. The need for power will vary with the nature of the PIE, and the nature of the safety duty to be performed will be reflected in the choice of means for each duty; in respect of number, availability, duration, capacity and continuity, for example."

In referring to emergency power systems (EPSs), IAEA Safety Standards Series No. NS-G-1.8 [42] states:

> "2.6. …The EPSs should be designed for high functional reliability and testability and to have the capability to carry out their safety functions. Their design requirements, form and layout should be consistent with all the requirements for the safety systems to be supplied with power".

This Safety Guide also states:

> "4.15. …The DC power system should be divided into redundant divisions .... Each division should consist of at least a battery, a battery charger and a distribution system."

The DC power supply design was robust against single failures, e.g. by having multiple DC busbars per unit. However, the physical layout of the associated switch gear and the batteries made the system vulnerable to common cause failure by flooding. There was neither sufficient diversity in the location of the system's facilities nor adequate protection against flooding (e.g. water-tight compartments for essential components).

For situations in which only DC power backed by batteries is available for a prolonged time, as was the case with Unit 3, high capacity batteries and the capability to replace or recharge them with mobile equipment would be beneficial.

Most of the problems in the event arose from the total unavailability of electrical power, a scenario which had not been anticipated in the plant design. This situation is potentially shared by most of today's operational reactors, as consideration of the total loss of electrical power has not been a design requirement. It is important to implement short term and long term solutions for this challenge in the future at existing NPPs. The design and layout of electrical equipment should be robust enough to avoid the possibility of common cause failures from credible beyond design basis events.

2.2.2.4. On-site electrical power distribution systems

The electrical power distribution system of each unit of the Fukushima Daiichi NPP consisted of a set of buses for different loads and various interconnections. On a generic level, these systems were the same at each unit. During normal power operation, the power required by a unit was provided via one or two house transformers from the generator to two normal buses (6.9 kV) which fed high power loads (e.g. the feedwater pumps), as well as two emergency buses at 6.9 kV which provided power to essential safety systems (e.g. the shutdown cooling pumps). Each of the four 6.9 kV buses were connected to 480 V (460 V at Unit 1) low voltage buses feeding power via separate transformers to smaller pumps and to 125 V DC buses via rectifiers backed by batteries and featuring additional inter-unit connectors [10].

In the absence of electrical power from the generator, that is, when the reactor is shut down, the required power is provided by the external grid. The corresponding transmission lines feed the common buses (6.9 kV) via a startup transformer. These common buses can be connected to other common buses, to normal buses of adjacent units and via transformers to low voltage buses of adjacent units. If off-site power supply was unavailable at the Fukushima Daiichi NPP, the EDGs supplied power to the 6.9 kV emergency buses.

When the earthquake struck the plant, Units 1–3 were in normal power operation, feeding power from the generator to the grid via the Okuma lines 1–3 and to their normal buses via their respective house transformers. The common buses associated with Units 1 and 2 were fed via the respective startup transformers. The circuit breakers and other devices for receiving power from the Okuma line 3 at the switchyard of Units 3 and 4 were not available due to maintenance. Therefore, the common bus of Unit 3 was connected to the common bus of Unit 2 rather than being fed by its startup transformer.

Units 4–6 were shut down for maintenance. They were receiving power to their common buses via their startup transformers from the Okuma line 4 and the Yonomori lines 1 and 2, respectively. The circuit breakers and other devices transmitting power to the Okuma line 4 at the switchyard of Units 3 and 4 were not available due to maintenance. Some buses at Unit 4 were not available due to maintenance of EDG 4A.

System response during the accident

There is no indication that the earthquake affected the function of the electrical power distribution systems in the different units of the Fukushima Daiichi NPP. Later on, after the tsunami, all the metal clad switch gear (M/C) for the 6.9 kV electrical power distribution installed in Units 1–6, except for three M/C in the Unit 6 reactor building, were exposed to water, leading to functional damage. Thus, in Units 1–5, both ordinary and emergency busbars became completely unavailable and could not have supplied power to the necessary equipment, even if off-site power supply or EDGs would have been available. Most of the 480 V power centres were also damaged by water (including all on the lowest basement floors and some power panels on the semi-basement floors), limiting the number of locations where portable high voltage power supplies could be connected during restoration efforts.

Assessment

The electrical power distribution system being the backbone linking sources of power supply to components and controls which are essential for the safe handling of the plant implies a high reliability requirement.

The design of the electrical power distribution system was robust against single failures. However, the physical layout of the associated switch gear made the system susceptible to common cause failure by flooding.

2.2.3. Ultimate heat sink (emergency seawater system)

Sea water was used in the six Fukushima Daiichi NPP units as an ultimate heat sink (UHS) to remove heat as well as to cool equipment in the plant. Emergency seawater system (ESS) pumps had been installed on the ocean side to provide sea water as a UHS. The pumps were located at an elevation lower than the plant grade level. The intake structures were placed inside an artificial seawater pond, partially closed by breakwaters.

System response during the accident

After the earthquake and tsunami, it was found that the facility inspection crane had collapsed (presumably from the earthquake), and the ESS pumps and ancillary equipment were damaged by collision with floating debris from the tsunami. Sea water had also entered into the lubrication oil of the ESS pumps' motor bearing. However, except for the RHS system and Unit 4 seawater system pumps A and C, which had been removed for inspection, the other pumps remained standing in their original locations, even after being flooded by the tsunami. No pumps were washed away, indicating limited mechanical damage to the ESS pumps. The water inside the artificial seawater pond appeared very dirty, with a considerable amount of debris from the backflow of the tsunami waves [10].

Assessment

The UHS water intake structure was designed in the 1960s. In 2006, new seismic safety guidelines were developed and released by the Nuclear Safety Commission [9]. TEPCO evaluated the new design basis earthquake of the Fukushima Daiichi NPP and confirmed that the intake structure could withstand the new design basis earthquake and maintain its function. This new design basis earthquake implied almost the same level of acceleration as the observed earthquake of 11 March 2011. The ground level of the area where the ESS pumps are located is at OP +4 m. Based on the assessment results of tsunami heights, countermeasures were implemented in the first decade of the twenty-first century to maintain functions for tsunami heights of 5.7–6.1 m [33, 43]. However, the tsunami of 11 March 2011 was much higher than this, causing the pump motors to be submerged into the sea water and resulting in the loss of the system's function.

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.41. Natural phenomena and human induced events shall be taken into account in the design of the systems and in the possible choice of diversity in the ultimate heat sinks and in the storage systems from which fluids for heat transfer are supplied".

The UHS intake structure is part of the first level of defence in depth for normal plant operation and the third level of defence in case of accident conditions. At the Fukushima Daiichi NPP, seawater system pumps were placed at OP +4 m level to ensure sufficient net positive suction head (NPSH). However, the pump motors were placed above ground level. The seawater pump motors were submerged under water when the tsunami wave inundated the plant. The design of the UHS was generally not sufficient to avoid damage by flooding, and hence this requirement of NS-R-1 [2] was not met. However, it should be noted that BWRs with Mark I containments are capable of using the atmosphere for the UHS by using such systems as the hardened containment vent or isolation condensers (see Technical Volume 1). The effectiveness of these systems is assessed in other sections of this technical volume.

The UHS is one of the most critical systems, and its failure may lead to core degradation. Therefore, prevention of loss of the UHS is important for removing the decay heat. The design of UHS structures should be enhanced by considering various means, such as making its doors water tight to avoid flooding. For the UHS, the availability of an additional water source located elsewhere on the site or

direct dissipation of heat to the atmosphere (such as a cooling tower) could be considered as a lesson learned.

2.2.4. Main control room and instrumentation and control

The main control rooms (MCRs) were designed for all the plants to be operated safely in all plant states, including accident conditions. In case of a design basis accident, the MCR habitability system was designed to ensure that the MCR would remain habitable by filtering out radioactive iodine through a charcoal filter.

Generally, in the BWR design, emergency procedures are based on a number of key parameters, e.g. neutron flux, reactor pressure vessel (RPV) pressure, containment pressure and temperature. Reactor water level is the key parameter for confirming adequate core cooling. In essence, the level is derived by subtracting the weight of the water of a known reference leg from the weight of the water between two pressure taps at different elevations in the pressure vessel. In case of prolonged loss of both off-site and on-site power, it is expected that boiling will occur in the reference legs of the reactor water level instruments, which may result in false (non-conservative) indications (water level indicating higher than it actually is) [10].

System response during the accident

The tsunami and subsequent flooding wetted or submerged the EDGs, the switch gear and the electrical distribution systems, resulting in a rapid loss of all AC (with the exception of Unit 6) and most of the DC power supplies. Subsequently, the control board instrumentation and control (I&C) room lighting in Unit 1 became unavailable. Units 2 and 4 were affected in a similar way, whereas the emergency lighting and some indications remained functional in Unit 3. The MCR functions, the lighting as well as both on-site and off-site means of communication were lost.

The post-accident reporting of TEPCO mentioned that adverse conditions in the dry well had probably resulted in the false reactor level indications as explained above [10]. Consequently, these conditions, in conjunction with the global loss of indications in the control rooms, strongly affected the decision making process during the accident progression. However, from time to time some indications were restored by the use of power from car batteries.

The capability to monitor radiological conditions, both on-site and off-site, was severely affected due to the unavailability of electronic personnel dosimeters, computer systems for activating and recording dose, contamination monitors and portable survey instruments. Radiation monitors essential for monitoring core, containment and spent fuel pool conditions were also lost when the electrical distribution equipment was flooded. In addition, radiological effluent and environmental and meteorological monitors were also rendered unavailable. This situation severely hampered TEPCO and the off-site agencies.

TEPCO's Safety Data Parameter Display System (SPDS) was designed to function using plant data from the process computer (which displays various data required to monitor the operation of the plant). However, during the course of the accident, the SPDS could not fulfil its role once the process computer became unavailable. The government's Emergency Response Support System (ERSS) that relied on the SPDS data also failed (see Technical Volume 3).

The loss of the MCR habitability system made it difficult for the operators to monitor the plant status and to bring the plant to a stable condition [32].

Assessment

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.71. A control room shall be provided from which the plant can be safely operated in all its operational states, and from which measures can be taken to maintain the plant in a safe state or to bring it back into such a state after the onset of anticipated operational occurrences, design basis accidents and severe accidents. Appropriate measures shall be taken and adequate information provided to safeguard the occupants of the control room against consequent hazards, such as undue radiation levels resulting from an accident condition or the release of radioactive material or explosive or toxic gases, which could hinder necessary actions by the operator."

Due to the loss of MCR habitability systems and instrumentation, this requirement was not fulfilled, since the MCR of Units 1–4 of the Fukushima Daiichi NPP could not perform their design functions due to the loss of these necessary power supplies. In addition, direct radiation exposure in the MCR, after the beginning of core degradation, was not preventable due to its location. The operators inside the MCR were subjected to the added stress of exposure to radiation. The report of the National Diet of Japan [32] highlighted that the workers were barely able to eat, sleep or use toilets, despite the fact that these activities are indispensable to supporting difficult emergency efforts over many hours.

One of the most significant aspects of the accident at the Fukushima Daiichi NPP was the progressive loss of all I&C, leaving the operators with few, if any, indications to assist them to understand, monitor and control the situation.

The beyond design basis event faced at the Fukushima Daiichi NPP emphasizes the importance of the continued functionality of a pre-defined set of essential instruments to manage an event to prevent the occurrence of a severe accident or to mitigate its consequences. The extent and nature of this minimal set of I&C need to be defined with care, according to the characteristics of each design. It must be protected, hardened and supported in such a way as to be available under all circumstances.

The Fukushima Daiichi accident also highlighted the importance of protecting the location(s) from which the operators will manage the accident (be it the MCR, an alternative control room or remote shutdown panels). The locations require, even in extreme hazard and severe accident conditions, adequate accessibility, functionality and habitability. This requires robustness against severe external hazards as well as radiation protection in case of significant radioactive releases.

2.2.5. Design features of Units 1–3 for maintaining fundamental safety functions

Units 1–3 were in operation at the time of the earthquake and successfully shut down the automatic signals initiated by earthquake monitoring instrumentation. However, decay heat was still being produced and needed to be removed by dedicated cooling systems. In Sections 2.2.6, 2.2.7 and 2.2.8, systems capable of maintaining fundamental safety functions will be discussed and an assessment will be made. Units 4–6 were in cold shutdown at the time of the event and hence will be discussed in separate sections.

2.2.6. Reactivity control

2.2.6.1. Reactor shutdown (trip) systems

The system primarily associated with controlling core reactivity in normal operations is the reactor control system, which acts through the control rod drive (CRD) system. The reactor protection system

(RPS) initiates a reactor scram (trip) signal to the CRD system that makes the reactor subcritical by quickly inserting safety rods.

The reactors also have backup systems to shut down the reactor, including an alternate rod insertion (ARI) system to initiate insertion of the safety rods if the RPS fails and the diverse standby liquid control system (SLCS), which injects borated water into the reactor core in case of failure of the CRD.

System response during the accident

During the earthquake at the Fukushima Daiichi NPP, the operating reactors were all automatically tripped by their RPSs after receiving the earthquake signal. The safety rods shut down the reactor cores, bringing them to the required subcritical condition.

Assessment

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.13. Means shall be provided to ensure that there is a capability to shut down the reactor in operational states and design basis accidents, and that the shutdown condition can be maintained even for the most reactive core conditions."

The RPS and CRD systems met both the IAEA and Japanese safety requirements.

2.2.7. Maintenance of core cooling

2.2.7.1. Isolation condensers of Unit 1

The isolation condenser (IC) removes the decay heat of the reactor in case the main steam isolating valves are closed. The operating requirement of the IC is high reactor pressure, and if the state of high reactor pressure continues for a certain period of time, the outboard isolation valve on the condensate line (which is the only isolation valve which is normally closed) automatically opens and the system starts to remove heat by natural circulation (see Fig. 1.2-8 of Technical Volume 1). This operational delay is to prevent the IC from operating due to a transient phenomenon of instantaneously high reactor pressure [3].

Unit 1 was equipped with two ICs which could remove decay heat up to 6% of rated power. The IC tank capacity was sufficient for approximately 10 h of operation without make-up water.

The ICs were used in older BWRs to remove decay heat from the reactor core at high reactor coolant pressure when the main condenser was not available. The design of the IC was not part of the emergency core cooling system (ECCS). The IC isolation logic is similar to the logic for other piping systems which are not required for postulated accident mitigation and which penetrate the primary containment and are also connected to the RPV, such as the main steam lines and their associated main steam isolation valves (MSIVs). Because these isolation logic circuits are powered by the DC power systems, an isolation signal is generated upon the loss of DC power to the logic circuits, taking into account that such an event results in the loss of the ability of the logic circuits to monitor for a pipe break or coolant leak.

The two isolation logic circuits, each powered from a different and redundant DC power supply system, are typically arranged so that one logic circuit closes the valves inside the containment and the other closes the valves outside the containment. This overall design arrangement ensures that at least one of the two isolation valves will close upon receipt of an isolation signal in the case of a loss of AC or DC power. Once the isolation signal is received, the associated isolation valve will close, provided

the required power is available (AC power for inboard valves and DC power for outboard valves). If motive power to the isolation valve is lost, then the valve will fail in its current position.

System response during the accident

After the earthquake and resultant loss of off-site power, the ICs were used for core cooling to remove the decay heat. Both ICs automatically started at 14:52 on 11 March 2011 on the RPV high pressure signal (7.13 MPa) to cool the reactor and maintain pressure less than the safety relief valve (SRV) lift set points. The operators who were monitoring RPV pressure and the subsequent cooldown rate (a limit of 55°C/h specified in the technical specifications) determined that one train was sufficient to cool the reactor. They closed the control valves (MO-3A and MO-3B) for both trains of the ICs around 15:03, and after that opened/closed only MO-3A to control reactor pressure. It was reported by TEPCO that the operators then manually started and stopped the ICs three times prior to the arrival of the tsunami. When the tsunami hit the site, both control valves were closed and no IC train was in operation. Based on the response of the measured parameters (RPV pressure and IC valve positions) following the earthquake and before the arrival of the tsunami, TEPCO concluded that no damage occurred to the ICs as a result of the earthquake.

During the event at Unit 1, the actual sequence of events concerning the loss of AC and DC power was not fully known, and therefore the final conditions of the isolation valves is also not known.

Assessment

For BDBAs, consideration should be given to the design of systems to remove decay heat which are independent of the normal cooling water systems. Examples of these types of systems are passive cooling systems or mobile equipment. As these systems can eventually be the last option in the case of extreme events, their design must pay special attention to their robustness in case of common cause failure events.

2.2.7.2. Reactor core isolation cooling system of Units 2 and 3

The RCIC system removes the decay heat from the reactor vessel when the main steam lines are isolated or the condensate and feedwater systems are not available. The system includes a steam turbine driven pump, with the capacity to inject at high pressure, whose operation depends only on DC power supply for control. The steam turbine takes its steam supply from the main steam line and the turbine exhaust is piped to the suppression pool to condense the steam. The system takes suction primarily from the condensate storage tank (CST); when this tank is depleted, the suction will be switched automatically (or manually) to the suppression pool.

System response during the accident

After the earthquake, the RCIC system of Unit 2 was manually started after the loss of feedwater as a direct consequence of the failure of external electricity supply. Following the tsunami, it was assumed that the RCIC system in Unit 2 was functioning due to the fact that prior to the tsunami, the reactor water level was stable. The operator manually switched the RCIC water source from the condensate water storage tank to the suppression pool at 04:00 on March 12 after the confirmation of the water level in the tank became low. Efforts were made by the Emergency Response Centre (ERC) to recover the power supply to monitor the water level in the reactor. The water level was confirmed at 21:50 on 11 March 2011 and operation of the RCIC system was confirmed at 02:55 on 12 March 2011. The RCIC continued to function for about three days after the earthquake. What eventually stopped the RCIC system has not been determined [32].

It is worth noting that the Unit 2 RCIC system remained operable far longer (nearly three days) than would have been expected, given the loss of DC power and the resulting uncontrolled operation. It is believed that in this uncontrolled operation mode, the RPV water level rose to the level of the steam lines, causing liquid water carryover into the RCIC system turbine, which in turn led to a reduced water injection rate and an effective self-regulating level control at the elevation of the steam lines. In addition, it is also believed that seawater flooding of the Unit 2 torus room led to significant heat rejection from the suppression chamber (SC), which prevented overheating of the water in the suppression pool and likely played a role in extending the operation time of the RCIC system. These effects need to be clarified in order to develop a better understanding of the operating behaviour of the RCIC system and its ability to prevent onset of core damage.

The RCIC system of Unit 3 was started up manually at 15:05 on 11 March 2011, as feedwater was lost as a direct consequence of the failure of external electricity supply, and maintained the reactor water level. Since the DC power remained functional in Unit 3, operators implemented contingency measures to avoid automatic shutdown of the RCIC system due to the high reactor water level by reducing the flow rate of the system. The system remained operational, allowing the reactor cooling function to be maintained for about 20 h. It was reported that the system unexpectedly shut down, resulting in a decrease of the reactor water level, which in turn led to the initiation of the high pressure coolant injection (HPCI).

Assessment

Based on the above, it is apparent that the RCIC system performed its function as per the design intent and that there was no failure of the system with respect to its design features. Further clarification is needed to understand the mode of operation in Unit 2 and what caused the unexpected shutdown in Unit 3. The system was not designed for prolonged loss of all AC (suppression pool heat removal) and DC (turbine control) power. Further analysis to identify additional ways of maintaining the operation of the RCIC system operation in case of extensive damage to the electrical systems could be carried out to reinforce the defence in depth concept.

2.2.7.3. Safety relief valves

The safety relief valves (SRVs) provide overpressure protection and depressurization for the RPV and associated steam piping. They are located on the main steam lines inside the dry well. The SRVs are spring type valves (with actuators) and function both as safety valves (spring type) and as relief valves (nitrogen type). In the safety mode, the high pressure steam acts on a pilot valve against a pre-set spring pressure. Once its set point is exceeded, it vents the steam which is holding the main valve closed, allowing the high pressure steam to escape through the main valve to the suppression pool. In the relief mode, pressurized nitrogen is applied through nitrogen cylinders, energized by a solenoid valve to move the pilot valve, allowing the main valve to open. The solenoids are energized by switches located in the MCR.

System response during the accident

According to the information released by TEPCO for Unit 1, it is not fully understood yet how the reactor depressurized. Reactor vessel and the containment pressures became equalized approximately 11 hours after the onset of the accident. The possibility of a leakage into the containment from in-core monitor dry tubes and/or SRV gaskets is being investigated. Any of these situations would have been induced by the extreme conditions existing in the reactor during this phase of the severe accident evolution.

For Units 2 and 3, operators encountered difficulties actuating the solenoid valves to operate the relief mode of the SRVs and depressurize the reactor when needed. These problems were caused by a lack

of DC power and high pressure air. Indications are that the SRVs in Units 2 and 3 were eventually opened, but the delay in depressurizing the Unit 2 reactor contributed to the amount of core damage because the alternate injection systems are incapable of injecting water into the reactor at high pressure.

Assessment

The reactor coolant system was designed with adequate SRVs to protect the pressure boundary of the reactor coolant system against overpressure to meet the requirement of IAEA Safety Standards Series No. NS-R-1 [2], which states:

> "6.21. The reactor coolant system, its associated auxiliary systems, and the control and protection systems shall be designed with sufficient margin to ensure that the design conditions of the reactor coolant pressure boundary are not exceeded in operational states. Provision shall be made to ensure that the operation of pressure relief devices, even in design basis accidents, will not lead to unacceptable releases of radioactive material from the plant. The reactor coolant pressure boundary shall be equipped with adequate isolation devices to limit any loss of radioactive fluid."

The SRVs were designed to handle DBAs. They performed their functions to control the pressure in the reactor successfully during the initial phase of the accident but lost their relief function when the accident became more severe and DC power and high pressure air were lost. Depressurization of the primary circuit depends on the relief mode of the SRVs and the importance of ensuring the availability of the DC power supply to energize the SRV solenoids and the availability of compressed air supplies to power the SRV pilot valves needs to be emphasized. Permanently installed or portable DC supplies and air supplies should be adequate to support SRV operation over extended times without AC power.

2.2.7.4. Emergency core cooling systems

The ECCS provides core cooling under loss of coolant accident (LOCA) conditions to limit fuel cladding damage. Across the various unit designs at the Fukushima Daiichi NPP, the installed ECCS equipment comprises a combination of two possible high pressure and two low pressure systems, with electrical power supplied by emergency sources and composed of different subsystems. The high pressure systems are the high pressure core spray (HPCS) system or the high pressure coolant injection system (HPCI), which injects water from the condensate storage tank (CST), or the suppression chamber, the core spray (CS) system and the automatic depressurization system (ADS). The low pressure systems are the low pressure core spray (LPCS) system, which injects water into the core upper plenum and the core bypass region, and the residual heat removal (RHR) system working in low pressure coolant injection (LPCI) mode. The LPCI protects against larger LOCAs to maintain the water level in the reactor when the reactor pressure is low enough to allow low pressure injection.

The HPCI or, for the newer BWR units, the HPCS, is the first line of defence in the ECCS. It is designed to prevent fuel cladding damage for small LOCAs of the reactor coolant system. These systems only require DC power to operate (for turbine control). They comprise a turbine driven pump, pipes, valves and ancillary systems. The turbine is driven by high pressure steam extracted from upstream of the isolation valve of a main steam line on the inner side of the dry well. Normally, the CST is used as a water source, but the system was designed so that the suppression pool water can also be used as a backup.

The LPCI system injects large volumes of water for large LOCAs. These are not discussed in detail, since they lost their function after the complete loss of AC power. Operators never tried to initiate them as they were aware of this situation.

The ADS is an I&C subsystem which generates the control signal to open the reactor coolant system SRVs to depressurize the reactor, allowing injection with the low pressure ECCS. In this sense, ADS is functionally redundant to the HPCI (single train) for accident initiators, which do not induce prompt reactor depressurization.

System response during the accident

Unit 1

After the earthquake and prior to the arrival of the tsunami at the site, there were no significant abnormalities found in the alarms and display lights for the ECCS. Reactor water levels were stable and reactor pressure was controlled via the IC. After the tsunami struck, the HPCI system control panel (fed by DC power) went off, and the system could no longer be started. Finally, the ADS was also inoperable as a consequence of the loss of DC power and high pressure air; nevertheless, the reactor eventually depressurized by some yet unconfirmed mechanism.

Unit 2

After the tsunami, the HPCI system control panel (fed by DC power) shut off. The system completely lost its functionality and could not be used as a backup to the RCIC, which had remained in operation and continued so for a long period of time. The loss of DC power equally affected the ADS, which also became inoperable. At some time during the accident, operators decided to depressurize the reactor in order to allow alternative water injection. This action was finally implemented by using portable batteries to open the solenoid valves.

Unit 3

In Unit 3, both the RCIC and HPCI systems remained operable, as the flooding did not affect the DC power supply. The turbine driven RCIC system eventually stopped on 12 March 2011. Shortly afterwards, the HPCI system started automatically on a low reactor water level signal. At this point, the reactor pressure was around 7.5 MPa. The flow rate of the HPCI was controlled by control room operators in such a way as to save battery power and to prevent its automatic shutdown due to high reactor water levels in the same way as had been previously done for the RCIC system. While this mode of HPCI operation avoided starting and stopping the HPCI system and the risk that the system would ultimately fail to restart, it may also have aggravated the attempt to maintain the RPV water level. Due to the depletion of the DC batteries, the water level indication was later lost, but the HPCI remained in operation. Operators monitored the HPCI system operation status via reactor pressure and pump discharge pressure.

The operators worked to switch reactor injection from the HPCI system to diesel driven fire pump (DDFP). The shift crew manually stopped HPCI on 13 March 2011, but their attempts to depressurize the reactor were unsuccessful and alternative water injection via fire trucks was ineffective. Attempts were made to open the SRV, but were not successful. At this stage, the operator tried to restart the RCIC and HPCI systems, but neither could be restored as the DC battery was depleted. The reactor pressure rose again to 4.0 MPa one hour after the HPCI stopped, and it further increased to 7.38 MPa in two hours, later reaching the safety valves' set-point. Based on the TEPCO evaluation, the depressurization of the Unit 3 RPV occurred because the ADS logic was successful [31].

Assessment

The Nuclear Safety Commission (NSC) of Japan issued a Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities (NSCRG: L-DS-I.0) in 1970, which was comprehensively reviewed and revised based on technological improvements and developments of

LWRs [22]. It also incorporated lessons learned from various events that occurred in nuclear power plants, such as the accident at the Three Mile Island NPP, in the USA. The NSC issued the latest revision of this guide on 30 August 1990. The ECCS design requirements given in Guideline 25 are [22]:

> "(1) The emergency core cooling system shall be designed to be capable of preventing serious damage of reactor fuel and of limiting the reaction between fuel cladding metal and water to a sufficiently small amount in case of a postulated loss of reactor coolant resulting from a break in piping, etc.
>
> (2) The emergency core cooling system shall be designed with redundancy or diversity and independence so that the system can fulfill its safety functions even in case of unavailability of off-site power in addition to an assumption of a single failure of any of the components that comprise the system.
>
> (3) The emergency core cooling system shall be designed to be capable of being tested and inspected on a periodical basis. The emergency core cooling system shall also be designed to allow testing and inspection of each constituent system independently so that the integrity and redundancy of the emergency core cooling system can be verified."

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.35. Core cooling shall be provided in the event of a loss of coolant accident so as to minimize fuel damage and limit the escape of fission products from the fuel. The cooling provided shall ensure that:
>
> (1) the limiting parameters for the cladding or fuel integrity (such as temperature) will not exceed the acceptable value for design basis accidents (for applicable reactor designs);
>
> (2) possible chemical reactions are limited to an allowable level;
>
> (3) the alterations in the fuel and internal structural alterations will not significantly reduce the effectiveness of the means of emergency core cooling; and
>
> (4) the cooling of the core will be ensured for a sufficient time."

In addition, NS-R-1 [2] states:

> "6.37. Adequate consideration shall be given to extending the capability to remove heat from the core following a severe accident."

IAEA Safety Standards Series No. NS-G-1.9, Design of the Reactor Coolant System and Associated Systems in Nuclear Power Plants [44], states:

> "4.81. Equipment for emergency core cooling should be adequately protected from the consequences of internal and external hazards such as seismic hazards that have the potential to jeopardize its safety functions."

NS-G-1.9 [44] further emphasizes:

> "3.30. Since redundant or diverse systems are also potentially vulnerable to events (e.g. fires, floods) resulting in common cause failures, appropriate physical barriers or physical separation or a combination of both should be used as far as is practicable."

The design of the ECCS system at the Fukushima Daiichi NPP was in accordance with the requirements of the NSC Regulatory Guidelines of 2006 [9] and those stipulated in IAEA Safety Standards Series No. NS-R-1 [2] because the system was designed for design basis accidents.

In summary, the ECCS was designed as part of defence in depth (DID) level 3 to mitigate the consequences of postulated design basis accidents, i.e. LOCAs. From the above discussion, it is clear that the LPCI systems could not operate in such circumstances, as they depend on AC power to drive valves and pump motors. The HPCI and ADS also were not designed to cope with situations without DC power. Further analysis to identify additional ways of maintaining the HPCI and ADS operation in case of extensive damage to the electrical systems could be carried out in order to reinforce the DID concept.

2.2.7.5. Alternate water injection system

The United States Nuclear Regulatory Commission, in NRC SECY 89-17 [45], January 1989, identified a number of plant modifications that substantially enhance the capability of a plant to both prevent and mitigate the consequences of severe accidents. The recommended improvements include an alternative water supply to the reactor vessel and dry well and updated emergency procedures and training. In light of these recommendations, severe accident countermeasures had been adopted at the Fukushima Daiichi NPP, such as the alternate water injection system provision using the fire protection system. The alternate water can be injected into the reactor core (through the core spray piping) or into the primary containment (through the suppression pool cooling return line) from other water sources (fresh water or sea water).

The alternate water injection system utilizes equipment capable of injecting cooling water into the nuclear reactor when the normal ECCS system fails to function. The purpose of the system is to inject water into the nuclear reactor and primary containment vessel (PCV), and this feature was implemented between 1996 and 2002 to provide water injection in the event of loss of core cooling and/or loss of molten core cooling. Initially, this system was utilizing the stable fire system as a source of water, which was not seismically resistant. This area was further considered and strengthened in 2007, and the system was upgraded by the installation of fixed connection points on the turbine building, which allowed use of the fire trucks as a source of coolant. All of the pumps used for this system are low pressure pumps and, therefore, the reactor and containment need to be depressurized using a combination of the SRVs and the containment venting systems.

System response during the accident

During the Fukushima Daiichi accident, the alternate water injection system injected water into the reactors after the failure of the conventional systems. Nevertheless, due to other circumstances external to the system, it could not be employed in a timely manner. For Unit 1, operators were able to use alternative injection without attempting to open SRVs, indicating that the reactor depressurized on its own via some unknown failure mechanism. For Units 2 and 3, operators were eventually able to open SRVs to depressurize the reactor, but as has been previously mentioned this was too late for alternative injection to prevent core damage. As will be assessed later in this section, the containments for Units 1–3 were also eventually depressurized.

Assessment

This assessment assumes that the system was intended to demonstrate compliance with para. 6.37 of IAEA Safety Standards Series No. NS-R-1 [2], which states: “Adequate consideration shall be given to extending the capability to remove heat from the core following a severe accident.” The system was ready to perform its intended function during the accident at the Fukushima Daiichi NPP and could

have played a vital role by injecting coolant into the reactor cores after failure of the capability to inject coolant into the reactors through the usual ECCS.

During the accident, different problems arose in Units 1, 2 and 3, related to the failure or delay of the depressurization of the reactor and/or the PCV and the shortage of readily available equipment. Furthermore, an assessment conducted by TEPCO [31] concluded that, for all units, an unknown amount of water was bypassed to the main condenser or the CST and was not injected into the core to either cool the fuel and fuel debris. Because of these problems the system was not functioning as designed and it is assessed, therefore, that the system did not meet the requirement stipulated in para. 6.37 of IAEA Safety Standards Series No. NS-R-1 [2].

2.2.8. Maintenance of containment integrity

2.2.8.1. Primary containment

The design of the Mark-I type primary containment is a dry well in the shape of a pear shaped bulb, containing the RPV and primary piping, and a wet well, which contains a torus shaped suppression chamber (SC). The SC is partly filled with water, and the large vent pipes that connect the dry well to the SC have their open ends submerged in the water of the suppression pool. Escaping steam from a LOCA in the dry well would be routed to the SC, where the water condenses the steam. The SC also condenses steam discharged from the HPCI/RCIC turbines and from the SRVs. The PCV is inserted with nitrogen to avoid the potential occurrence of hydrogen ignitions during accidents.

The design pressure of the Mark I-type PCV is the highest transient pressure expected to be caused during the worst postulated accident, i.e. a sudden double ended guillotine break of the largest diameter pipe in the recirculation outlet loop (LOCA). However, the design assumes that the ECCS activates automatically at the moment when a pipe break occurs. It did not assume the scenario of a total loss of AC power with extensive loss of DC power, which in the end caused complete failure of the ECCS [3].

Containment heat removal would, under design basis accidents, be provided by the RHR system in its containment cooling mode. The containment cooling mode includes suppression pool cooling and containment spray. As the RHR system is AC powered, it was not available to help with removing the heat from the containment.

System response during the accident

After the core became damaged, large amounts of steam, hydrogen and radioactive material were released inside the primary containment due to opening of SRVs and other potential leakage paths. This release of large quantities of steam pressurized the PCV and increased the temperature as well, since cooling was also lost in the suppression pool. Sometime after core damage, the PCV failed to maintain its integrity, and a large quantity of steam, along with hydrogen and other radioactive effluents, was released into the reactor building. Even in the major consequences of the accident, the primary containment performed its intended functions according to its design characteristics. No hydrogen deflagration was reported inside the PCV; however, its eventual loss of leaktightness was a consequence of continuous operation under environmental conditions far beyond its design limits for an extended period of time.

Assessment

IAEA Safety Standards Series No. NS-R-1 [2] states:

> "6.43. A containment system shall be provided in order to ensure that any release of radioactive materials to the environment in a design basis accident would be below prescribed limits. This system may include, depending on design requirements: leaktight structures; associated systems for the control of pressures and temperatures; and features for the isolation, management and removal of fission products, hydrogen, oxygen and other substances that could be released into the containment atmosphere."

NS-R-1 [2] also emphasizes:

> "6.46. Provision for maintaining the integrity of the containment in the event of a severe accident shall be considered. In particular, the effects of any predicted combustion of flammable gases shall be taken into account."

NS-R-1 [2] further states:

> "6.64. Systems to control fission products, hydrogen, oxygen and other substances that may be released into the reactor containment shall be provided as necessary:
>
> …….
>
> (2) to control the concentration of hydrogen, oxygen and other substances in the containment atmosphere in design basis accidents in order to prevent deflagration or detonation which could jeopardize the integrity of the containment."

Moreover, NS-R-1 [2] requires that:

> "6.65. Systems for cleaning up the containment atmosphere shall have suitable redundancy in components and features to ensure that the safety group can fulfil the necessary safety function, on the assumption of a single failure."

In para. 6.66 of NS-R-1 [2], it is also stated that: "Adequate consideration shall be given to the control of fission products, hydrogen and other substances that may be generated or released in the event of a severe accident."

The containment of the Fukushima Daiichi NPP reactors was designed in accordance with IAEA safety standards. As explained in Section 2.2.8.2, the containment functionality for severe accident conditions depended on the hardened containment venting system, which, due to the accident management strategy in use at the Fukushima Daiichi NPP and the hardware provisions derived from this strategy (i.e. rupture disc set points), did not function as designed.

2.2.8.2. Hardened containment venting system

The United States Nuclear Regulatory Commission, in Generic Letter 89-16 [46], recommended enhancements to the performance of the containment, including the installation of a pressure resistant (hardened) containment venting system. The purpose of the hardened containment vent was to provide a method of relieving containment pressure to maintain it below the primary containment pressure limit and accommodate a steam flow equivalent of 1% decay heat power without adversely impacting the mitigating equipment. The hardened vent was not designed to operate during a severe accident.

The NSC established the Common Issue Committee in July 1987 to investigate approaches to severe accidents, probabilistic safety assessment (PSA) techniques and the containment function during severe accidents. In the 1990s, hardened venting systems were installed in all of the units of the Fukushima Daiichi NPP.

The system had the capacity to vent from either the dry well or the wet well. The operators were capable of controlling the PCV pressure, maintaining it below the threshold that would affect the PCV's integrity and enabling water injection into the RPV with low pressure systems. In the case of a total loss of AC and DC power, the vent system isolation valves could only be actuated manually and locally from inside the reactor building by the use of compressed air.

System response during the accident

In Units 1 and 3, venting from the wet well enabled the PCV to be depressurized significantly. The Diet report [32] concluded that, despite several attempts, the PCV of Unit 2 could not be depressurized. The loss of DC power and high pressure air led to the loss of the remote control capability of the vent valves. In addition, at the time of the decision to open the PCV vent valves, the radiological conditions in the reactor building prevented the implementation of the required manual local actions.

Assessment

Containment venting would have allowed for more effective core cooling via alternative means and the migration of hydrogen from the containment to the reactor building could have been prevented. The combination of core damage, high containment pressure and high containment temperature compromised the containment, allowing hydrogen to escape from the PCV, which led to the explosions in Units 1, 3 and 4. The hydrogen explosion in Unit 4 was caused by the migration of hydrogen from Unit 3 to Unit 4 via an interconnected ventilation system (see Section 2.4).

2.2.8.3. Reactor building

During a design basis accident, the standby gas treatment (SBGT) system — a specially designed safety feature — is expected to maintain the reactor building at subatmospheric pressure in order to collect potential radioactive leakage from the PCV. It is a safety related system which is redundant, with electrical power supplied by EDGs and which is fitted with high efficiency filters in the exhaust line of the stack.

System response during the accident

In the Fukushima Daiichi accident (after the tsunami struck), the SBGT system remained inactive due to the loss of electrical power. This contributed to the consequences of the accident, both with regard to the radiological conditions in the reactor building and the physical process of gravity driven hydrogen migration to the upper parts of the reactor building. After core damage in Units 1–3, steam and hydrogen were released into their respective PCVs and eventually leaked to the reactor buildings. Hydrogen explosions occurred in the reactor buildings of Units 1, 3 and 4.

A factor that influenced the progression of the accident in Unit 2 was the unit's proximity to Unit 1. The impact of the hydrogen explosion in the reactor building of Unit 1 caused a blowout panel on the wall of the reactor building in Unit 2 to open. The main objective of a blowout panel was to prevent damage to the reactor building as a result of the rapid increase in internal pressure. The hydrogen probably leaked from the PCV and did not accumulate in the reactor building, as it escaped directly to the external atmosphere, along with some radioactive products. This was the likely reason why no hydrogen explosion occurred in the reactor building in Unit 2. The explosion in the Unit 4 reactor building occurred due to backflow of hydrogen containing gases from the Unit 3 reactor building through its SBGT system, as explained in Section 2.2.9

Assessment

The reactor buildings of Units 1, 3 and 4 were severely damaged because hydrogen mitigation had not been properly considered. This situation occurred because the leakages induced by the failure of the integrity of the primary containments had not been anticipated and hydrogen mitigation efforts were focused on the PCV with features such as making the atmosphere inert. However, due to the failure of the containment heat removal systems, the long term pressurization and temperature increases in the PCV, the leakage of hydrogen to the reactor building ultimately resulted in multiple explosions, since there were no systems installed to manage hydrogen.

2.2.9. Design features of Unit 4

Unit 4 was a BWR/4 type reactor, similar to those of Units 2 and 3, except for some minor design differences. It was shut down for reload and maintenance at the time of the earthquake and tsunami. All the fuel was in the spent fuel pool (SFP) to facilitate work on the reactor internals. The upper pool cavity gate was installed, isolating the SFP from the reactor well. EDG 4A was out of service for planned maintenance, and EDG 4B was operable and in a standby state. The SFP water temperature was maintained at approximately 27°C.

Response during the accident

After the earthquake and tsunami, the operators in the control room of Units 3 and 4 focused on the stabilization of Unit 3, since it was in operation and had a large amount of decay heat compared with the heat load in the SFP of Unit 4. There was no fuel in the Unit 4 reactor vessel, and hence safety systems were not actuated. The only concern was the cooling of the Unit 4 SFP, which had been lost due to the station blackout condition.

Assessment

The hydrogen explosion in the reactor building of Unit 4 on 15 March 2011 received considerable attention and resources because the explosion was unexpected, as operators did not believe that there was enough decay heat in the SFPs to result in rapid overheating and subsequent high temperature interaction of zirconium and water to produce hydrogen. Given this uncertainty, considerable efforts were undertaken to ensure that the fuel in the SFP was properly cooled because a release from the pool would lead directly to the atmosphere. The subsequent analyses and inspections performed by TEPCO revealed that the water level in the SFP of Unit 4 never dropped below the top of active fuel (TAF), and no significant fuel damage occurred. Nevertheless, according to information released by TEPCO, SFP water did reach saturation conditions [10] and the impact of this uncertainty shows the importance of reliable monitoring systems for transmitting the status of the SFP during accidents.

Regarding the cause of the explosion in Unit 4, recent assessments have concluded that the hydrogen migrated from Unit 3 to Unit 4 via the vent lines of the containments of Units 3 and 4 which were connected to the exhaust vent piping. This piping arrangement allowed gases from the Unit 3 containment to be vented into the Unit 4 reactor building as a result of reverse flow through the Unit 4 SBGT system. One design feature which may have prevented or mitigated the migration of hydrogen is backflow dampers, which were not included in the design of the Unit 4 SBGT system [18]. This indicates that the interfaces between the common exhaust ventilation systems of Units 3 and 4 were not designed to isolate these units appropriately in the event of an accident.

2.2.10. Design features of Units 5 and 6

Unit 6 of the Fukushima Daiichi NPP has a structure consisting of a reactor wing with an annex on the outside. In contrast, Unit 5 has a stand-alone type reactor building, consisting of a reactor wing with

no annex. Two of the Unit 6 EDGs (EDG A and EDG HPCS) were installed in the basement of the reactor building annex; a third (EDG B) was located on the ground floor of a separate EDG building. Both EDGs of Unit 5 were installed in the basement of its turbine building. The reason for installing EDGs on the foundation (lowest basement floor) level had been the need to deal with the vibration and seismic safety of large size equipment. At the time of the earthquake, Unit 5 was going through periodic inspection and RPV pressure leakage tests were being conducted with fuel loaded in the reactor. Unit 6 was also undergoing periodic inspection, and the reactor was in cold shutdown condition (i.e. all control rods inserted) with the fuel being loaded.

Response during the accident

Loss of the external power supply was caused by the earthquake, and the subsequent large tsunami knocked out the four water cooled EDGs of Units 5 and 6. While the EDGs were installed in the basement, their air supply louvres were above the inundation level, and no other water ingress pathways, such as ducts or trenches, existed. What caused the EDGs to stop functioning was the loss of cooling using the sea as the ultimate heat sink. The air cooled EDG of Unit 6 and the associated electrical distribution system survived the flooding, and they were used to re-establish cold shutdown in Units 5 and 6. Similarly, the DC power supply in Units 5 and 6 installed in the mezzanine basement floors was not damaged by flooding. The charging of the DC power supply of Unit 5 was restarted by using power from the EDG of Unit 6, using temporary cross-tie electrical connections.

Assessment

Loss of cooling was prevented in Units 5 and 6 by directly connecting a power source of one air cooled EDG to the equipment available for cooling. It was still possible to inject cooling water using the make-up water condensate (MUWC) system, and the cooling of the reactor was maintained with the discharge of steam to the SC by SRVs. However, the RHR and cooling seawater systems, which both discharge heat into the ocean as the UHS, stopped functioning due to the unanticipated size of the tsunami. The seawater pumps and their motors were at a lower level than the reactor building, and they were flooded and damaged. Thus, even if electricity had been available to drive the ECCS, there would have been no way of dissipating the heat. However, temporary submersible pumps were used in Units 5 and 6 to restore the function of each RHR system. The system at Units 5 and 6 was re-established by using substitute RHR pumps. The supply of water to the SFP was also carried out in a similar manner. The mechanical damage to ESS pumps was limited. The seawater pumps to cool EDG A at Unit 6, for example, were restarted on 18 March 2011 without having to be repaired. They then allowed EDG A at Unit 6 to start up on 19 March. Cold shutdown of these two units was declared on 20 March 2011. No other damage to the reactor buildings or SFPs was reported.

The prevention of core damage in Units 5 and 6 was to a large extent the result of the survival of a single EDG. This was due to its different cooling mechanism and its location, but also to the location of the associated switch gear. This example reinforces the assessment that an analysis of flooding hazards could have shown the importance of siting the EDGs in a safer location.

2.2.11. Spent fuel storage facilities at the Fukushima Daiichi NPP

The inventory of spent fuel being stored at the Fukushima Daiichi NPP on the day of the accident is shown in Table 2.2–1.

TABLE 2.2–1. NUMBER OF SPENT FUEL ASSEMBLIES BEING STORED AS OF 11 MARCH 2011 ACCORDING TO THE INDEPENDENT TECHNICAL EVALUATION AND REVIEW, MAY 2011 [47]

Unit	Spent fuel assembly (units)	New fuel	Decay heat (MW)
Unit 1	292	100	0.18
Unit 2	587	28	0.62
Unit 3	514	52	0.54
Unit 4	1331	204	2.26
Unit 5	946	48	1.01
Unit 6	876	64	0.87
Common pool	6375	0	1.13
Cask storage building	408	0	—

Response during the accident

In the course of the accident, the systems of Units 1–5 and the common pool which were designed for cooling the spent fuel inventory and injecting make-up water became unavailable due to the loss of AC power from both the external grid and the EDGs. The UHS was also unavailable due to damage to the intake structure from the tsunami and the loss of power. Moreover, key parameters, such as the water temperature or the water level in the SFP were unknown because of the loss of DC power. However, in the case of Unit 6, one EDG (6B) survived, as explained earlier, but the SFP cooling in Unit 6 was unavailable due to damage to its seawater cooling pump. The cask storage building also experienced SBO, but the dry storage casks were designed to be air cooled through natural convection.

Spent fuel pools

In the first few days following the tsunami, the operators considered that there was sufficient water in the SFPs and that overheating of the fuel was not an immediate issue. This view changed on 15 March, when the Unit 4 reactor building exploded. As previously described, it was thought that the cause of the explosion was hydrogen, and the only possible source of hydrogen in Unit 4 was thought to be from overheated fuel in the SFP due to the loss of water cover. This immediately raised concerns about how much water remained in that pool and efforts were made to determine the water level in the SFPs.

On 16 March, visual inspections indicated that there was still water in the pool at Unit 4. However, concerns were raised about the status of Unit 3, which led to various mitigation efforts, including the airdrop of water from helicopters. Subsequent analysis and inspections revealed that the water level in the SFPs of both Units 3 and 4 had not dropped to the level of the spent fuel. These inspections confirmed that the explosion in Unit 4 was caused by hydrogen, and that the source of the hydrogen was not the fuel in the Unit 4 SFP but the migration of hydrogen from Unit 3 to Unit 4 via a connected PCV venting piping. However, the lack of knowledge about the actual conditions in the SFPs during the accident, due to the loss of instrumentation, led to the effort to add water to the pool. In the days and weeks that followed, the SFPs for Units 1–4 were cooled by a combination of external injection via concrete pumper trucks and, by the end of March 2011, the hook-up of external water sources which were connected to the installed SFP cooling piping. Units 5 and 6 were cooled via the cross-connection of the operational EDG from Unit 6.

Assessment

The result of the assessment of the performance of the SFPs points directly to the lack of knowledge regarding the actual water level and temperature in the pools. While it was necessary to take action to

restore lost water inventory and cool the SFPs, these actions were not as high a priority on 15 March as was thought following the hydrogen explosion in Unit 4. The lack of instrumentation to indicate to operators the actual conditions in the SFP led them to prioritize spent fuel pool cooling as a high priority action. It should be pointed out, however, that given the information available at the time of the accident to operators, their concerns were justified.

An inspection of the dry cask storage facility revealed that, while the building was damaged by the tsunami, the dry storage casks did not appear to have been damaged. The casks became wet because of the tsunami, but they were not moved from their storage locations by the force of the waves or debris. No abnormalities have been seen in the dry storage cask area as its cooling was maintained with the circulation of air.

2.2.12. Application of defence in depth

The concept of defence in depth (DID) referenced by the IAEA was first introduced by the International Nuclear Safety Group (INSAG) [48]. It is now widely recognized as a fundamental safety approach for ensuring the safety of nuclear installations. IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [1], states that DID is the primary means of preventing accidents and mitigating their consequences. DID is implemented through the combination of a number of consecutive and independent levels of protection that would have to fail before harmful effects could be caused to people and/or to the environment. If one level of protection were to fail, the subsequent level would be available. When properly implemented, DID ensures that no single technical, human or organizational failure could lead to harmful effects, and that the combinations of failures that could give rise to significant harmful effects are of a very low probability. The independent effectiveness of the different levels of defence, and thus the resistance to common cause failures, is a necessary element of DID. It ensures that a high level of safety is achieved with sufficient margins to compensate for potential equipment, human or organizational failures.

The strategy for DID is twofold: first, to prevent accidents; and second, if prevention fails, to limit their potential consequences and to prevent any progression to more serious conditions. Accident prevention is the first priority. The rationale for the priority is that provisions to prevent deviations of the plant state from well known operating conditions are generally more effective and more predictable than measures aimed at mitigation of the consequences of such a departure, since the plant's performance generally deteriorates when the status of the plant or a component departs from normal conditions. Consequently, preventing the degradation of plant status and performance will generally provide the most effective protection of the public and the environment, as well as assuring the productive capacity of the plant. Should preventive measures fail, however, mitigatory measures — in particular the use of a well designed confinement function — can provide the necessary additional protection of the public and the environment.

IAEA safety standards [2, 17] reflect today's consensus that for nuclear power plants, DID consists of five levels, which are summarized as follows:

Level 1. The aim of the first level of defence is to prevent deviations from normal operation and to prevent system failures. This leads to the requirement that the plant be soundly and conservatively designed, constructed, maintained and operated in accordance with appropriate quality levels and engineering practices, such as the application of redundancy, independence and diversity. To meet this objective, careful attention is paid to the selection of appropriate design codes and materials, and to the control of fabrication of components and of plant construction. Design options that can contribute to reducing the potential for internal hazards (e.g. controlling the response to a postulated initiating event (PIE)), to reducing the consequences of a given PIE or to reducing the likely release of the source term following an accident sequence contribute at this level of defence. Attention is also paid to the procedures involved in the design, fabrication, construction and in-service plant inspection,

maintenance and testing, to the ease of access for these activities, to the way the plant is operated and to how operational experience is utilized. This whole process is supported by a detailed analysis which determines the operational and maintenance requirements for the plant.

Level 2. The aim of the second level of defence is to detect and intercept deviations from normal operational states in order to prevent anticipated operational occurrences from escalating to accident conditions. This is in recognition of the fact that some PIEs are likely to occur over the service lifetime of an NPP, despite the care taken to prevent them. This level necessitates the provision of specific systems as determined in the safety analysis and the definition of operating procedures to prevent or minimize damage from such PIEs.

Level 3. For the third level of defence, it is assumed that, although very unlikely, the escalation of certain anticipated operational occurrences or PIEs may not be halted by a preceding level and a more serious event may develop. These unlikely events are anticipated in the design basis for the plant, and inherent safety features, fail-safe design, additional equipment and procedures are provided to control their consequences and to achieve stable and acceptable plant states following such events. This leads to the requirement that engineered safety features be provided that are capable of leading the plant first to a controlled state and subsequently to a safe shutdown state, and maintaining at least one barrier for the confinement of radioactive material.

Level 4. The aim of the fourth level of defence is to address severe accidents in which the design basis may be exceeded and to ensure that radioactive releases are kept as low as practicable. The most important objective of this level is the protection of the confinement function. This may be achieved by complementary measures and procedures to prevent accident progression, and by mitigation of the consequences of selected severe accidents, in addition to accident management procedures. The protection provided by the confinement may be demonstrated using best estimate methods.

Level 5. The fifth and final level of defence is aimed at mitigation of the radiological consequences of potential releases of radioactive material that may result from accident conditions. This requires the provision of an adequately equipped emergency control (see Technical Volume 3).

The earthquake on 11 March 2011 caused major damage to the infrastructure in the region, including the loss of connections from the off-site power grid to the Fukushima Daiichi NPP. This resulted in a deviation from the normal operation of the plant (DID Level 1). After the earthquake, the power supply was successfully provided from on-site sources, and all safety systems at DID Level 3 continued to function as designed. This indicated that the safety systems and equipment withstood the seismic hazard [10].

The plant was built close to sea level and protection against flooding hazards was not sufficient, as the risk of flooding was not appropriately estimated [2]. Key safety equipment was not protected in leaktight compartments or by locating it at higher elevations to provide protection from flooding. This led to the loss of provisions for residual heat removal and containment cooling at DID Levels 1, 2 and 3.

The flooding was the common cause of failure of the emergency power supply system, the near complete loss of systems providing DC power to measuring and control devices, and the destruction of the structures and components providing seawater cooling for the plant.

The objectives of DID Level 4 are the prevention of accident progression and the mitigation of the consequences of a severe accident. For actions at Level 4, the operators needed to use all available means to supply water to the reactor in order to ensure the adequate removal of residual heat. This required the availability of instruments which provide reliable information on the key safety

parameters and simple, reliable means for pressure relief in the reactor. In addition, the operators needed clear guidance and be trained to be able to initiate accident management measures [49].

As the accident progressed, operators lost the ability to reliably measure important safety parameters from the control room. This information was needed to assess the reactor status and to take well informed decisions on unusual actions and methods to cool the reactors. Nevertheless, the operators gave high priority to reactor cooling and managed to quickly prepare water supply lines with the intention of injecting coolant into the reactors using available low pressure pumps. However, the attempts to relieve reactor pressure failed because no provisions had been made to carry out this function after a complete loss of power. The required control power could not be restored in time to prevent core damage [10].

The last physical barrier included in DID Level 4 is reactor containment. Its purpose is to mitigate the consequences of accidents by preventing large radioactive releases to the environment after reactor damage. Depending on the containment type, various systems or kinds of equipment are needed to protect the containment against physical phenomena associated with core damage accidents that could challenge the containment integrity. The units at the Fukushima Daiichi NPP included means for the controlled venting of the containment to relieve the overpressure that might be caused by a steam leakage from the reactor cooling circuit. In addition, the atmosphere inside the containment was filled with inert nitrogen in order to eliminate hydrogen burn and prevent possible explosions.

Measurements taken during the accident indicate that the containment pressures of Units 1, 2, and 3 at certain times increased to levels that were near, or higher than, those for which the respective containments had been designed. This increase in pressure was due to the loss of containment cooling systems and the generation of steam by the overheated reactor cores. Although some containment venting systems were successfully opened, indications are that the containments of Units 1, 2 and 3 failed, leading to the release of radioactive material and hydrogen. The nitrogen atmosphere inside the containments had effectively prevented hydrogen burn and explosions from occurring in that confined space. However, as hydrogen leaked from the containments to the reactor buildings, hydrogen explosions occurred at Units 1, 3 and 4 [10].

The Fukushima Daiichi accident demonstrated that extreme natural hazards have the potential to invalidate or impair multiple levels of defence in depth [50, 51]. A systematic identification and assessment of external hazards and robust protection against these hazards needs therefore to be considered for all levels of DID. Furthermore, the accident showed that alternative design provisions and accident management capabilities could still ensure the supply of cooling water to the reactor even if all prime safety systems designed to protect the reactor against accidents were lost. However, the timely use of such provisions requires instruments that can provide reliable information on the key safety parameters and simple, reliable means to relieve the pressure in the reactor so that any means can be used to supply cooling water to the reactor.

Summary of the Fourth International Conference on Topical Issues in Nuclear Installation Safety

On 21–24 October 2013, the IAEA convened an international conference on Topical Issues in Nuclear Installation Safety, in Vienna [51]. This conference both summarized the latest assessments regarding the application of DID and identified future activities. The Conference President summarized the meeting as follows:

— Although the DID concept remains valid after the Fukushima Daiichi accident, it has to be strengthened and extensively applied in order to meet most recent safety objectives for nuclear plants, such as the ones adopted by the Contracting Parties during the extraordinary meeting of the Convention for Nuclear Safety. DID is not only relevant for the design of new installations, but should also be maintained/improved by periodic safety reviews over the entire life of installations.

— While DID remains an essential tool for safety and should continue to be applied, further development and guidance are required on several subjects such as:
  - Consistent application of design basis definitions at the international level;
  - Postulation of multiple failures in reactor design;
  - Practical elimination of sequences, in relation with the use of deterministic and probabilistic approaches;
  - Assessment of independence and reliability of different levels of DID;
  - Approach to be adopted for very low probability events leading to very large health and societal consequences;
  - Tools to be based on already developed methodologies to ensure that safety provisions are comprehensive enough to ensure DID.
— One important lesson from the Fukushima Daiichi accident is that extreme external hazards can result in common cause failures simultaneously jeopardizing several levels of defence. Such common cause failures can result in complete loss of the instrumentation of the plant, inducing extreme difficulties in the management of a severe accident. Special attention should be given to these risks when implementing DID.
— Hazards, as well as the combination of hazards, to be taken into account in relation to DID need further work and international guidance.
— Effective implementation of DID requires that the most recent knowledge resulting from operational experience feedback as well as research and development are taken into account. Human factors and reliability of instrumentation and control systems are subjects that require further development and guidance.
— Approaches have already been developed and efforts are underway to improve robustness of plants, taking into account the current lessons learned from the Fukushima Daiichi accident. However, such approaches still need to be matured on several topics such as:
  - Criteria to choose between fixed and mobile equipment;
  - Design approach for equipment or ‘hardened safety core’ of equipment ensuring fulfilment of safety functions under extreme conditions.
— As already highlighted by the IAEA, the World Association of Nuclear Operators (WANO) and the OECD Nuclear Energy Agency (OECD/NEA), mitigation levels of DID should be enhanced in operational safety, while prevention should also be maintained. The IAEA’s Operational Safety Review Team (OSART) missions and WANO peer reviews have already been extended to cover some design aspects related to continuous improvement of operating plants.
— Wider use of IAEA review services, especially those related to siting, design and emergency preparedness, should be promoted and established, contributing to the prevention of nuclear accidents and emergency management. Peer pressure should be extended to ensure the implementation of their recommendations. The topics of these peer reviews could be chosen in light of operating experience feedback.
— Realistic drills are essential for the effectiveness of emergency preparedness. They should involve all the key players, at all levels, in decision-making and communication. They should be designed, as much as possible, to train individuals and to prepare organizations to react in a flexible manner to unexpected situations.
— An idea was proposed that the technical concept of DID is necessary but not sufficient to ensure safety. Effective institutional systems need to be set up, applying the same DID concept and principles, involving all stakeholders (operators, regulators, industry, etc.). To address this issue, a peer-review service was suggested to be established jointly by the IAEA and WANO, using the expertise of the OECD/NEA, with initial self-assessment feeding into Nuclear Safety Convention review meetings.
— Following the Fukushima Daiichi accident, WANO adopted a strategic orientation to increase its strength and its focus on nuclear safety. It improved its peer review process and expanded its scope to integrate some design aspects, as well as corporate peer reviews. Overall, the peer pressure was increased in order to enhance commitment to safety of the operators worldwide.

— The safety of nuclear and non-nuclear industries would benefit from closer collaboration, allowing better sharing of experience feedback, as well as education and training methods. Nuclear safety could also benefit from the experience of first response organizations, such as the police or fire brigades.

2.2.13. Summary

The tsunami caused a station wide loss of AC power and, in most units, an immediate loss of DC power. The operators struggled in extremely difficult conditions to re-establish cooling to the cores of Units 1, 2 and 3. In addition, due to the combined impact of the explosion in the reactor building of Unit 4 and the loss of instrumentation, the operators believed that the spent fuel in the storage pool in Unit 4 was damaged. The fundamental safety functions that must be maintained are: (1) reactivity control; (2) core cooling; and (3) containment integrity. Reactivity was successfully controlled. Core cooling was not maintained, primarily because of the failure of the high pressure injection systems and the inability to depressurize the reactors to allow for alternative modes of water injection. The high pressure injection systems failed because the loss of DC power made it difficult to operate steam driven systems. The operators were also unable to deploy alternative water injection systems due to the loss of DC power and the high pressure nitrogen system, which is needed to open the SRVs. Finally, the containment function was lost due to the inability to remove heat from the containment caused by the loss of AC and DC power, which rendered both containment cooling systems and containment ventilation systems inoperable.

The status of the various means of heat removal on Units 1–3 was as follows.

Unit 1 had a system called an isolation condenser (IC), which would have been able to remove decay heat via natural circulation without power for about ten hours if it had been working. The system had started automatically when the off-site power was lost following the initial earthquake. At the time the tsunami struck, the operators had just closed some valves in the system in order not to cool down the reactor too quickly. Without power, it was not possible to reopen them.

In order to use an alternative mode of water injection (from the stationary diesel driven fire pump or mobile pumpers), the operators needed to depressurize both the RPV and the containment. Following successful opening of the containment vent, and after the RPV had depressurized to the same pressure as the containment, the operators were eventually able to use fire trucks to inject water into the reactor vessel to cool the damaged fuel. It is not known exactly how hydrogen escaped from containment, but it led to the explosion on 12 March.

Units 2 and 3 had a different means of removing decay heat, known as the reactor core isolation cooling (RCIC) system, which used a steam turbine driven from the main steam line. The RCIC systems for both Units 2 and 3 were manually started when off-site power was lost. However, DC power was needed to control them, so once the tsunami struck, the systems could only be controlled in Unit 3, whose batteries had survived.

In Unit 2, the RCIC system was believed to have continued to operate without operator control until it failed about three days after the earthquake. The assessment is that in this uncontrolled mode the RPV water level rose to that of the steam lines, causing water carryover into the RCIC turbine, which in turn led to a reduced water injection rate and effective self-regulating level control at the elevation of the steam lines. It is also believed that sea water which had flooded the torus room, cooled the torus, which prevented overheating of the suppression pool and extended the RCIC's operating time. The operators were unable to open the containment vent in Unit 2, resulting in the PCV being maintained at a high pressure for a considerable period of time. On 15 March, the sound of an explosion was heard, followed by a drop in the Unit 2 suppression chamber pressure.

Unit 3 was the most complex accident to analyse because some systems did function and DC power remained available for some time. Because of this, operators had instrumentation and were able to control vital core cooling systems until the station batteries were depleted after about two days. Initially, the RCIC system was functioning and under control, enabling the water level in the reactor to be maintained. After about 20 hours, it failed for unknown reasons, causing the HPCI system to start automatically and inject water into the RPV. Since this is a relatively large capacity system, the operators reduced the flow rate by opening a return line to provide a bypass around the RPV. Even with this flow bypass, the HPCI system caused a dramatic reduction in RPV pressure, which led the operators to shut down the HPCI system after about 14 hours because they were concerned about pump shaft oscillation and failure. Following this, an attempt was made to use the fire trucks but this failed to inject much water into the RPV, leading to the core being uncovered and fuel failure.

On 13 March, the RPV was depressurized and the containment vent was opened which allowed the fire trucks to inject water into the RPV to cool the fuel. However, significant core damage had already occurred due to the prolonged period of high pressure and the lack of an available high pressure injection source. From this time on, the RPV remained depressurized, with water injection from the fire trucks continuing.

At the time of the accident, the fuel from Unit 4 had been removed from the reactor and was in the SFP at the top of the building. An explosion occurred which damaged the masonry structure around the SFP. Because the operators had no information about conditions in the pool, they became concerned that the fuel may be overheating and generating hydrogen itself. This led them to divert resources from re-establishing cooling to the other units. It is now understood that the explosion was a result of leakage of hydrogen from Unit 3 through shared systems.

Since the PCVs of the reactors at the Fukushima Daiichi NPP were not designed to withstand the severe accident conditions, containment venting systems had been installed. At various stages during the accident, the PCVs for Units 1, 2 and 3 either failed for unknown reasons or were opened via the containment hardened vents. Even when the containment hardened vents were successfully opened, the assessment, based on records of containment pressure, found that these PCVs eventually failed as well. The damage to the cores released large amounts of steam, hydrogen and radioactive material inside the PCVs through the SRVs and other leakage paths, which both pressurized and heated the PCVs, causing them to lose their integrity. This led to the release of steam, hydrogen and radioactive material into the reactor building.

Despite these failures, it is important to note that the PCVs performed their primary function. The eventual loss of integrity was a consequence of operation under temperatures and pressures far beyond their design limits, caused by overpressurization and the inability to remove heat for an extended period of time. Even with the PCV failures, leakage of radioactive material from the cores to the environment was likely mitigated by the suppression pools, which would have retained various fission products discharged from the RPVs through the SRVs.

Further work is needed in order to more fully understand additional details of the progression of the accident in the various units, particularly the failures which led to the RPVs of Units 1–3 becoming depressurized and to the PCVs of Units 1–3 being breached.

Regarding the application of DID, the tsunami was so powerful that it defeated Levels 1 to 3 by a common mode failure which meant that operators were forced to rely on provisions designed for Levels 4 and 5. The provisions designed for Level 4, such as containment venting and alternative water injection, proved inadequate which ultimately led to offsite releases.

2.2.14. Observations and lessons

— **Provisions need to be made for ensuring fundamental safety functions in case of loss of DID Level 3, including core cooling, spent fuel cooling and containment integrity.**
Robust equipment to manage DID Level 4 provides the operators with greater capability to prevent an accident from progressing. For example, operation of the containment vent valves manually from a nearby shielded location would allow for the depressurization of the containments to aid in heat removal. Similarly, opening the SRVs from a nearby shielded location would have depressurized the reactors and allowed water injection to remove heat from the cores.

— **Personnel need to be trained to manage severe plant conditions (Level 4). This training needs to include consideration of the extreme environmental conditions which may prevail during a severe accident.**
Although the operators had severe accident operating procedures available, the equipment and training on its use proved to be ineffective. Moreover, the possibility of a multi-unit severe accident or of an accident which simultaneously impacted other nuclear stations or damaged the local infrastructure had not been considered.

— **Defence in depth Level 4 provisions need to be independent from those of Level 3. They need to be sufficiently flexible and robust to make options for SAM available to the operators.**
Although it is not possible to provide mitigating equipment for all possible severe accidents, thought needs to be given to providing the operators with flexible and robust options that would allow them to respond to several plant situations.

— **Interconnections between units need to be designed to prevent an accident from migrating from one unit to another.**
The interconnection between Units 3 and 4 caused the migration of hydrogen from Unit 3 to Unit 4, causing an explosion in the Unit 4 reactor building. This explosion further complicated the response to the event by causing resources to be diverted to address the situation.

— **Critical instrumentation needs to be designed and maintained so that it continues to function during severe accidents.**
Equipment important for providing information about the plant status needs to be resistant to severe accident conditions. For example, with instrumentation available in Units 1–3, the operators would understand what was happening in the reactors and would be able to take action to further mitigate the consequences of the event. Similarly, operator awareness of the real condition of the SFP in Unit 4 would have enabled them to know that, in spite of the explosion, there was no immediate threat from the fuel in the SFP in Unit 4.

— **Provision needs to be made for the removal of decay heat by alternative means (such as mobile equipment) should the permanently installed equipment not be operable.**
The operators were aided in their attempts to restore cooling to the reactors by the connections that had been installed based on the experience of the Niigata-Chuetsu-Oki earthquake that affected the Kashiwazaki-Kariwa NPP in 2007. This allowed them to use diesel driven fire pumps or mobile pumpers to inject water into the reactors to cool the cores. This equipment needs to be reliable and diverse and has to be inspected regularly and tested to ensure its operability under station blackout conditions.

2.3. ASSESSMENT OF THE TREATMENT OF BEYOND DESIGN BASIS EVENTS

2.3.1. Introduction

This section reviews the beyond design basis accident (BDBA) probabilistic and deterministic safety assessments for the Fukushima Daiichi NPP and the insights from these assessments that were applied to the plant design. Of particular note are the measures against the extreme natural hazards that led to the total loss of AC power, referred to as a station blackout (SBO) because of its particular relevance to the accident. An SBO is often considered as a loss of normal and emergency AC power, which does not imply the loss of DC electrical supply or other AC power sources. The loss of DC power at

Fukushima Daiichi Units 1 and 2 played a central role in the development of the accident because it impeded the correct diagnosis of plant conditions, including the status and operation of safety systems.

Certain beyond design basis aspects are considered elsewhere. For instance, Section 2.1 addresses beyond design basis external event (BDBEE) assessments, while Section 2.4 focuses on provisions to mitigate severe accidents, such as the use of fire systems for core cooling injection.

The accident at the Fukushima Daiichi NPP exceeded its design basis in several respects. It was a severe accident, impacting multiple units, and it was an accident during which the operators were left with little indication to aid their understanding of what was happening, rendering them unable to control the situation. The interference between the units (hydrogen explosions and the allocation of limited resources) contributed to the severity of the accident. The level of devastation and isolation of the site, the scarcity of information available to the operators and the multiple unit effects come out as new features to be considered in accident management.

A major characteristic of the Fukushima Daiichi NPP accident was the massive common mode failure induced by the earthquake and subsequent flooding due to the tsunami. This common mode failure reached a scale considerably beyond that usually addressed in the assessment of BDBAs. This common mode failure impaired both the AC and DC electrical systems depriving the operators of almost all means of control over multiple units.

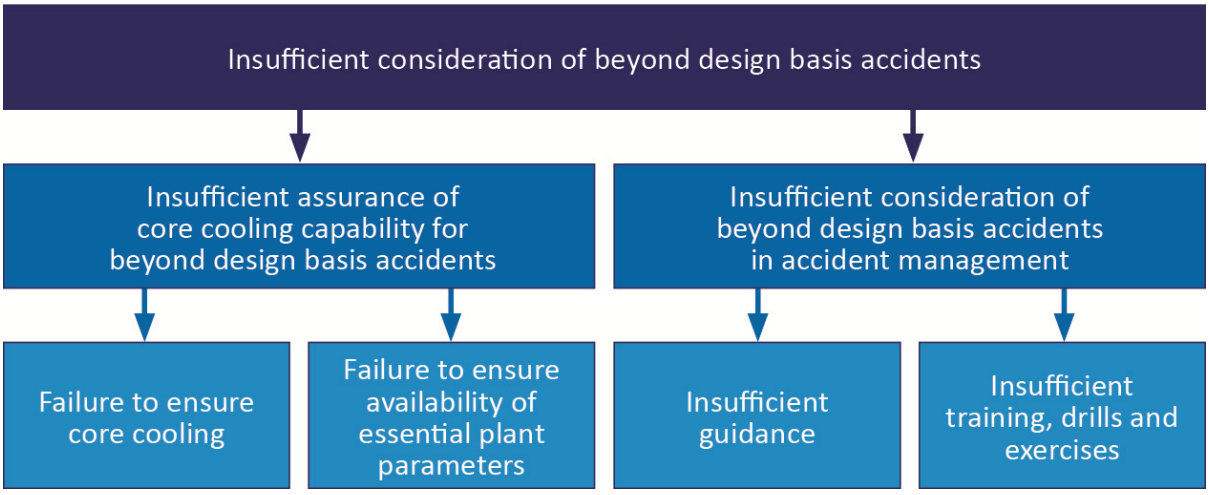


FIG. 2.3–1. Summary of insights from beyond design basis considerations.

Figure 2.3-1 describes some of the specific challenges encountered during the accident which are related to this lack of consideration of beyond design basis conditions. Some of the direct challenges in managing the accident were that components failed in such a way that core cooling was not maintained and the lack of critical safety parameter information did not allow the emergency response centres (ERCs) and main control rooms (MCRs) to have a clear understanding of the status of core cooling, to track the status of safety systems and to facilitate appropriate decision making. These challenges could have been mitigated by considering the ability to remove decay heat during beyond design basis conditions (see para. 6.37 of IAEA Safety Standards Series No. NS-R-1 [2]). Another challenge was that personnel were not prepared to manage the combined loss of power and instrumentation following flooding at the plant. Without proper plant instrumentation, as well as working in a harsh environment with inadequate SAMGs, plant personnel struggled to promptly implement the mitigation actions.

2.3.2. Review of deterministic safety assessment

2.3.2.1. IAEA requirements on deterministic safety assessment

A number of IAEA safety standards recommend that plant specific deterministic BDBA analyses be performed [5, 52] to investigate credible scenarios that lead to improvements in accident management. Thus, it is necessary to determine whether safety functions can be fulfilled in BDBA conditions and to demonstrate the capability of the design to mitigate such accidents.

Neither the Establishment Permit nor the periodic safety reviews (PSRs) for the Fukushima Daiichi units contained deterministic safety analyses of BDBAs, including severe accidents [3], contrary to what would be contained in Refs [5, 52]. One reason for this is that it was not a regulatory requirement, as was noted in the report of the IAEA Integrated Regulatory Review Service (IRRS) mission conducted in June 2007, which concluded that:

> "There are no legal regulations for the consideration of beyond the design basis, as Japanese plants are considered to be adequately safe as ensured by preventive measures" [53].

Some of the reasons why the SBO did not warrant detailed analysis and additional mitigation were an assumed high likelihood of grid recovery within a short space of time and design features to mitigate single unit SBO events such as unit electrical cross-connections [10]. Consequently, a multi-unit extended loss of AC power was not considered [54], though it should be kept in mind that the assessment of multi-unit events was not common practice for nuclear utilities prior to the Fukushima Daiichi accident. In addition, the reactors were equipped with systems able to cool the core for substantial periods of time in the absence of AC power, such as the isolation condenser (IC), reactor core isolation cooling (RCIC) and the high pressure coolant injection (HPCI) systems.

Furthermore, other BDBAs pertinent to the events of March 2011, such as the total loss of the ultimate heat sink, loss of DC power and the loss of SFP cooling, were also not assessed deterministically in the Establishment Permit or in the PSRs, which only include the analyses of design basis accidents.

The EDGs and battery rooms in the basement floor of the turbine building and the emergency electrical switch gear on the first floor of the turbine building were vulnerable to flooding, as was demonstrated by a plant event involving flooding at Unit 1 in 1991 [55]. Sea water leaked from a corroded pipe inside the turbine building, flooding an EDG room through its door and cable penetrations. Given the vulnerability to flooding from internal and external hazards of the EDGs, battery rooms and rooms containing emergency electrical switch gear, an assessment of flooding should have been performed and documented in the plant safety analysis. Such an assessment, required by IAEA safety standards [52], would have highlighted this vulnerability and the need for safety improvements, such as protecting the EDGs, battery rooms and switch gear from flooding.

TEPCO had performed some limited deterministic safety analyses of BDBAs in the early 1990s for those accident sequences that dominated the results of the PSAs. However, given that the PSA only studied single unit internal events, these deterministic safety analyses did not provide enough elements for accident management preparations to cope with the events that occurred in March 2011. Thus, although the plant was located in an area prone to tsunamis possibly larger than that considered in the design basis, these BDBA analyses did not include flooding of the site or the extended loss of AC power. At about the same time, the accident management guidelines were developed to support some of the generic BWR Owners' Group (BWROG) accident management updates. Thus, the severe accident operating procedures at the Fukushima Daiichi NPP contained some of the generic guidance provided by the BWROG. These updates were also inadequate in addressing the multi-unit event of March 2011, since the event substantially exceeded that postulated with particular reference to both

the additional resources necessary to cope with such an event and the potential impact of one severe accident on adjacent units [10].

The extent of the deterministic BDBA analyses for the Fukushima Daiichi NPP were inadequate, which accounts partially for the inadequacies in the plant hardware, accident guidance and training to cope with the events of March 2011 [54]. More comprehensive deterministic BDBA analyses enables the identification of the plant vulnerabilities and highlights the need to protect the EDGs, battery rooms and emergency electrical switch gear from flooding. Without current beyond design basis assessments, the extent of the safety margin and the possible consequences of insufficient margin in beyond design basis modifications and BDBA management strategies cannot be determined. These beyond design basis assessments needed to include credible beyond design basis conditions (such as from internal and external flooding hazards which likely lead to the loss of all AC and DC power in the absence of adequate protection).

2.3.2.2. Ensuring the core cooling function under beyond design basis conditions

Paragraph 6.37 of IAEA Safety Standards Series No. NS-R-1 [2] states that: "Adequate consideration shall be given to extending the capability to remove heat from the core following a severe accident." In addition, para. 4.81 of IAEA Safety Standards Series No. NS-G-1.9 [44] states that: "Equipment for emergency core cooling should be adequately protected from the consequences of internal and external hazards such as seismic hazards that have the potential to jeopardize its safety functions."

Core cooling at the Fukushima Daiichi NPP was not maintained in Units 1–3, largely because they were not adequately protected from the consequences of external hazards, and insufficient provision was made to ensure core cooling in beyond design basis conditions. Three examples are described below that indicate some of the challenges experienced in maintaining or re-establishing cooling.

The first case involves the valves on the IC in Unit 1. By design, each division of the containment isolation system protective logic closes all valves within that division upon the loss of DC power to the protective circuit because containment isolation is required by the design basis. However, because the operators failed to notice that the system was isolated, it could not then be readily used for core cooling operation without operator intervention. In the March 2011 event, it was preferable to keep the IC operating. Given the loss of system indication (due to the loss of DC power) and the belief by the personnel within the ERC of its continued operation, attempts to recover core cooling using the IC were delayed and core melt resulted.

The second case concerns the safety relief valves (SRVs), which failed in the closed position upon the loss of DC power and high pressure air and could not be readily opened. However, the SRVs failing open would be detrimental to the operation of the RCIC and HPCI, and result in loss of coolant inventory prior to the availability of low pressure injection systems. If depressurization and injection with low pressure systems is a defined accident management strategy, then guidance in accident management procedures needs to be provided on how to achieve this under all plant conditions. This guidance was not readily available, which contributed to the delays in depressurizing the RPV in Units 2 and 3. This in turn contributed to the delays in establishing adequate low pressure injection flow, and exacerbated the consequences.

The third case relates to the containment ventilation system, where the vent isolation valves were closed and did not readily open upon the loss of DC power and high pressure air. The vent valve had to be operated in the field under challenging conditions due to the loss of PCV vent valve actuating power and compressed air, necessitating procedures to be developed and battery power provided to aid the local operation of these valves. The resultant delays in venting the PCV delayed the depressurization of the RPV (because the RPV pressure cannot be lower than the PCV pressure under these conditions), which in turn led to a delay in the injection of coolant into the reactor vessel from

low pressure sources. The lack of coolant resulted in uncovering of the core, core damage, high radiation levels, hydrogen production and, ultimately, PCV failure. Thus, because the operators were unable to successfully operate the containment venting system, they were unable to reduce the containment pressure, which inhibited their efforts to cool the core. Accident management measures need to be in place to depressurize the containment earlier (in conjunction with a rupture disc design change) and to allow operators to implement strategies using low pressure water sources to limit or prevent damage to the reactor core.

From the above examples, it can be concluded that greater provision could have been made to ensure core cooling capability in beyond design basis conditions.

2.3.3. Review of the probabilistic safety assessment

2.3.3.1. IAEA requirements on probabilistic safety assessment

This section compares the scope and results of the PSA for the Fukushima Daiichi NPP with the requirements in IAEA standards. For example, para. 4.31 of IAEA Safety Standards Series No. GSR Part 4 [52] states that the "external events that could arise for a facility or activity have to be addressed in the [facility's] safety assessment, and it has to be determined whether an adequate level of protection against their consequences is provided." Paragraph 5.73 of IAEA Safety Standards Series No. NS-R-1 [2] reiterates the expectation that external hazards, in particular those unique to the plant site, are assessed and mitigated. IAEA Safety Standards Series Nos SSG-3 [56] and SSG-4 [57] also highlight the need for the verification of plant safety in relation to potential internal initiating events and internal and external hazards, specifically stating that consideration should be given to cases where one external hazard can induce other hazards (such as seismically induced flooding).

However, it was common practice for Japanese plants to perform PSAs of limited scope only, since existing regulations did not require more detailed assessments to demonstrate plant safety. Internal and external hazards were mostly excluded in the PSA, although NISA's instruction to NPP owners to perform seismic PSAs in 2006 had yet to be completed for the Fukushima Daiichi NPP. Thus, for this NPP, the PSA was limited to the determination of core damage frequency (CDF) and containment failure frequency arising from internal events. A more comprehensive assessment of the core damage risk would have indicated both how vulnerable the plant was to flooding and the high likelihood of flooding. A full scope Level 2 PSA would have indicated a low probability of success for severe accident interventions given the limited training and guidance provided in SAM and thus the plant's vulnerability to common cause effects.

There was an important precursor event involving flooding at the Fukushima Daiichi NPP Unit 1 in 1991 [55], when sea water leaked from a pipe inside the turbine building, flooding an EDG room. Both the EDG room and the seawater pipe were located in the basement of the turbine hall. The corroded pipe leaked water at a rate of 20 m^3/h, which penetrated the room with the reactor's EPS through the door and cable penetrations.

Given such a precursor, the frequency of flooding of the EDGs, battery rooms and both AC and DC electrical switch gear, all located in the lower levels of the turbine hall, would not be lower than 10^{-3} per reactor-year, which, given the challenges faced in mitigating the total loss of both trains of AC and DC electrical power, would likely result in core damage. Thus, an internal flooding PSA would have highlighted this risk, suggesting the need for safety improvements such as protecting the EDGs, battery rooms and switch gear from flooding or moving them to a higher elevation.

The Fukushima Daiichi NPP PSAs did not include tsunamis in their scope, even though they were a significant contribution to the overall risk [32]. Technical evaluations in 2001 of the 869 Jogan tsunami [58] concluded that the recurrence interval for a large scale tsunami was 800–1100 years and

that since more than 1100 years had passed since the Jogan tsunami, the possibility of a large tsunami striking the Sendai plain was high. Their numerical findings indicate that a tsunami similar to Jogan would inundate the present coastal plain for about 2.5–3 km inland. TEPCO was aware in 2008 of the importance of evaluating the existence of a tsunami source along the Japan Trench off the coast of Fukushima Prefecture [54]. According to a report by the Institute of Nuclear Power Operations (INPO) [59], TEPCO derived in 2006 the probability of the Fukushima coast experiencing a tsunami greater than 6 m to be less than 1.0×10^{-2} in the next 50 years, and others had drawn a similar conclusion on the relatively high likelihood of a tsunami occurring that would exceed the design basis [60].

Given the location of the battery rooms, switch gear rooms and (some) EDGs in the lower levels of the turbine hall, it was known that flooding could lead to the total loss of all AC and DC power, which would likely result in core damage [10]. Thus, a basic tsunami PSA would have indicated a CDF greatly exceeding that reported for internal events and in excess of the IAEA target for existing NPPs of 1.0×10^{-4} per plant operating year [61] and would be considerably greater than the reported CDF for unit 1 of 3.9×10^{-8} per year. The large uncertainties associated with external hazards do not prevent their risk quantification since reporting uncertainties and performing sensitivity analyses are part of the normal PSA process. TEPCO has used these large uncertainties, combined with the lack of an established formal PSA tsunami methodology, as the reasons for not assessing and mitigating this risk [10].

Comprehensive level 2 PSAs tend to contain human error probabilities higher than those contained in level 1 PSAs because of the reduced guidance, training and knowledge of plant personnel on SAM. In addition, actions within a level 2 PSA are often implemented in a harsh environment, further reducing the probability of success. A comprehensive level 2 PSA for the Fukushima Daiichi NPP would have indicated the challenges experienced in reflooding a molten core using mobile equipment, and the necessity for design changes such as improvements in the ability to depressurize both the RPV and PCV, improved guidance, improved plant indication and improved training.

The limited Fukushima Daiichi NPP level 2 PSAs contained the use of the hardened containment vent system through the application of a fault tree approach to model the equipment failures. The human error probability for manual operation provides a failure probability of 1.9×10^{-3} for Fukushima Daiichi Unit 6. A more thorough assessment that investigated the challenges in SAM would have suggested the improvements that would have been made.

In summary, the Fukushima Daiichi plant design had some weaknesses that would have been discovered by performing a more comprehensive PSA, as recommended by IAEA safety standards [43, 61]. Rectification of these weaknesses may have prevented core damage. Examples include the lack of protection of the EDGs, battery rooms and switch gear from flooding, which would have been found by performing an internal hazards PSA, the lack of protection from tsunamis exceeding the design basis, and the low likelihood of success of severe accident interventions given the limited training, guidance and knowledge of plant personnel in this area. Hence, the calculated frequency of core damage for the Fukushima reactors was underestimated by the Japanese PSA requirements.

The Nuclear Safety Commission (NSC) released a report entitled Accident Management for Severe Accidents at Light Water Power Reactor Installations in May 1992. The amended version of this report, issued in October 1997 [62], established the PSA approach for internal events during plant operations. However, a PSA was not required for internals hazards (such as fire and flood) or external hazards (such as seismic activity and tsunami), and therefore these risks were not assessed. In the report, the NSC recommended that the regulatory body and utilities introduce accident management measures, although in the decision it was stated that:

— The safety of reactor facilities in Japan was sufficiently ensured by current safety regulations and the risk from reactor facilities was considered to be sufficiently low.
— The development of accident management measures was significant in further reducing the risk, which was already low.

This is one of the reasons why the PSAs for the Fukushima Daiichi units prior to the accident in March 2011, which were referenced in the PSRs, were limited to internal events. Internal hazards, external hazards, SFP accidents and multi-unit events were not considered in the PSAs.

After the Niigata-Chuetsu-Oki earthquake damaged the Kashiwazaki-Kariwa NPP in 2007, a PSA standard for seismic events was established and plant specific seismic PSAs were in the process of being finalized by TEPCO. Operating experience from the severe earthquake damage to the Kashiwazaki-Kariwa NPP had resulted in a design change to the Fukushima Daiichi units, with a flange being installed for the connection of mobile equipment. A seismic PSA should have highlighted a potential safety concern, since there was considerable pipework in the turbine building (including pipework carrying sea water through the turbine hall basement) that was not of a high safety grade. Consequently, it would have been assessed as having a significant likelihood of failure under severe seismic loading, which would then have resulted in the flooding of the EDGs and essential switch gear, leading to the failure of AC and DC power.

2.3.3.2. Results of the Fukushima Daiichi NPP PSA

The PSRs issued every ten years for each unit include the PSA results for internal at-power and shutdown events. For Fukushima Daiichi Unit 1, the third PSR was issued in November 2010. It reported a CDF of 3.9×10^{-8} per year and a containment failure frequency (CFF) of 1.3×10^{-8} per year. The CDF for SBO was 2.5×10^{-9} per year (for at-power internal events), which was only 6% of the total risk and was a small fraction of the overall calculated risk of a core damage event. The CFF from SBO was 1.5×10^{-9}, or 12% of the total.

These very low probabilistic results show the limitations of PSA modelling and assumptions applied for internal events. In addition, if internal hazards such as fire and flood and external hazards, such as seismic activity and tsunami, had been included, the risk of core damage from an extended loss of AC power would have been even greater, possibly by several orders of magnitude.

The CDF, CFF and SBO risks for the other units were similarly presented as being very low, as shown in the following:

— Unit 2 (from the second PSR issued in June 2001):
  - CDF for internal at-power events of 9.9×10^{-8} per year (SBO contribution of 44%, with a frequency of 4.3×10^{-8} per year);
  - CFF for internal at-power events of 1.1×10^{-8} per year (SBO contribution of 38%, with a frequency of 4.2×10^{-9} per year).
— Unit 3 (from the second PSR issued in March 2006):
  - CDF for internal at-power events of 1.3×10^{-7} per year (SBO contribution of 16%, with a frequency of 2.1×10^{-8} per year);
  - CFF for internal at-power events of 1.1×10^{-8} per year (SBO contribution of 11%, with a frequency of 1.2×10^{-9} per year);.
— Unit 4 (from the second PSR issued in March 2008):
  - CDF for internal at-power events of 1.6×10^{-7} per year (SBO contribution of 25%, with a frequency of 4.0×10^{-8} per year);
  - CFF for internal at-power events of 3.2×10^{-8} per year (SBO contribution of 20%, with a frequency of 1.6×10^{-8} per year).

Another reason why the SBO risk was reported as being low, and therefore not a major contributor, was the estimated high likelihood of recovering external AC power supplies (estimated at a 95% chance of recovery within the first 30 minutes) and the ability to cross-connect power supplies from an adjacent unit. Consequently, without considering multi-unit accident initiators and the extended loss of off-site power, which could result from external hazards, the SBO risk was very low.

Extreme external events may result in common mode failures, such as an SBO or a loss of ultimate heat sink (LUHS) if adequate provisions are not taken. In particular, flooding can cause massive common mode failures of all components which are not water resistant, whatever their redundancy, their diversity, their classification or their ranking in terms of defence in depth. Thus, with the inclusion of external hazards, an SBO would have been prominent among the overall risks of a severe accident.

The confirmed effectiveness of accident management measures by means of limited PSAs was also a factor contributing to the self-confidence about the high safety level of the plant. This self-confidence was derived from the limited scope of the PSAs, which did not take into account the importance of both internal and external hazards.

Venting of the PCV was considered in both the level 1 and level 2 PSAs for the units at the Fukushima Daiichi NPP. For accident sequences where heat removal from the PCV has failed, there is a possibility that the pressure of the PCV will be in excess of its design value before core damage occurs, in which case there is a procedure for using the hardened venting system to reduce this pressure. This is modelled in the level 1 PSAs. PCV venting in the level 2 PSA is assumed to occur at twice the design pressure at 8.53 kPa (gauge) for Unit 1 and 7.69 kPa (gauge) for Units 2–4. Procedures did not exist to address how to accomplish venting when all power, compressed air, lighting and indications are lost and when the actions need to be performed in a harsh work environment. These performance shaping factors were not adequately considered in deriving such a low human error probability of 1.9×10^{-3} for PCV venting. The use of mobile equipment, such as fire engines for water injection, was not considered within the PSAs.

2.3.3.3. Consideration of cliff edge effects

Paragraph 5.73 in IAEA Safety Standards Series No. NS-R-1 [2] states that: "A probabilistic safety analysis of the plant shall be carried out in order...to provide confidence that small deviations in plant parameters that could give rise to severely abnormal plant behaviour (cliff edge effects) will be prevented."

A report had been issued by JNES [63] for the development of tsunami PSA methodology, where it was assumed that complete loss of the safety function occurs when the inundation height exceeds its installed level if additional flooding protection was not present. Given the location of the battery rooms, switch gear rooms and EDGs in the lower levels of the turbine hall, it could be foreseen that flooding would lead to total loss of all AC and DC power which would likely result in core damage.

The plant would have been strengthened if critical equipment had been protected from flooding or moved to a higher elevation, or if mobile equipment to mitigate flooding had been stored remotely with the ability to access the reactors. Such measures add additional defence in depth and so would have removed this cliff edge effect. After the accident in March 2011, NISA emphasized that preventing the loss of a safety function due to common cause failure (such as flooding) was of the utmost importance [64] requiring the application of the principles of diversity and independence.

2.3.4. Summary

The accident at the Fukushima Daiichi NPP exceeded the design basis of the units in several respects. It was a severe accident involving multiple units and it was an accident during which the operators had little information on what was happening, rendering them unable to control the situation. Neither the Establishment Permit (under which the NPP was constructed) nor the PSRs for the Fukushima Daiichi units included deterministic safety analyses of BDBAs, which was not in line with IAEA safety standards. Some of the reasons why the particular BDBA of SBO did not warrant detailed analysis and additional mitigation were an assumed high likelihood of grid recovery within a short space of time and the existence of design features to mitigate single unit SBO events, such as unit electrical cross-connections. Consequently, a multi-unit extended loss of AC power was not considered in the assessment. The other BDBAs pertinent to the events of March 2011, such as the total LUHS, loss of DC power and the loss of SFP cooling, were also not assessed deterministically in the Establishment Permit or in the PSRs, which contained only DBAs.

Once TEPCO began preparing probabilistic risk assessments (later PSAs) in the early 1990s, some limited deterministic safety analyses of BDBAs were performed for those accident sequences that dominated the results of the PSA. However, given that the PSAs only covered single unit internal events, these deterministic safety analyses did not help in the accident management of multi-unit events such as the one that occurred. These BDBA analyses did not include flooding of the platform or extended loss of AC power.

The inadequacy of the deterministic BDBA analyses partially accounts for the inadequacies in plant hardware, accident guidance and training to cope with the events of March 2011. A comprehensive deterministic BDBA analyses allows for the identification of plant vulnerabilities and the need to protect the EDGs, battery rooms and emergency electrical switch gear from flooding.

It was common practice for Japanese plants to perform only limited scope PSAs, since existing regulations did not require more detailed assessments to demonstrate plant safety. Internal hazards (such as fire and flood) and external hazards (both natural and human-made) were mostly excluded from the PSAs, although NISA had instructed NPP owners in 2006 to perform seismic PSAs. The PSA for the Fukushima Daiichi NPP had yet to be completed and it was limited to the determination of CDF and CFF arising from internal events. A more comprehensive assessment would have indicated both how vulnerable the plant was to flooding and the high likelihood of flooding. A full scope level 2 PSA would have indicated a low probability of success for severe accident interventions given the limited training and guidance provided in SAM and the plant's vulnerability to common cause events.

2.3.5. Observations and lessons

— **Deterministic and probabilistic beyond design basis safety analyses need to be comprehensive and take into account both internal and external events, including internal flooding and external hazards such as seismic events and flooding.**
The combination of DSA and PSA needs to be used to assess factors such as cliff edge effects, realistic equipment and personnel performance, and the relative contribution of various accident sequences to the overall plant risk. For the sequences with the highest possibility of contributing to core damage or challenging the containment integrity, the operating organization should evaluate the need for taking actions to mitigate the consequences of these sequences.
— **Extremely low numerical values from PSAs need to be reviewed and confirmed.**
Comparison of the CDF calculated for the Fukushima Daiichi NPPs to the worldwide average for similarly designed BWRs would have indicated that the values calculated by TEPCO were at least two orders of magnitude lower than the other plants. This difference should have been investigated which may have highlighted weaknesses in the procedures and training being used at the Fukushima Daiichi NPP. However, this investigation was not conducted, which highlights the

issue that numerical values obtained from PSAs need to be used with caution when making decisions about the overall safety of the plant.

2.4. ACCIDENT MANAGEMENT PROVISIONS AND THEIR IMPLEMENTATION

2.4.1. Introduction

This section summarizes the status and implications of the accident management provisions available at the Fukushima Daiichi NPP. In accordance with IAEA terminology, both preventive (before core melt) and mitigative (after core melt or severe accident) parts of accident management are covered. All components of accident management (AM) are discussed, including hardware provisions, emergency operating procedures (EOPs) and severe accident management guidelines (SAMGs), human resources and organizational arrangements, including training and drills. The interface with the emergency arrangements is also discussed. Gaps in the provisions are identified based on a comparison of the situation prior to the accident with the relevant IAEA safety standards in effect at that time. The final part of the section is focused on the assessment of actual plant staff actions during the accident, discussing the key factors causing severe consequences of the accident.

2.4.2. Accident management provisions available at the Fukushima Daiichi NPP

2.4.2.1. National regulatory requirements related to accident management

The AM provisions available in Japan before the Fukushima Daiichi accident have been most comprehensively described in Accident Management for Severe Accidents at Light Water Power Reactor Installations, issued by the Nuclear Safety Commission (NSC) on 28 May 1992 [62]. This document describes the role and significance of AM, both preventive and mitigative parts of AM, and the results of the technical evaluation of provisions relevant for AM in BWRs and PWRs in Japan. Practices and measures taken in different countries and associated issues are described. In the conclusions, it was stated, based on a level 1 PSA, that the possibility of a severe accident in Japan was sufficiently low. Nevertheless, it was strongly recommended that AM measures be developed and implemented. Based on the document, there was an NSC decision of 28 May 1992 [62], amended on 20 October 1997, which strongly recommended that the regulatory body and utilities introduce AM measures at NPPs.

The NSC decision stated that:

— The safety of reactor facilities in Japan is sufficiently ensured by current safety regulations and the risk from reactor facilities is considered to be sufficiently low.
— The development of AM measures is significant in further reducing the risk, which is already low.
— Effective AM should be developed by licensees on a voluntary basis, and its proper implementation in the event of an emergency is strongly recommended.
— In order to further improve the safety of reactor facilities, licensees should continue to develop AM using specific proposals made by NSCRG: L-AM-II.01 [62].
— Government agencies should define their roles in the promotion and development of AM, and should continue to work on the details of these roles.
— For reactor facilities in operation or under construction, a report was expected from the government agency to the NSC review on AM implementation policies.
— The authorities concerned and licensees should continue severe accident studies.

Although the document describes the components of AM, it is clear that it is neither a regulation nor a regulatory guide which follows the IAEA safety standards, and that implementation of measures was left to the operators on a voluntary basis. There does not seem to have been an update of the document

since 1997, so more stringent recommendations that were included in the relevant IAEA safety standards on design (IAEA Safety Standards Series No. NS-R-1 [2], in 2000) or on SAM (IAEA Safety Standards Series No. NS-G-2.15 [49], in 2009) were not reflected in the NSC guidance.

2.4.2.2. Relevant findings from periodic safety reviews and international missions

The IAEA conducted an Integrated Regulatory Review Service (IRRS) mission from 25 to 30 June 2007 to the Japanese regulatory body, the Nuclear and Industrial Safety Agency (NISA) [53]. Although the mission did not explicitly deal with the safety assessment of individual NPPs, in reviewing the regulatory arrangements it identified some issues relevant for the area of AM. In the mission findings, the continuous efforts by NISA to update the legislative and governmental framework was acknowledged, but the mission also noted that:

> "There are no legal regulations for the consideration of beyond the design basis, as Japanese plants are considered to be adequately safe as ensured by preventive measures. The regulatory body has strongly requested licensees to voluntarily implement severe accident management (SAM) and carry out probabilistic safety assessment (PSA) including preventive and mitigatory measures in line with the guide for SAM review prepared by METI. Accident management measures are taken by licensees on a voluntary basis" [53].

Subsequent to this finding, the mission suggested that NISA should continue to develop a systematic approach to the consideration of BDBAs, and the complementary use of PSA and SAM in the assessment process for risk reduction purposes. In addition, the mission also suggested that the PSR should be more focused in order to provide a comprehensive picture of the plant safety status at certain intervals.

In the mission report it was also stated that all Japanese NPPs older than ten years, including the Fukushima Daiichi NPP, were the subjects of PSRs. The latest PSR for the Fukushima Daiichi NPP was performed in 2010 for Unit 1 and earlier for other units. However, there was no finding in the area of AM, nor were any relevant plant modifications proposed in the reports.

After the IRRS mission, several discussions regarding the need for the development of AM regulations or updating of the guidelines were initiated (including shortly before the accident), but no effective action was taken.

Although the IAEA, through its Operational Safety Review Team (OSART) missions, was invited to some Japanese NPPs, it was not invited to the Fukushima Daiichi NPP, nor was the World Association of Nuclear Operators (WANO) and its review missions.

2.4.2.3. Basic approach and strategies for implementation of accident management programmes

The recommendations in the area of AM made by the NSC (briefly described in Section 2.4.2.1) have been implemented in accordance with the guidelines contained in Refs [65, 66].

In response to the decision by the NSC given in NSCRG: L-AM-II.01 [62], the Ministry of International Trade and Industry (MITI), which was the regulatory body for NPPs at that time, encouraged the utilities in July 1992 to establish AM implementation plans using the insights obtained from PSAs. The utilities submitted their AM implementation plans to MITI in March 1994. MITI reviewed these plans and prepared a report in October 1994 entitled Accident Management for Light Water Nuclear Power Reactors [67]. In the report, MITI recommended that the utilities undertake the AM implementation plans, prepare AM operating procedures and establish the necessary administrative framework by 2000.

The utilities completed implementation of AM measures by February 2002 and reported to NISA, which was the new regulatory body for NPPs. In addition, the utilities submitted evaluations of the effectiveness of AM measures for eight representative BWR and PWR plants to NISA. After reviewing the evaluations, with the assistance of the Japan Nuclear Energy Safety Organization (JNES), NISA confirmed their validity. NISA recognized that it was also important to evaluate the effectiveness of AM measures for NPPs other than the eight representative plants and requested the utilities to perform evaluations of all plants. The utilities performed evaluations of the effectiveness of AM measures for individual plants in two steps: through level 1 and level 2 PSAs. From the results of the first step, summarized in [68], it is seen that:

— For the BWR-3 Mark-1 type, implementation of the AM measures led to a reduction in the core damage frequency (CDF) from 4.3×10^{-7} to 2.8×10^{-7} per year (discounting internal and external hazards which were not assessed).
— For the BWR-4 Mark-1 type, implementation of the AM measures led to a reduction of the CDF from 3.5×10^{-7} to 1.4×10^{-7} per year.
— For the BWR-3 Mark-1 type containment, implementation of AM measures led to a reduction in containment failure frequency (CFF) from 3.7×10^{-7} to 2.1×10^{-8} per year.
— For the BWR-4 Mark-1 type containment, implementation of the AM measures led to a reduction in the CFF from 2.8×10^{-7} to 5.5×10^{-8} per year.

The results were submitted to NISA in March 2004 as PSA Evaluation Report after AM implementation. NISA reviewed these reports with assistance from JNES and published an evaluation report of PSAs for all existing operating plants [69]. Based on comments from NISA, the PSA models were modified and new results were obtained as follows (examples for existing BWR-4):

— Frequency of core damage: 1.6×10^{-7}/reactor-year;
— Frequency of containment failure: 1.2×10^{-8}/reactor-year.

The assumed effectiveness of the AM measures, confirmed by PSA studies, was also a factor contributing to the confidence about the high safety level of the plant, although it was derived from limited scope PSAs which did not take fully into account the importance and significant contribution to risk of both internal and external hazards.

2.4.2.4. Summary of accident management provisions available at BWR plants

The AM provisions implemented at Japanese BWRs are summarized in Tables 2.4–1 and 2.4–2. The utilities selected AM measures focusing on the essential safety functions of NPPs. Specifically, reactor shutdown, coolant injection to the reactor vessel and the containment vessel, heat removal from the containment vessel, and supporting function to the safety systems were chosen as the four essential functions for BWRs, after which relevant AM measures were selected for each safety function.

TABLE 2.4–1. SAM FOR BWRs IN JAPAN — PREVENTIVE AM MEASURES

AM functions	Equipment and systems	Accident sequences	Details
Reactor scram	ARI activation with signals for high pressure of the RCS, or low liquid level. RPT activation with the same signals above.	Transients without scram.	New signals are independent of conventional scram and ECCS signals. These systems have already been implemented to ABWR in the design stage.
Depressurization	The ADS is activated by a signal with low liquid level of the reactor vessel.	Transients with failure to depressurize.	Not applied to BWR-3 and ABWR. BWR-3: isolation condenser was implemented. ABWR: high pressure ECCSs were already reinforced.
Alternative water injection	Use of the make-up line. Water supply from the fire protection system.	Transients with loss of ECCS injection.	—
Alternative heat removal	Containment hardened vent.	Transients with loss of decay heat removal.	—
Supply of AC power	Accommodation of 6.9 kV and 480 V from the adjacent plant.	Loss of all AC power.	This AM measure is applied to the Fukushima Daiichi NPP.

ABWR: advanced boiling water reactor; AC: alternating current; ADS: automatic depressurization system; AM: accident management; ARI: alternate rod insertion; BWR: boiling water reactor; ECCS: emergency core cooling system; RCS: reactor coolant system; RPT: recirculation pump trip.

TABLE 2.4–2. SAM FOR BWRs IN JAPAN — MITIGATIVE AM MEASURES

AM functions	Equipment and systems	Accident sequences
Depressurization (same as prevention)	The ADS is activated by a signal with low liquid level of the reactor vessel.	Transients with failure to depressurize.
Hydrogen control	Inerting of the primary containment by nitrogen.	Any accident including severe accident.
Alternative water injection to the reactor core	Use of the make-up line. Water supply from the fire protection system. External connection allows the use of mobile equipment such as fire trucks.	Transients with loss of ECCS injection.
Alternative water injection to containment	Use of the make-up line. Water supply from the fire protection system. External connection allows the use of mobile equipment such as fire trucks.	Same as above.
Alternative heat removal	Use of the dry well cooler and use of the heat exchanger in the make-up line. Recovery of the RHR system. The containment hardened vent.	Same as above.
Supply AC power	Accommodation of 6.9 kV and 480 V from the adjacent plant. Power supply from the EDGs.	Loss of all AC power.

ADS: automatic depressurization system; AM: accident management; ECCS: emergency core cooling system; EDG: emergency diesel generator; RHR: residual heat removal.

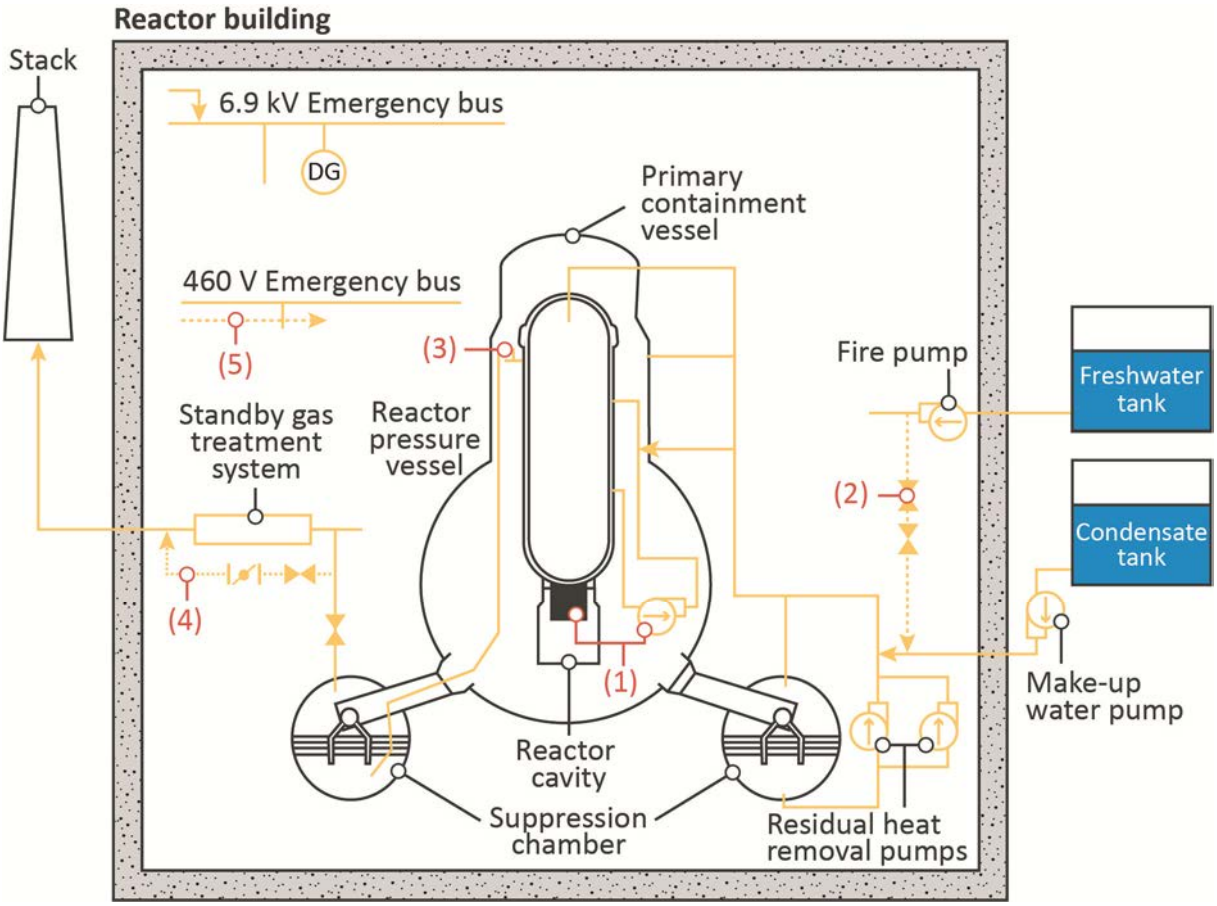


FIG. 2.4–1. Examples of AM actions for BWRs in Japan (DG: diesel generator).

Examples of AM measures are illustrated in Fig. 2.4–1:

(1) Reactivity control (automatic insertion of control rods or automatic stopping of reactor recirculation pumps);
(2) Water injection to the reactor and reactor containment vessel (pumps of condensate make-up water system or fire protection system);
(3) Reactor depressurization system;
(4) Heat removal from the reactor containment vessel (through dry well cooler and reactor coolant cleanup system or hardened containment vent piping);
(5) Means for power supply from adjacent nuclear units.

In addition to the hardware provisions explained above, the organizational provisions that have been established in Japanese NPPs for implementation of AM hardware are summarized as follows [66]:

— Organization: To implement the AM provisions, supporting organizations, in addition to the operators, are also involved focusing on technical evaluation, communication, dose assessment and restoration. Operational actions are carried out mainly at the discretion of a central control room. Furthermore, when an accident has escalated to core damage and requires a decision, the supporting organization provides the technical evaluation to support the decision making of operators. There was a seismically robust technical support centre (TSC) at the plant that was suitable for the supporting team.
— Procedures: Consistent with the plant upgrades, the electric utilities have prepared procedures for operators and for supporting organizations based on the progression of the event. For operators, in addition to emergency operation manuals (for BWR plants) to prevent core damage, emergency

operation manuals for post-core damage were provided to respond to a severe accident. Procedures and manuals, developed in 1987 in the USA by the BWR Owners' Group (BWROG), were used as a basis for development of the plant specific documents. Japanese BWR utilities conducted a joint research programme to develop unique accident management guidelines. These utilities also benchmarked the BWROG procedures in the joint research programme. For supporting organizations, in order to judge the mitigation measures in a comprehensive manner after core damage, the AM guide included procedures and criteria, knowledge bases such as technical data, and projected consequences.

— Education, training and communications system: The electric utilities have programmes in place for periodic education to enhance knowledge on plant behaviour during a severe accident and drills for examining the effectiveness of the organizations for implementing AM. A desktop training method was used for AM training, with the scope and frequency of training established in the plant's technical specifications. The knowledge base consists of information, including types of information and criteria for identifying operating status and making correct decisions during the implementation of the AM measures. Furthermore, systems have been developed to provide training to notify and communicate with the internal and external organizations about the plant conditions and the status of implementation of AM measures, and also to exchange information and to receive guidance and advice.

The course and consequences of the accident demonstrated that the organizational provisions were not adequate.

2.4.2.5. Accident management provisions at the Fukushima Daiichi NPP Units 1–4

From the point of view of AM, the similarities and differences between the individual units at the Fukushima Daiichi NPP can be summarized as follows:

— Unit 1 of Fukushima Daiichi was equipped with the BWR-3 type, while Units 2–4 were equipped with the BWR-4 type; however, this difference was not essential for AM.
— All units had the same Mark-I type containment.
— For a reactor scram, all of the units had the same provisions, consisting of a control rod drive hydraulic control system (CRDHCS) and standby liquid control system (SLCS).
— Automatic depressurization was available in Units 1–4. All units had provision for 6.9 kV and 480 V emergency electric power supply from adjacent units.
— All units had two EDGs.
— For emergency core cooling at high pressure, all units had steam driven high pressure coolant injection (HPCI).
— Unit 1 had two trains with isolation condensers (IC).
— Units 2–4, of more recent design, had, instead of ICs, a reactor core isolation cooling (RCIC) system.
— For emergency core cooling at low pressure, all units had two trains of core spray (CS); in addition to CS, Units 2–4 also had two trains of a low pressure coolant injection (LPCI) system.
— For containment heat removal, Unit 1 had two trains of a shutdown reactor cooling system and two trains of containment cooling systems (CCSs). On the other hand, Units 2–4 had just two trains of a residual heat removal (RHR) system.

2.4.3. Comparison of accident management provisions at Fukushima Daiichi Units 1–4 with IAEA safety standards

This section includes a comparison of AM provisions available at the Fukushima Daiichi NPP prior to the accident with the IAEA safety standards that were in effect at the time of the accident. Although severe accidents were not part of the design basis for existing plants, they were sufficiently well established and described in a number of IAEA safety standards and other guidance published in

reaction to the Three Mile Island and Chernobyl accidents, long before the Fukushima Daiichi accident.

The assessment in this section is based on a comparison with IAEA Safety Standards Series No. NS-G-2.15 [49], issued in 2009, while hardware and procedural provisions at Fukushima Daiichi were implemented in 2002, with some updating in 2007. Even though the safety standard was issued following the hardware modifications, such an assessment is still considered as a source of lessons learned.

The most important principles in the IAEA safety standards available prior to the Fukushima Daiichi accident are summarized in the text below, followed by the assessment of the provisions available at the NPP. Information about the equipment, procedures and staffing of the NPP presented in Technical Volume 1, as well as relevant sections of Technical Volume 2, were extensively used for the assessment. Among other sources, Refs [70, 71] provided additional valuable inputs.

2.4.3.1. Availability and results of plant specific analytical studies supporting the development of procedures and guidelines

Recommendations in IAEA safety standards

In accordance with IAEA Safety Standards Series Nos NS-R-1 [2], GS-G-4.1 [5], NS-G-1.10 [72] and NS-G-2.15 [49], the development of the AM programme should be based on insights into possible plant damage states, which can be obtained by best-estimate analysis using up to date, validated computer codes in all phases of the development, from the initial considerations up to the validation of procedures and guidelines. Analyses are needed to investigate the effectiveness of the proposed actions, including assessment of potential negative consequences of the actions. Uncertainties in the determination of timing and severity of phenomena should be taken into account in the use of the results. If generic results are used, they should be adapted to the specific plant. Use of PSA levels 1 and 2 is encouraged as a valuable input for the development of AM guidance. However, in view of the inherent uncertainties involved in determining credible events, the PSA should not be used a priori to exclude accident scenarios from the development of SAM guidance. Identification of potential challenges should be sufficiently comprehensive to provide a basis for guidance for plant personnel even if the scenario constitutes a very unlikely path within the PSA or is not identified in the PSA at all.

Assessment of the plant status using the applicable IAEA safety standards

As described in Section 2.3, the approach to implementation of SAM provisions was based mainly on a generic risk informed approach, where the BWROG analysis was reviewed for the PSA impact. Several results of analysis considered relevant for the development of SAM strategies (symptoms, time windows, prioritization and effectiveness of the strategies, including recovery actions, determination of environmental conditions both for staff as well as equipment) were not included in sufficient detail. Sensitivity studies with varying values of symptoms and time windows important for demonstration of the effectiveness of the strategies were not covered. It is clear that there was no analysis considering the possibility of recovery actions in the worst case scenario. It was assumed that even during the severe accident progression there would be some means available for successful recovery actions, the feasibility of which was not investigated in sufficient detail.

2.4.3.2. Procedures and guidelines for accident management

Recommendations in IAEA safety standards

In accordance with IAEA Safety Standards Series Nos NS-R-1 [2], NS-R-2 [73], NS-G-2.2 [74] and NS-G-2.15 [49], development of an AM programme consisting of EOPs and SAMGs is a requirement to be implemented at any NPP. For the beyond design basis area the emergency operating procedures (EOPs) and SAMGs should be symptom based, with clear interfaces between them. They should cover prioritization of actions, initiations and termination criteria, time windows for actions and their duration, equipment and resources needed for an action, cautions in performing the action and monitoring the plant response. Procedures and guidelines should consider using any plant equipment available and should be consistent with available hardware provisions. Possible positive and negative consequences should be specified in using the SAMGs. The AM guidance should address the full spectrum of credible BDBAs; that is, all accidents considered credible on the basis of possible initiating events, and possible complications during the evolution of the accident that could be caused by additional hardware failures, human errors and/or events from outside including issues which are not considered in the safety analysis.

The procedures and guidelines should be written in a user friendly way so that they can be executed under high stress conditions. Pre-calculated graphs or simple formulas (computational aids) should be developed in order to facilitate decision making. There should be adequate background material available to provide information for understanding the procedures and for training. In the development of EOPs and SAMGs, habitability of the control places should be taken into account.

EOPs and SAMGs should be independently reviewed, and they should be validated in full using appropriate simulation methods (simulator, computer simulation, tabletop exercise). Validation should be done under conditions that realistically simulate conditions present under an emergency.

Assessment of the plant status using applicable IAEA safety standards

Accident management guidance in place at the Fukushima Daiichi NPP units at the time of the accident included abnormal operating procedures (AOPs), EOPs, and severe accident operating procedures used by control room operators. In addition, accident management guidelines (AMGs) were in place for use by the technical support staff in the Emergency Response Organization. Collectively, these documents covered the realm of response from abnormal conditions, DBAs and BDBAs, including severe accidents.

The plant specific EOPs were based on generic emergency procedure guidelines (EPGs) developed by the BWROG in January 1987 [75]. In 1992, the Nuclear Safety Commission (NSC) recommended to Japanese utilities that they implement AM measures to address severe accident conditions. In response, the Japanese utilities performed joint research programmes, which included plant specific evaluations using PSA methodology and the development of AMGs. The completed AM reports were submitted to the Ministry of Trade and Industry (MITI) in March 1996. Based on insights from the PSAs, modifications to the Fukushima Daiichi NPP were made and AM measures, including severe accident operating procedures and AMGs, were implemented between 1997 and 2002. These improvements included the use of alternate injection systems such as the water used for fire fighting and MUWC system, a hardened primary containment vent, alternate rod insertion (ARI) system, and reactor recirculation pump trip (RPT) system. After this effort was completed, a report was submitted to NISA summarizing the actions that were implemented to address severe accident conditions.

During the late 1990s, the US nuclear industry undertook a significant effort to identify vulnerabilities and to develop guidance to address severe accidents which involved the loss of core cooling and subsequent core damage. This industry effort was conducted in accordance with NEI 91-04, Severe

Accident Issue Closure Guidelines [76]. The SAM closure process, as described in NEI 91-04, consisted of the following steps:

— Evaluate industry developed bases and owners group SAMGs, along with the plant individual plant examination (IPE), individual plant examination of external events (IPEEE) and current capabilities, to develop SAMGs for accidents found to be important to each plant;
— Interface SAMGs with the plant's emergency plan;
— Incorporate severe accident material into appropriate training programmes;
— Establish a means to consider and possibly adopt new severe accident information from self-assessments, applicable regulatory communications, PSA studies, etc.

In support of this effort, the BWROG performed a number of improvements to the emergency procedure guidelines (EPGs) and created new SAGs. Revision 2 [77] to the BWROG EPGs/SAGs was implemented in March 2001 and was the most current revision at the time of the Fukushima Daiichi accident.

Some of the key improvements in accident response that were implemented in the BWROG EPG/SAGs included:

— New SAGs which specify optimized strategies for events in which core cooling can no longer be ensured. The SAGs provide specific strategies to deal with phenomena such as core melt progression, recriticality, creep rupture, high pressure melt ejection, Mark I containment liner challenges, hydrogen generation, core–concrete interaction and fission product release.
— Comprehensive anticipated transient without scram (ATWS)/stability modifications, including the injection of soluble boron to mitigate the consequences of large irregular oscillations by limiting their duration.
— Optimized hydrogen control strategies, including strategies to address combustible gas concentrations above the deflagration limits.
— Addition of the IC as a system that may be used to rapidly depressurize the RPV, since the IC rejects heat outside containment with no net loss of inventory and provides a relatively large heat sink.
— Revised guidance on the utilization and termination on dry well and suppression pool sprays, including the authorization to use sprays for fission product scrubbing at low pressures or if the containment has failed. This included the use of alternate systems if normal spray systems are unavailable.
— Restricted the use of external injection and spray sources only under conditions which would not challenge primary containment integrity.
— Authorized defeating interlocks such as HPCI and RCIC high temperature trips and suppression pool and dry well spray interlocks under certain conditions.
— Added new cautions to warn of the effects of high cooling water temperatures upon HPCI and RCIC turbines and to emphasize that reducing primary containment pressure will reduce available net positive suction head (NPSH) for pumps drawing suction from the suppression pool.

Although TEPCO was a member of the BWROG and had acquired the updated BWROG EPG/SAG products, they had not implemented these improvements in AMG at their NPPs. Delays in implementing the improved industry guidance was based on the belief that their existing procedures and guidelines were adequate and the need to prioritize station resources on addressing other issues at the plant.

Although the relevant procedures were available in the plant, their effective use was not feasible. From the description of the provisions available in the plant, it is clear that the AM programme was developed with the assumption that AC power would always be available, either from its own power sources in the unit or that it could be easily re-established by connecting with the neighbouring units.

In addition, it was assumed that DC power would always be available for the proper functioning of the instrumentation and for manipulating valves. These assumptions turned out to be incorrect. For these reasons, the procedures did not cover contingency actions for situations without the availability of instrumentation needed to show key plant parameters. The plant procedures were not established for performing the action, when all safety related electrical distribution systems, and subsequently many of the safety systems, become inoperable due to a single event. In the absence of AC power, with limited possibilities of manual actions and without adequate information about the plant status, it was very difficult to perform any effective actions.

Although mobile sources of coolant (such as fire trucks) were available on the site and provisions for connection of these sources to the plant had been made, the use of these sources failed or was delayed either due to the absence of adequate procedures or other obstacles in the implementation of the procedures. No alternative methods were prepared for the assessment of the plant status, in the case of complete absence or very limited quantity of information obtainable from the instrumentation. Operating procedures also did not adequately cover the situation of prolonged loss of power, e.g. how to vent the containment under conditions associated with limited possibility of monitoring the plant status.

2.4.3.3. Hardware provisions for SAM and their survivability under conditions of extreme external hazards and severe accident conditions (including instrumentation and power supply)

Recommendations in IAEA safety standards

Guidance on hardware provisions is described in IAEA Safety Standards Series Nos NS-G-1.10 [72] and NS-G-2.15 [49]. According to these guides, the plant should be equipped with adequate hardware provisions in order to fulfil the fundamental safety functions as far as is reasonable for BDBAs and severe accidents as well. Modification of the plant should be considered whenever needed for the development of a meaningful AM programme. Hardware implementation or upgrading should focus on preservation of the containment function.

The equipment needed to mitigate a severe accident should be, to the extent possible, independent of the equipment available to fulfil design basis requirements. Special attention should be devoted to the I&C as an essential component for effective AM. The plant parameters needed for AM measures should be identified and be available from the instrumentation. Dedicated instrumentation that is qualified for the expected environmental conditions is the preferred method to obtain the necessary information. The ability to infer important plant parameters from local instrumentation or from unconventional means should also be considered. The need for the development of computational aids to obtain information where parameters are missing or their measurements are unreliable should be identified and aids developed accordingly.

Appropriate measures should be taken to remove the decay heat from the corium debris to an ultimate heat sink. Where it is needed to remove the decay heat by repeated or continuous venting of the containment atmosphere, such venting should take place through a pathway that can provide an appropriate reduction in the fission product releases, e.g. by filtering or scrubbing.

Assessment of plant status against IAEA safety standards

Although some design provisions aimed at strengthening AM capabilities were implemented at the Fukushima Daiichi NPP, there remained several weaknesses that contributing significantly to the transition of the initiating event into a severe accident in parallel at several units. The most important issues were as follows:

— Difficult access to some manually operated valves under degraded environmental conditions;

— Limited means of communication for conditions of prolonged loss of power supply;
— No hydrogen countermeasures in the reactor building, outside the primary containment vessel;
— Insufficient radiation protection equipment available for response to the accident;
— Insufficient supply of fuel and other consumables needed for continuous operation of the fire trucks and of compressed air for the manipulation of valves;
— Unavailability of monitoring equipment independent of DC power (pressure and temperature monitors) as well as equipment allowing local manipulation of valves. Lack of independent battery powered lighting of the MCR and access pathways.

2.4.3.4. Organization and arrangements of the licensee to manage accidents (including training and drills)

Recommendations in IAEA safety standards

IAEA Safety Standards Series Nos NS-R-2 (superseded by SSR-2/2) [73, 78], NS-G-2.8 [79] and NS-G-2.15 [49] require that there should be appropriately staffed and qualified teams responsible for SAMG execution as well as for the technical support centre (TSC). The functions and responsibilities of the staff should be clearly specified, considering that there is a need for specialized experts serving as evaluators, decision makers and implementers of the actions. The transfer of responsibilities between the teams should be clearly defined. Integration of the AM programme within the overall emergency arrangements for the plant should include possible interaction between security measures and the execution of AM actions. Reliable methods of communication, under conditions of prolonged SBO, should be available, in particular between the MCR, TSC and the ERC. Criteria for activation of the TSC should be specified. Decision making authority should be assigned to a high level plant (or site) manager.

In order to comply with these needs, there should be adequate training organized by professionals for all individuals and groups involved in the application of the AM programme, using a combination of classroom training, exercises and drills. Training on severe accident phenomena at the necessary technical level to the appropriate individuals should be provided. The training should cover the use of non-conventional line-ups and equipment, such as mobile equipment. Refresher training should be organized at appropriate intervals, with periodic confirmation of competences of the personnel. Exercises and drills should require the application of a substantial portion of the overall SAMG package and should involve the participation of all individuals and groups, with local, national and, where appropriate, international participation. It should be verified that the emergency response and all related duties can be carried out in a timely manner according to the schedule and under conditions of stress. There should be full scale exercises involving external organizations such as police, fire services, ambulance teams, rescue teams and other emergency services. Training programmes should be reviewed and updated periodically.

Assessment of the plant status against IAEA safety standards

Organizational arrangements and the managerial decisions taken were appropriate for normal operation. However, in spite of large human and equipment resources, summarized in Section 1.2 of Technical Volume 1, the arrangements and decisions were inadequate for this emergency, as explained below:

— Communication between the main control room and the site ERC was insufficient or ineffective.
— The operators did not have adequate access to the external engineering experts who could have provided advice on SAM.
— Insufficient communication between the MCR and the ERC did not provide the latter the opportunity to provide advice on mitigatory actions.

— The transfer of responsibilities between different decision makers was not clear. In particular, the transfer of responsibilities from the MCR staff to other decision makers was delayed, contributing to greater stress for the staff.
— Plans for replacing operating shifts were not adequate for conditions of severely damaged infrastructure and plant surroundings.
— There was no possibility for external qualified engineering support for independent assessments and advice on recovery actions.

Information about the arrangements for staff training is provided in Section 1.2 of Technical Volume 1. Based on the information presented there, it can be concluded that the approaches and means used in training were similar to other NPPs worldwide. Since the occurrence of a severe accident was considered extremely unlikely, staff training did not pay enough attention to severe accidents and was not performed to the level required for an accident situation. More specifically, the following weaknesses in training were identified:

— Infrequent refresher training for dealing with severe accidents (once in every three years) did not provide the basis for sufficient knowledge and depth of understanding.
— Staff was not trained to perform AM actions under conditions of prolonged SBO, with extremely limited information about the plant status and limited possibility to use equipment which was dependent on availability of AC or DC power.
— Operator training for Unit 1 was performed on a Unit 3 reference simulator, which did not include IC systems, and therefore did not correspond to Unit 1; only a limited scope (compact) simulator and plant analyser was available for Unit 1.
— SAM training was not sufficiently detailed regarding assessment of the plant status under conditions of missing or limited information.
— Without information from the TEPCO's Safety Data Parameter Display System (SPDS) for the monitoring of fundamental safety functions during the accident, the personnel were not trained to use contingency means for monitoring the functions.
— Drills did not include consideration of inaccurate or missing information to Off-site Centre (OFC) personnel which would enhance their capability in diagnosing the event.

2.4.3.5. Interface with off-site emergency arrangements

Recommendations in IAEA safety standards

According to IAEA Safety Standards Series No. GS-R-2 [80] and NS-G-2.15 [49], there should be a clear determination of responsibility, coordination and exchange of information between all organizational units involved in emergency actions, including interfaces with off-site emergency arrangements. Off-site and on-site emergency response should be coordinated between all responding organizations. If off-site organizations have responsibilities in AM, this should be described. Roles and responsibilities for the different members of the emergency response organization involved in AM should be clearly defined and coordination among them should be ensured. Where the members of the emergency response organization are not at the same location, a reliable communication network between the different locations should be used. The impact of external events, such as extreme weather conditions, seismic events or events that are disruptive to society should be considered when assigning the decision making authority for SAM at an off-site location. Guidance should be available for measures to be taken if off-site communication fails and only the part of the emergency response organization located at the plant site remains functional. Arrangements for local response should be integrated with the arrangements at the national level concerning functions, responsibilities, authorities, allocation of resources and priorities. This objective requires effective communication between all the organizations involved. It is the responsibility of the regulatory body to ensure that such arrangements are in place.

Assessment of the plant status against IAEA safety standards

As stated by TEPCO [70], the combination of earthquake and tsunami was not considered in disaster management plans and engineering before 2011. Plans for utilizing off-site support, including both national industry as well as international support by operators and vendors, were not adequate for the accident. Coordination between the site ERC and corporate ERC personnel was not effective. Capabilities to predict the evolution of the accident, both for the site staff as well as for corporate ERC staff, were limited. The Off-site Centre, which was essential for coordination of external support at the corporate and governmental levels was not functional. The facility was not designed to be robust enough, so that both normal and backup power was lost, and without filtered ventilation it was not habitable due to high dose rates. There was no contingency plan for relocation of the Off-site ERC to other places under the harsh conditions. Organizational arrangements for sharing responsibility among the site ERC, corporate ERC and the government did not function as planned. There was no access by plant staff to reactor vendors and architect–engineering personnel with specialized knowledge and experience.

2.4.4. Evaluation of accident management actions at the Fukushima Daiichi NPP and identification of key factors leading to severe consequences of the accident

This section evaluates the performance of the AM actions during the course of the accident and identifies the most important factors that increased the severity of the accident. After presenting general issues affecting the performance of the AM actions at all units, more specific issues relevant for each of the units in Sections 2.4.4.1–2.4.4.4. Section 2.4.4, in combination with findings in Section 2.4.2, provides the basis for the formulation of lessons learned in the area of AM presented in Section 2.4.6.

In terms of the general issues affecting the implementation of AM actions at all units, although the staff's response was extraordinary under the harsh conditions, their actions were not optimum. In addition to the issues identified in Section 2.4.2, more specific reasons for the difficulties in preventing and later mitigating the severity of the accident at the Fukushima Daiichi NPP can be summarized as follows:

— The combined impact of the earthquake and tsunami resulted in the complete loss of all AC and DC power sources at Units 1, 2 and 4, and only limited, temporary, DC power at Unit 3, rendering the majority of systems inoperable.
— Core melting occurred in Units 1–3 due to the inability to inject water caused by the SBO and the loss of DC power.
— Primary containment vessel cooling was lost due to the loss of AC and DC power and compressed air.
— The challenges with the depressurization of the reactors contributed to the severity of the accident.
— The lack of immediately available external pumps and coolant supply.
— Depressurization of the reactor without adequate heat removal from the primary containment vessel led to high temperature, leading to the loss of containment integrity.
— Containment venting was delayed until a late stage during the accident, causing the primary containment vessel to lose its integrity. As a result, large quantities of steam, hydrogen and fission products were released into the reactor building, leading to hydrogen explosions.
— The control room became uninhabitable after some time and was accessible only with special protective clothing.
— AM measures relied heavily on the indication of the reactor water level, which due to the loss of DC power and the harsh environmental conditions resulted in false non-conservative indications.
— Lack of instrumentation on plant parameters prevented the staff from having a clear understanding of core cooling or the status of safety systems in order to take appropriate actions.

— Both on-site and off-site radiation monitors for dose rate and contamination were lost due to the loss of AC power.
— In spite of a substantial body of knowledge on severe accidents, misunderstanding of the plant status led to less than optimum decisions on AM actions and their prioritization.
— Lack of effective communication significantly extended the time needed to perform verification and control actions.
— The absence of a proper means of communication and high radiation levels seriously complicated the coordination of containment venting with emergency planning actions.
— Opening of direct release path from the primary containment vessel to the reactor building and to the environment without filters resulted in a substantial release of radioactive material.
— Contaminated debris of the reactor building structure were spread widely due to hydrogen explosions, resulting in large scale contamination of the site. This greatly complicated the recovery actions.
— The relationship of actions contained in the plant procedures and emergency plans was not clear enough (it was not clear if venting could start before the end of evacuation was confirmed), possibly contributing to a delay in containment venting.
— The established strategy delaying containment venting was not optimum since venting took place under conditions of a severely damaged core (high source term, large amount of hydrogen) — both factors significantly increasing the release.
— Insufficient communication between the MCR and the ERC did not allow for the opportunity to provide advice on mitigatory actions.
— There was no ready availability of external qualified engineering support.
— There was a need to perform AM actions on several units in parallel with inadequate human and equipment resources.
— Difficulties in replacing operating shifts led to the necessity for many workers to stay very long on-site under difficult living conditions which led to fatigue and possibly contributed to the difficulty in making complex decisions.
— The effectiveness of external support from the local government was significantly reduced due to the recovery actions that were required as a result of large scale infrastructure damage.

2.4.4.1. Unit 1: Specific issues

Key factors in the progression of the accident at Unit 1 included the following:

— After the earthquake, but prior to the tsunami, the operators, according to procedures, were cooling the reactor by cycling the operation of the IC in order to control the reactor pressure. During this procedure, they switched off the IC because they were exceeding the operational technical specification (OTS) cooling limit of 55°C/h just before the impact of the tsunami. The plant supervisor and operator did not notice that the IC was isolated, which led to a delay in the initiation of recovery actions, so that subsequent core damage and reactor vessel failure occurred much earlier than at Units 2 and 3 The fact that the operator did not have full knowledge of the status of the IC and the valves contributed to the unavailability of this system.
— The unclear and inappropriate instructions for operating the containment vent system, and a lack of appropriate training for the staff where containment exceeded its design pressure, were allowed for a relatively long time. Furthermore, the delay in lowering the containment pressure hindered the efforts of the field operators to implement an alternative type of water injection into the reactor vessel.
— The inappropriate design of the containment venting system, with shutoff valves not designed to be operated under severe conditions, loss of DC power and compressed air and, later on, the harsh environmental conditions in the reactor building.

2.4.4.2. Unit 2: Specific issues

Key factors influencing the progression of the accident at the unit included the following:

— The RCIC was started manually when the feedwater was lost due to the lack off-site AC power following the earthquake. After depletion of the water storage tank, the RCIC suction was switched over to the suppression chamber. There were difficulties in confirming the operational status of the RCIC due to the loss of instrumentation power. Nevertheless, the RCIC maintained reactor inventory and cooling for almost three days.
— The RCIC was not designed to operate during the prolonged loss of AC power (without cooling of the suppression chamber) and without DC power (with loss of turbine control). As a result, the RCIC was lost on 14 March, but a clear reason for this was not determined.
— The HPCI could not be used when the RCIC was lost because of the lack of DC power.
— Effective venting of the containment vessel was not implemented before RCIC failure, preventing heat removal from the primary containment vessel.
— The hydrogen explosion in Unit 1 caused a blow-out panel on the wall of the reactor building of Unit 2 to open; the hydrogen released from the primary containment vessel did not accumulate in the reactor building, but was released directly into the atmosphere.

2.4.4.3. Unit 3: Specific issues

Key factors in the progression of the accident in the unit included the following:

— Emergency lighting and some indications remained functional after the tsunami due to the availability of DC power, attributable to the higher elevation of the batteries and busbars compared with Units 1 and 2 (the battery discharge time being about 8–10 hours).
— The RCIC system was manually started at 15:05 on 11 March. More optimum operation of RCIC by the operators was possible due to the availability of DC power avoiding automatic reactor high level RCIC shutdown (bypassing part of the injected water). The RCIC system operated for more than 20 hours until its unexpected shutdown, with attempts to restart it being unsuccessful.
— Following the failure of the RCIC system, the HPCI system started at 12:35 on 12 March due to the low RPV water level. The operators ran the system continuously to conserve DC power until 02:42 on 13 March, when the HPCI system was manually shut off.
— The longer availability of DC power was achieved by switching off unnecessary loads and controlling the water injection rate manually to prevent the unnecessary start and stop of the HPCI/RCIC systems.

2.4.4.4. Unit 4: Specific issues

Key factors for damage of the unit included the following:

— Since there was a serious concern about the status of the SFP, a great deal of effort was devoted to delivering coolant to the pool by various means (e.g. helicopters and fire trucks).
— Late containment venting under conditions of severe core damage in Unit 3 led to the accumulation of leaked hydrogen in the reactor building of Unit 4 through the shared reactor building ventilation system. This was caused by the inadequate design of the venting system common to Units 3 and 4, which led to the accumulation and eventual explosion of hydrogen in the Unit 4 reactor building.

2.4.5. Summary

Although severe accidents were not part of the design basis for the units, requirements and guidance for severe accidents were included in the IAEA safety standards well before the accident at the

Fukushima Daiichi NPP. Japanese practice at the time of the accident was not fully in line with these requirements and guidance. TEPCO had developed emergency and accident management procedures, which had been strongly recommended by the Nuclear Safety Commission, but which were not a requirement. The IAEA's International Regulatory Review Service (IRRS) mission in 2007 had suggested that the regulatory body continue to develop a systematic approach to BDBAs, and the complementary use of PSA and SAM in the assessment process. However, this was not done.

The AM programme and procedures assumed that AC power would always be available at a unit, either from its own power source or through a connection with the neighbouring units. It was also assumed that DC power would always be available for the proper functioning of the instrumentation and for manipulating valves. These assumptions turned out to be incorrect. The procedures also did not consider the possibility that a severe accident could impact several units simultaneously or that the off-site infrastructure could be seriously disrupted, making it more difficult to receive support in responding to an event or accident.

The combined impact of the earthquake and tsunami resulted in complete loss of all AC and DC power at Units 1, 2 and 4, with only limited DC power being temporarily available in Unit 3. This caused the cores of Units 1, 2 and 3 to melt because of the inability of the operators to inject water to cool them. Primary containment vessel cooling was also lost due to the loss of AC power, which, combined with the delay in venting the containments until a late stage of the accident, resulted in their failure. As a result, large quantities of steam, hydrogen and fission products were released into the reactor buildings, leading to three hydrogen explosions.

Accident management actions relied strongly on the indication of the reactor water level, which due to the loss of DC power and harsh environmental conditions, resulted in no (or false non-conservative) indications. The lack of instrumentation meant that staff did not have a clear understanding of plant parameters on core cooling or the status of safety systems in order to take appropriate actions.

Beyond design basis accidents were not addressed sufficiently, either by deterministic or probabilistic methods. Design basis accident analyses cannot be the sole basis for efficient development of defence in depth, since these analyses do not deal with BDBAs. The Fukushima Daiichi units were reasonably well equipped with systems to cool the core in the absence of AC power. However, the complexity of system performance under beyond design basis conditions together with inadequate training meant that the operators were not able to operate the systems, contributing to the severity of the accident.

The lack of effective communications significantly extended the time needed to perform verification and control actions. Lack of the proper means of communication and high radiation levels seriously complicated coordination of containment venting with emergency planning actions. Problems with communication between the MCR and the ERC did not allow the centre the opportunity to provide advice on mitigatory actions.

Operating experience from the 2007 earthquake that affected the Kashiwazaki-Kariwa NPP had resulted in the fitting of the means for the injection of cooling water via external portable pumps into all reactors. This was essential to the restoration of cooling water injection into the reactors at Units 1-3. However, training in the use of this equipment and other installed equipment under extreme environmental conditions was insufficient to allow for its timely use, given the complete loss of power. The weaknesses in the training and the available strategies for severe accident response are in part related to the fact that although TEPCO had access to the latest guidance from the BWROG, it did not implement this guidance at its reactors. As a result, operators and emergency response personnel were not able to address the degraded plant conditions that occurred following the earthquake and tsunami because the necessary accident mitigation strategies were not in place.

The need to perform AM actions on several units in parallel with an inadequate number of people and equipment caused great problems for the operators. Difficulties in replacing operating shifts led to many workers staying on-site for a very long time under difficult living conditions, which led to fatigue and possibly contributed to the difficulty in making complex decisions. There was no engineering support readily available from off-site sources. External support from the local government was significantly reduced due to the large scale infrastructure damage.

2.4.6. Observations and lessons

— **Accident management provisions need to be clear, comprehensive and well designed.**
Accident management strategies need to be based on a plant specific analysis performed by using a combination of deterministic and probabilistic approaches. Accident management guidance procedures need to consider events taking place in several units simultaneously and in SFPs. These provisions need to take into account disrupted regional infrastructure, including serious deficiencies in communication, transportation and utilities.
— **Regulatory bodies need to ensure that adequate AM provisions are in place, taking into account severely damaged infrastructures and long duration accidents.**
The Nuclear Safety Commission (NSC) recommended in 1992 that the regulatory body and the utilities introduce AM measures, although this had not been a requirement. In response, TEPCO had developed emergency and AM procedures. An IAEA IRRS mission to Japan in 2007 noted that AM measures were "taken by licensees on a voluntary basis" [51]. Therefore, it was suggested that the regulatory body develop a systematic approach for BDBAs, and the complementary use of PSAs, and SAM in the assessment process was recommended. However, no effective action was taken.
— **Training and exercises need to be based on realistic severe accident conditions.**
Special attention in personnel training needs to be devoted to performing actions under conditions of prolonged SBO with limited information about the plant status or the unavailability of important safety parameters. Staff training, exercises and drills need to realistically simulate the progression of severe accidents, including the simultaneous occurrence of accidents in several units. Training, exercises and drills need to involve not only on-site AM personnel or personnel executing on-site emergency plans, but also all off-site responders at corporate, local, regional and national levels.
— **Provisions for the proper management of hydrogen need to be considered.**
The hydrogen explosions at the Fukushima Daiichi NPP significantly affected the ability of operators to respond to the accident. Hydrogen monitoring and removal equipment should be installed in the plant to prevent hydrogen deflagration or explosions.

2.5. ASSESSMENT OF THE EFFECTIVENESS OF REGULATORY PROGRAMMES

2.5.1. Introduction

This section describes and evaluates the governmental, legal and regulatory framework for nuclear safety in Japan up to the time of the accident at the Fukushima Daiichi NPP. It focuses on the framework's contribution to the accident, and identifies lessons learned.

2.5.2. Governmental, legal and regulatory framework for nuclear safety in Japan

The evolution of the governmental and regulatory organizations prior to the accident at the Fukushima Daiichi NPP has been divided into three periods according to H. Shiroyama [81]: (1) from 1957 to 1978; (2) from 1978 to 1999; and (3) from 1999 to 2011. What distinguishes each of these periods from each other is that significant changes to the Japanese regulatory structure were enacted in

response to an event at a nuclear installation in Japan. The historical development of the regulatory framework in Japan is described in Annex I of this volume.

The criticality accident that occurred on 30 September 1999 at the JCO fuel fabrication facility at Tokaimura initiated the third period in the evolution of the Japanese governmental and regulatory structure. The accident was, at that time, Japan's worst nuclear accident, and was classified at level 4 on the International Nuclear and Radiological Event Scale (INES) [82]. Two workers died [83] as a result of exposure to radiation and hundreds of other workers and members of the public received radiation doses. Although the direct causes of the accident were linked to unsafe acts and faulty procedures on the part of the operator, contributing factors included the failure of the former Science and Technology Agency (STA) to adequately assess the hazards of the facility and detect non-compliances with the conditions of its licence [84, 85].

The NSC set up an investigative committee on the JCO's Tokaimura criticality accident which recommended actions to strengthen the regulatory framework. Several changes were made to laws and organizational arrangements following these recommendations [84-86]:

— Strengthening the Nuclear Safety Commission: To strengthen the NSC, it was transferred from the Nuclear Safety Bureau of the Science and Technology Agency (STA) to the Prime Minister's Office on 1 April 2000. The NSC staff was increased from 20 to 92 members, and its involvement in regulatory oversight was subsequently institutionalized, providing a double-check system in the regulatory activities.
— Amendment of the Reactor Regulation Act: The Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (Reactor Regulation Act) was amended in 2000 to strengthen the nuclear safety requirements for the management, operation and inspection of nuclear processing plants and nuclear energy facilities [87].
— Enactment of the Act on Special Measures Concerning Nuclear Emergency: The Act on Special Measures Concerning Nuclear Emergency Preparedness (Nuclear Emergency Act) was adopted in December 1999 [88]. This legislation complemented the provisions for response to natural disasters established in the Disaster Countermeasures Basic Act [89]. The Nuclear Emergency Act set out roles and responsibilities of the national government, local governments, and licence holders in case of emergencies at nuclear facilities.
— Amendments of Ordinances for the Compensation Law and the Law on the Indemnity Agreement for Compensation of Nuclear Damage: The implementing ordinances for the Compensation Law and the Law on the Indemnity Agreement for Compensation of Nuclear Damage were amended by Cabinet Order in 1999 to establish the amounts for which nuclear operators are liable, and to include nuclear damage resulting from transport, storage or disposal incidental to the storage of nuclear spent fuel within their scope.
— Revision of the Emergency Preparedness Guidelines: The guidelines on technical and special matters of nuclear emergency measures were revised by the NSC in May 2000 [90].
— Reorganization of government bodies with responsibilities for nuclear safety: A reorganization of the Japanese central government took effect on 6 January 2001. The reorganization had been planned for several years, according to the Basic Act on Central Government Reform (No. 103 of 12 June 1998) and other laws related to administrative reform. It was aimed broadly at reducing costs and improving the efficiency of government [91]. However, a number of specific measures were implemented with the intention of strengthening the governmental organizations responsible for nuclear safety.

The laws that were in place following the changes during this third period are shown in Fig. 2.5-1.

The former MITI was reformed as the Ministry of Economy, Trade and Industry (METI) with responsibilities for ensuring a stable and efficient energy supply, including the use of nuclear energy. METI was also put in charge of nuclear safety regulation and the licensing of nuclear installations.

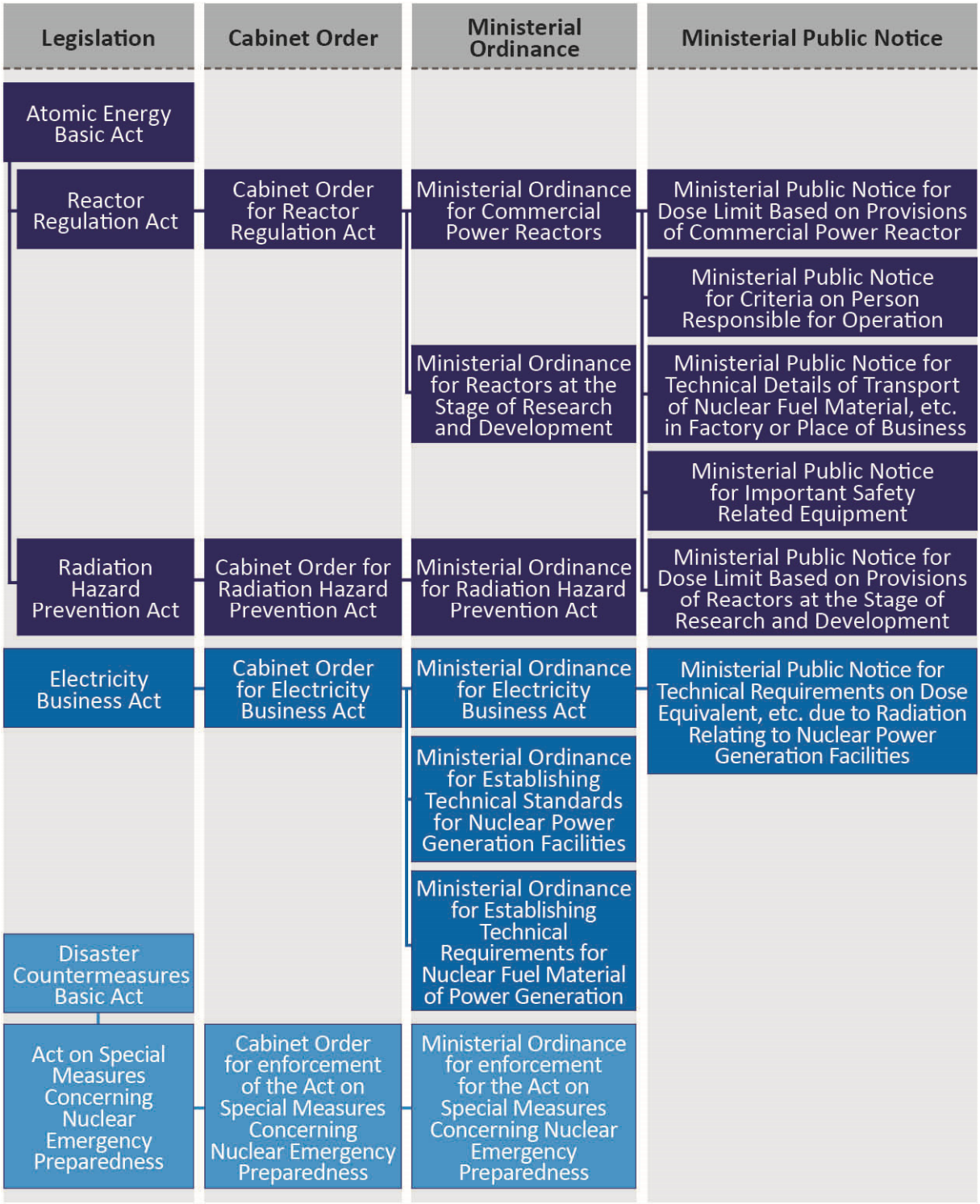


FIG. 2.5–1. Japanese nuclear safety legislation as of March 2011 [92].

Within METI, specialized structures were set up to carry out different tasks. The Agency for Natural Resources and Energy (ANRE) within METI had responsibility for planning and overseeing the national energy supply. ANRE's Department of Electricity and Gas Industry managed nuclear energy policy and radioactive waste management.

The Nuclear and Industrial Safety Agency (NISA) was set up within ANRE to regulate the safety of nuclear and other energy sources as well as industrial safety. NISA's main functions comprised the

following, as set out by the Law for Establishment of The Ministry of Economy, Trade and Industry (Law No. 99 of July 16, 1999) [53, 93]:

— Regulating nuclear power refining, fabrication, storage, reprocessing and waste disposal businesses and nuclear power generation installations and matters relating to ensuring the safety of these businesses and installations;
— The safety of nuclear power relating to its utilization as an energy source;
— Control of explosives, safety of high pressure gas, mine safety, and other safety matters under its jurisdiction (hereinafter referred to as industrial safety);
— International cooperation pertaining to affairs under its jurisdiction.

The new Ministry of Education, Culture, Sports, Science and Technology (MEXT) was created through a merger of the STA and the Ministry of Education. The former responsibilities of the STA for nuclear safety regulation were reallocated between METI and MEXT. Accordingly, the regulation of nuclear fuel cycle facilities, including uranium refining and fuel fabrication, spent fuel storage, reprocessing, nuclear waste management business, and related transport of nuclear material, were transferred from STA to NISA. About 90 employees were also transferred from STA to NISA, approximately 35% of NISA's initial complement of 260 people [94].

MEXT retained responsibility for the science and technology aspects of nuclear energy, including: policy and the development of nuclear technologies; safety regulations governing research reactors, protection against radiation hazards; and the use and transport of nuclear and radioactive material; and safeguards. MEXT also supervised the National Institute of Radiological Sciences (NIRS), the Japan Atomic Energy Research Institute and the Japan Nuclear Cycle Development Institute. The latter two organizations merged in 2005 to become the Japan Atomic Energy Agency (JAEA) [94, 95].

The Nuclear Safety Commission (NSC) and the Japan Atomic Energy Commission (JAEC) were relocated from the Nuclear Safety Bureau of the STA to the Cabinet Office to continue their respective roles as senior advisory bodies on nuclear safety and nuclear policy. The NSC was empowered by law to require reports from NISA and performed double-check reviews of NISA's work.

The Ministry of Foreign Affairs (MOFA) was responsible for the international aspects of nuclear energy utilization, including the implementation of the related international treaties and conventions.

Later, in 2003, the Japan Nuclear Energy Safety Organization (JNES) was established in order to enhance regulatory safety activities together with NISA. The law establishing JNES was enacted by an extraordinary session of the Japanese Diet held in autumn 2002, following a crisis in public confidence precipitated by the discovery of TEPCO's falsification of safety records at its nuclear facilities [54]. JNES's main functions, as set out in its establishment law, consisted of conducting inspections at nuclear facilities, review of licensees' periodic inspections, safety analysis and evaluation, nuclear emergency preparedness support, research and testing for code/standard development, and collection, analysis and distribution of safety information. In practical terms, JNES was formed by merging parts of the former Nuclear Power Engineering Corporation (NUPEC), the Japan Power Engineering and Inspection Corp (JAPEIC), and the Nuclear Safety Technology Centre (NUSTEC) [93, 96].

The Japanese legal framework comprised numerous laws which had been revised over the years in response to accidents and incidents and which, as a whole, clouded the authorities and responsibilities for nuclear safety. The National Accident Independent Investigation Commission of the Japanese Diet has commented critically on this matter, describing the legal framework as a 'patchwork' and stating [32]:

> "The laws and regulations governing Japan's nuclear power industry at the time of the accident were outdated relative to those of other countries and, in some cases, obsolete."

The independence of the regulatory body from entities with interests that could unduly influence its safety related decision making is another important principle. The Government of Japan has claimed that NISA and ANRE were effectively separate agencies [93]. The IAEA's International Regulatory Review Service (IRRS) mission to Japan observed that:

> "NISA is effectively independent from ANRE, in correspondence with the requirements of GS-R-1. This situation could be reflected in the legislation more clearly in future" [53].

In retrospect, it is evident that NISA lacked the requisite de jure independence from entities responsible for the promotion of nuclear energy. NISA as a department within METI was subordinate to the Minister. NISA's lack of clarity on its legal authority was illustrated by the repeated cases of data falsification by NPP operators. The Minister was also responsible for national policy on the utilization of nuclear energy, yet at the same time was also responsible for enforcement action against his licensees in the light of, in the NSC's words, their "repeated malicious conduct" [97] in relation to safety.

The complex arrangement of organizations at different levels within the Government of Japan appears to have hampered the effective regulation of safety. Many government ministries, agencies and quasi-governmental organizations played influential roles with regard to the utilization and regulation of nuclear energy in Japan. The NSC was an important body with both advisory and supervisory roles in the system of 'subsequent regulation review'. In the opinion of the IRRS mission, the role of NISA as the regulatory body in relation to NSC was in need of clarification [53]. Inspection activities, an important part of the functions and responsibilities of the regulatory body, were assigned by law partly to JNES. Consequently, NISA had to manage the interface with JNES with regard to its inspections.

2.5.3. Organization and staffing of the regulatory body

This section describes the nuclear regulatory body staffing and organization, management systems, and regulatory functions in place prior to the Fukushima Daiichi accident.

NISA was organized with 11 divisions reporting to the Director General at the Tokyo headquarters. Nuclear safety inspectors and senior specialists for nuclear emergency preparedness were stationed at each nuclear facility NISA's budget was allocated within the government which had the final decision on matters such as staff numbers and the number of divisions. The government was seeking generally to reduce staff numbers in administrative posts. Although NISA had been relatively successful in defending its budget, its allocation of Yen 32.6 billion (US $330 million) in fiscal year 2010 was 12% less than the previous year [53].

NISA was subject to a rule for government personnel whereby staff members were expected to rotate jobs every two to three years, which hampered NISA's ability to develop and retain specialist expertise. NISA tried to retain expertise in two ways. First, experts were rotated within NISA, thus retaining their knowledge. Second, policy makers were expected to stay at least three years and were thereafter rotated to other departments of METI [93].

JNES was established as a technical support organization to NISA in 2003, funded mainly by NISA, 60% of NISA's fiscal year 2010 budget being allocated to JNES, which had approximately 400 employees as of 1 April 2010. JNES had the status of an 'incorporated administrative agency'. As such, JNES was free of some of the administrative rules that applied to central government departments. Consequently, JNES had more flexibility on matters of staffing and budget which better enabled it to retain a cadre of professional experts [93].

The NSC had become considerably stronger since its foundation 30 years earlier. It was supported by its own secretariat, composed of a Secretary-General and six divisions with a total of about

100 members of staff. Several advisory councils and committees on safety, emergency preparedness and other regulatory matters also supported it. In order to increase transparency, the NSC had also taken steps to open the deliberations of its committees to the public [93, 96].

The budget pressures and administrative rules for job rotation of civil servants to which NISA was subject were important factors that limited the technical and regulatory competence of its staff.

2.5.4. Regulatory management systems and safety culture

The IRRS mission to Japan commended NISA for its recognition of the importance of adopting a comprehensive quality management system and for having set out its management policy and developed a quality management manual. However, although some instructions and guides were available at the time of the mission, particularly for periodic and operational safety inspection, they were not available for all key regulatory process tasks and activities; nor did they appear to be linked to an overall process map for NISA as a whole and nuclear safety regulation in particular. The IRRS found that further development was needed to fully establish the management system within NISA [53]. While the Japanese national report to the 2011 review meeting on the Convention on Nuclear Safety (CNS) referred to NISA's management system, there was no further information on its implementation as of that date [92, 96].

NISA embraced a code of conduct based on the following four values:

— Strong sense of mission;
— Scientific and rational judgments;
— Neutrality and justice;
— Transparency in operations.

NISA described its decision making process and public communication as being based on scientific and rational judgment, while less account was taken of issues related to management of safety and human performance [53].

Although NISA had recognized the importance of developing a management system to direct its activities, the management system had not been effectively implemented by the time of the accident. The internal culture of the regulatory body valued hard science over softer subjects.

2.5.5. Authorization of facilities and activities by the regulatory body

The Fukushima Daiichi NPP is one of Japan's oldest nuclear sites, dating from the early days of the nuclear programme in Japan. The licence for establishment of the Fukushima Daiichi NPP was issued on 1 December 1966 by the Prime Minister, after consideration of TEPCO's application by the Nuclear Reactor Safety Review Committee of the JAEC.

The JAEC Safety Review Committee had established five expert groups which conducted the safety review of the proposed facility at the Fukushima Daiichi NPP:

— Reactor Group responsible for review on physics, thermal and mechanical, fuel and material;
— Environment Group responsible for review on meteorological and radiological effects;
— Seismic Group responsible for review on seismic designs;
— Plant and Power Generation Group responsible for evaluation on plant performance;
— Safety Review Group responsible for evaluation on accidents and disasters.

The review was carried out by referring to various guides prepared by the JAEC Committee on Nuclear Reactor Safety Standards as well as information from other countries such as the draft US

General Design Criteria. After the reactor Establishment Permit was granted in 1966 for the first unit, the Ministry of International Trade and Industry (MITI) reviewed and approved the Construction Plan in September 1967, conducted the pre-service inspection and tests before fuel loading and commissioning, according to the Electricity Business Act. The construction of later units at the Fukushima Daiichi NPP was the subject of amendments to the original Establishment Permit.

In the authorization process prior to the formation of the NRA, the planning and design stage was completed by an application for an establishment licence under the Nuclear Regulation Law. The design review was conducted following a double-check approach: a primary review performed by NISA and a secondary review by NSC and JAEC. Since 2001, both commissions provided opinions to METI, which the Minister had to take into account before the establishment licence could be granted.

Having received an establishment licence, the operator had to apply for the construction plan under Article 47 of the Electricity Business Act. This approval was granted in several steps, based on compliance of the detailed design with technical standards. Further approvals were needed for the pre-service inspection, the safety management review for welding, the fuel design and the fuel inspection. Since 2003, JNES had performed assessments and pre-service inspections of equipment in support of NISA. After completion of construction work, the operator applied for approval of the operational safety programme. Approvals were signed by the Minister of METI. There was no requirement for submittal of a Final Safety Analysis Report (FSAR). The same authorization procedure was followed for major modifications that had a safety significant impact on the basic design.

The initial authorization for the Fukushima Daiichi NPP was granted in 1966, in the early years of nuclear power development in Japan. The construction of additional units at the site was treated as an amendment to the Establishment Permit. The operator was not required to submit or to maintain up to date an FSAR or an equivalent document describing the design and operating arrangements for the facility. Not updating the documentation which describes the revised safety case is not in line with IAEA safety standards.

2.5.6. Severe accident assumptions and countermeasures

The NSC published a regulatory guide on Accident Management for Severe Accidents at Light Water Power Reactor Installations in May 1992 [62]. Shortly afterwards, in July 1992, MITI published a document titled Roadmap of Accident Management [98] and requested nuclear operators to take action in response. However, the AM measures were limited in scope. Moreover, the measures were regarded as voluntary initiatives by nuclear operators and not as regulatory requirements [99]. TEPCO prepared AM measures which included primary containment vessel venting systems and EDGs over the period from 1994 to 2002. The authorities in Japan believed that the safety of reactor facilities was sufficiently ensured by existing safety regulations. The NSC decision appended to its guide states [62]:

> "The safety of reactor facilities in Japan is sufficiently ensured by current safety regulations... The possibility of severe accidents is sufficiently low due to these measures, to the extent that such accidents could not occur from an engineering viewpoint, and thus the risk from reactor facilities is considered to be sufficiently low.... The Commission believes that effective accident management should be developed by licensees on a voluntary basis..."

The NSC based its assessments on level 1 PSAs, which showed the estimated frequency of reactor core damage to be comparable to reactors in other countries [62]. The apparent acceptability of the CDF was used to justify the limited measures taken by licensees to mitigate the consequences of a severe accident. However, the PSAs considered only internal events within the NPPs, such as equipment failures and human errors. External hazards, such as earthquakes or tsunami, and internal hazards were not included in the scope of the PSAs (see Section 2.3). Since the PSAs did not consider

these initiating events, the estimates of reactor CDF were optimistic. Nor did the PSAs evaluate the potential for large releases of radioactivity outside the reactor containment.

The 2007 IAEA IRRS mission noted the lack of regulatory requirements for BDBAs and made a suggestion that NISA continue to develop a systematic approach to consideration of such events and the complementary use of PSA and SAM [53]. Neither the IRRS mission suggestions, nor the actions in such as the USA and Europe to enhance accident measures in the light of external events and terrorist incidents, appear to have spurred further efforts in this area.

2.5.7. Authorization of long term operation: Requirements for periodic safety review and backfit

The Establishment Permits for Japanese NPPs were issued for an unlimited period. The Ministerial Ordinance under the Nuclear Regulation Law required an ageing management technical review for plants that reached 30 years of operating life, and ongoing Ageing Management Technical Assessments (AMTA) at ten year intervals thereafter. The AMTA covered the functional soundness of selected components and the status of checkout/inspection, functional surveillance test, monitoring and repair/replacement of the portions evaluated. The licensee was required to develop a ten year Long-term Maintenance Programme (LTMP) based on the evaluation results. NISA and JNES checked the operator's implementation status of the LTMP during their Periodic Inspection and the Safety Management Review. The IRRS peer review mission concluded that: "Ageing phenomena in general are carefully studied in Japan" [53].

TEPCO submitted the results of the AMTA for the 40th year of operation and the LTMP for Unit 1 of the Fukushima Daiichi NPP to NISA on 25 March 2010. NISA reviewed the report with JNES and held committee meetings to incorporate the experts' opinions in the review. NISA approved the report and operation of the unit for a further ten years on 7 February 2011, just one month before the accident.

Licensees in Japan also conducted PSRs every ten years after the commencement of operation. The PSRs started as a voluntary activity in 1992 and were made a legal requirement in 2003 through an amendment to the Ministerial Ordinance on Rules for the Installation, Operation of Commercial Power Reactors under the 'Nuclear Regulation Act' [99]. All NPP units more than ten years of age were reported to have conducted at least one PSR at the time of the IRRS mission in 2007.

The licensees were not, however, required to submit the results of their PSRs to NISA. Before the 2003 amendment, PSR reports were provided to MITI or to METI/NISA who reviewed them and reported to the NSC. After the 2003 amendment, PSRs — although now mandatory — were regarded as self-assessments and the licensees were not required to submit them to NISA. The regulatory body confirmed that each licensee had adequately conducted PSRs during its inspections.

The PSRs that were conducted in Japan did not entail re-examination of the adequacy of the design of the NPP or the reassessment of external hazards in the light of new standards, data and methods. The Japanese national report to the 5th Review Meeting of the CNS in 2010 states that:

> "The Periodic Safety Review in Japan covers the operator safety activities at nuclear installations in operation, but it does not cover the design review. The nuclear installations have been designed with sufficient safety margin, than that they just met the necessary design criteria so that back-fitting has not been institutionalized" [92].

The IRRS mission to Japan made the suggestion that:

> "The PSR should be made a more focused and periodic effort to give a comprehensive picture of the plant safety status at certain intervals. All its conclusions should be reported to NISA in one summary report" [53].

There was no other established process in Japan for deciding on backfits to a plant (where backfit means the application of current requirements to an existing facility). NISA did not have a legal basis to order backfits on items covered by the technical standards referenced in the plant establishment permit. NISA's policy was to request the licensees to conduct so-called backchecks when technical standards were revised or new knowledge was gained.

The original Establishment Permit for the Fukushima Daiichi NPP was granted on the basis of a maximum tsunami height of 3.1 m [99]. TEPCO performed a re-evaluation of tsunami hazards in 2002 on a voluntary basis following which the design tsunami height was increased without changing the licensing documents. When the Seismic Design Review Guide, first issued by the NSC in 1978, was fully revised in 2006, NISA requested that the licensees conduct a backcheck to re-evaluate seismic and tsunami hazards. The re-evaluation was done on a voluntary basis and not in the framework of a formal PSR. The licensees' voluntary activities were delayed. TEPCO had not finished its re-evaluation by the date of the accident at Fukushima.

The approach to PSR in Japan was not fully in line with guidance from the IAEA [100]. IAEA Safety Standards Series No. NS-G-2.10, Periodic Safety Review of Nuclear Power Plants [100], recommends a comprehensive review of the design and operation of an existing NPP, including re-evaluation of external hazards, with the objective of determining its adequacy against the current licensing basis and national and international standards, requirements and practices. NS-G-2.10 [96] also recommends that the results of the PSR be submitted to the regulatory body for review.

Had a more rigorous approach to PSR been implemented in Japan in accordance with NS-G-2.10 [100], it would have provided a formal mechanism for re-examination by the licensees and the regulatory body of the design and external hazards in the light of new information and current standards and technology. As it was, the lack of a requirement to submit results of the PSR described in the Japanese national reports to the CNS may have contributed to the failure of the licensee and the regulator to rigorously consider new information on vulnerabilities related to earthquakes and tsunami.

The new Japanese NRA has begun consideration of a PSR process aligned with IAEA safety standards. It was enforced in December 2013 as a system which requires NPP licensees to evaluate the safety of reactors comprehensively and submit the results. In order to improve safety at NPP installations, licensees are to submit documents which show the following to the NRA in principle within six months, after the end of periodic inspection:

— The extent of conformity with regulatory requirements;
— Measures for improving safety on a voluntary basis;
— Assessing and reviewing safety margins for improvement and a PSA;
— Comprehensive re-evaluation based on the above results and action plans for improving safety.

2.5.8. Inspections of facilities and activities

The Nuclear Regulation Law was amended after the JCO's Tokaimura criticality accident to correct the regulatory shortcomings the accident revealed and to institute regular inspections by the authorities of the management and operation of nuclear facilities. The IRRS mission in 2007 found that NISA was actively working on tying together the lessons learned from previous incidents and to develop an inspection system that focused not only on hardware, but also on licensees' operational management [53].

Despite NISA's efforts toward improvement, the regulatory inspection programme was rigidly structured by law, including the type and frequency of inspections. The presence of NISA inspectors was required before the operator could complete certain tests and surveillances, and there were only specific periods in which NISA was permitted access for inspection. This approach limited the powers

of NISA to perform inspections as needed and made it difficult for NISA to change the inspection type or frequency. The restrictions also affected the operator's conduct of tests and surveillance based on the availability of NISA inspectors [53].

The repeated discoveries of licensees' falsification of safety records in 2002 and 2007 suggest shortcomings in the effectiveness of regulatory inspection and enforcement programmes. The initial discovery was a result of allegations raised by employees. In a sense, therefore, this discovery represented a success for the allegation system that had been instituted after the JCO's Tokaimura criticality accident. However, in spite of follow-up inspections by NISA, regulatory orders to licensees, and various other measures to strengthen self-checking and regulatory oversight, the true extent of records falsification did not come out until several years later. The Fukushima Daiichi NPP was implicated in several cases: one such case involved the past falsification of containment leak rate tests by employees at Unit 3, for which METI imposed a one year licence suspension as punishment [93].

Enhancements to the inspection system were instituted by a revised Ministerial Order issued in January 2009. Greater flexibility was introduced, considering the characteristics of individual nuclear installations, and enhancements were made to inspections during operation and plant shutdown in response to lessons learned from the data falsification events in 2006 [96].

By 2011, the Japanese national report to the Convention on Nuclear Safety stated [92] that operator's safety management activities were governed by the operational safety inspections that NISA had approved. NISA conducted quarterly safety preservation inspections to check the operator's compliance with the PSRs. Periodic inspections were also conducted by NISA and JNES at intervals not exceeding 13 months, focused on the operator's maintenance of the SSCs of the NPPs. The periodic inspections focused on the safety significant SSCs, for example, belonging to the reactor shutdown system, the reactor coolant pressure boundary, the RHR system and the containment system. These regulatory procedures were in addition to the licensees' own walkdown and maintenance management of nuclear installations, periodic safety assessments, and ageing technical evaluations [96]. Figure 2.5-2 illustrates the regulatory inspection process for the operating stage of NPPs at the time of the accident at Fukushima Daiichi NPP.

The regulatory inspection programme at the time of the accident at the Fukushima Daiichi NPP was rigidly structured by law, including the type and frequency of inspections and the rights of access by inspectors. This approach limited the effectiveness of regulatory inspection and enforcement in verifying the safety of licensees' activities and compliance with requirements.

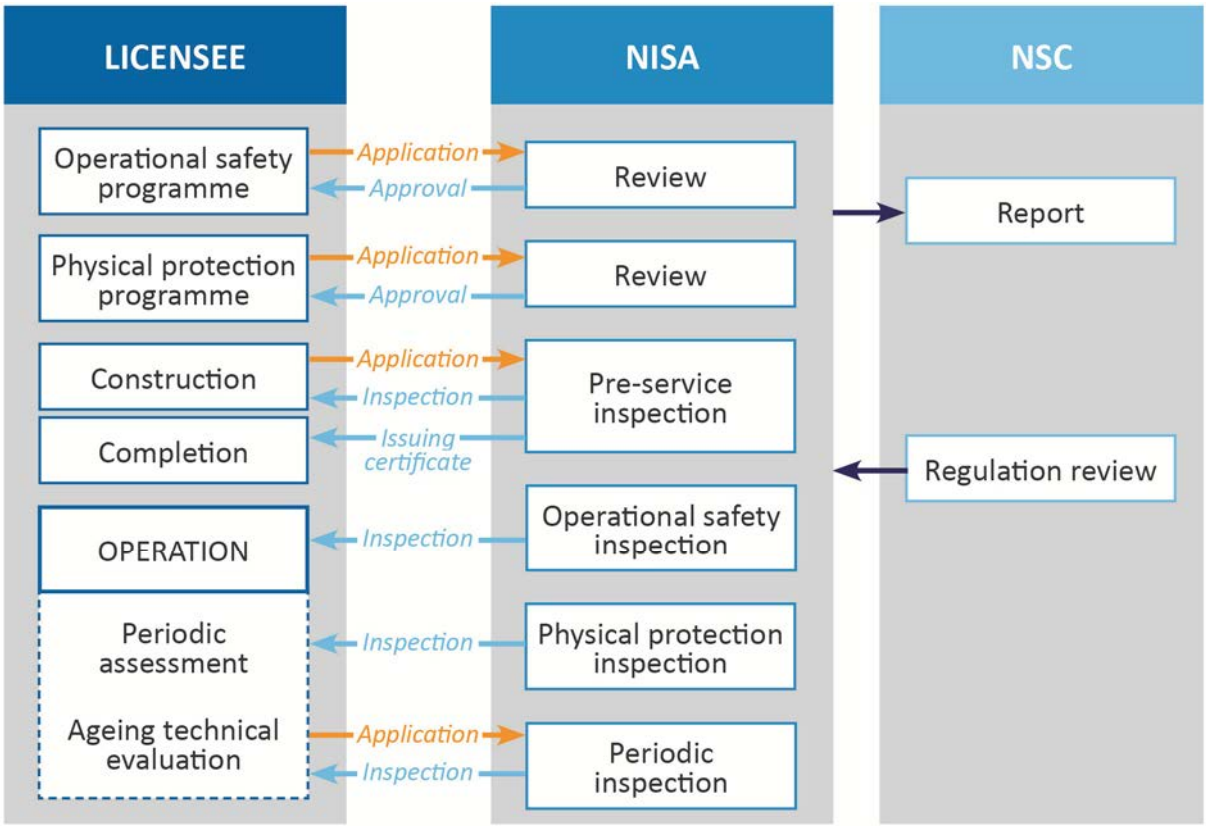


FIG. 2.5–2. The regulatory inspection process at the time of the accident for the operating stage of NPPs [92].

2.5.9. Regulatory requirements and guidance

As noted in previous subsections, the national laws and ministerial ordinances that formed the top two levels of the legal hierarchy were primarily administrative in nature. NISA was not authorized by its statutes to issue regulations binding on applicants and licensees. Two more levels in the hierarchy of documents provided technical criteria for safety.

The NSC had prepared a number of regulatory guides over many years. The NSC guides for power reactors were in five divisions, namely: siting, design, safety evaluation, radiation exposure and accident management. The NSC Regulatory Guides were used by the NSC and NISA to conduct safety reviews. The NSC guides were not requirements, nor were they legally binding, although the IAEA fact finding mission was informed that the NSC guides were considered in practice as requirements [6]. The IRRS mission had discussed these arrangements and had recommended that NISA take the major responsibility in the development and endorsement of regulations and guides for safety [53].

The IRRS mission also learned that NISA drafted technical standards in the form of ministerial orders. Draft standards were discussed with subcommittees and working groups set up under the Nuclear and Industrial Safety Subcommittee and were also subject to external consultation with the public and electric utility stakeholders and to ministerial approval prior to publication.

The fourth level of the hierarchy comprised private consensus standards published by academic and professional societies, such as the Japan Society of Mechanical Engineers, the Atomic Energy Society of Japan, the Electric Association, the Thermal and Nuclear Power Engineering Society in Japan, which NISA endorsed. Figure 2.5-3 outlines the system of technical standards for nuclear power plants in Japan prior to the accident.

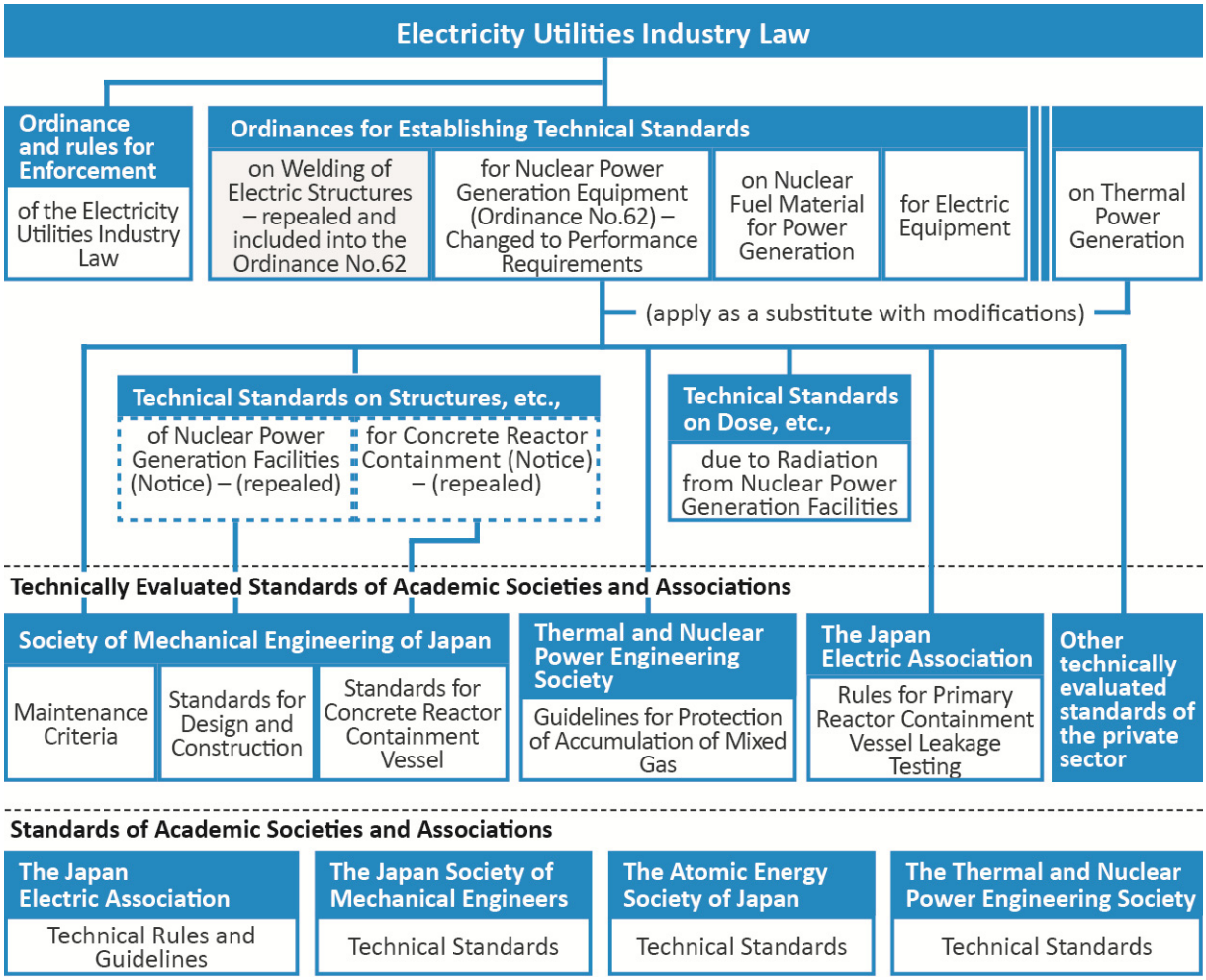


FIG. 2.5–3. System of technical standards for NPPs in Japan.

The Japanese regulatory framework did not include regulations specifying the requirements and criteria for safety upon which regulatory judgements, decisions and actions were based. A series of guides were issued by the NSC which were regarded as requirements in practice. The NSC guides were supplemented by consensus standards published by professional and academic societies.

With regard to tsunami safety, the 2006 revision of the NSC Seismic Safety Guidelines did not contain concrete criteria that could be used in re-evaluation of tsunami hazards. Therefore, an effective regulatory framework was not available to provide for the tsunami safety of the NPPs through their life [99].

2.5.10. International cooperation

Japan has participated in many multilateral and bilateral cooperation activities over the years. Regarding the CNS, Japan participated in the discussion for its creation from the early phase and became a Contracting Party in May 1995. Since then, Japan has participated in all the Review Meetings. In the third Review Meeting, Commissioner Soda of the NSC served as the President. Japan became a Contracting Party to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management in August 2003. Japan was also a party to the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency and the Convention on Early Notification of a Nuclear Accident since 1987.

Japan has also actively participated in other activities of the IAEA. For example, it participated in the International Nuclear Safety Group (INSAG) for many years and also the Commission on Safety Standards (CSS) and its four committees, the Nuclear Safety Standards Committee, Radiation Safety Standards Committee, Waste Safety Standards Committee and the Transport Safety Standards.

In 1997, the IAEA launched an extrabudgetary programme aimed at safety enhancement in South-east Asia, Pacific and Far East countries which evolved into the Asian Nuclear Safety Network (ANSN) in 2002. Japan has played a major role in providing funds and human resources to support the activity. After the Niigata-Chuetsu-Oki earthquake that struck the Kashiwazaki-Kariwa NPP in 2007, the IAEA established the International Seismic Safety Centre (ISSC) in 2008 to which Japan has contributed from the beginning.

With regard to the safety services supplied by the IAEA, Takahama Units 3 and 4 of the Kansai Electric Power, Company (KEPCO) invited an OSART mission in 1988; Hamaoka Units 3 and 4 of the Chubu Electric Power Company in 1995; Kashiwazaki-Kariwa NPP of TEPCO in 2004; and Mihama Unit 3 of KEPCO in 2009. The Nuclear and Industrial Safety Agency (NISA) in METI received the IRRS mission in 2007.

Japan is also a member of the OECD Nuclear Energy Agency (OECD/NEA). It has participated in the activities of the Committee on Nuclear Regulatory Activities (CNRA), Committee on Safety of Nuclear Installations (CSNI), Committee on Radiation Protection and Public Health (CRPPH) and Radioactive Waste Management Committee and on related Working Groups and Task Groups. For example, Japanese delegates have participated for many years in the operating experience feedback activities in the Working Group on Operating Experience (WGOE) in CNRA. Also, many research engineers and experts from the Japan Atomic Energy Agency (JAEA), Japan Nuclear Energy Safety Organization (JNES) and others have joined the safety research activities under CSNI including the Joint Research Projects. JAEA has hosted some of these projects.

The International Nuclear Regulators Association (INRA) has held meetings every year since 1997 where the top regulators from Canada, France, Germany, Japan, the Republic of Korea, Spain, Sweden, the United Kingdom and the United States of America have discussed regulatory issues. From Japan, both the NSC and NISA have attended these meetings.

Japan has had active bilateral cooperation activities for many years. For example, information exchange on nuclear regulation has continued regularly with China, France, Germany, the Republic of Korea, Sweden and the United Kingdom. The JAEA and JNES have also conducted information exchange on safety research with the USA, European countries and others.

2.5.11. Current status of regulatory requirements in Japan

On 19 September 2012, the NRA was established to replace the structure that existed prior to the accident. Following its creation, the NRA carried out a complete review of safety guidelines and regulatory requirements with the aim of formulating a set of new regulations to protect people and the environment. On 8 July 2013, the new regulatory requirements for commercial power reactors entered into force. Based on the concept of defence in depth, importance was placed on the third and fourth layers of defence and the prevention of simultaneous loss of all safety functions due to common causes. In this regard, the previous assumption on the impact of earthquakes, tsunamis and other external events such as volcanic eruptions, tornadoes and forest fires were re-evaluated, and it was decided to enhance countermeasures for nuclear safety against these external events. Furthermore, it is required to take countermeasures against internal fires and internal flooding, and to enhance the reliability of on-site and off-site power sources to deal with the possibility of an SBO.

In addition to the enhancement of countermeasures established at design basis, countermeasures for severe accident response against core damage, containment vessel damage and diffusion of radioactive material, enhanced measures for water injection into the SFP, countermeasures against malicious airplane crashes and an installation of emergency response building are also required.

The items described below are the highlights of new regulatory requirements which have been established by NRA after the Fukushima Daiichi NPP accident:

(1) Reinforced requirements for seismic/tsunami resistance.
   (a) Measures against tsunamis have been enhanced significantly. The standards define a 'design basis tsunami' as one which exceeds the largest ever recorded and also require protective measures, such as sea walls to prevent site inundation, and watertight doors to prevent the flooding of buildings.
   (b) Standards to deal with displacement and ground deformation have been clarified. The standards require the construction of S-class (the highest seismic safety classification) buildings and structures on the surface of the ground surface without outcrop of active fault preventing a risk of fault displacement damaging the buildings and equipment therein.
(2) Reinforced or newly introduced requirements for design basis.
   (a) Design basis and protective measures against volcanic eruptions, tornadoes and forest fires have been enhanced significantly for preventing simultaneous loss of all safety functions due to a common cause. The measures against power failure which may trigger simultaneous loss of all safety functions due to common causes other than natural phenomena have been significantly strengthened.
   (b) Measures have been strengthened for fire protection and against internal flooding as events other than natural phenomena which trigger simultaneous loss of all safety functions due to common causes.
(3) Newly introduced requirements for measures against severe accidents.
   (a) Measures to prevent core damage. Based on this requirement, in case of power failure, for example, SRVs will be opened by using mobile power sources to reduce the pressure inside the RPV until water can be injected using a mobile water injection system or other devices. After reducing the pressure inside the RPV, water will be injected into the RPV using a mobile water injection system.
   (b) Measures to prevent containment vessel failure. A filtered venting system should be installed to reduce the pressure and temperature inside the containment vessel and to reduce the escape of radioactive material through the exhaust. In additions, systems (mobile pumps, etc.) are needed to inject water into the lower part of the containment vessel to cool the core to prevent containment vessel failure due to a molten core.
   (c) Measures to suppress radioactive material dispersion. In particular, outdoor water spraying equipment to douse the reactor building and prevent radioactive material from contaminating the atmosphere.

The roles and responsibilities that had previously been assigned to different governmental organizations were integrated into the NRA. The NRA holds jurisdiction over some of the activities of the NIRS and the JAEA. The main nuclear safety technical support organization JNES was merged with NRA on 1 March 2014.

The NRA has adopted a PSR process aligned with IAEA safety standards that was enforced in December 2013. The system requires nuclear power reactor licensees to comprehensively evaluate the safety of reactors and to submit the results to the NRA within six months of the end of periodic inspection, showing the following:

— Compliance with regulatory requirements;
— Measures for improving safety on a voluntary basis;
— Assessing and reviewing safety margins for improvement and a probabilistic risk assessment;

— Comprehensive re-evaluation based on the above results and action plans for improving safety.

Japan requested the IAEA to carry out an IRRS mission towards the end of 2015, aiming at strengthening nuclear safety and enhancing NRA's competence as an independent nuclear regulator through a continuous, transparent and open learning process.

2.5.12. Summary

The initial authorization for the Fukushima Daiichi NPP was granted in 1966, construction of the additional units being treated as an amendment to the Establishment Permit. Japanese regulations in effect at the time of the accident did not require the operator to submit or to maintain an up to date FSAR or an equivalent document describing the design and operating arrangements for the facility. Not updating the documentation which describes the revised safety case is not fully in line with IAEA safety standards.

The Japanese regulatory framework has evolved in three distinct phases since the authorization of the first units at Fukushima Daiichi NPP in the 1960s. Based on the conclusion of the 2007 IRRS mission to Japan and the peer reviews conducted under the CNS, the Japanese regulatory system that was in place prior to the accident had the organizations and systems necessary to meet IAEA safety standards. However, there were weaknesses in the implementation of these systems and the performance of the organizations such as unnecessary constraints on inspections, limited enforcement authority, inability to compel operators to make safety upgrades to their facilities, and difficulty in staffing and training at the regulatory authority.

The Japanese regulatory framework as it existed at the time of the accident had been created in 2001 following the JCO's Tokaimura criticality accident in 1999. It was then revised following discovery of the falsification of records by operators in 2002 and 2006. The organizations involved were [93]:

— The Nuclear and Industrial Safety Agency (NISA), which was part of the Ministry of Economy, Trade and Industry (METI). NISA was responsible for regulating the safety of nuclear energy as well as industrial safety and had about 260 staff.
— METI was also responsible for ensuring a stable and efficient energy supply, including the use of nuclear energy.
— The Ministry of Education, Culture, Sports, Science and Technology (MEXT) was responsible for the nuclear energy policy, the development of nuclear technologies, protection against radiation hazards, the use and transport of nuclear and radioactive material and safeguards. MEXT also supervised the Japan Atomic Energy Research Institute and the Japan Nuclear Cycle Development Institute, which merged in 2005 to become the Japan Atomic Energy Agency.
— The Nuclear Safety Commission, which reported to the Cabinet Office and provided a double-check on NISA's regulatory activities.
— The Ministry of Foreign Affairs (MOFA), which was responsible for international aspects of nuclear energy, including the implementation of related international treaties and conventions.
— The Japan Nuclear Energy Safety Organization (JNES), which was established in 2003 as a technical support organization to NISA. Its functions included conducting inspections at nuclear facilities, reviewing licensees' periodic inspections, safety analysis and evaluation, nuclear emergency preparedness support, and research and testing for code/standard development.

The independence of the regulatory body from entities with interests that could unduly influence its safety related decision making is another important safety principle. NISA as a department within METI was subordinate to the Minister and hence lacked the requisite de jure independence from entities responsible for the promotion of nuclear energy. NISA suffered from the expectation that its staff, like all civil servants, rotate jobs every two to three years and had struggled to maintain its budget within the government. NISA's regulatory inspection programme was rigidly structured by law, including the type and frequency of inspections. The presence of NISA inspectors was required

before the operator could complete certain tests and surveillances, and there were only specific periods in which NISA was permitted access for inspection. This approach limited the ability of NISA to perform inspections as needed and made it difficult for NISA to change the inspection type or frequency. Following the discovery of the falsification of data records by operators, enhancements to the inspection system were instituted in January 2009 introducing greater flexibility for regulatory inspections [93].

2.5.13. Observations and lessons

— **Where several bodies have responsibilities for safety, the government needs to effectively coordinate their regulatory functions to avoid omissions or duplications that may jeopardize safety.**
The Japanese nuclear legal framework comprised numerous laws and arrangements at different governmental levels that had been revised over the years in response to accidents and incidents. Many government ministries, agencies and quasi-governmental organizations played influential roles with regard to the utilization and regulation of nuclear energy in Japan. These complex arrangements appear to have hampered the implementation of effective actions and regulatory activities for enhancing safety. The NSC was an important body with both advisory and supervisory roles in the system of subsequent regulation review. In the opinion of the IAEA's IRRS mission, the role of NISA as the regulatory body in relation to NSC was in need of clarification.

— **The regulator should require that the operator of a facility update its safety demonstration on an ongoing basis to reflect changes in the status of the facility.**
Although improvements in safety rely primarily on the actions of operators, regulatory oversight will be a driving force. In particular, regulatory bodies should promote continuous safety improvement processes, fostering an environment that encourages licensees to invest in improvements beyond national requirements. The regulatory body needs to review and approve the safety demonstration. In addition, any proposed modification of a facility that might significantly affect safety needs to be subject to review and assessment by the regulatory body.

— **Regulatory independence, competence, strong legislative authority and adequate resources, including qualified personnel, are essential in order to perform the required regulatory functions.**
NISA lacked the requisite de jure independence from the entities responsible for the promotion of nuclear energy. In addition, the budget pressures and administrative rules for job rotation of civil servants to which NISA was subject limited the technical and regulatory competence of its staff. The regulatory body needs to make independent regulatory judgements and decisions, free from any undue influences that might compromise safety, such as pressures associated with changing political circumstances or economic conditions, or pressures from government departments or from other organizations.

— **The regulatory body needs to review and inspect the safety of a facility throughout its lifetime.**
The goal is to verify: the extent to which the facility conforms to safety standards and practices; the extent to which the licensing basis remains valid; the adequacy of the arrangements that are in place to maintain safety until the next PSR or the end of plant lifetime; and the safety improvements to be implemented to resolve the safety issues that have been identified. These reviews and inspections require unimpeded access to documentation and the plant.

2.6. HUMAN AND ORGANIZATIONAL FACTORS

2.6.1. Introduction

This section analyses the question of why the Fukushima Daiichi nuclear accident happened despite the nuclear community's progress in nuclear safety, brought about by internationally agreed upon safety

standards, comprehensive review services, well developed regulatory frameworks, establishment of effective safety assessment methodologies, rigorous approaches to risk management, solid design, years of successful operating experience, defence in depth, emergency preparedness, severe accident management guidelines (SAMGs) and a strong international commitment to enhance nuclear safety.

The causes of the accident go beyond the above mentioned factors and are related to the ability of organizations to detect latent flaws in the sociotechnical system, i.e. the interaction between the human, technical and organizational factors [1]. They reach the deepest level of safety culture — the basic assumptions about understanding and perceptions of reality related to nuclear safety [101]. This level of safety culture is the basis from which people operate — and hence the basis from which decisions and actions are taken. This section examines the basic assumptions on nuclear safety by the main stakeholders involved in the accident at the Fukushima Daiichi NPP. The systemic analysis will show how the actions of stakeholders were interrelated and interconnected, and thereby reinforced basic assumptions about nuclear safety that prevented them from adequately preparing for and preventing the accident on 11 March 2011. It should also be pointed out that the safety culture within the Japanese stakeholders' organizations was not sufficiently evaluated before the accident to identify proactively the areas for improvement [32, 54, 102]. This is not unique for Japan, as effective, continuous safety culture improvements constitute challenges for all organizations globally. There is no perfect safety culture condition; it is an ongoing process to assess and advance the understanding of the organizational basic assumptions which drives nuclear safety [1, 103-106].

The Fukushima Daiichi accident was characterized by a high degree of complexity. Not only did this complexity constrain those who were directly involved in the accident response, but it also continues to affect the understanding of the accident. The following biases (see Annex II of this volume for a more detailed account of these biases) influencing the understanding of, and lessons learned from, complex accidents are discussed in this section:

— The hindsight bias explains the pitfalls of understanding an event retrospectively. Processes are often judged by their outcome, and the knowledge of the outcome thus deeply influences the understanding, potentially leading to an event being seen as "more predictable after it becomes known than it was before it became known" [107, 108].
— Oversimplification: Despite the efforts made to analyse the Fukushima Daiichi accident from many different perspectives, what happened is described in a chronological manner, unit by unit, topic by topic. This natural constraint in writing accident reports can create an oversimplification of the full picture making it hard to acknowledge the full complexity the actors had to deal with.
— Distancing through differencing is a common human mechanism preventing understanding and learning. This happens through people's excessive focus on the "differences, real and imagined, between the place, people, organization and circumstances where an incident happens and their own context", leading to a failure to see lessons applicable for their own operation [109].

The lessons to be learned from a human and organizational perspective are applicable to all States and all organizations worldwide, in order for them to proactively detect the flaws in the sociotechnical system to become resilient before and during the emergence of something unexpected.

2.6.2. Methodology

The human and organizational analysis was conducted in accordance with social and behavioural science procedures, which comprise four equally important elements:

— Recognized methodology;
— Unbiased data;
— Scientifically recognized theory;
— Knowledgeable experts.

The methodology used for this human and organizational assessment is based upon the IAEA safety culture assessment methodology. This has been successfully applied in evaluating safety culture at licensees' sites, corporate centres and their interactions with regulatory bodies. For the purpose of this Technical Volume, the IAEA safety culture assessment methodology was extended and applied to a larger sociotechnical system encompassing not only safety culture but also the whole range of interactions between human, organizational and technical factors as well as interorganizational interactions [1] as outlined in more detail in Annex II of this volume. Consideration was also given to best practices in other industries and state of the art sociotechnical approaches applied to evaluate complex events. In order to capture the relationships and synergies among the human and organizational factors contributing to the Fukushima Daiichi accident, this systemic approach was used for the analysis of the accident and for the development of this section. A systemic approach allows for the consideration of the complex relationships of a sociotechnical system with a broader network of other sociotechnical systems, and how those affect and are affected by each other. This includes "factors that lie far away in time and space from the moment things went wrong" [110].

The methodological approach to conduct a systemic analysis captured factual data from a number of sources, including primary and secondary sources, expert meetings and information provided by Japanese experts, and information provided by other experts from the working groups. The systemic and systematic methodology encompassed a number of steps. As the human and organizational factors permeated the available information sources, the factual related information was first extracted, examined and cross-checked by the experts. The information was subsequently categorized using a classification system, and entered into a sortable database. This resulted in the accumulation of approximately 4900 facts classified into 26 categories, 96 attributes, 3 periods of time (before, during and after the accident of 11 March 2011) and various interrelated stakeholders. The facts were identified and categorized as part of an iterative process involving the examination, validation and discussion within the team of experts on human and organizational factors. The assessment and lessons learned presented in this section are all based on the facts in the database.

Facts from selected categories of the database were further examined for themes[7] through a mapping process to identify relationships, concepts and trends. The final analytical step consisted of determining the important relationships, concepts and trends to fit together into an overarching theme. This process was accompanied by focused discursive analysis that capitalized on the diversity of scientific perspectives, knowledge and experience of the experts.

The facilitated discussions, structured readings, database construction and thematic analysis were all essential parts of this systemic analysis and enhanced the understanding of the sociotechnological features that led to an understanding of the evolution of certain aspects of the accident.

There are inherent biases in understanding a complex accident such as the one at the Fukushima Daiichi NPP, which may constrain the opportunity to learn. Some of these biases were introduced above and are further explained in Annex II of this volume, namely: hindsight bias, oversimplification and distancing through differencing.

The human and organizational assessment of the Fukushima Daiichi accident has taken these biases into account during the analysis of the data. The identified generic systemic safety factors contributing to the accident should be considered for all nuclear stakeholders worldwide, not only for the Japanese stakeholders. The human and organizational learning opportunities are valid for each and every organization in enhancing nuclear safety to become more resilient to unexpected situations.

[7] Themes are patterns identified through analysing cultural expressions, such as physical artefacts, verbal expressions, espoused values and norms.

It is critical to keep in mind that the concepts and definitions used in this section are not unique to Japan, but, rather, they are applicable to all societies.

2.6.3. Basic assumptions of the main stakeholders regarding nuclear safety and their impact on the conditions for the Fukushima Daiichi accident

2.6.3.1. The basic assumption related to the accident

To understand the Fukushima Daiichi NPP accident, it is necessary to explain the underlying mechanism of human and organizational behaviour in the context of safety culture, i.e. basic assumptions about nuclear safety. Knowledge of safety culture concepts is recognized as a way to enable the understanding of why people in organizations act the way they do in relation to safety. In both theory and practice, there are different levels on which safety culture operates. The first level is the visible, covering, for example, behaviour and physical objects; the second level is more indirect, covering the shared values, attitudes; and, finally, the deepest level covers the basic assumptions about nuclear safety [111]. In this analysis of the Fukushima Daiichi NPP accident, the focus is on the basic assumption about nuclear safety which preconditioned the actions and decisions prior to the accident. These assumptions were shared by the main stakeholders' organizations.

Assumptions are socially constructed when people interact with each other. People develop a common understanding of the things around them and come to share a common assumption of what those things mean [111-113]. When exposed to information from the world around them, people perceive and interpret the information, build expectations of the future based upon it and then act on the basis of these processes. The basic assumption resulting from this process is maintained by people and reinforced by human cognitive processes to uphold a shared reality and to reduce ambiguity about uncertainties. This cognitive process also helps justify the rationale behind decisions already taken and helps create stability. This is a well known phenomenon that is generally a healthy and necessary cognitive mechanism to cope with complexities and uncertainties. Yet, unfortunate effects of this phenomenon have been observed in many accidents in safety critical industries.[8]

Consciously and/or unconsciously, humans tend to select information which does not jeopardize their basic assumption in order to avoid inconvenient information. As will be shown throughout this section, this happened in many instances with regard to the Fukushima Daiichi accident. For example, NISA did not agree to proposals to change the emergency preparedness for a major accident in part because the agency had previously informed citizens that a major accident would not happen [102]. Over time, such collectively developed and basic assumptions and understanding of how the world functions become the socially accepted reality in which people act and interact and which reproduces itself in the way in which new information is integrated from the outside.

2.6.3.2. Why the Fukushima Daiichi accident was unexpected

One feature of improving safety culture is to examine the scope and boundaries of the basic assumption about nuclear safety, i.e. determining what are seen as plausible risks which can jeopardize nuclear safety. Two sets of knowledge are located within the boundaries of the basic assumption. Basically, it is possible to identify issues which can be regarded as known, i.e. so-called known knowns, and issues that humans are aware that they do not know about, i.e. so-called known unknowns [115]. An example of known knowns is the fact that earthquakes and tsunamis occur. An example of known unknowns is when an earthquake will occur or which magnitude it will have — people are aware of not knowing these parameters.

[8] This has been shown, for instance, in aviation research; see Ref. [114].

Despite knowing about the possibility that it might happen, humans are surprised when a known unknown occurs. This kind of surprise is defined as a situational surprise [116, 117] and can be regarded as a surprise within the boundaries of one's basic assumption. Its consequences are, in principle, preventable by utilizing available knowledge and information to anticipate and prepare for handling the known unknown (e.g. by building the infrastructure able to withstand earthquakes up to a certain envisaged magnitude). Probabilistic and deterministic safety analyses thus capture potential risks posed by known unknowns within their domains.

However, as the analysis below shows, the Fukushima Daiichi NPP accident was not part of either the known knowns or the known unknowns for the stakeholders involved, as several facts demonstrate that they were not able to imagine that such a complex event could occur. Importantly, when looking at each of the elements that were part of the accident in a separate manner, one may conclude that several of the precursors of the accident were known knowns and known unknowns. For example, as explained previously, calculations were made prior to the accident, showing a relatively high likelihood of a beyond design basis tsunami height at the Fukushima Daiichi NPP, making the tsunami a known unknown for some stakeholders.

Nevertheless, when investigating the accident from a human and organizational perspective, evidence showed that the stakeholders involved lacked an understanding of the systemic implication of the nuclear risk. Simply put, the stakeholders were not able to understand and anticipate the combined effect of the multitude of events taking place almost simultaneously.

Table 2.6-1 shows the different elements of knowledge that belonged to the known knowns and known unknowns of the relevant stakeholders prior to the accident, e.g. the elements of knowledge situated within the boundaries of the basic assumption held by these stakeholders. It further illustrates that, by combining these different elements, one can describe how the stakeholders involved experienced the situation triggered on 11 March 2011. As they had not imagined that the different elements in the table could combine in the way they did when the tsunami hit the Fukushima Daiichi NPP, they were effectively facing a surprise outside the boundaries of their basic assumption. It should be underlined that this table serves as an illustration encompassing only a few of the entirety of events that the people involved in accident response were faced with.

TABLE 2.6–1. EXAMPLES OF KNOWN KNOWNS, KNOWN UNKNOWNS AND UNKNOWN UNKNOWNS RELATED TO THE FUKUSHIMA DAIICHI NPP ACCIDENT

Topic	Known knowns	Known unknowns	Unknown unknowns
	Within the boundaries of the basic assumption of main stakeholders		Outside the boundaries of the basic assumption of main stakeholders
Seismic event	Design basis of the Fukushima Daiichi NPP and prediction of its design basis seismic performance.	Response of the Fukushima Daiichi NPP to a seismic event exceeding its design margin.	—
Tsunami	Tsunamis are co-related events to seismic events.	The prediction of tsunami heights.	—
Loss of off-site power (LOOP)	The Fukushima Daiichi NPP was designed for a loss of off-site power, with the expectation that the grid would be restored quickly.	The extent of grid damage and infrastructure disruption for a very large earthquake and tsunami.	—
SBO	Should SBO occur, the DC power (batteries) would last for about 4-6 hours. If AC was not restored in that time, core damage was to be expected.	—	—

TABLE 2.6–1. EXAMPLES OF KNOWN KNOWNS, KNOWN UNKNOWNS AND UNKNOWN UNKNOWNS RELATED TO THE FUKUSHIMA DAIICHI NPP ACCIDENT (cont.)

Topic	Known knowns	Known unknowns	Unknown unknowns
	Within the boundaries of the basic assumption of main stakeholders		Outside the boundaries of the basic assumption of main stakeholders
Batteries	Designed to provide power for about 4–6 hours.	How the batteries could be managed in an event.	—
EDGs	Expected to function on LOOP to provide AC power. Endurance based on diesel stock replenishment capability	Diesels can fail to start and duration of service may be unpredictable.	—
Switch gear	Interconnections allow cross feeding of power from one unit to its neighbour.	Availability of equipment and/or staff to effect interconnection in a severe accident.	—
Procedure for notification of a nuclear emergency	After NPP Site Superintendent is notified or discovers the specific event defined in Article 10 (1) of the Nuclear Emergency Preparedness Act, he/she shall, within a targeted time frame of 15 minutes, simultaneously notify all relevant entities by fax.	Site Superintendent's perception of severity of event, communication infrastructure available.	—
Staffing on-site	Minimum number of staff available on-site at the beginning of the accident at a given moment.	Capability to relieve staff if severe condition persists over prolonged period in case of damage to outside infrastructure.	—
Capability of staff for accident response	Formal competences of staff to respond to an anticipated type of accident (training, experience).	Psychological and physical condition and ability of staff to respond to an event under severe conditions in a given moment	—
Sum	—	—	**combination of all elements above = Unknown unknown**

When events are experienced as totally unexpected, they constitute so-called unknown unknowns, as people are not aware of the fact that they do not know about them — they happen outside the boundaries of their basic assumption. At the moment they occur, they are so unexpected and astonishing that one can neither understand nor explain them through the normal application of the knowledge and information available before their occurrence. Unknown unknowns profoundly surprise humans and suddenly reveal the incompatibility between one's self-perception of what is possible and what actually happens [118]. As such surprises lie outside the basic assumption of reality, even the availability of advance information is hardly useful in preventing people from experiencing such surprises because of the human tendency to interpret information in a way that suits one's basic beliefs [116].[9]

[9] In studying the accidents at the Three Mile Island and Chernobyl NPPs, researchers such as Reason [119] and Woods [120] differentiate between 'situational' and 'fundamental' surprises and utilize the term 'fundamental surprise' to describe a surprise that "reveals a profound discrepancy between one's perception of the world and the reality" [119], i.e. a surprise occurring outside the boundaries of one's basic assumptions. This term was originally coined by Lanir [116].

As shown in Table 2.6-1, such unknown unknowns can occur through the complex outcome created by the combination of several known knowns and known unknowns. As mentioned above, although advanced knowledge about the different elements present in the Fukushima Daiichi accident was available, much of this knowledge was not effectively shared among the stakeholders but only known by individual groups of people prior to the accident.[10] Both this lack of sharing knowledge and the general lack of realizing that the combined knowledge elements could reveal the possibility of an accident can be attributed at least in part to the basic assumption about nuclear safety held by the main stakeholders. As shown in Fig. 2.6-1, this basic assumption led the stakeholders to believe an accident of this kind would not happen and resulted in their conscious and unconscious rejection of the importance of certain knowledge elements and undermining the importance of sharing and combining them.

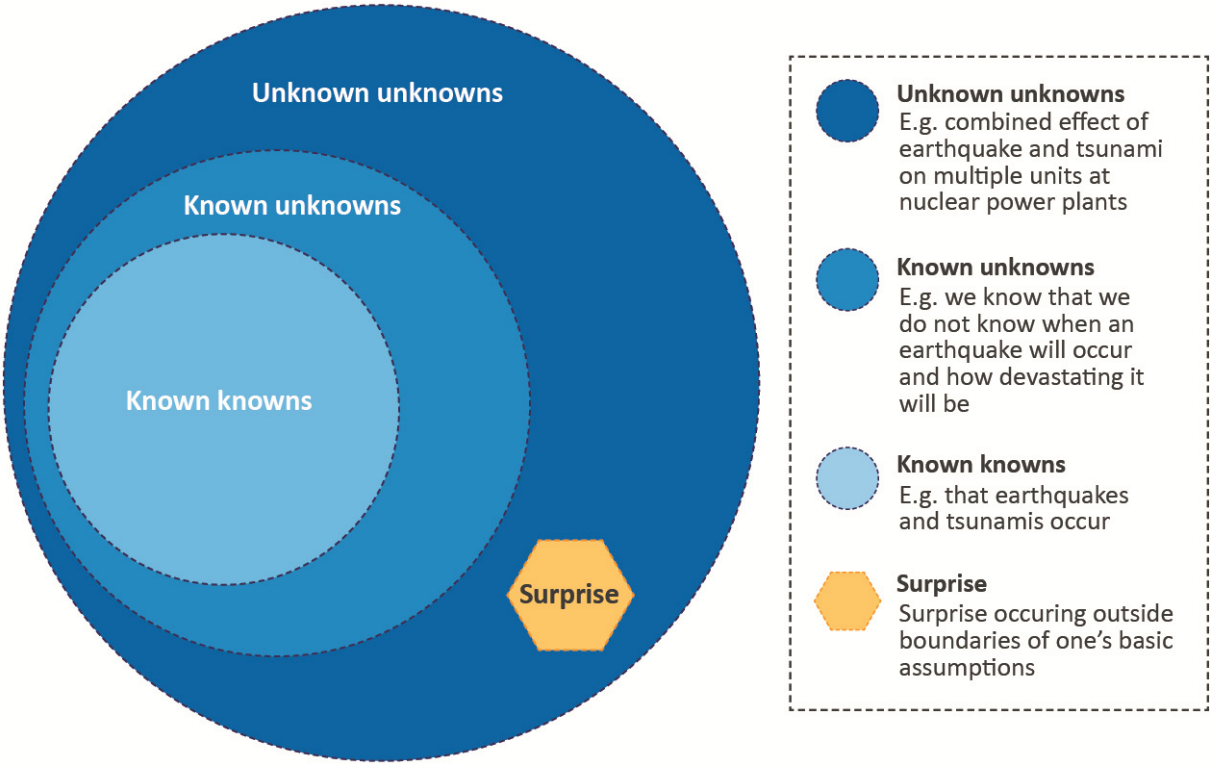


FIG. 2.6–1. The impact of unknown unknowns.

From a human and organizational perspective, it is concluded that the Fukushima Daiichi NPP accident was a surprise outside the boundaries of the basic assumption for the key stakeholders and that this prevented these stakeholders from effectively anticipating, preventing and mitigating the effects of the accident on 11 March 2011.

2.6.3.3. Nuclear safety in Japan

Once Japan decided to embark upon a nuclear power programme, many organizations began building the necessary nuclear infrastructure. TEPCO was one of the first companies to be licensed to construct and operate an NPP in Japan. Unit 1 of the Fukushima Daiichi NPP was the first TEPCO plant to operate. This reactor was a US design and was turned over to TEPCO after construction [54]. After the

[10] It should be noted again that, in hindsight, it is much easier to see the trajectory of an accident than it is to recognize the complexity and the systemic implications before and while the accident occurs [107, 108].

startup of Unit 1, there was a significant expansion in the development and use of Japanese nuclear power technology. Among other factors, the oil crisis of the 1970s was an impetus for this rapid development, as Japan wished to further reduce its dependence on energy imports [121]. By 11 March 2011, nuclear power accounted for nearly one third of the country's electrical energy production. The aim was to maintain or increase this capacity to 30–40% by 2030 [122].

In order for the decision to be made to use nuclear power for electricity production both in Japan and across the world, the risks of nuclear power needed to be understood and controlled. Advanced technological solutions were developed to provide robust safety margins. Over time, it became evident that not only the technical design, but several factors such as the associated infrastructure (procedures, processes, systems, etc.) and human and organizational factors also needed to be considered as part of operational safety. Multiple methods were developed and applied to calculate and assess the risks associated with nuclear power, such as PSAs and deterministic safety assessments. In addition, legislative frameworks, regulatory infrastructures, oversights and assessments (e.g. independent national regulators and IAEA peer reviews), and management systems were gradually put in place.

In addition to meeting the technological challenge of making nuclear power plants as safe as reasonably possible, it was essential to make sure that the public would consider nuclear energy production as safe, in order to gain support for its implementation and use.

The assumptions surrounding nuclear matters and nuclear safety were developed within the different main nuclear industry stakeholders over time. The prevailing assumption was that postulated risks could effectively be eliminated or mitigated through a combination of a robust technical design, the associated infrastructure (procedures, processes, systems, safety standards, etc.) and the capability of humans and organizations of operating and controlling the plant. This basic assumption that the robustness of the technical design and existing measures would maintain and protect the safety of nuclear plants against postulated risks was developed, maintained and mutually reinforced among the main stakeholders[11] in the operation of the Fukushima Daiichi NPP, i.e. the licensee, the regulatory body and the public. As a result of the prevalent technical assumption that the design and existing measures would be sufficient to maintain safety, non-technical factors such as the associated infrastructure and cultural, human and organizational factors were not adequately assessed and strengthened — particularly regarding the treatment of low probability, external events, accident management procedure improvements, and general actions to prepare for a complex accident.

2.6.3.4. Stakeholder: The regulatory body

This analysis of the Fukushima Daiichi NPP accident suggests that relevant regulatory bodies acted on a basic assumption considering the robustness of the technical design and existing measures to protect the nuclear plants against postulated risks as sufficient to ensure nuclear safety. In some instances, NISA did not agree to improve some safety standards proposed by other bodies. For example, when the Working Group for Reviewing the Regulatory Guide for Emergency Preparedness for Nuclear Facilities of the NSC proposed introducing the concept of the precautionary action zone (PAZ), NISA pointed out that:

> "in Japan it was extremely unlikely that a serious accident leading to a release of a large amount of radioactive materials would occur; even if such an accident occurred, it was unlikely to continue for a long period of time, and thus, there was no need to immediately evacuate residents within a 5-km radius of a nuclear power station [102]."

Rationalizations such as these served to protect the collective trust in safety [102]. Prioritization of tasks which were compatible with the basic assumption of nuclear safety and procrastination in

[11] Other stakeholders were also involved but to a lesser degree.

decisions and activities that would have led to a reconsideration of the accepted approaches and beliefs [102] were among other collective and individual mechanisms that led to a continuation of the existing situation.

The role of the regulatory bodies

IAEA Safety Standards Series No. GSR Part 1 [123] states in Requirement 17 that regulators shall hold a strong and independent position and be able to exert the necessary authority over the industry they oversee. NISA did not hold such a position, was not given sufficient authority and was thus not able to challenge its own basic assumptions or those of others regarding nuclear safety [32]. Regulatory bodies have both a formal role and authority, as provided in laws and regulations [99] and official mission statements (de jure authority), and a more informal role that it is implemented and perceived in day to day situations (de facto authority). In order to be effective in fulfilling its intended mission of ensuring protection of the people and the environment, a regulatory body not only needs to be provided with the necessary formal power and legal framework, but it also needs to be accepted by the operator. NISA was apparently unable to practice either de jure or de facto authority at the time of the accident. The affiliation of NISA with METI, which was responsible for the promotion of nuclear energy in Japan [32], as well as NISA's dependence on other governmental bodies for personnel and budget management issues [32, 53], appears to have hampered its formal independence. Moreover, the distinction between NISA's role and that of the NSC was not clear, as identified by the IAEA Integrated Regulatory Review Service (IRRS) team during its mission to Japan in 2007 [53] (see also Section 2.5.3. for a description of NISA's and NSC's formal roles as provided in the Japanese legal framework). NISA was often perceived as not having or exerting a strong influence on the nuclear industry, including on TEPCO [32]. It appears that NISA was also not fully respected by TEPCO as a strong regulatory body [32], despite some instances in which NISA showed strength in enforcing its decisions, for instance after it became known that TEPCO had covered up problems in the late 1990s and early 2000s [54].

NISA's lack of authority seems most likely to have been at least partially linked to a series of constraints. NISA was inhibited in the fulfilment of its oversight role by the lack of an appropriate regulatory framework [6] and by explicit legal constraints. For instance, the Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities [9] was revised in 2006 to also address tsunamis as an event accompanying earthquakes [99], but there was no legal framework to apply this guideline retroactively to NPPs licensed before the guideline was in place [32].

NISA also faced restrictions of its oversight activities due to explicit legal constraints. For instance, the IAEA IRRS mission in 2007 found that NISA inspectors did not have unfettered access to licensees' utilities to perform inspections and were only allowed to conduct inspections during certain times [53]. In addition, there were also organizational constraints. NISA and the NSC seemed to suffer from a lack of resources [102]. Moreover, NISA's ability to properly adhere to its duties was also hampered by a lack of competence, making it dependent on the competence and expertise of the operators in carrying out its tasks [32]. This lack of competence is considered to be in part linked to the government's staffing policy [32]. NISA's employees comprised two categories, the policy makers and the experts [53]. The policy makers were recruited from universities to METI and rotated within different departments of METI, including NISA. They often had little specific knowledge relevant to the work at NISA and they stayed within NISA for only a few years. The experts were recruited from the industry, with specific knowledge and expertise in the nuclear field. This category of staff rotated within NISA, according to the government rule which required a job rotation every two to three years [53]. However, mastering and understanding of the technology and the tasks associated with a nuclear regulatory body can take a number of years; as a result, it would be very challenging for rotating staff (whether as policy makers or experts) to become fully effective in their nuclear regulatory role over such a short duration.

The relationship of the regulatory body with the licensee

The human and organizational factor analysis suggests a lack of effective independence of NISA and the NSC from the industry they regulated. An example of this is the active influence of the operators, through the Federation of Electric Power Companies (FEPC) of Japan [32], and the active involvement of the licensees in writing reports or guides or their participation in regulatory forums and committees [32, 102]. For instance, the NSC invited licensees to be heavily involved in the process of revising the Safety Design Guide with regard to SBO. The resulting report noted that an SBO lasting for many hours may cause damage to the reactor core, but emphasized the high reliability of external and emergency power sources in Japan; it thus concluded that nuclear power plants had sufficient defences against an SBO. As a result, the Safety Design Guide remained unchanged up to the time of the Fukushima Daiichi accident [32].

Besides the issue of effective independence, the nature of the day to day relationship between a regulatory body and the organizations it oversees and the regulatory approach taken by the regulatory body need to be considered. The interaction between a regulatory body and an operator is a two way relationship, in which both organizations exert explicit or implicit influence on each other. The basic assumptions about nuclear safety are critical — they will direct the behaviour of the actors but will also be mutually shaped through this interaction process. The way the regulatory body fulfils its oversight and regulatory activities influences the licensee's behaviour and its attitude to safety, and vice versa. For example, the way in which the licensee follows requirements will influence the expectations and priorities of the regulatory body in the future.

The analysis has shown that the regulatory body in Japan worked in a non-strategic or reactive manner in its regulatory and oversight work. For instance, since its establishment in 2001, NISA focused on short term activities reacting to various incidents in Japanese nuclear installations [102] and dealing with the various falsifications of safety records that were revealed from the late 1990s onwards [54]. It was therefore not able to address more fundamental and long term issues, such as the consideration and implementation of international fundamental safety principles and developments [102]. NISA's oversight and regulatory activities were often based on compartmentalized thinking, i.e. it did not sufficiently address issues in a broad, systemic manner, considering all aspects relevant to safety [53, 102]. Particular emphasis was placed on technical issues, compared with operational aspects and human and organizational factors [53], although efforts were made by NISA to improve in this respect [53]. In some instances, the regulatory body demonstrated limited risk awareness (e.g. concerning the relevance of tsunamis for the safety of Japanese nuclear installations [99]), acceptance of insufficient assumptions (e.g. about the possibility and probability of a severe accident [32]), a limited sensitivity for safety relevant information and a lack of urgency to act upon such information [99], thereby precluding the swift implementation of appropriate safety measures.

NISA demonstrated a lack of enforcement and failure to take actions in its oversight activities [99], or exhibited a tendency to procrastinate [102]. The relationship between the regulatory body and TEPCO was described as "cozy" in the report by the National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission (Diet Report) [32]. It was a typical pattern for NISA to refrain from formulating clear requirements towards TEPCO in a written form [32] and enforcing their fulfilment [32, 102]. Many issues were recommended to the operators to be implemented on a voluntary basis [53, 99]. The lack of competence at NISA did not contribute to a constructive dialogue on safety issues and regulations with TEPCO [54].

In addition, the regulatory bodies were less disposed to learning from international experience [32], showing a clear tendency for isolation [102], frequently arguing that lessons learned and approaches from other countries were not applicable to Japan [102]. In conclusion, the basic assumption that the regulatory bodies were acting upon dissuaded them from taking firm actions to enhance safety.

The relationship of the regulatory body with the public

There was a frequent concern at NISA that stricter regulations or new safety requirements would be interpreted by the public as an indication that the nuclear installations were not sufficiently safe [102], and that this would cause confusion and anxiety among people [99]. This perception led NISA to develop a lack of transparency in its communication with the public [32]. Although in hindsight there is evidence of failures on the side of the regulators and for flawed regulatory practices, the overall picture conveyed may include some hindsight bias. It should be noted that the regulatory bodies in Japan, just as regulatory bodies all over the world, were indeed engaged in continuous efforts to improve their regulatory practices and frameworks, as was also shown by the IAEA IRRS mission in 2007 [92]. In particular, they include lessons from some events in the beginning of the 2000s or the JCO's Tokaimura criticality accident. Therefore, although the picture might seem clear in retrospect, it might have not been evident to the regulators at the time.

If the regulator requires safety related improvements to an operating plant, it may indirectly trigger the assumption among the public that the plant, without the improvement, would be unsafe. On the other hand, if the regulator does not request improvements, it may indirectly perpetuate the notion that the safety of the plant is adequate and that risks are well managed. The regulator is particularly challenged by having to simultaneously carry out its role and mandate to protect the people and environment, while, at the same time, being conscious of the implications of its decisions, including the public perception of safety.

2.6.3.5. Stakeholder: The public

As the Japanese Government decided to establish its nuclear power programme, there were multiple reasons why, to some extent, the term 'nuclear' elicited negative perceptions among the public. Faced with this situation, the importance of assuring the public that nuclear technology could be trusted, and that an accident was most unlikely to occur, was therefore present from the start of the Japanese nuclear power programme. As described above, the basic assumption about nuclear safety was built upon the technical robustness of nuclear engineering capabilities. Beginning with the first stages of searching for sites for nuclear installations, the national government provided extensive support to the electrical power utilities, in order to assure the local governments and communities of potential sites of the reliability and safety of nuclear power plants. Although governmental support of an important national industry is common, it has been pointed out that the relationship resulted in lost opportunities to increase safety that might have come about through interaction with an engaged and informed civil society [121, 124].

The basic assumption concerning nuclear safety was also affected by the way in which radiation and radiation effects were treated. Several Japanese accident investigation reports pointed out the need to improve the Japanese educational system, to provide a sufficient understanding of radiation and its effects [32, 99, 125]. Investigating "the status of how the topic of radiation had been taken up in the school curricula in the compulsory school education history in Japan", the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company (ICANPS) concluded that it was:

> "hard to accept that the general public had sufficient opportunities to learn about scientific characteristics of radiation or its effect [on the] human body at schools or in a community" [99].

The Diet report concluded that the Japanese educational programme lacked the inclusion of "social and actual issues" dealing with nuclear matters in order to be able to communicate risk to the public [32]. Furthermore, the Rebuild Japan Initiative Foundation pointed out that the Ministry of Education, Culture, Sports, Science and Technology (MEXT) worked with the objective of emphasizing the positive sides of nuclear power in the educational programmes under its supervision [125].

It was stated, as part of the Diet report that, even in locations near the plant, "only 10–15 percent of residents reported receiving evacuation training, and less than 10 percent were told of the possibility of a nuclear accident" [32]. When the local population in Fukushima was asked about the first thing that came to mind after the earthquake, concerns regarding the nearby nuclear power plant were not a common response [32]. It is important to provide a balanced picture that includes a discussion of the risks posed by the technology in an open and transparent manner. By ensuring such a balanced understanding, the social preparedness to handle a nuclear emergency is enhanced, and the public is able to judge radiation risks on the basis of accurate information, avoiding both unnecessary fear and underestimation of radiation risks.

The relationship of the public with the regulatory body

The reluctance of NISA to update regulations was based, at least in part, on the fear that the public might get the impression that NPPs were not as safe as promoted, and they would consider NISA responsible [91]. While other countries with comparable nuclear programmes implemented significant updates to regulations [32], NISA contributed to maintaining the basic assumptions concerning nuclear safety vis-à-vis the public.

The concern about worrying the public about nuclear risks also characterized the decision making on preparedness for possible nuclear emergencies. After the 2007 event at the Kashiwazaki-Kariwa NPP, resulting from the Niigata-Chuetsu-Oki earthquake, the Niigata Prefectural Government considered conducting evacuation drills assuming the simultaneous occurrence of an earthquake and a nuclear emergency. The initial feedback from NISA was that the likelihood of such a scenario was extremely low, based both on the seismic structural design of nuclear reactors and the fact that the event at the Kashiwazaki-Kariwa NPP did not develop into a nuclear emergency. In addition, the relevant government agencies and local government organizations provided comments to the effect that the implementation of such a scenario would not only require major modifications to the existing emergency framework, but could also result in the public forming "the mistaken view that major natural disasters are likely to initiate a nuclear emergency" [99]. It was finally decided to abandon the idea, although, in the same year, the Niigata Prefectural Government organized a drill combining a nuclear emergency with the occurrence of heavy snowfall [99].

The efforts of the regulators to uphold the safe image of nuclear matters also resulted in a lack of transparency. For example, NISA's efforts to protect itself from potential lawsuits was shown by its failure to disclose information regarding nuclear safety, such as proceedings from evaluations or results of assessments [32].

The relationship of the public with the licensee

Possible reactions from the public also strongly influenced the way risk management was carried out by licensees. For example, when TEPCO considered risks related to natural disasters, they were considered primarily in terms of jeopardizing public trust and increasing legislation [32]. After the accident, TEPCO admitted that there "was apprehension that, if the possibility was acknowledged that a situation exceeding design standards might occur, it might lead to the cancellation of the establishment permit or prolonged shutdown" [54]. With regards to the treatment of tsunamis, this same logic was applied:

> "We were concerned that, if the risk of a tsunami strike exceeding assumptions had been announced, then there would have been demands for absolutely safe countermeasures to

perfectly protect against any impact resulting from a tsunami. Operations would have been unavoidably shut down until such measures had been completed" [54].[12]

In general, the communication with the public, for example during hearings, on these issues, did not address the challenges of the safety of nuclear plants [32].

2.6.3.6. Stakeholder: The licensee

Many aspects of the role of the licensee have been explained above in the context of the roles of other stakeholders — the regulatory body and the public. For example, the issue of independence, the way the regulatory bodies and licensees interacted with each other on routine and non-routine activities, as well as the approach used by the regulatory body, all impacted the basic assumption held about nuclear safety. Furthermore, the way the licensee acted towards the public with regard to sharing information on the risks posed by nuclear power production is also likely to have impacted the licensee's own perception of these risks. Other aspects specifically related to the licensee are described below.

Confidence

The confidence in the technical features of nuclear safety contributed to TEPCO not implementing certain safety measures in the event of a nuclear accident. While the international community began to advance in the area of SAM, TEPCO did not adopt some of these developments. At the time of the accident, TEPCO's AM measures addressed internal cause events only [99]. TEPCO also did not examine and prepare accident management measures for a tsunami, believing that they could "respond to natural disasters including tsunami within design" [99]. In addition, the measures assumed normal operation of any adjoining reactor units and did not consider an event that could simultaneously affect multiple reactor units [99].[13] As a result, TEPCO had not planned how to address a situation where a unit lost all power and was not able to receive power from an adjacent unit.

Furthermore, after new regulations regarding SBO and the associated countermeasures were established in other countries [32][14], TEPCO and the Kansai Electric Power Company stated that "[r]eflecting SBO in the design guide is going too far". "If the intent is to make SBO a design basis accident, the concept of the design guideline would be fundamentally changed" [32]. It was subsequently agreed that the reliability of DC power sources, external power sources and diesel generators was high and that there were no cases of DC power source failures [32]. At the time of the event, there were "no legal regulations for the consideration of beyond the design basis, as Japanese plants [were] considered to be adequately safe as ensured by preventive measures" [53]. In addition, TEPCO executives and others did not assume that a natural disaster beyond design basis assumptions could occur and therefore did not establish measures for such an event [99].

---

[12]TEPCO elaborated on its position as follows:

> "Looking back on the results of this accident, we believe that the risk of a tsunami strike exceeding assumptions should have been announced, and we should have communicated that the possibility of a severe accident occurring even with various safety measures in place was not zero. Also, we should have explained the necessity of measures for mitigating the effects of an accident. We believe that there were problems underlying our not having been able to provide explanations of these risks" [54].

[13] It should be mentioned that prior to the Fukushima Daiichi accident, considerations of multi-unit events had not been made by most countries operating NPPs:

> "Historically, nuclear regulators have not required nuclear operators to include multi-unit accidents at a single site or multi-site accidents in their design basis." [126] .

[14] Although other countries had implemented SBO countermeasures, an SBO of the length that occurred at Fukushima Daiichi had not been considered.

Risk management

TEPCO's decisions related to risk management — and more specifically related to low probability, high consequence events — were not sufficiently evaluated and acted upon. In several instances, the risks identified were not considered to be based on validated facts or identified by sufficiently qualified experts. Developing accurate assumptions for low probability events can be particularly challenging, as fewer examples and much less verified information exist to support them. In the case of the Fukushima Daiichi NPP accident, the height of the tsunami waves which struck the Fukushima Daiichi and Daini NPPs on 11 March 2011 was generally assumed not to be plausible. This assumption was based on the selective collection of scientific evidence and historical records and on the results of different simulations that applied methodologies and models. In 2008, when re-evaluating the tsunami risks at the Fukushima Daiichi NPP, TEPCO requested estimates provided by the Headquarters for Earthquake Research Promotion (HERP), which indicated that the wave height could exceed 15 m. During the same year, TEPCO engineers calculated another estimate of a wave height at the Fukushima Daiichi NPP of approximately 9 m, based on the wave source model presented in a study of the Jogan 869 tsunami [106]. TEPCO did not take concrete measures to protect the Fukushima Daiichi NPP from tsunamis in response to these estimates for two main reasons. First, TEPCO asked the Japan Society of Civil Engineers (JSCE) to determine the validity of the 15 m estimate, which was based on a wave source model and a postulated model with characteristics similar to an earthquake that took place in Iwate Prefecture (approximately 200 km north of the Fukushima Daiichi site). At the time of the accident, this virtually derived value remained under review. Second, the 9 m value was also seen as not sufficiently reliable as "the source model had not yet been finalized" [99, 106].

Taking into account the hindsight bias, it should be noted that TEPCO did take several actions related to tsunami protection. The design basis postulations for tsunami height were re-evaluated at least five times throughout the lifetime of the Fukushima Daiichi NPP. Tsunami height assumptions were increased from sea level +3.1 m to sea level +5.7 m in 2002, and increased again to sea level +6.1 m in 2009 to "address uncertainties in the calculated values based on improved assessment methods developed by the seismic and tsunami experts associated with the Japan Society of Civil Engineers (JSCE)" [106].[15] Seawater pumps were accordingly raised in 2002 and 2009. In order to validate the Jogan tsunami assumptions, TEPCO further arranged studies in 2009 and 2010, performing "core borings at five locations near the Daiichi and Daini sites" [106].[16] These facts illustrate that some actions were being taken. There were other instances where TEPCO did not consider safety measures based on the low probability of the initiating event [32] or lack of sufficient scientific knowledge. For example, following an FEPC discussion in 2010, a decision was made to only take internal events into consideration in safety assessments, as the assessments of "external events were considered significantly more uncertain than assessments of internal events" [32]. At the time of the accident, the Fukushima Daiichi NPP was undergoing seismic and tsunami safety assessments on all units, and associated construction work was in various stages across the units (planning, scheduled and under way). Some countermeasures, such as the water tightening of seawater pumps at Units 5 and 6, had been completed [32].

When sufficient knowledge and experience were present, such as in the case of the earthquake at the Kashiwazaki-Kariwa NPP in July 2007, TEPCO acted proactively to apply countermeasures for a similar type of event. The IAEA sent a fact finding mission to the plant in August 2007; in early 2008, the IAEA follow-up mission reported [127]:

[15] The JSCE was recognized by all Japanese nuclear organizations as the authority specifying seismic and tsunami design criteria [106].

[16] The maximum tsunami height shown by the deposits was 4 m.

> "Since August 2007 there has been a very significant amount of high quality work performed in all areas that were considered during the follow-up mission including the establishment of required regulations and the participation of recognized institutions in Japan in the area of earthquake engineering and nuclear safety. NISA, JNES, TEPCO and a large number of specialized institutions and universities as well as experts have performed activities relating to the evaluation, regulation and the review aspects of the situation of the plant after the earthquake."

Less than four years after the Kashiwazaki-Kariwa event, seismically isolated buildings were constructed at the TECPO nuclear sites to serve as the ERC in the event of a nuclear accident. These buildings also included communications facilities and meeting rooms [99]. The seismically isolated building at the Fukushima Daiichi site was critical for supporting the event response on and after 11 March 2011. Based on the experience with the Kashiwazaki-Kariwa NPP, TEPCO also installed fire engines that were used as pumps for coolant injection during the accident [10]. These measures demonstrate the importance of the learning attitude.

Human and organizational factors

In the years prior to the Fukushima Daiichi accident, TEPCO completed several actions to improve its management and organizational processes. These were largely triggered by TEPCO's cover-up scandal of 2002 [54].

The large scale scandal was exposed in 2002, when NISA announced the results of an investigation of 29 cases of falsifications of inspection records produced for voluntary inspections at the Fukushima Daiichi NPP, Fukushima Daini NPP and Kashiwazaki-Kariwa NPP between the second half of the 1980s and 2001 [99]. This investigation led to NISA shutting down all of TEPCO's plants for inspection and revising its regulations on voluntary inspections [54].

By the end of the 1990s, TEPCO had already attempted to deal with the issue of falsification, following the discovery of the falsification of some NPP pipe welding data and spent fuel transport container data. In 1998, a Cultural Reform Review Committee was established to investigate the corporate culture and context in order to identify problem areas and review countermeasures and background analyses. This led to several initiatives aiming to reform the corporate culture, including a cultural change action plan with various initiatives to increase cross-hierarchical dialogue and "instill morality and manners of each and every employee" [54]. In spite of these efforts, the 2002 scandal was revealed — and, referring to the reforms prior to 2002, TEPCO admitted in hindsight that "these efforts at corporate cultural reform merely imposed idealism and did not lead to actual reform" [54].

After 2002, TEPCO stated that the company strived to increase transparency, to overcome its closed nature, and to develop an open corporate culture by proactively inviting third party perspectives [54]. The third party perspectives included facilitation of discussions on nuclear safety and quality assurance by external experts, reviews by domestic and foreign specialized organizations and cross-divisional personnel exchanges [10]. In addition, a series of nuclear renaissance activities were launched to make "recurrence prevention measures more widespread and [to become] an outstanding world-class nuclear operator" [54]. These included a leadership development exchange, which was successful according to its students, but seemed to have failed in producing a significant organizational impact owing to a lack of management support in utilizing the developed competences [54]. The latter was also the case with a peer activities programme introduced to improve work processes by learning from international peers. It was ineffective due to a lack of visible sponsorship or commitment and ineffective implementation processes. A final example includes TEPCO's construction of a management framework to monitor progress and achieve overall optimization through performance reviews. In hindsight, TEPCO reported that the ambitious programmes did yield some results, but that, in addition to the problems cited above, a recurring issue

was the lack of management support and a lack of accountability for the implementation of the programmes [54].

In November 2009, TEPCO developed 7 Principles of Safety Culture after receiving comments on its safety culture from an external review [10]:

> "Principle 1: All personnel shall be aware of their involvements in nuclear safety
> "Principle 2: Leaders shall autonomously set examples of safety culture principles
> "Principle 3: Promote mutual trust among all concerned parties within or outside TEPCO
> "Principle 4: Make decisions by placing the first priority on nuclear safety
> "Principle 5: Be strongly aware of the inherent risks of nuclear power generation
> "Principle 6: Always maintain a questioning attitude
> "Principle 7: Learn systematically on a daily basis".

In addition to the principles, management communicated the approach of safety first and activities were conducted through safety caravans and case studies to help employees understand safety culture. Action plans, which included actions related to the results of recent safety culture assessments, were also developed and implemented to further assist in cultivating the desired safety culture. In addition, safety activities and events at the nuclear sites were evaluated against the seven principles [54]. Despite these activities, TEPCO concluded the following after the Fukushima Daiichi Accident:

> "[T]he deterioration of a safety culture throughout the entire organization, which underlay the occurrence of events which posed an issue, was limited to the assessment that 'there was no inclination toward a decline in the safety culture.' It did not result in an effort to deduce issues to be addressed based on how the whole operation proceeded. Based on this situation, past efforts to create a culture of safety were confined to so-called campaign-style content, and it is believed that measures did not go deep enough to the heart of measures which should have been addressed and evaluated" [54].

Other accident reports have reached similar conclusions to those of TEPCO, challenging the safety culture within TEPCO and also within the regulatory authority [32, 99]. A full, detailed assessment of TEPCO's safety culture is outside the scope of this t volume. Nevertheless, IAEA safety standards state that effective safety culture improvement activities need to address the deepest level of the culture, i.e. basic assumptions. TEPCO safety culture initiatives were not effective at challenging basic assumptions.

2.6.4. The impact of basic assumptions on the accident response

Those who directly responded in the early stages of the accident did so under extreme circumstances. The anxiety and stress associated with their actions was further exacerbated by the fact that the personnel often did not know the situation of their families nor the condition of their homes. They faced an extremely adverse work environment from both physical and psychological perspectives. Plant personnel worked often in darkness, without any indications of the status of the plant. They had to cope with working among debris and damaged structures and, as time progressed, their environment further degraded owing to the risks posed by hydrogen explosions and radiation exposure. Working under such conditions must have been fraught with fear, uncertainty, frustration and anxiety. However, personnel displayed a strong dedication to their tasks and worked for days without an uninterrupted break for sleep, remaining at the site and performing critical tasks that could affect their survival.

2.6.4.1. Preparedness decisions

As explained above, there was an underlying basic assumption among the nuclear industry stakeholders that the robustness of the technical design would maintain and protect the safety of plants

against postulated events and that extreme external events were of low probability. This basic assumption led to an inability to anticipate or even imagine that an extreme external event, such as the earthquake and tsunami of 11 March 2011 causing a multi-unit accident, could take place. From a human and organizational perspective, this surprise outside the boundaries of the stakeholders' basic assumptions contributed to a lack of preparedness that ultimately resulted in personnel being exposed to extremely challenging working conditions in trying to respond to the events at the Fukushima Daiichi NPP. This seriously affected their ability to be effective in the mitigation of the accident.

At the time of the accident, as described in Section 2.6.7:

> "There [were] no legal regulations for the consideration of beyond the design basis, as Japanese plants [were] considered to be adequately safe as ensured by preventive measures" [53].

In addition, a report entitled, Station Blackout at Nuclear Power Plants [128], released in June 1993 by a Working Group on Station Blackout set up under the NSC's Committee on Analysis and Evaluation of Nuclear Accidents and Failures,

> "underscored the high reliability of Japan's external and emergency power sources, concluding that the probability of an SBO occurring was low and that nuclear power plants had sufficient defenses against SBO" [32].

There was a view within NISA that:

> "[W]ith regard to nuclear emergency preparedness, it was not necessary to anticipate an accident that would release enough radioactive material as to actually require protective actions, since rigorous nuclear safety regulations, including safety inspections and operation management, were in place in Japan" [32].

Even in light of the lessons learned from the 2007 Niigata-Chuetsu-Oki earthquake,

> "no integrated efforts had been made by the central government and municipal governments to establish disaster preparedness against complex disasters prior to the accident at the Fukushima Daiichi plant" [32].

The decision to not drastically change the existing emergency preparedness structure is reflected in the following quote by NISA:

> "It is reasonable for us to implement effective and efficient measures against complex disasters in line with the current nuclear emergency preparedness structure, since complex disasters are highly unlikely to occur" [32].

Finally, there was also a concern that developing countermeasures against a nuclear accident coupled with a complex disaster could lead people to think that a major natural disaster could initiate a nuclear emergency and that major modifications to regional disaster prevention plans would be required [99].

The scale of the earthquake and tsunami experienced on 11 March 2011 was not anticipated and the complexity of subsequent events was not considered. As a consequence of this basic assumption, insufficient infrastructure, protocols, procedures, equipment and training were in place to respond to such a situation.

> "The expansion of damage caused by this accident is attributed to the insufficient preparedness on the part of the central government and municipal governments in facing a complex disaster involving earthquakes and tsunamis occurring simultaneously with a nuclear disaster" [32].

The situation faced by operators and other key stakeholders on 11 March 2011 did not fit with what had been previously included in their basic assumptions about nuclear safety. As a result, personnel were forced to improvise and adapt to the evolving situation under severe time pressure, with recurrent earthquake aftershocks, the risks and fear of additional tsunami waves, sometimes in almost complete darkness, in areas scattered with debris and objects, (potentially) contaminated water, high radiation dose rates and a range of other physical safety hazards. The workers' ability to work effectively was also affected by the need to wear cumbersome full body protective clothing and full face masks and, in some instances, self-contained breathing apparatuses.

2.6.4.2. Infrastructure: Buildings, communications and human resources

The infrastructure in place to address emergencies was not adequate to respond to the event at the Fukushima Daiichi NPP. Buildings essential for the implementation of accident response actions were rendered inoperable as a consequence of the accident. For instance, the Local Nuclear Emergency Response Headquarters (NERHQ) at the Off-site Centre (OFC) was located and established without sufficient consideration of access road damage or communication system breakdown that could occur as a result of an earthquake. Consequently, the centre immediately lost its functionality from the beginning of the complex accident [102]. Some personnel were unable to reach the centre because of infrastructure damage. Those who did reach the centre despite the infrastructure damage experienced a loss of normal and backup power and could not remain because the centre had not been built with adequate protection against high radiation or a contaminated environment [106]. No plans were in place for dealing with the situation in the event that such centres and headquarters needed to be relocated [106].

As assessed in Section 2.4.2, the unavailability of proper means of communication and the huge volume of communications also challenged the event response. A situation that involved the loss of all power sources for a long period of time had not been anticipated [99] and, as a result, procedures to restore electronic telecommunication systems did not exist [99]. Such a loss of power rendered normal communications systems as well as some backup systems unavailable. Communications at the site were generally limited to two hotlines that could be used to communicate between the control rooms and the on-site ERC. These limitations not only hindered internal communications, but they also had an impact on external communications making it difficult to understand and mitigate the accident conditions which were changing continuously. For example, the loss of power led to plant data and information being unavailable. This contributed to misunderstandings regarding core cooling and challenged overall decision making. In addition, without the necessary information, government personnel found it hard to provide advice [99]. In some instances, direct calls to the site were made by senior government officials to obtain information or make recommendations.

Staffing issues as assessed in Section 2.4.2 also impacted those responding to the accident at the Fukushima Daiichi NPP. A staffing plan/strategy on how to respond to a multi-unit, high stress, long duration event did not exist [106], and the "corporate and station structure and staffing were not designed to support the number of units that may be affected by a common-cause event" [106]. As a result, operators worked for several days with minimal rest, and personnel in the on-site ERC carried out their functions continuously for a number of weeks. In addition, some contractors who worked on the site during normal conditions left it when radiological conditions worsened. In response, TEPCO personnel remaining at the site were trained, if possible, to perform the critical functions previously carried out by contractors [106].

The radiological conditions present during the event also posed a staffing challenge. As conditions exceeding normal radiologically controlled area (RCA) conditions expanded to include outdoor areas, there were not enough radiation control workers [10]. Insufficient staffing resources also affected TEPCO's communication capability relating to press conferences.

2.6.4.3. Protocols: Roles, responsibilities and decision making

As assessed in Section 2.4.3, clear roles and responsibilities for addressing simultaneous accidents on multiple units had not been established, or roles adopted during the accident differed from those previously assigned. The normal staffing at the site included a site superintendent, two unit superintendents, shift supervisors and assistant shift supervisors for Units 1–4 and Units 5 and 6, in addition to the associated control room crew for each two unit control room [106]. During the accident, the site superintendent, with support from the shift supervisors and general managers of the operations department, was responsible for managing the response to the events at all units. Decisions related to core cooling and venting containment were the responsibility of the site superintendent. However, in some instances, instructions were provided directly by the NSC or members of the Prime Minister's Office [32].

The roles and responsibilities of the headquarters of the Prime Minister, national and local governments, and nuclear plant operators were not clearly defined in the Nuclear Emergency Preparedness Act [88], nor were the defined roles and responsibilities always followed [32]. Several instances serve to illustrate this situation. For instance, even though its official role was to support the station, the ERC at TEPCO's headquarters was forced to exchange information with and answer to inquiries from both the central government and external parties [10]. This ad hoc structure is reported to have caused TEPCO to "lose the sense of responsibility and autonomy that is so essential for an operator in their on-site emergency response" [32].

The conflicting instructions issued by various decision makers also led to confusion. This was the case with the contradictory instructions received by the Site Superintendent regarding the startup of seawater injection into Unit 1 on 12 March 2011 [32]. In this case, METI Minister first ordered TEPCO to inject sea water, and operators at the Fukushima Daiichi site started the appropriate preparations. However, about one hour later, the Prime Minister refused to approve the seawater injection due to concerns over the issue of recriticality. Therefore, the Site Superintendent was asked to suspend the seawater injection while awaiting the Prime Minister's decision. However, based on his understanding of the situation, the Site Superintendent decided on his own to disregard this new instruction, and continued with the seawater injection. As the Prime Minister decided shortly afterwards to approve the injection, this confusion had no real consequences for the Unit 1 seawater injection. Nevertheless, given the time pressure and stress that the stakeholders were under, such misunderstandings and conflicting instructions did not help in ameliorating the situation [10, 32].[17]

A similar situation involving the Prime Minister's Office and the Site Superintendent developed over the decision to vent the primary containment vessel (PCV) of the Unit 1 reactor. The chairman of the NSC notified the Site Superintendent that depressurization and injection should be prioritized over venting; however, at that time, field work was being performed to prepare for venting [10]. After receiving this notification, the operators at the site and officials at TEPCO's ERC in Tokyo deliberated over the request and reconfirmed the policy to prepare for venting before depressurization [10].

Such situations were cited as leading to confusion with respect to the decision making authority and the review and the decision itself, especially since it appeared to some workers that "external opinions were given priority over judgment of the director of the ERC at the power station (Site

[17] While Site Superintendent Yoshida at the Fukushima Daiichi NPP did not follow the instruction to stop the seawater injection, TEPCO Headquarters meant to do so and reported that the company had instructed Mr. Yoshida to stop the injection after conferring with the Prime Minister's Office. The TEPCO Fukushima Nuclear Accident Analysis Report points to several factors as to why TEPCO Headquarters made this decision, highlighting the company's concern that

> "[F]uture coordination with necessary government organizations would be impeded even further if field work proceeded without the approval of the Prime Minister, as the PM is the chief of the Nuclear Disaster Response Headquarters" [10].

Superintendent)" [10]. In general, the lack of clarity about roles and responsibilities increased stress and confusion for all parties, worsening the situation from a human and organizational point of view.

2.6.4.4. Procedures and guidance

Procedures and guidance were also not adequate to address the complex accident conditions experienced at the Fukushima Daiichi NPP. In the area of emergency preparedness and response, "little thought had been given in the Emergency Preparedness Guide to a situation in which commerce and logistics came to a standstill" [32]. The NSC's Nuclear Emergency Preparedness Guide had been established in 1980 and was subsequently revised; a larger revision to comply with international standards was initiated in 2006 (see Technical Volume 3) [32].All of these reviews did not lead to the guide being fully in line with IAEA safety standards [80]. The underlying reason for this has been the basic assumption that "a Chernobyl type nuclear accident could not occur in Japan" [32]. In addition, the Prefectural Regional Disaster Prevention Plan did not anticipate a nuclear accident of such a scale. Consequently, a 20 km radius evacuation zone was not designated prior to the accident, nor were measures specified to deal with complex accident situations associated with a natural hazard [32]. Other regional disaster plans were developed for an accident similar to those previously experienced, leaving hospitals to develop their own evacuation plans and to evacuate patients on their own [32]. The resulting situation led to challenges in evacuating people from their homes and patients from hospitals.

With respect to operating the plant, the AM measures used at the time of the accident "assumed normal operation of [the] adjoining reactor unit and did not consider the possibility of multiple reactor units simultaneously being affected by external events such as natural hazards. Therefore, TEPCO did not plan any action that can be taken when a reactor unit has lost all power and is not able to receive power from the adjoining reactor unit" [99]. In addition, procedures to direct how to "manually perform critical actions in the field concurrent with a loss of all AC and DC power (including loss of compressed air)" were not in place [106]. Furthermore, procedures to direct how to restore measuring instrument functionality and power, and how to vent and depressurize the reactor under such conditions did not exist [32].

2.6.4.5. Equipment

Following the events at the Fukushima Daiichi NPP, requests were made by TEPCO for a variety of equipment and material, including "fire trucks, generator trucks, hoses and cables, fuel, batteries, pumps, motors, reactor cooling water, radioactive protection gear, consumables and other supplies" [32]. While some equipment was available at the Fukushima Daiichi NPP, in many cases the quantity or capacity was not enough to address the situation at hand. For example, the station had the minimum number of charcoal masks required, but "a sufficient number was not available for all plant workers" [32]. Not only did the station fail to have the equipment readily available, but TEPCO was also "not prepared to immediately secure and implement a number of the necessary equipment and materials" [32].

2.6.4.6. Training and drills

While comprehensive nuclear emergency preparedness drills were conducted annually by order of the national government, they did not simulate the event or conditions experienced on 11 March 2011, nor did they emulate severe accidents or complex disasters. A staff member of the Fukushima Prefecture Hospital Association was quoted as saying that:

> "...neither the earthquake evacuation drills nor the nuclear accident drills were implemented based upon a prior anticipation of having to evacuate all hospitalized patients. Furthermore, they were based on the assumption that the lifeline would be functioning" [32].

In addition, when responding to the proposal to conduct a drill with a scenario that included "the simultaneous occurrence of a nuclear disaster and an earthquake, with no direct cause-and-effect relationship between them," NISA commented that:

> "[T]he national government could not support the drills, since the scenario suggested that even limited damage to evacuation routes and facilities by an earthquake could result in problems at a nuclear reactor, and drills conducted based on this ambiguous scenario could worry local residents unnecessarily" [32].

Emergency drills conducted at the Fukushima Daiichi NPP also did not simulate an event of the complexity and severity of that experienced on 11 March 2011. For example, an emergency drill conducted in February 2011 involved a scenario in which external power was lost to a unit following an earthquake in conjunction with the failure of an EDG to start, resulting in a loss of AC power. However, the drill assumed that the EDG would be recovered after a period of time [102]. In addition, no drills were conducted that included events or abnormalities at multiple units simultaneously, nor were drills that simulated a loss and recovery of information sources or communication challenges [118].

Training to prepare personnel to respond in the event of a nuclear accident was limited. Computer based AM training was conducted, but it lacked the detail necessary to develop the skills and knowledge needed to respond to an accident [32]. Additional training following the computer based simulation was provided at three year intervals. In addition, the simulator used for operator training did not include the isolation condenser, nor did personnel have experience operating the system. Training on the system was based primarily on classroom and on the job-site training [118].

2.6.5. Human and organizational assessment

To acknowledge that what happened on 11 March 2011 was a surprise outside the boundaries of the basic assumption of stakeholders in Japan as well as the international nuclear community, has important implications for what can be learned to enhance the safety of NPPs throughout the world. The difference between surprises within or outside the boundaries of the basic assumption has previously been explained. Although the stakeholders involved were aware of different safety issues related to the accident, it is a complex task to put all these issues together and to realize that such a complex accident may indeed occur. The full complexity of the accident needs to be considered comprehensively in order for the nuclear safety community to learn crucial lessons from the event. The accident would only reinforce the familiar knowledge about nuclear safety, i.e. the known knowns and known unknowns. It would open up the possibility of being again unprepared and exposed to unexpected situations outside the boundaries of the basic assumption. Lessons learned from surprises inside the boundaries of the basic assumption (known knowns and known unknowns) are often limited in scope and involve local, often technology based, fixes (e.g. increased redundancy of components or design changes) [118]. On the other hand, a surprise which disrupts the basic assumptions offers an opportunity for fundamental learning through changing the basic assumptions which are driving behaviours. The very human tendency of avoiding the psychological discomfort emerging from questioning one's basic assumption and from acknowledging the existence of unknown unknowns means that the opportunity to learn from surprises outside the boundaries of the basic assumption could easily be missed. This would often result in failing to see the systemic explanations of why something happened.

To effectively learn from a surprise outside the boundaries of the basic assumptions, it is necessary to overcome three main obstacles which hinder a comprehensive and thorough learning process.

The first challenge is to manage to treat the event as a surprise outside the boundaries of the basic assumptions. This is often avoided by treating it as a situational surprise or rejecting (consciously or

unconsciously) any learning opportunity through the mechanism of distancing through differencing. It is certainly necessary to identify attitudes and practices that are unique to the main stakeholders in Japan, but one also needs to attend to general processes, system relations, etc. that may occur at other places.

The second challenge is to synthetize the new lessons and understanding with the pre-existing basic assumption. Being a surprise, outside the boundaries of the basic assumption, incorporating the lessons may require a considerable revision of existing assumptions. In a complex system, there may be processes that appear to fix standard problems, but often these same processes hide more fundamental weaknesses. Integrating lessons requires a willingness to examine systemic relations that may risk disrupting standard practices.

The third and most difficult challenge to be overcome is at the institutional level. Organizational systems become more permanent as they are supported by policies, actions and attitudes of organizational personnel and so forth. A surprise outside the boundaries of the basic assumption may require changes involving much that is deeply entrenched inside the organization. It is thus necessary for the sociotechnical system as a whole to identify and implement the new learning, new practices, a new language and a new way of seeing and interpreting things for it to be institutionalized and brought into the basic assumption within the organizations' safety culture [129].

2.6.6. The implications for the nuclear community

Having expanded on the human and organizational aspects of the accident in the first part of this section, the implications for the nuclear community and society all over the world and the key messages are described below.

2.6.6.1. Treating the accident as a surprise outside the boundaries of the basic assumption

The analysis has shown that the main stakeholders involved in the Fukushima Daiichi accident assumed that the robustness of a nuclear plant's technical design would maintain and protect the safety of plants. The belief in the robustness of the nuclear installations appeared to be so strong that the stakeholders did not recognize the existence of the unknown. Thus, the occurrence of a very high tsunami having a deleterious impact on the NPP constituted a surprise outside the boundaries of the basic assumption that dramatically disrupted and changed the existing reality. For the same reason these stakeholders were not sufficiently prepared to technically and organizationally deal with a long duration SBO or with a multi-unit, long duration accident. This may also be true for other countries and warrants continuing analysis to identify the boundaries of the basic assumption.

2.6.6.2. Difficulty in acknowledging complexity

One reason why the unknown unknowns can be fundamental in nature and their sudden discovery can have such a disruptive impact on one's basic assumption is the fact that it is very difficult to recognize and understand the full complexity of a (sociotechnical) system such as a nuclear power programme and its assessment and regulation. This encompasses many different stakeholders with different roles, tasks and interests interacting with each other regarding the operation and safety of a complex technology. As the analysis shows, not only TEPCO but also the other stakeholders failed to comprehend the full extent the complexity. This led to reduced risk awareness and to a simplified consideration of the sources of risks, including, for instance, external events.

Comprehending and accounting for the complexity was made even more difficult for TEPCO and other stakeholders by the fact that, even though in hindsight it might be perceived as such by some, the degree of safety of an NPP is not simply quantifiable or always easily recognizable. As has been shown, TEPCO as well as the regulatory bodies had made substantial efforts to improve the safety of

the nuclear installations over the years, e.g. after events such as the falsification scandal in 2002 or the Niigata-Chuetsu-Oki earthquake in 2007 that affected the Kashiwazaki-Kariwa NPP. These improvements might have contributed to upholding and even reinforcing the belief in the NPPs being sufficiently safe. This suggests that it is necessary to allow for the fact that vulnerabilities can develop in the system over years and remain concealed by the organizations' (long) experience of success as well as by their belief that they have risks under control. "This…is how a successful system produces failure as a normal, systematic by-product of its creation of success" [110].

2.6.6.3. Acknowledging the possibility of the unexpected

This reasoning leads to the necessary acknowledgement of the fact that it will never be possible to consider, anticipate and prepare for all possible contingencies. The possibility of unexpected events — that is, of events no one has thought of before, as they lie outside the boundaries of one's basic assumption and which, as a consequence, an organization did not specifically prepare for — is always present. "Things that never happened before, happen all the time" [130]. It therefore appears necessary to question whether the current practice of the nuclear industry and the engineering culture, which aims to anticipate all possible scenarios and to develop in advance targeted (technical and administrative) solutions, is enough to account for the ever present threat, however improbable it might be, of something unexpected happening. Nuclear safety would be further improved by acknowledging the possibility of the unexpected.

The nuclear industry and its regulators therefore need to become more resilient, i.e. better able to adapt the industry's functioning under varying conditions, both expected and unexpected [131] and to mobilize additional resources when it approaches its margin of manoeuvre [132]. In other words, the nuclear organizations and the industry need to be prepared to be unprepared [114]. Such preparation should explicitly take into account the unexpected and therefore also needs to focus on the ability of the organization and individuals to adapt and respond to unexpected and unknown events, including events implying extreme physical and psychological conditions.

2.6.6.4. Preparation for the unexpected

Organizations need to be prepared for the unexpected, i.e. to be "prepared to be unprepared". This includes providing appropriate training to all individuals on how to respond to unexpected events and to provide adequate equipment and procedures. However, this preparation and training does not only mean to prepare technically and organizationally for all scenarios one can think of. It also means to develop generic competencies and resources within the organization that help the personnel to quickly and flexibly adapt to new situations, to improvise and develop new solutions for unknown problems; in other words: to be resilient in unexpected situations. This kind of human and organizational resilience capabilities needs to developed under normal operation and well in advance.

2.6.6.5. Taking a systemic approach

The analysis of the accident highlights the need for a systemic approach to be taken both in the analysis itself and in learning how to treat nuclear safety in the future. To understand the accident from a systemic perspective, one cannot look at each element of the nuclear system singularly. This accident clearly cannot be attributed to one licensee, one management group, one NPP or one regulator alone, but must rather be considered holistically by looking at and understanding the systemic interactions between all the stakeholders involved prior and during the accident. As explained above, the stakeholders (for instance, the licensees, the regulators, the government and the public) constructed and maintained together and over many decades a perception of risks and nuclear safety that turned out not to have been adequate.

A systemic approach to safety needs to be implemented by all participants and in all types of activities within the nuclear power programme and throughout the entire life cycle of nuclear installations, including review services offered by international organizations. As was shown by the analysis, in Japan, nuclear installations, TEPCO and NISA primarily focused on the technical aspects of nuclear safety. A systemic approach to safety implies that all stakeholders, besides the technical factors, take comprehensively into account the human and organizational factors, including safety culture, to build resilient capabilities.

2.6.6.6. Stakeholders' roles and responsibilities

In line with the systemic approach, each stakeholder plays an important role in achieving the level of safety necessary in nuclear power production. As IAEA Safety Standards Series No. SF-1, Fundamental Safety Principles [1], states: "The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation". Principle 1 emphasizes: "The prime responsibility for safety must rest with the person or organization responsible for facilities and activities that give rise to radiation risks" [1]. Principle 2 states that: "An effective legal and governmental framework for safety, including an independent regulatory body, must be established and sustained" [1]. This establishes prerequisites necessary for the whole system to reach the safety objectives.

Thus, the licensee always bears the responsibility for the safety of its nuclear installations, as stated by SF-1 [1]. It needs to take ownership of safety and cannot delegate its responsibility to other stakeholders such as the regulatory body.

The regulatory body needs to take ownership of the protection of people and the environment through recognizing its role and its impact on the safety and safety culture of the licensees and of their willingness and ability to take ownership of safety. This entails not only ensuring technical compliance with regulations, but also comprehensively addressing human, organizational and cultural factors [123]. The task of the regulatory body is highly demanding and entails the duty of continuously challenging and questioning the basic assumption held by the industry it regulates and by itself. This implies high demands on the regulator's self-reflecting capability to put its own role and its impact on nuclear safety and on the collective perception of nuclear safety under constant self-scrutiny. As the analysis has shown, the Japanese regulatory bodies, NISA and NSC, seemed to have insufficient capabilities to apply this questioning role owing to a lack of authority, resources and de jure independence.

As for the public, it is important to maintain a transparent dialogue between the public and the other stakeholders that supports this questioning and challenging attitude on an ongoing basis. A constructive dialogue between the public and the nuclear industry and regulators needs to be built on mutual trust and respect for the different roles the stakeholders play in the national nuclear infrastructure. As the analysis has demonstrated, the Japanese licensees and regulatory bodies feared the public reaction to proposed improvements in the regulatory framework, the nuclear installations or the preparation for severe accidents. This led to a lack of transparency toward the public, which in turn made a constructive dialogue with an informed public impossible. In order to allow an open and constructive dialogue among the public and other stakeholders, the public needs to be openly and competently informed not only about the advantages of using nuclear power, but also about the risks that this technology entails as well as how safety is maintained. The regulatory bodies have a particularly important role to play in informing the public in a competent, understandable and up to date way as a reliable and trustworthy body.

2.6.7. Summary

The accident at the Fukushima Daiichi NPP came as a surprise outside the boundaries of the basic assumption of the operators, the utility, the regulator, the government and the people of Japan. It had been accepted that the nuclear power plants in Japan were safe and able to withstand any external events.

When nuclear power began to be developed in Japan, an approach to nuclear safety was developed within the main nuclear industry stakeholders. Over time, a basic assumption emerged that the robustness of the nuclear plant's technical design and existing measures would maintain and protect the safety of plants against postulated risks. This basic assumption was developed, maintained and mutually reinforced over time among the main stakeholders, namely the government departments, regulatory body, the licensee and the public. As a result, the risks faced were not sufficiently assessed, nor the defences against them strengthened — particularly regarding the treatment of low probability external events, accident management procedure improvements, and preparations for a complex accident that could affect all the reactor units simultaneously. The basic assumption prevented the stakeholders from effectively preparing for and mitigating the consequences of the tsunami caused by the Great East Japan earthquake of 2011.

This was manifested by the decisions and actions of all main stakeholders, i.e. the governmental ministries, the regulatory body, the licensee and the public. The regulatory body at the time of the accident was not able to exert the necessary authority over the industry it was meant to oversee. It worked generally in a reactive manner, focusing on short term activities, and did not address more fundamental and long term issues, such as the consideration and implementation of the IAEA safety principles and developments. In its relation to the public, the regulator was, for example, reluctant to update regulations or to allow complex emergency drills out of concern that the public might get the impression that nuclear power plants were not safe.

The operators were so confident that the superior technical features of their plants would make nuclear accidents highly unlikely that they did not prepare sufficiently to mitigate the results of such accidents. TEPCO's AM measures addressed internal events only; they did not prepare for a tsunami, as it was thought that any NPP could respond to natural disasters including tsunami within design. In addition, the management measures assumed that, in the event of an accident at one reactor, adjoining reactor units would continue to operate normally, and they did not take into account an event that could simultaneously affect all the reactor units. When the international community began to advance in the area of severe accident management (SAM), TEPCO did not adopt some of these developments. As a result, TEPCO had not planned how to address a situation in which several units lost all power and were unable to receive power from an adjacent unit.

One part of a healthy safety culture of organizations is the capability to challenge or re-examine the basic assumption for safety. As all stakeholders involved in the nuclear industry will develop their own basic assumptions with regard to nuclear safety, it is of universal importance to be mindful of such assumptions and work proactively to understand their impact on nuclear safety.

The human and organizational factor analysis also concludes that it is important to take a systemic approach to nuclear safety by embracing the complexity of the full range of interactions between human, technical and organizational factors. One of the underlying causes of the Fukushima Daiichi accident was the inability of the stakeholders to comprehend and work with this complexity in order to proactively prevent the accident. Other parts of this volume show how the stakeholders involved in the accident had knowledge of several of the flaws in the system prior to the accident. The human and organizational factor analysis explains how these stakeholders, despite their knowledge, were unable to proactively understand and imagine how these flaws could come together to produce an accident in the way they did following the earthquake on 11 March 2011. Through the analysis, it has been shown

how the stakeholders involved were mutually influencing each other. Thus, the scope of the systemic approach needs to encompass the interactions between all stakeholders involved in nuclear safety. In the case of the accident at the Fukushima Daiichi NPP, the unchallenged reinforcing interactions among the stakeholders strengthened the basic assumption that the robustness of the nuclear plant's technical design and existing measures would maintain and protect the safety of plants against postulated risks and prevented the necessary countermeasures from being taken in a timely manner.

Two main observations have been made in this section:

First, the analysis has shown that, over time, the stakeholders of the Japanese nuclear industry developed a shared assumption that the robustness of the nuclear plants' technical design and existing measures would maintain and protect the safety of plants against postulated risks. This shared assumption led the stakeholders to believe that a nuclear accident would not happen and thus thwarted their ability to anticipate, prevent and mitigate the consequences of the earthquake triggering the Fukushima Daiichi Accident.

Second, while the stakeholders involved in the accident at the Fukushima Daiichi NPP were aware of the possibility of the single safety issues related to the accident in advance (e.g. SBO, extreme tsunami heights and multi-unit accidents), they were not able to anticipate, prevent or successfully mitigate the outcome of the complex and dynamic combination of these issues within the sociotechnical system.

2.6.8. Observations and lessons

— **The accident at the Fukushima Daiichi NPP was a surprise outside the boundaries of the basic assumption of the key stakeholders, meaning the stakeholders had not been able to imagine that such an accident could occur. From this, the lesson learned for the international nuclear community is that the possibility of the unexpected needs to be integrated into the existing worldwide approach to nuclear safety.**
When unexpected situations occur outside the boundaries of the basic assumption of nuclear safety, people and organizations need to be prepared to be unprepared. Resilience competencies and resources have to be developed well in advance within organizations to help personnel to quickly and flexibly adapt to new situations, to develop new solutions for blind spots — in other words: to be resilient in unexpected situations.

— **Individuals and organizations need to consciously and continuously question their own basic assumption and their implications on actions that impact nuclear safety.**
This is part of sustainable safety culture improvement; the basic assumption about safety is recognized as fundamentally directing safety culture. To enable this, individuals and organizations need to systematically question the nature, boundaries and potential challenges of one's own assumptions of nuclear safety, particularly beyond technical safety matters. Reflection and dialogue are needed within an organization in order to become aware of possible blind spots in basic assumptions. This can be achieved through periodic safety culture assessments (both independent and self-assessment reviews) based on the IAEA's approach to the assessment of safety culture and other IAEA peer reviews, such as the IAEA's IRRS and OSART missions. In addition, the utilization of a diversity of expertise and experience is important in order to avoid undue simplifications in interpretations and to better recognize the full picture.

— **Nuclear organizations need to critically review their approaches to emergency drills and exercises to ensure that they take due account of harsh complex conditions and unexpected situations.**
Harsh complex conditions include both physical and psychological aspects. Unexpected situations that may be considered for implementation in the framework of emergency exercises include a shaking ground (earthquake), large scale fires and flooding, a dark work environment, unfamiliar sounds and the loss of vital information. In addition, resilience competencies need to be developed

well in advance to prepare humans and organizations for quick and flexible adaptation to unexpected situations ('unknown unknowns').

— **The results of research on complex sociotechnical systems for safety need to be taken into account.**
In order to proactively deal with the complexity of nuclear operations, licensees, regulators, designers, peer reviewers and other relevant stakeholders need to consider the research on sociotechnical systems when designing nuclear technology, operating and overseeing nuclear installations and developing industry standards. The development of human and organizational resilience capabilities should also be based upon state of the art research on complex sociotechnical systems.

— **A systemic approach to safety needs to be taken in event and accident analysis, considering all stakeholders and their interactions over time.**
Stakeholders include, among others, licensees, regulators, political leaders and the public. The systemic approach includes human, technological and organizational considerations and is necessary to understand how the components of the overall (sociotechnical) system functioned, interacted and succeeded in everyday situations and over the decades before the accident, as well as during accident response. To accomplish this, a diversity of expertise is needed to cover the human, technical and organizational factors.

— **The regulatory body needs to acknowledge its role within the national nuclear system and the potential for its impact on the nuclear industry's safety culture.**
The regulatory body has the challenging role of questioning the nuclear industry's approach to safety. Therefore, the regulatory body needs a critical, profound self-reflecting and questioning ability. This may include institutionalizing an ongoing dialogue within the organization and with other stakeholders on the regulatory body's safety culture and its impact on nuclear safety.

— **Licensees, regulators and governments need to conduct a transparent and informed dialogue with the public on an ongoing basis.**
This may include explanation of the risks that the use of nuclear technology for energy production entails.

2.7. APPLICATION OF OPERATING EXPERIENCE TO IMPROVE PLANT DESIGN AND OPERATION

Applying operating experience is a key contributor to maintaining continuous improvement in nuclear safety; it supports the defence in-depth philosophy. One of the key lessons learned from the severe accident at the Three Mile Island NPP in 1979 is that the accident could have been prevented through the effective application of operating experience. Furthermore, as noted by the International Nuclear Safety Group in its publication Improving the International System for Operating Experience Feedback [133]:

> "It is widely observed in all fields of human activity that serious accidents are nearly always preceded by less serious precursor events. If lessons can be learned from the precursors and these lessons put into practice, the probability of a serious accident occurring can be significantly reduced."

The global nuclear industry has recognized the vital importance of operating experience in improving operational performance and preventing nuclear accidents, and has made significant strides in improving its operating experience programmes. The Convention on Nuclear Safety, which entered into force in October 1996, reinforces the international commitment to the application of operating experience to improve nuclear safety. Article 19 of the convention [134], concerning operation, states:

"Each Contracting Party shall take the appropriate steps to ensure that:

.....

(vi) incidents significant to safety are reported in a timely manner by the holder of the relevant licence to the regulatory body;

(vii) programmes to collect and analyse operating experience are established, the results obtained and the conclusions drawn are acted upon and that existing mechanisms are used to share important experience with international bodies and with other operating organizations and regulatory bodies".

As part of their obligations under the convention, contracting parties are required to report on their compliance with the articles of the convention approximately every three years.

The term 'operating experience' as used in this section includes:

— Industry events;
— Research findings;
— New analytical methods;
— Learning acquired through periodic safety reviews.

2.7.1. Significant operating experience events relevant to the accident at the Fukushima Daiichi NPP

There have been three well documented, beyond design basis natural events (i.e. combinations of earthquakes, tsunamis, high winds and floods) at NPPs that provide important operating experience that could have impacted the consequences of the accident at the Fukushima Daiichi NPP:

— In December 1999, a storm surge caused flooding at two reactors at Le Blayais NPP, in France.
— The Indian Ocean tsunami of 26 December 2004 flooded seawater pumps at the Madras Atomic Power Station, in India.
— On 16 July 2007, an earthquake exceeded the design basis of TEPCO's Kashiwazaki-Kariwa NPP, in Niigata Prefecture.

The IAEA and the OECD/NEA analyse events reported through the Incident Reporting System (IRS) and jointly issue a report every three years highlighting significant trends. The three events listed above, as well as others, were included in reports produced between 1999 and 2008. These triennial reports represent a synthesized summary of the most important learning points from operating experience and are openly available to all members of the public and provide focus areas for utility self-assessment as well as regulatory review. They also provide an opportunity for other external reviews, such as the IAEA's OSART missions, whose scope includes a review of operating experience. The relevant sections from these respective reports are reproduced below:

"Experience with system losses due to severe weather conditions

.....

"Severe weather conditions resulted in the formation of waves moving up the river along which the plant is located, causing a partial flooding of two reactor units. External power supplies were lost momentarily due to the loss of the grid. Mechanical and electrical penetrations were damaged. Rooms housing safety related components were flooded causing their unavailability.

This included portions or all of the Essential Service Water System, the Safety Injection System, and the Containment Spray System.

“Moreover, due to the consequences of the storm, the site was momentarily isolated, impairing emergency help from outside. The plants were placed in a safe shutdown state.

“Safety significance

“Bringing and maintaining the reactor in a safe shutdown state to cope with the consequences of the flood requires the availability of the corresponding equipment. Some of the equipment was made unavailable by flooding. A failure of a penetration protecting one train of the Essential Service Water System, similar to the one having affected the redundant train, would have led to a loss of the ultimate heat sink. This scenario is addressed by the safety related studies, but the flooding conditions of the rooms would have complicated the management of the situation” [135].

“Experience with external hazards

“In the period 2005–2008 three events caused by earthquakes were reported. In the most severe event, a strong earthquake occurred in the vicinity of a multi-unit plant site. The actual damages from the earthquake did not affect the safe shutdown and cooling of the reactor cores. But some minor failures led to an on-site fire and the release of a small amount of radioactivity. No protective measures for the public had to be taken. The technical analysis of the earthquake impact revealed that the design acceleration values had been exceeded. The event resulted in a complete recalculation of the acceleration values to be expected due to earthquakes.

“Another event occurred during the disastrous tsunami in the Indian Ocean. Thousands of kilometres from the site of the tsunami’s origin, a nuclear power plant site was flooded by the unexpected high waves.

“One nuclear power plant reported an all time high seawater level. The level just missed the declaration setpoint for a site emergency. Due the conservative design of the plant, no actual flooding occurred.

“A plant at a riverside that is known for water level fluctuations and the forming of sand banks experienced a massive silting of the raw water intake channel. The plant decided to remove the sand from the sand trap installed in the intake water tunnel. Because there was a risk that the sand heap might become unstable during the removal operation and thus could block the entire intake, the plant operating organization introduced a specific operating instruction to cope with the situation in case of sand heap collapse. Contributing to this event was the fact that the sand had not been industrially extracted from the river for some years and the plant had not re-evaluated the potential consequences.

“Safety significance

“External hazards may lead to multiple system failures in a plant, either by flooding or mechanical loads, e.g. due to earthquakes. Because these hazards cannot be prevented, the design must take into account the challenges they pose. The vital functions of the plant — criticality control, removal of the residual heat and enclosure of the radioactivity — have to be ensured through all hazards. Special attention must be paid to environmental changes due to global warming, as well as to industrial activities in the vicinity of a plant. Tide heights, flooding by the sea as well as rivers, and draughts have to be taken into account to a greater

extent than 30 years ago. Environmental changes may require backfitting measures at the plants" [136].

A more detailed description of these important events is provided in Annex III of this Technical Volume.

The review of the National Reports to the Convention on Nuclear Safety noted similarities in the actions taken in the responses by France to the Le Blayais event; by Japan to Kashiwazaki-Kariwa and by India to the Madras event [92, 137, 138]. These three events demonstrate that operators and regulators appear to put more emphasis on domestic operating experience than on operating experience from other countries [138]. The review determined that the application of domestic operating experience led to safety improvements, whereas the application of international operating experience was not as comprehensive.

Paragraph 1.2 of IAEA Safety Standard Series No. SSG-25, Periodic Safety Review for Nuclear Power Plants [139], specifies that:

> "Routine reviews of nuclear power plant operation (including reviews of modifications to hardware and procedures, significant events, operating experience, plant management and personnel competence) and special reviews following major events of safety significance are the primary means of ensuring safety."

In addition, para. 62 of INSAG-23, Improving the International System for Operating Experience Feedback [133], states:

> "Reporting on events and other safety relevant observations needs to be coupled with programmes that transform the lessons learned into risk reducing measures. The recipients of such reports, both operators and regulators, should close the feedback loop by providing information on their actions in response to a report. This information from recipients should be collected, summarized and made available to all potential users."

In 2011, the IAEA updated the IRS process to allow operators and regulators to close the feedback loop, and encouraged Member States to provide information on their actions in response to a report. In 2013, the IAEA received a total of only 15 items of feedback from only six Member States in response to approximately 80 operating experience reports. In the absence of more comprehensive reporting on the actions taken in response to operating experience, it is difficult to draw conclusions on the appropriateness of these actions.

2.7.2. Effectiveness of application of TEPCO's operating experience programme

2.7.2.1. Application of learning from industry events

The three major events noted in Section 2.7.1 were screened by TEPCO through its operating experience programme for applicability to its plants. In the aftermath of the earthquake at the Kashiwazaki-Kariwa NPP, TEPCO took extensive action at all of its plants to address lessons learned, demonstrating that its process for screening and acting on operating experience can be effective if appropriately applied. At each of its stations, it constructed seismically isolated emergency buildings, improved the firefighting systems, and installed modifications to enable the use of portable pumpers as an alternate source of water injection into the reactor. It also enhanced its site evacuation plans. All these improvements proved to be of significant benefit in the response efforts following the tsunami at the Fukushima Daiichi NPP.

Following the river flooding and high wind events at the Le Blayais NPP, the operator, Electricité de France (EDF), took extensive action to improve defences at all its plants [140], such as:

— Identifying all phenomena which can result in a flood at any of its 19 sites, including those located near an ocean or an estuary, and those located near rivers;
— Completing a reassessment of flood hazards and their associated impacts at each site;
— Identifying the equipment to be protected;
— Reviewing the existing protective measures, including structures, devices, procedures and organizational factors to identify gaps;
— Completing modifications and improvements to resolve gaps.

Actions taken by EDF included raising, extending, or reinforcing dykes and sea walls and improving resistance to water ingress by installing watertight doors, and sealing openings and penetrations. EDF also identified off-site factors that could impact the site response, including loss of off-site power, site inaccessibility and communications breakdowns, and developed mitigation and coping strategies [140].

Had TEPCO taken similar measures to those implemented by EDF after the Le Blayais flood, this may have impacted the consequences of the earthquake and tsunami at the Fukushima Daiichi NPP.

During the Indian Ocean Tsunami of December 2004, seawater pumps were flooded at the Madras Atomic Power Station, resulting in a potentially significant challenge to fuel cooling that was successfully mitigated through operator action. There was no plant damage other than to seawater pumps at lower elevations.

This event was classified as Level 0, the lowest level, on the International Nuclear and Radiological Event Scale (INES). However, the potential for more serious consequences was recognized by both the operator and the regulator, which resulted in the implementation of a number of improvements, including:

— Installation of an additional diesel generator at 2 m above grade level;
— Relocation of the uninterrupted power supply system to a higher elevation;
— Installation of a diesel driven air compressor at a higher level;
— Installation of a dedicated pump for transfer of de-aerator water to steam generators (emergency boiler feed pumps);
— Installation of two diesel driven fire pumps located 2 m above grade level;
— Construction of a tsunami protection wall;
— Installation of a tsunami warning system [138].

The case of the tsunami and flood at the Madras Atomic Power Station was deemed by TEPCO not to require further evaluation on the basis that it did not result in significant consequences (i.e. it was classified as a Level 0 on INES. The potential for more serious consequences was not recognized by TEPCO during the screening process.[18]

Following the accident at the Kashiwazaki-Kariwa NPP, TEPCO took extensive action in response to the operating experience, demonstrating that its process for screening and acting on operating experience could be effective if appropriately applied. However, in the other two cases, a narrow

[18] IAEA Safety Standards Series No. NS-G-2.11, A System for the Feedback of Experience from Events in Nuclear Installations [141] specifies in the footnote to para. 2.7 that "…the distinction should be maintained between a low level event (with no consequences) as contrasted with a reportable condition, which may have a high significance for risk even though it has no immediate consequences."

perspective led to missed opportunities to learn from valuable operating experience. As discussed in TEPCO's root cause report [54], the following aspects contributed to this narrow perspective:

— Results of analysis of internal events using PSA methods contributed to overconfidence in the safety of the NPPs. Had the PSA analysis been extended to include common cause and/or external events, it would have exposed a higher probability of severe core damage and yielded insight into the potential vulnerability to a loss of all sources of power.
— There was apprehension that publicly acknowledging a potential vulnerability to an event that exceeded the design basis for the plant might lead to the inference that the plant was unsafe to operate and result in the prolonged shutdown of the plant and/or costly backfits.
— There existed an inherent organizational bias to avoid actions requiring a significant expenditure of resources, particularly if such actions could not be directly linked to improved production.
— The screening of operating experience, together with the associated evaluations, was performed by departments external, and not accountable, to those directly responsible for the operation of the plant.

TEPCO's senior management was not closely involved in the initial screening process for operating experience and did not have the opportunity to provide a broader perspective.

These organizational factors, taken collectively, suggest that, within TEPCO's management system, nuclear safety was not given priority over all other demands, which resulted in weaknesses in the effective implementation of the operating experience programme.[19]

2.7.2.2. Application of learning from new analytical methods

The following provides a brief overview of TEPCO's assessment of the tsunami hazard at the Fukushima Daiichi NPP [10]. A more detailed discussion is provided in Section 2.1.

The initial design tsunami height for the Fukushima Daiichi NPP was selected as 3.1 m, based on historical information. Specifically, the highest recorded tidal level at Onahama Port from the Chile earthquake and tsunami of 1960 was defined as the design condition. This approach of using historical information rather than numerical simulation was consistent with the accepted methodology at the time.

Between the time of its initial design and the accident of March 2011, as new knowledge and analytical methods became available, TEPCO re-evaluated and revised upwards its estimate of the design tsunami height several times. For example, the design tsunami height for the Fukushima Daiichi NPP was revised from 3.1 m in 1966, to 3.5 m in 1994, then to 5.7 m in 2002, and finally to 6.1 m in 2009.

This practice was not unique to TEPCO; other NPPs owned and operated by other companies in Japan also revised their design tsunami heights as new knowledge and analytical methods became available. For example, in the case of the Onagawa NPP, operated by Tohoku Electric Power Company and located in Miyagi Prefecture, the design tsunami height was revised upwards from an initial value of ~3 m in 1970 to 9.1 m in 1987 and then to 13.6 m in 2002.

[19] Paragraph 2.2 of IAEA Safety Standards Series No. GS-R-3, Management System for Facilities and Activities [104], states that: "Safety shall be paramount within the management system, overriding all other demands". Annexes I and II of the IAEA Safety Culture Assessment Review Team Guidelines (IAEA Service Series No. 16) [142] provide a set of characteristics, attributes and guiding questions that are helpful in assessing whether an organization is effectively upholding nuclear safety as taking priority over all other demands.

The stark difference in design tsunami heights between the Fukushima Daiichi and Onagawa NPPs, which are located 120 km apart along the east cost of Japan's main island of Honshu, is due largely to two main factors.

First, there are significant differences in the shape of the coastlines at the two sites. The location of the Fukushima Daiichi NPP, along a rectilinear coastline, made it inherently less vulnerable to large tsunamis as compared with the Onagawa NPP, whose V shaped coastline was expected to amplify tsunami height for a given wave source. Figures 2.1–7 and 2.1–8 provide an illustration of this effect.

Second, most large historical earthquakes in the Japan Trench off the eastern coast of Honshu were concentrated closer to Iwate and Miyagi Prefectures as compared with Fukushima Prefecture. As noted in TEPCO's Fukushima Nuclear Accident Analysis Report, there were no records of large earthquakes in the region along the Japan Trench offshore from Fukushima Prefecture. Figure 2.1–5 provides an overview of the regions that had the largest historical earthquakes and tsunamis (see also Section 2.1).

In 2007, Fukushima Prefecture and the neighbouring Ibaraki Prefecture updated their tsunami wave source models for their respective Disaster Prevention Plans. TEPCO and the Japan Atomic Power Company (JAPC), the operator of the Tokai Daini NPP, calculated their tsunami heights based on these new wave source models, to maintain alignment with the assumptions in the Disaster Prevention Plans. In the case of the Fukushima Daiichi NPP, no action was required as the resultant tsunami height was less than 5.7 m; in the case of the Tokai Daini NPP, the design tsunami height had to be revised upwards, and the JAPC decided to construct a 7.0 m high wall at the Tokai Daini NPP to protect the emergency seawater pump room [10]. This wall was effective in protecting the plant from the 5.4 m tsunami wave that struck the plant in March 2011.

In 2009, TEPCO used updated topography and bathymetry data to revise its design tsunami height to 6.1 m, and accordingly made further modifications to the plant.

Table 2.7–1, reproduced from the TEPCO Accident Analysis Report of June 2012 provides a timeline of the revisions to the design tsunami height, and the actions taken in response to these revisions, for the Fukushima Daiichi, Fukushima Daini, Tokai Daini and Onagawa NPPs. It is evident from this information that TEPCO recognized, analysed and took corrective action based on improved analytical methods concerning new tsunami knowledge.

In addition to the studies completed by TEPCO between 2002 and 2009 based on the JSCE methodology and its standard wave source models, TEPCO completed two trial calculations using wave source models or methodologies that went beyond the JSCE approach. Each of these trial calculations predicted a tsunami wave height considerably greater than the design tsunami height of 5.7–6.1 m, calculated by the JSCE methodology [33]. It is important to note that the JSCE method was the accepted consensus standard at the time of March 2011.

In one trial calculation, TEPCO applied a wave source model based on the Jogan 869 tsunami proposed by Satake et al. [143] in 2008. The trial calculation yielded a tsunami wave height of approximately 9 m. Since this model was based solely on tsunami deposit survey results, TEPCO decided to perform a tsunami deposit survey to confirm the validity of the 9 m prediction. Approximately 50 bore holes were dug at five locations along the coast in Fukushima Prefecture. Of these, the three southern locations yielded no evidence of tsunami deposit, one of the northern locations yielded evidence of a tsunami deposit of 0.5 m thickness, and the other northern location yielded evidence of a tsunami deposit of 3–4 m thickness [33].

TABLE 2.7–1. EVALUATION OF TSUNAMI EVENTS [10]

Time of tsunami evaluation	Fukushima Daiichi	Fukushima Daini	Tokai No. 2	Onagawa
At the time of approval for establishment	1966 OP +3.122 m (1960 Chilean earthquake and tsunami)	1972 Unit 1 OP +3.122 m 1978 Units 3 and 4 OP +3.705 m (1960 Chilean earthquake and tsunami)	— (Highest high water level 27 September 1956 Kanogawa Typhoon TP +3.24 m)	1970 OP +2~3 m 1987 OP +9.1 m (1611 Keicho Sanriku tsunami)
1994	OP +3.5 m Measures unnecessary (determined based on the Chilean earthquake and tsunami. Calculations were also made with the Keicho Sanriku tsunami, but the values were below that of the Chilean earthquake and tsunami)	OP +3.6 m Measures unnecessary (Same as left)	—	—
2002	JSCE issues Tsunami Assessment Method			
	OP +5.7 m (Determined based on the Shioyazaki-oki earthquake. Calculations were also made with the Keicho Sanriku tsunami, but the values were below that of the Shioyazaki-oki earthquake)	OP +5.2 m (Same as left)	TP +4.88 m	OP +13.6 m (Determined based on offshore Sanriku earthquakes)
	Measures implemented (Pumps made 200 mm higher, etc.)	Measures implemented (Watertight heat exchanger buildings, etc.)	Measures unnecessary	Measures unnecessary
2007	Estimation of tsunami height by utility company using the wave source model set by Fukushima Prefecture			
	Around OP +5 m Measures unnecessary	Around OP +5 m Measures unnecessary	—	—
	Estimation of tsunami height by utility company using the wave source model set by Ibaraki Prefecture			
	OP +4.7 m Measures unnecessary	OP +4.7 m Measures unnecessary	OP +5.72 m Measures implemented (Higher walls of the pump room)	—
2009*	OP +6.1 m Measures implemented (pumps made higher, etc.) (Determined based on the Shioyazaki-oki earthquake)	OP +5.0 m Measures implemented (Determined based on the Shioyazaki-oki earthquake)	—	—
2011	Great East Japan earthquake			
	Tsunami height OP +13.1 m	Tsunami height OP +9.1 m	TP +5.4 m	OP +13.8 m

* Evaluated with the same method as that of 2002 using bathymetric data updated to the newest occurrences.

In the second trial calculation, TEPCO applied the JSCE method, but used an approach proposed in 2002 by HERP, which was to assume that an M 8.2 earthquake could occur anywhere along the Japan Trench, even in regions where there was no record of a major historical earthquake. HERP did not specify a wave source model, and TEPCO conservatively used the wave source model of the Meiji

Sanriku earthquake of 1896 (M 8.3). This earthquake occurred off the coast of Iwate Prefecture, more than 100 km north of Fukushima Prefecture, and resulted in a tsunami of 38 m. The result of the trial calculation showed a maximum tsunami height of 8.4 m to 10.2 m at the front of the intake at the Fukushima Daiichi NPP and a flood height of 15.7 m, taking runup into account [33].

As a result of these trial calculations, TEPCO departments responsible for civil engineering and tsunami evaluation had information indicating that an earthquake in the Japan Trench larger than historically observed in the vicinity of Fukushima Prefecture, and comparable to the largest earthquakes observed elsewhere along the Japan Trench, had the potential to result in a tsunami whose height significantly exceeded the site elevation. Notwithstanding, they had doubts regarding the appropriateness of the trial calculations and remained confident that the safety margin was adequate. This confidence was based largely on the long held basic assumption that the site was not prone to large historical tsunamis, as described in the preceding section, even though some experts, including those at HERP, did not share this confidence in the safety margin (see Section 2.6).

The JSCE was asked to review the appropriateness of the wave source models and determine whether a revision to the corresponding standard was warranted. In the meantime, TEPCO did not initiate action to make changes to station design or operation pending confirmation by the JSCE, and communicated the results of its findings and its planned actions to the Japanese regulatory agencies [32]. The review by the JSCE was in progress at the time of March 2011.

The nuclear safety implications of the tsunami evaluations were not recognized. The engineers and managers involved in the tsunami evaluations had not received training on nuclear systems and did not understand that a flooding event had the potential to lead to severe damage of the reactor core due to a total loss of all sources of power. Furthermore, they did not communicate to the departments responsible for the safety and design of the facility that the tsunami evaluation results had the potential to vary greatly depending upon the assumptions used in the analysis, and had the potential to significantly exceed the site elevation [54]. When confronted with new information that is based on new research findings or new analytical methods, it is reasonable to seek expert input and to perform additional confirmatory analysis to determine the appropriate long term corrective action; such re-analysis may take months, perhaps years, particularly for situations where there is a paucity of information. However, when confronted with new information, it is also necessary to assess, without delay, the credibility of the new information and the potential safety consequences; if the new information is judged to be credible and to have a potential safety consequence, it is necessary to establish interim compensatory measures pending confirmation of the new findings and pending the implementation of the long term corrective actions. The urgency of the response to the new findings needs to be commensurate with their potential safety significance.

It is vital in any nuclear organization for senior decision makers and managers to have sufficient knowledge and experience to recognize and understand the nuclear safety significance of new information and to apply a strong questioning attitude to challenge the organization to consider all potential nuclear safety consequences and potential mitigating actions. A good question to ask whenever confronted with new information is: “What is the worst that can happen?”

Paragraph 4.4 of IAEA Safety Standards Series No. GS-R-3 [104] specifies:

> “Senior management shall ensure that individuals are competent to perform their assigned work and that they understand the consequences for safety of their activities. Individuals shall have received appropriate education and training, and shall have acquired suitable skills, knowledge and experience to ensure their competence.”

Moreover, paragraph 6.16 of GS-R-3 stipulates:

> "Potential non-conformances that could detract from the organization's performance shall be identified. This shall be done: by using feedback from other organizations, both internal and external; through the use of technical advances and research; through the sharing of knowledge and experience; and through the use of techniques that identify best practices."

2.7.2.3. Application of learning from periodic safety reviews

TEPCO has been actively engaged in developing improved BWR designs based on its own operating experience, as well as international advances in BWR technologies. Improvements have been reflected primarily in new construction, with less emphasis placed on backfitting safety design improvements to existing reactors [54]. For example, the EPS for Unit 6 at the Fukushima Daiichi NPP featured more separation in the design and layout of its electrical distribution system that made it more resilient to common cause events. However, the earlier units at the Fukushima Daiichi NPP were not similarly retrofitted leaving them more vulnerable to common cause events.

Part of the rationale for not backfitting design improvements to the older units at the Fukushima Daiichi NPP was that the PSAs for these units indicated that they posed an acceptably low risk. However, the scope of the PSA was limited to internal events and did not take account of all hazards, such as internal hazards posed by internal flooding and external hazards posed by tsunamis, and all potential sources of radioactive releases, such as the SFPs and multiple units on a single site. As a result, the PSA did not provide a full characterization of the risk. This led to a widely held belief that the nuclear safety risk posed by the plant was acceptable, and the cost of retrofits was not commensurate with the safety benefit (see Section 2.6).

Although TEPCO implemented a PSR process starting in 1994, its scope was focused narrowly on ageing management and did not include a detailed review of the PSA.

Paragraph 5.61 of IAEA Safety Standards Series No. SSG-25 [139] states:

> "A review of the probabilistic safety assessment (PSA) should be conducted to identify weaknesses in the design and operation of the plant and, as part of the global assessment, to evaluate and compare proposed safety improvements."

In addition, para. 5.62 of SSG-25 specifies that the scope of the PSA should include all operational states and identified internal and external hazards.

2.7.3. Regulatory oversight of TEPCO's operating experience programme

Regulators worldwide have access to international operating experience events reported through the IAEA–OECD/NEA Incident Reporting System, discussed earlier, including access to the triennial reports that provide a synthesized summary of the most important learning points from operating experience.

However, as discussed in Section 2.5, the regulatory framework within Japan was such that NISA had no legal mechanism to enforce new requirements upon the licensees in response to operating experience, and did not have a backfit rule. This limitation extended to PSRs, which were focused more on ageing management [7].

There is one example where NISA requested licensees to take action in response to international operating experience relating to the potential loss of post-LOCA recirculation capability due to

insulation debris. Aside from this, NISA was not able to identify other examples where it had requested licensees to take action in response to operating experience [7].

Paragraph 3.3 of IAEA Safety Standards Series No. NS-G-2.11 [141] specifies that:

> "…Regulatory bodies should review the screening of events to gain insights that can be used to inform their inspection programmes, licensing activities, and the elaboration of regulations and requirements for safety backfits. Regulators should screen national reports for their international use."

2.7.4. Summary

Over the past 15 years, there have been several international precursor events where natural hazards exceeded the design basis for the affected NPPs. In general, less emphasis is given to the actions taken by countries in response to events that occurred elsewhere than the actions taken in the country where the accident happened. For an operating experience programme to be effective, it must function within a management system where nuclear safety is paramount and overrides all other demands. It is important to periodically check if the organization is effectively upholding nuclear safety as the overriding priority.

A pipe break in the turbine hall in 1991, which allowed sea water to enter into an EPS room, should have revealed the susceptibility of the EDGs to flood, but no action was taken by TEPCO. The operator should also have recognized from its operational experience programme events, where two other NPPs were exposed to beyond design basis natural hazards. These were a storm surge in December 1999, which caused flooding at two reactors at the Le Blayais NPP in France, and the Indian Ocean Tsunami of 26 December 2004, which flooded seawater pumps at the Madras Atomic Power Station in India. TEPCO had made no design or operational changes as a result of these events.

By comparison, TEPCO had made many changes following the earthquake of 16 July 2007, which exceeded the design basis of the Kashiwazaki-Kariwa NPP in Niigata Prefecture. At each of its stations, it constructed seismically isolated emergency buildings, improved firefighting systems and implemented modifications to enable the use of portable pumpers as an alternate source of water injection into the reactor. All these improvements proved to be of significant benefit for the response to the accident. This demonstrates that TEPCO's process for screening and acting on operational experience could be effective if appropriately applied.

Trial calculations using new analytical methods for assessing tsunami hazards in Japan indicated that the tsunami hazard had the potential to be worse than assumed in the design of the Fukushima Daiichi NPP. When confronted with new information and experiences based on new research findings or new analytical methods, it is important to seek expert inputs and, if necessary, to perform additional confirmatory analysis to determine the corrective actions needed. However, it is also necessary to assess, without delay, the credibility of the new information and the potential safety consequences. The nuclear safety implications of the new tsunami evaluations were not recognized, because the engineers and managers involved in these evaluations had not received training on nuclear systems and did not consider that a flooding event had the potential to lead to severe damage of the reactor core. It is vital in any nuclear organization that senior decision makers and managers have sufficient knowledge and experience to recognize and understand the nuclear safety significance of new information, and to apply a strong questioning attitude to challenge the organization to consider all potential nuclear safety consequences and potential mitigating actions.

The regulatory framework within Japan was such that there was no legal mechanism to enforce new requirements upon the licensees in response to operating experience. While operators have the primary responsibility for implementing operating experience, it is important for regulators to have authority to

require operators to take action when they deem that operation of the NPP poses an unreasonable risk to the public.

2.7.5. Observations and lessons

— **The effectiveness of operating experience programmes needs to be confirmed periodically and independently through a detailed review of the specific actions taken in response to international operating experience.**
This review can be made a standard part of existing oversight processes considering relevant sources such as the Incident Reporting System (IRS) by the IAEA and the OECD/NEA.

— **When assessing the applicability of significant operating experience with limited consequences, it needs to be considered whether the consequences could have been much worse had there been a small difference in the initiating event, or in the progression of the event.**
When assessing the applicability of significant operating experience, the potential for similar consequences from different initiators needs to be considered.

— **The operating experience programme needs to function within a management system where nuclear safety is paramount and overrides all other demands.**
The management system needs to include objective risk informed decision making criteria to support decisions for retrofitting safety design improvements. It is important to periodically check if the organization is effectively upholding nuclear safety as the overriding priority.

— **The potential implications of new safety issues need to be assessed without delay, and interim compensatory actions need to be taken to maintain the safety margin pending final confirmation of the problem.**
New safety issues could arise from research findings, new analytical methods or learning from experience. The consideration and effective implementation of interim actions need to be part of the operating experience programme. It is vital in any nuclear organization that senior decision makers and managers have sufficient knowledge and experience to recognize and understand the nuclear safety significance of new information, and to apply a strong questioning attitude to challenge the organization to consider all potential nuclear safety consequences and potential mitigating actions. While operators have the primary responsibility for implementing operating experience, it is important for regulators to have authority to require operators to take action when they deem that operation of the NPP poses an unreasonable risk to the public.

— **Objective risk informed decision making criteria need to be used to support decisions for retrofitting safety design improvements as part of a periodic safety review process.**
Risk assessment tools (e.g. PSAs) used to support risk informed decision making need to take account of all hazards, all operation modes and all potential sources of radioactive releases.

— **Regulatory bodies need to perform independent reviews of national and international operating experience to confirm that licensees are taking appropriate action in response to operating experience.**
This does not override the primary responsibility of the operators for implementing operating experience.

REFERENCES

[1] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, International Atomic Energy Agency, Vienna (2006).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. NS-R-1, IAEA, Vienna (2000). (This publication is superseded by SSR-2/1 (2012)).

[3] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Fukushima Daiichi Unit 1 Establishment Permit, NISA (1966) (in Japanese).

[4] Nuclear Reactor Establishment Change Permit Application, Nuclear Industry Report to the Government No. 5–11 (1993).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Format and Content of the Safety Analysis Report for Nuclear Power Plants, IAEA Safety Standards Series No. GS-G-4.1, IAEA, Vienna (2004).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Fact Finding Expert Mission Report of the Fukushima Daiichi NPP Accident Following the Great East Japan Earthquake and Tsunami (2011).

[7] NUCLEAR REGULATION AUTHORITY, MINISTRY OF ENVIRONMENT, Replies from the Consultancy Meeting on Regulatory Activities and Operating Experience, official communication (2014).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Design and Qualification for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.6, IAEA, Vienna (2003).

[9] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities, NSC, Tokyo (2006).

[10] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report, TEPCO, Tokyo (2012).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, Safety Series No. 50-SG-S1, IAEA, Vienna (1979). (This publication is superseded by SSG-9 (2010)).

[12] NUCLEAR REGULATORY COMMISSION, Revised Livermore Seismic Hazard Estimates for Sixty-Nine Nuclear Power Plant Sites East of the Rocky Mountains, Rep. NUREG-1488, Office of Nuclear Reactor Regulation, Washington, DC (1994).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Earthquakes and Associated Topics in Relation to Nuclear Power Plant Siting, Safety Series No. 50-SG-S1 (Rev.1), IAEA, Vienna (1991). (This publication is superseded by SSG-9 (2010)).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Seismic Hazards for Nuclear Power Plants, Vienna, IAEA, IAEA Safety Standards Series No. NS-G-3.3, IAEA, Vienna (2002) (This publication was superseded by SSG-9).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Seismic Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-9, IAEA, Vienna (2010).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. NS-R-3, IAEA, Vienna (2003).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1, IAEA, Vienna (2012).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Flood Hazard for Nuclear Power Plants on Coastal and River Sites, IAEA Safety Standards Series No. NS-G-3.5, IAEA, Vienna (2003). (This publication is superseded by SSG-18 (2011)).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, External Events Excluding Earthquakes in the Design of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.5, IAEA, Vienna (2003).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD METEOROLOGICAL ORGANIZATION, Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations, IAEA Safety Standards Series No. SSG-18, IAEA, Vienna (2011).
[21] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Nuclear Reactor Site Evaluation and Application Criteria, NSCRG: L-ST-I.0, NSC, Tokyo (1964).
[22] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Safety Design of Light Water Nuclear Power Reactor Facilities, NSCRG: L-DS-I.0, NSC, Tokyo (1990).
[23] NUCLEAR REGULATION AUTHORITY, Regarding Reviews of the Additional Inspection Process on the In-site Fracture Zone in Tsuruga Nuclear Power Station and the Additional Inspection Process Relating to the Interlock of Active Faults Conducted by the Japan Atomic Power Company (2012), http://www.nsr.go.jp/data/000067165.pdf
[24] NUCLEAR REGULATION AUTHORITY, Enforcement of the New Regulatory Requirements for Commercial Nuclear Power Reactors (2013), http://www.nsr.go.jp/data/000067212.pdf
[25] INTERNATIONAL ATOMIC ENERGY AGNECY, Seismic Analysis and Testing of Nuclear Power Plants, IAEA Safety Series No. 50-SG-S2, IAEA, Vienna (1979) (This publication is no longer valid).
[26] JAPAN SOCIETY OF CIVIL ENGINEERS, Tsunami Assessment Method for Nuclear Power Plants in Japan (2002) (in Japanese), http://committees.jsce.or.jp/ceofnp/node/5
[27] INTERNATIONAL ATOMIC ENERGY AGENCY, Code on the Safety of Nuclear Power Plants: Siting, Safety Series No. 50-C-S (Rev. 1), IAEA, Vienna (1988). (This publication is superseded by NS-R-3 (2003)).
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Evaluation of Seismic Safety for Existing Nuclear Installations, IAEA Safety Standards Series No. NS-G-2.13, IAEA, Vienna (2009).
[29] UNIVERSITY OF TOKYO, KATSUDANSO KENKYU, Active Faults in Japan (New Edition), University of Tokyo Press, Tokyo (1991) (in Japanese).
[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Seismic Evaluation Methodologies for Nuclear Power Plants Based on a Benchmark Exercise, IAEA-TECDOC-1722, IAEA, Vienna (2013).
[31] TOKYO ELECTRIC POWER COMPANY, Report on the Investigation and Study of Unconfirmed/Unclear Matters in the Fukushima Nuclear Accident. Progress Rep. No. 2 (2014), http://www.tepco.co.jp/en/press/corp-com/release/betu14_e/images/140806e0101.pdf
[32] NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission, National Diet of Japan, Tokyo (2012).
[33] SAKAI, T., TOKYO ELECTRIC POWER COMPANY, "Past tsunami assessments and tsunami on 11 March 2011", paper presented at 5th Meeting of Working Group 2, Vienna, 2014.
[34] TOKYO ELECTRIC POWER COMPANY, TEPCO tectonic deformation, official communication (2014) (in Japanese).
[35] SATAKE, K., et al., "Tsunami source of the unusual AD 869 earthquake off Miyagi, Japan, inferred from tsunami deposits and numerical simulation of inundation", Proc. Eos Trans. AGU, 88(52), Fall Meet. Suppl., San Francisco (2007).
[36] HEADQUARTERS FOR EARTHQUAKE RESEARCH PROMOTION, On the Long-term Evaluation of Seismic Activity off Eastern Japan between the Sanriku Coast and the Boso Peninsula (2002) (in Japanese), http://www.jishin.go.jp/main/chousa/kaikou_pdf/sanriku_boso.pdf
[37] NUCLEAR REGULATORY COMMISSION, General Design Criteria for Nuclear Power Plants, 10 CFR 50, US Govt Printing Office, Washington, DC (2007).
[38] NUCLEAR REGULATORY COMMISSION, Reactor Safety Study — An Assessment of Accident Risks in U.S. Commerical Nuclear Power Plants (WASH-1400), Rep. NUREG-75/014, Office of Nuclear Regulatory Research, Washington, DC (1975).
[39] NUCLEAR REGULATORY COMMISSION, Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, Rep. NUREG-1150, Office of Nuclear Regulatory Research, Washington, DC (1990).
[40] JAPAN ELECTRIC ASSOCIATION, Guide for Seismic Design of Substation Equipment, JEAG 5003-2010, JEA, Tokyo (2010) (in Japanese).

[41] MORIYA, K., SATO, K., “Plant design and preliminary observations”, paper presented at Int. Cong. on Advances in Nuclear Power Plants, Nice, (2011), https://www.sfen.fr/content/download/30420/1606953/file/3-ICAPP-0503P_Sato.pdf
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, Design of Emergency Power Systems for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.8, IAEA, Vienna (2004).
[43] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: The Accident at TEPCO’s Fukushima Nuclear Power Stations, Second Report (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Design of the Reactor Coolant System and Associated Systems in Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.9, IAEA, Vienna (2004).
[45] NUCLEAR REGULATORY COMMISSION, Mark I Containment Performance Improvement Program, SECY 89-17, NRC, Washington, DC (1989).
[46] NUCLEAR REGULATORY COMMISSION, Installation of a Hardened Wetwell Vent, Generic Letter 89-16 (1989), http://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1989/gl89016.html
[47] INDEPENDENT TECHNICAL EVALUATION AND REVIEW CONSULT, Fukushima Daiichi Nuclear Accident — First Considerations (2011), http://www.iter-consult.it/ITER_Report_Fukushima_Accident.pdf
[48] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Defence in Depth in Nuclear Safety, INSAG-10, IAEA, Vienna (1996).
[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Severe Accident Management Programmes for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.15, IAEA, Vienna (2009).
[50] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Reactor and Spent Fuel Safety in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2012).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Topical Issues in Nuclear Installation Safety: Defence in Depth — Advances and Challenges for Nuclear Installation Safety, IAEA-TECDOC-CD-1749, IAEA, Vienna (2014).
[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment For Facilities And Activities, IAEA Safety Standards Series No. GSR Part 4, IAEA, Vienna (2009).
[53] INTERNATIONAL ATOMIC ENERGY AGENCY, Integrated Regulatory Review Service (IRRS) to Japan, IAEA-NSNI-IRRS-2007/01, IAEA, Vienna (2007).
[54] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Summary and Nuclear Safety Reform Plan, TEPCO, Tokyo (2013).
[55] KONDO, N., “Important lessons learned from the severe accident at Fukushima Daiichi”, paper presented at Conf. on Probabilistic Safety Assessment and Management, Honolulu, 2014, http://psam12.org/proceedings/plenaries/4-Kondo.pdf
[56] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-3, IAEA, Vienna (2010).
[57] INTERNATIONAL ATOMIC ENERGY AGENCY, Development and Application of Level 2 Probabilistic Safety Assessment for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-4, IAEA, Vienna (2010).
[58] MINOURA, K., IMAMURA, F., SUGAWARA, D., KONO, Y., IWASHITA, T., The 869 Jogan Tsunami Deposit and Recurrence Interval of Large-scale Tsunami on the Pacific Coast of Northeast Japan, Nat. Disaster Sci. 23 2 (2001) 83–88.
[59] INSTITUTE OF NUCLEAR POWER OPERATIONS, Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005, INPO, Atlanta (2011).
[60] MOHRBACH, L., LINNEMANN, T., SCHÄFER, G., VALLANA, G., Earthquake and Tsunami in Japan on March 11, 2011 and Consequences for Fukushima and other Nuclear Power Plants (2011), http://www.vgb.org/vgbmultimedia/News/Fukushima_VGB_rev16.pdf
[61] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Basic Safety Principles for Nuclear Power Plants: 75-INSAG-3 Rev. 1, INSAG-12, IAEA, Vienna (1999).

[62] NUCLEAR SAFETY COMMISSION, Accident Management for Severe Accidents at Light Water Power Reactor Installations, NSCRG: L-AM-II.01, NSC, Tokyo (1997).
[63] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Improvement in Probabilistic Safety Assessment Concerning Earthquake Events — Trial Analysis of BWR Accident Sequences, JNES, Tokyo (2014).
[64] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Technical Knowledge of the Accident at Fukushima Dai-ichi Nuclear Power Station of Tokyo Electric Power Co., Inc., NISA (2012), http://www.nsr.go.jp/archive/nisa/english/press/2012/06/en20120615-1-1.pdf
[65] FUJIMOTO, H., et al, "Circumstances and present situation of accident management implementation in Japan", Proc. OECD/NEA Workshop on Implementation of Severe Accident Management Measures, Böttstein, 2009, OECD/NEA, Issy-les-Moulineaux (2010).
[66] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Severe Accident and Accident Management, JNES R1, Tokyo (2009).
[67] MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY, Accident Management for Light Water Nuclear Power Reactors, MITI, Tokyo (1994).
[68] TAKAHASHI, H., et al, "Evaluation of technological appropriateness of the implemented accident management measures for PWRs by level 1 and level 2 PSA methods", Proc. Workshop on Implementation of Severe Accident Management Measures, Villigen, 2001, OECD/NEA, Le Seine Saint-Germain (2001).
[69] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, The Evaluation Repot for AM for Light Water NPPs Using the Insights Obtained from PSAs, NISA, Tokyo (2004).
[70] TOKYO ELECTRIC POWER COMPANY, "TEPCO's insight based on the lessons learned at Fukushima accident", paper presented at 5th meeting of Working Group 2, Vienna, 2014.
[71] SWISS FEDERAL NUCLEAR SAFETY INSPECTORATE, Analysis Fukushima 11032011 — In-depth Analysis of the Accident at Fukushima on 11 March 2011 with Special Consideration of Human and Organisational Factors, ENSI, Brugg (2011).
[72] INTERNATIONAL ATOMIC ENERGY AGENCY, Design of Reactor Containment Systems for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.10, IAEA, Vienna (2004).
[73] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Operation, IAEA Safety Standards Series No. NS-R-2, IAEA, Vienna (2000). (This publication is superseded by SSR-2/2 (2011)).
[74] INTERNATIONAL ATOMIC ENERGY AGENCY, Operational Limits and Conditions and Operating Procedures for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.2, IAEA, Vienna (2000).
[75] BWR OWNERS GROUP, Safety Evaluation of "BWR Owners Group — Emergency Procedure Guidelines" — Revision 4, NEDO-31331 (1987), http://pbadupws.nrc.gov/docs/ML1325/ML13255A426.pdf
[76] NUCLEAR ENERGY INSTITUTE, Severe Accident Issue Closure Guidelines, NEI 91-04 Revision 1, NEI, Washington, DC (1994).
[77] BWR OWNERS GROUP, Emergency Procedure and Severe Accident Guidelines - Revision 2 , General Electric (2001).
[78] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series No. SSR-2/2, IAEA, Vienna (2011).
[79] INTERNATIONAL ATOMIC ENERGY AGENCY, Recruitment, Qualification and Training of Personnel for Nuclear Power Plants Safety Guide, IAEA Safety Standards Series NS-G-2.8, IAEA, Vienna (2002).
[80] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE CO-ORDINATION OF HUMANITARIAN AFFAIRS AND WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

[81] SHIROYAMA, H., “Regulatory failures of nuclear safety in Japan — the case of Fukushima accident”, paper presented at Earth System Governance Tokyo Conf.: Complex Architectures, Multiple Agents, Tokyo, 2013, http://tokyo2013.earthsystemgovernance.org/wp-content/uploads/2013/01/0202-SHIROYAMA_Hideaki-.pdf
[82] INTERNATIONAL ATOMIC ENERGY AGENCY, INES — The International Nuclear and Radiological Event Scale (2015), http://www-ns.iaea.org/tech-areas/emergency/ines.asp#1
[83] OECD NUCLEAR ENERGY AGENCY, Reorganisation of the Japanese Government in the Nuclear Sector (2001), Nuclear Law Bulletin 66 (2000) 42.
[84] INTERNATIONAL ATOMIC ENERGY AGENCY, Lessons Learned from the JCO Nuclear Criticality Accident in Japan in 1999 (2009), http://www-ns.iaea.org/downloads/iec/tokaimura-report.pdf
[85] INTERNATIONAL ATOMIC ENERGY AGENCY, Report on the Preliminary Fact Finding Mission Following the Accident at the Nuclear Fuel Processing Facility in Tokaimura, Japan, IAEA, Vienna (1999).
[86] OECD NUCLEAR ENERGY AGENCY, Nuclear Law Bulletin 65 1 (2000) 44–46.
[87] Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, Act No. 166; 10 June 1957, as last amended by Act No. 84 of 2007 (Japan), http://www.nsr.go.jp/archive/nisa/english/resources/legislativeframework/files/ReactorRegulation.pdf
[88] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006 (Japan), http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf
[89] Disaster Countermeasures Basic Act, Act No. 223 of 15 November 1961, as last amended in 1997 (Japan), http://www.adrc.asia/documents/law/DisasterCountermeasuresBasicAct.pdf
[90] OECD NUCLEAR ENERGY AGENCY, Nuclear Law Bulletin 2 68 (2001).
[91] OECD NUCLEAR ENERGY AGENCY, Regulatory and Institutional Framework in Japan against the Background of Fukushima, Nuclear Law Bulletin 1 87 (2011) 27–44.
[92] GOVERNMENT OF JAPAN, Convention on Nuclear Safety National Report of Japan for the Fifth Review Meeting (2010), http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/conventions/2011.pdf
[93] GOVERNMENT OF JAPAN, Convention on Nuclear Safety National Report of Japan for the Third Review Meeting, Government of Japan (2004).
[94] GOVERNMENT OF JAPAN, Convention on Nuclear Safety National Report of Japan for Fourth Review Meeting, Government of Japan (2007).
[95] INTERNATIONAL ATOMIC ENERGY AGENCY, Country Nuclear Power Profiles, IAEA, Vienna (2013).
[96] KATO, S., “Recent development in safety regulation of nuclear fuel cycle activities”, Proc. Int. Conf. on Topical Issues in Nuclear Safety, Vienna, 2001, IAEA, Vienna (2002).
[97] NUCLEAR SAFETY COMMISSION OF JAPAN, Actions to Take Concerning the Malicious Conduct of Unreported Alteration and Concealment at Nuclear Facilities, NSC Decision No. 2007-D8, NSC, Tokyo (2007). http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/decisions/2007/2007_D8.pdf
[98] MINISTRY OF INTERNATIONAL TRADE AND INDUSTRY, Roadmap of Accident Management, MITI, Tokyo (1992) (in Japanese).
[99] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Interim Report, Cabinet Secretariat of the Government of Japan (2011).
[100] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review of Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-2.10, IAEA, Vienna (2003). (This publication is superseded by SSG-25 (2013)).
[101] WEICK, K. E., SUTCLIFFE, K. M., Managing the Unexpected: Resilient Performance in an Age of Uncertainty, 2nd edn, John Wiley & Sons, Inc., New York (2007).

[102] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Final Report, Cabinet Secretariat of the Government of Japan (2012).
[103] INTERNATIONAL ATOMIC ENERGY AGENCY, Manual for First Responders to a Radiological Emergency, IAEA, Vienna (2006).
[104] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).
[105] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).
[106] INSTITUTE OF NUCLEAR POWER OPERATIONS, Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005 Addendum, INPO, Atlanta (2012).
[107] ROESE, N. J., VOHS, K. D., Hindsight bias, Perspect. Psychol. Sci. 7 5 (2012) 411–426.
[108] HOLLNAGEL, E., Cognitive Reliability and Error Analysis Method (CREAM), Elsevier, Oxford and New York (1998).
[109] COOK, R. I., WOODS, D. D., Distancing through differencing an obstacle to organizational learning following accidents, Resilience Engineering: Concepts and Precepts (HOLLNAGEL, E., WOODS, D. D., LEVESON, N., Eds), Ashgate, Burlington (2006).
[110] DEKKER, S., Drift into Failures, Ashgate, Farnham (2011).
[111] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Culture in Nuclear Installations, IAEA-TECDOC-1329, IAEA, Vienna (2002).
[112] BERGER, P. L., LUCKMANN, T., The Social Construction of Reality — A Treatise in the Sociology of Knowledge, Doubleday, Garden City, NY (1966).
[113] SCHEIN, E. H., Organizational Culture and Leadership, 3rd edn, Jossey-Bass Publishers, San Francisco (1985).
[114] PARIES, J., "Resilience in aviation: the challenge of the unexpected", paper presented at IAEA Technical Meeting on Managing the Unexpected — From the Perspective of the Interaction between Individuals, Technology and Organization, Vienna, 2012.
[115] TALEB, N. N., The Black Swan: The Impact of the Highly Improbable, Random Hose, New York (2007).
[116] LANIR, Z., Fundamental Surprises, Center for Strategic Studies, Tel Aviv (1993).
[117] WEARS, R. L., WEBB, L. K., "Fundamental on situational surprise: A case study with implications for resilience", Proc. 4th Resilience Engineering Symp., Sophia Antipolis, 2011, Presses des Mines, Sophia Antipolis (2011).
[118] WOODS, D. D., DEKKER, S., COOK, R., JOHANNESEN, L., SARTER, N., Behind Human Error, Ashgate, Farnham (2010).
[119] REASON, J., Human Error, Cambridge University Press, New York (1990).
[120] WOODS, D., "Technology alone is not enough", Human Reliability in Nuclear Power (ANTHONY, R. D., Ed.), IBC Technical Services, London (1987).
[121] ALDRICH, D. P., Post-crisis Japanese Nuclear Policy: From Top-down Directives to Bottom-up Activism, Asia Pac. Issues 103 (2012) 12.
[122] JAPAN ATOMIC ENERGY COMMISSION, Framework for Nuclear Energy Policy (2005) (Tentative Translation), http://www.aec.go.jp/jicst/NC/tyoki/taikou/kettei/eng_ver.pdf
[123] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standards Series No. GSR Part 1, IAEA, Vienna (2010).
[124] ALDRICH, D. P., Location, Location, Location: Selecting Sites for Controversial Facilities, Singapore Econ. Rev. 53 1 (2008) 145–172.
[125] INDEPENDENT INVESTIGATION ON THE FUKUSHIMA NUCLEAR ACCIDENT, The Fukushima Daiichi Nuclear Power Station Disaster — Investigating the Myth and Reality, Routledge, London (2014).
[126] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Safety Review 2013, GC(57)/INF/3 (2013), http://www.iaea.org/About/Policy/GC/GC57/GC57InfDocuments/English/gc57inf-3_en.pdf

[127] INTERNATIONAL ATOMIC ENERGY AGENCY, Follow-up IAEA Mission in Relation to the Findings and Lessons Learned from the 16 July 2007 Earthquake at Kashiwazaki-Kariwa NPP, IAEA, Vienna (2009).
[128] SHAPIRO, C. S., Station Blackout at Nuclear Power Plants (1986), http://www.osti.gov/scitech/servlets/purl/6593812-YJ6oK4/
[129] DEETZ, S., "The learning journey: IAEA safety culture continuous improvement", paper presented at IAEA Leadership and Safety Culture Workshop for Senior Managers, Vienna, 2013.
[130] SAGAN, S., The Limits of Safety: Organizations, Accidents, and Nuclear Weapons, Princeton University Press, Princeton (1993).
[131] HOLLNAGEL, E., PARIÈS, J., WOODS, D., WREATHALL, J., Resilience Engineering in Practice: A Guidebook, Ashgate, Farnham (2011).
[132] WOODS, D. D., BRANLAT, M., Basic patterns in how adaptive systems fail, Resilience Engineering in Practice a Guidebook (HOLLNAGEL, E., PARIÈS, J., WOODS, D. D., WREATHALL, J., Eds), Ashgate, Farnham (2011).
[133] INTERNATIONAL NUCLEAR SAFETY GROUP, Improving the International System for Operating Experience Feedback, INSAG-23, IAEA, Vienna (2008).
[134] Convention on Nuclear Safety, INFCIRC/449, IAEA, Vienna (1994).
[135] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Nuclear Power Plant Operating Experiences from the IAEA/NEA Incident Reporting System 1999-2002, IAEA, Vienna (2003).
[136] INTERNATIONAL ATOMIC ENERGY AGENCY, OECD NUCLEAR ENERGY AGENCY, Nuclear Power Plant Operating Experience from the IAEA/NEA International Reporting System for Operating Experience 2005–2008, IAEA, Vienna (2010).
[137] AUTORITÉ DE SÛRETÉ NUCLÉAIRE, Complementary Safety Assessments of the French Nuclear Installations (2011), http://www.french-nuclear-safety.fr/Media/Files/5eme-Rapport_National_France_CSN
[138] GOVERNMENT OF INDIA, Actions Taken for Indian NPPs Subsequent to Fukushima Nuclear Accident. National Report to the Convention on Nuclear Safety (2012), http://www.aerb.gov.in/AERBPortal/pages/English/t/documents/CNS2012.pdf
[139] INTERNATIONAL ATOMIC ENERGY AGENCY, Periodic Safety Review for Nuclear Power Plants, IAEA Safety Standards Series No. SSG-25, IAEA, Vienna (2013).
[140] GORBATCHEV, A., MATTÉI, J. M., REBOUR, V., VIAL, E., Report on Flooding of le Blayais Power Plant on 27 December 1999, ISPN, Fontenay-aux-Roses (2000).
[141] INTERNATIONAL ATOMIC ENERGY AGENCY, A System for the Feedback of Experience from Events in Nuclear Installations, IAEA Safety Standards Series NS-G-2.11, IAEA, Vienna (2006).
[142] INTERNATIONAL ATOMIC ENERGY AGENCY, Scart Guidelines: Reference Report for IAEA Safety Culture Assessment Review Team (SCART), Services Series No. 16, IAEA, Vienna (2008).
[143] SATAKE, K., NAMEGAYA, Y., YAMAKI, S., Numerical Simulation of the AD 869 Jogan Tsunami in Ishinomaki and Sendai Plains, Active Fault Paleoearthquake Res. 8 (2008) 71–89 (in Japanese).

CONTENTS OF CD-ROM

The following annexes to Technical Volume 2 are included on the attached CD-ROM:

Annex I: Historical development of the governmental, legal and regulatory framework for nuclear safety in Japan.

Annex II: Aspects related to the human and organizational factors of the accident.

Annex III: Detailed description of relevant operating experience.

ABBREVIATIONS

ABWR	advanced boiling water reactor
ADS	automatic depressurization system
AM	accident management
AMTA	Ageing Management Technical Assessment
ANRE	Agency for Natural Resources and Energy
ANSN	Asian Nuclear Safety Network
AOPs	abnormal operating procedures
ARI	alternate rod insertion
ATWS	anticipated transient without scram
BDBA	beyond design basis accident
BDBEE	beyond design basis external event
BWR	boiling water reactor
BWROG	BWR Owners Group
CCS	containment cooling system
CDF	core damage frequency
CDMC	Central Disaster Management Council
CFF	containment failure frequency
CNRA	Committee on Nuclear Regulatory Activities
CNS	Convention on Nuclear Safety
CRD	control rod drive
CRDHCS	control rod drive hydraulic control system
CRPPH	Committee on Radiation Protection and Public Health
CS	core spray
CSNI	Committee on Safety of Nuclear Installations
CSS	Commission on Safety Standards
CST	condensate storage tank
DBAs	design basis accidents
DC	direct current
DDFP	diesel driven fire pump
DID	defence in depth
EBP	extrabudgetary programme
ECCS	emergency core cooling system
EDG	emergency diesel generator
EOP	emergency operating procedure
EP	Establishment Permit
EPG	emergency procedure guideline
EPS	emergency power system
ERC	Emergency Response Centre
ERSS	Emergency Response Support System
ESS	emergency seawater system
FEPC	Federation of Electric Power Companies
FSAR	Final Safety Analysis Report
GMPE	ground motion prediction equation
HCLPF	High Confidence of Low Probability of Failure
HERP	Headquarters for Earthquake Research Promotion
HP	Hitachi Port
HPCI	high pressure coolant injection
HPCS	high pressure core spray
I&C	instrumentation and control
IC	isolation condenser
ICANPS	Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company

IPE	individual plant examination
IPEEE	individual plant examination of for external events
INES	International Nuclear and Radiological Event Scale
INPO	Institute of Nuclear Power Operations
INRA	International Nuclear Regulators Association
INSAG	International Nuclear Safety Group
IRRS	Integrated Regulatory Review Service
IRS	Incident Reporting System
ISSC	International Seismic Safety Centre
JAEA	Japan Atomic Energy Agency
JAEC	Japan Atomic Energy Commission
JAPC	Japan Atomic Power Company
JAPEIC	Japan Power Engineering and Inspection Corp
JEA	Japan Electric Association
JCO	Japan Nuclear Fuels Conversion Company
JNES	Japan Nuclear Energy Safety Organization
JSCE	Japan Society of Civil Engineers
KEPCO	Kansai Electric Power Company
LOCA	loss of coolant accident
LOOP	loss of off-site power
LPCI	low pressure coolant injection
LPCS	low pressure core spray
LTMP	Long-term Maintenance Programme
LUHS	loss of ultimate heat sink
M/C	metal clad switch gear
MCR	main control room
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MITI	Ministry of International Trade and Industry
MOFA	Ministry of Foreign Affairs
MSIV	main steam isolation valve
MUWC	make-up water condensate
NERHQ	Nuclear Emergency Response Headquarters
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPSH	net positive suction head
NRA	Nuclear Regulation Authority
NRC	United States Nuclear Regulatory Commission
NSC	Nuclear Safety Commission
NUPEC	Nuclear Power Engineering Corporation
NUSS	Nuclear Safety Standards
NUSSC	Nuclear Safety Standards Committee
NUSTEC	Nuclear Safety Technology Centre
OECD/NEA	OECD Nuclear Energy Agency
OFC	Off-site Centre
OP	Onahama Port
OSART	Operational Safety Review Team
OTS	operational technical specification
PAZ	precautionary action zone
PCV	primary containment vessel
PIE	postulated initiating event
PSA	probabilistic safety assessment
PSHA	probabilistic seismic hazard analysis
PSR	periodic safety review

RCA	radiologically controlled area
RCIC	reactor core isolation cooling
RCS	reactor coolant system
RHR	residual heat removal
RPS	reactor protection system
RPT	recirculation pump trip
RPV	reactor pressure vessel
PWR	pressurized water reactor
SAM	severe accident management
SAMG	severe accident management guideline
SAR	safety analysis report
SBGT	standby gas treatment
SBO	station blackout
SC	suppression chamber
SFP	spent fuel pool
SLCS	standby liquid control system
SPDS	Safety Data Parameter Display System
SRV	safety relief valve
SSC	structures, systems and components
STA	Science and Technology Agency
TAF	top of active fuel
TEPCO	Tokyo Electric Power Company
TP	Tokyo Peil
TRANSSC	Transport Safety Standards Committee
TSC	technical support centre
U-D	up-down (vertical)
UHS	ultimate heat sink
WANO	World Association of Nuclear Operators
WASSC	Waste Safety Standards Committee
WGOE	Working Group on Operating Experience
ZPGA	zero period ground acceleration

CONTRIBUTORS TO DRAFTING AND REVIEW

WORKING GROUP 2 (WG2): SAFETY ASSESSMENT

Co-Chairs

Chande, S.
Atomic Energy Regulatory Board
India

Hughes, P. (until August 2014)
Department of Nuclear Safety and Security
IAEA

Ulses, A. (August 2014 onwards)
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Aparkin, F.
Department of Nuclear Safety and Security
IAEA

Members

Alonso, J.R.
Nuclear Safety Council
Spain

Ayub, M.
Pakistan Nuclear Regulatory Authority
Pakistan

Bucalossi, A.
European Commission Joint Research Centre

Chaikiat, P.
Swedish Radiation Safety Authority
Sweden

Dermarkar, F.
CANDU Owners Group
Canada

Foucher, L.
French Nuclear Safety Authority
France

Gauntt, R.
Sandia National Laboratories
USA

Giannelli, I.A.
Slovenské Elektrárne, a.s. (subsidiary of Enel)
Italy

Godoy, A.R.
James J. Johnson and Associates
Argentina

Gonzalez, V.
Nuclear Safety and Safeguards National Commission
Mexico

Harrison, S.
Office for Nuclear Regulation
United Kingdom

Heppell-Masys, K.
Canadian Nuclear Safety Commission
Canada

Hoshi, H.
Nuclear Regulation Authority
Japan

Kajimoto, M.
Nuclear Regulation Authority
Japan

Kuivalainen, H.
Radiation and Nuclear Safety Authority Finland

Lankin, M.
Federal Environmental, Industrial and Nuclear Supervision Service of Russia
Russian Federation

de L'Epinois, B.
AREVA
France

Macchi, L.
Dédale
France

Mildenberger, O.
Gesellschaft für Anlagen- und Reaktorsicherheit gGmbH
Germany

Misak, J.
UJV Řež a.s.
Czech Republic

Perryman, L.
Eskom, EOPs/SAMGs
South Africa

Ryser, C.
Swiss Federal Nuclear Safety Inspectorate
Switzerland

Song, J.H.
Korea Atomic Energy Research Institute
Republic of Korea

Weidenbrück, K.
Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety
Germany

Invited experts and contact points

Donges, A.
Institute of Nuclear Power Operation
USA

Haber, S.
Human Performance Analysis, Corp.
USA

Harter, R.
Boiling Water Reactors Owners Group
USA

Hatamura, Y.
University of Tokyo
Japan

Ihara, T.
Tokyo Electric Power Company
Japan

Iino, K.
SYDROSE
Japan

Kunito, S.
Tokyo Electric Power Company
Japan

Nakagawa, Y.
Tokyo Electric Power Company
Japan

Takizawa, S.
Tokyo Electric Power Company
Japan

Watford, G.
GE Hitachi Nuclear Energy
USA

Yamanaka, Y.
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG2

Beltran, F.
Earle, K.
Haage, M.
Haber, S.
Roveti, B.
Rycraft, H.
Skarbo, B.
Yllera, J.
Yoshimoto, Y.

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom
International Nuclear Safety Group

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization of the United Nations

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Mohammad Jais, A.
International Nuclear Safety Group

Niu, S.
International Labour Organization

Sharma, S.K.[†]
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

[†] Deceased

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

12–13 September 2013
3rd meeting of WGs 1 and 2, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

6–7 August 2013
CS on Source Term, Vienna

29–31 October 2013
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 November 2013
CS on Human and Organizational Factors and Safety Culture, Atlanta

13–17 January 2014
CS on Human and Organizational Factors and Safety Culture, Vienna

17–21 March 2014
CS on Human and Organizational Factors and Safety Culture, Ottawa

Bilateral meetings in Japan

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

15-1816



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)

The Fukushima Daiichi Accident



Technical Volume 3/5
Emergency Preparedness and Response

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 3
EMERGENCY PREPAREDNESS AND RESPONSE

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 3
EMERGENCY PREPAREDNESS AND RESPONSE

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.
STI/PUB/1710
ISBN 978–92–0–107015–9 (set)
Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This publication has been prepared from contributions submitted by many international experts to the five Working Groups for the preparation of the technical volumes. The content does not necessarily reflect the views of IAEA Member States, or the organizations nominating experts.

Great care has been taken to maintain the accuracy of information contained in this publication. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with this publication.

This publication is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from this publication may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this publication indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continued existence of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from this report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

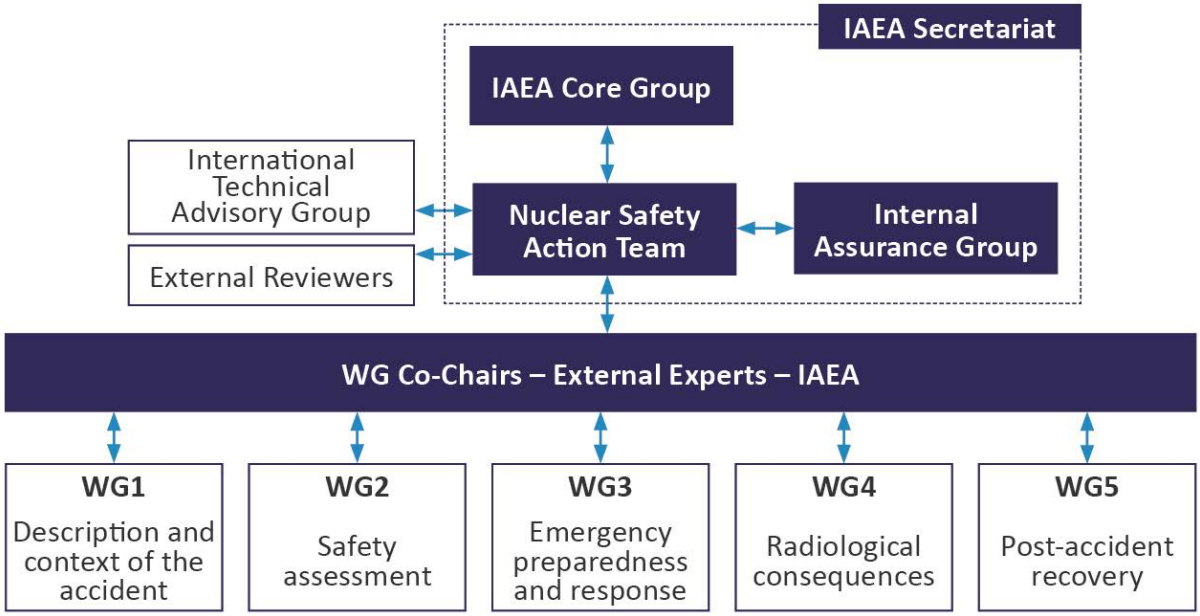


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

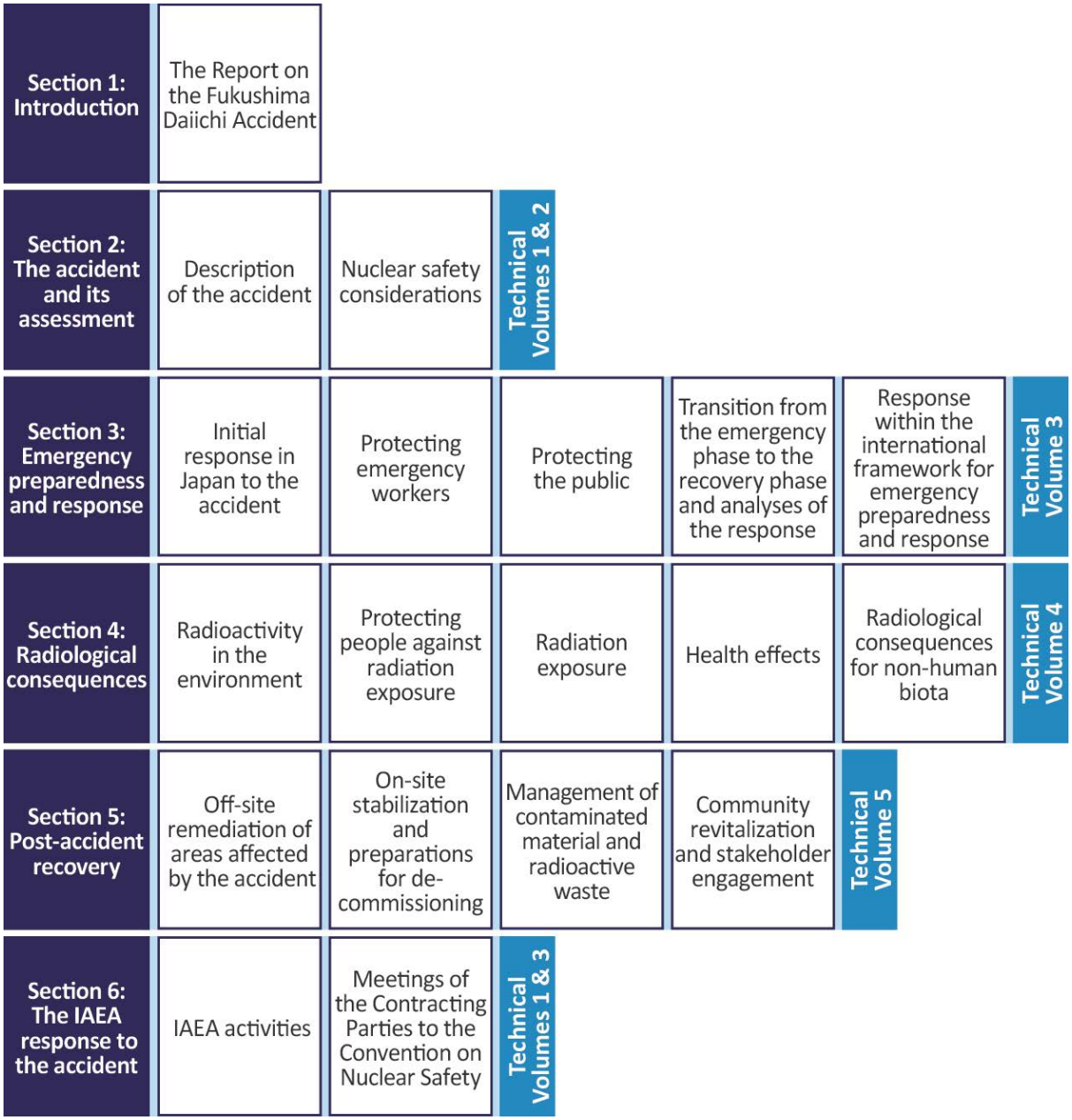


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

EMERGENCY PREPAREDNESS AND RESPONSE 1

3. INTRODUCTION 1
3.1. INITIAL RESPONSE IN JAPAN TO THE ACCIDENT 4
3.1.1. Relevant EPR arrangements in Japan prior to the accident 4
3.1.2. Identification, notification and activation in response to the accident 10
3.1.3. Mitigatory actions 13
3.1.4. Management of the off-site response 18
3.1.5. Summary 24
3.1.6. Observations and lessons 25
3.2. PROTECTING EMERGENCY WORKERS 26
3.2.1. Relevant arrangements in Japan prior to the accident 29
3.2.2. Protection of personnel at the NPP following the earthquake and tsunami 30
3.2.3. Protective measures for emergency workers 30
3.2.4. Medical management of emergency workers 38
3.2.5. Voluntary involvement of members of the public in the emergency response 42
3.2.6. Summary 42
3.2.7. Observations and lessons 43
3.3. PROTECTING THE PUBLIC 44
3.3.1. Arrangements for protecting the public in Japan prior to the accident 44
3.3.2. Urgent protective actions 48
3.3.3. Early protective actions 60
3.3.4. Use of the dose projection model SPEEDI as a basis for decisions on protective actions during the accident 71
3.3.5. Environmental monitoring 74
3.3.6. Public information 84
3.3.7. International trade 93
3.3.8. Waste management in the emergency 94
3.3.9. Summary 96
3.3.10. Observations and lessons 99
3.4. TRANSITION FROM THE EMERGENCY PHASE TO THE RECOVERY PHASE AND ANALYSES OF THE RESPONSE 101
3.4.1. Transition from the emergency phase to the recovery phase 101
3.4.2. Analyses of the response 108
3.4.3. Summary 116
3.4.4. Observations and lessons 117
3.5. RESPONSE WITHIN THE INTERNATIONAL FRAMEWORK FOR EMERGENCY PREPAREDNESS AND RESPONSE 117
3.5.1. International EPR framework for a nuclear or radiological emergency prior to the accident 117
3.5.2. IAEA response 129
3.5.3. Protective actions recommended to foreign nationals within Japan 147
3.5.4. Response of international organizations 148
3.5.5. Provision of international assistance 155
3.5.6. Summary 157
3.5.7. Observations and lessons 159

APPENDIX I. KEY DOCUMENTS AND ELEMENTS THAT DEFINED THE NATIONAL EPR SYSTEM FOR RESPONSE TO A NUCLEAR EMERGENCY IN JAPAN PRIOR TO THE ACCIDENT 161

APPENDIX II. RADIATION AND DISASTER EMERGENCY MEDICAL SYSTEMS IN JAPAN PRIOR TO THE ACCIDENT 169

APPENDIX III. PLANS FOR EMERGENCY DRILLS AND EXERCISES PRIOR TO THE ACCIDENT 171

REFERENCES 173
CONTENTS OF CD-ROM 188
ABBREVIATIONS 189
CONTRIBUTORS TO DRAFTING AND REVIEW 192
INTERNATIONAL TECHNICAL ADVISORY GROUP 195
MEETINGS 196

EMERGENCY PREPAREDNESS AND RESPONSE

3. INTRODUCTION

This volume describes the key events and response actions from the onset of the accident at the Fukushima Daiichi nuclear power plant (NPP), operated by the Tokyo Electric Power Company (TEPCO), on 11 March 2011. It also describes the national emergency preparedness and response (EPR) system in place in Japan and the international EPR framework prior to the accident. It is divided into five sections.

Section 3.1 describes the initial actions taken by Japan in response to the accident, involving: identification of the accident, notification of off-site authorities and activation of the response; mitigatory actions taken on-site; and initial off-site response.

Section 3.2 describes the protective measures taken for personnel in response to the natural disaster, protection of emergency workers, medical management of emergency workers and the voluntary involvement of members of the public in the emergency response.

Section 3.3 describes the protective actions and other response actions taken by Japan to protect the public. It addresses urgent and early protective actions; the use of a dose projection model, the System for Prediction of Environmental Emergency Dose Information (SPEEDI), as a basis for decisions on protective actions during the accident; environmental monitoring; provision of information to the public and international community; and issues related to international trade and waste management.

Section 3.4 describes the transition from the emergency phase to the recovery phase. It also addresses the national analysis of the accident and the emergency response.

Section 3.5 describes the response by the IAEA, other international organizations within the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), the actions of IAEA Member States with regard to protective actions recommended to their nationals in Japan and the provision of international assistance.

A summary, observations and lessons conclude each section.

There are three appendices and two annexes that provide supplementary information. Appendix I describes the key documents and elements of Japan's EPR system that existed prior to the accident. Appendix II describes the radiation emergency medical system that was in place in Japan prior to the accident. Appendix III describes the emergency drills and exercises that took place prior to the accident. Annex I contains a provisional English translation by the IAEA of the notification faxes sent by the Fukushima Daiichi NPP Site Superintendent to off-site officials on 11 March 2011. Annex II reproduces a copy of a message issued by the International Commission on Radiological Protection (ICRP) on 21 March 2011 that includes quotes from its generally applicable recommendations. The annexes are included on the attached CD-ROM.

Key events relevant to the EPR area and response actions during the first year after the accident have been compiled in chronological order and are presented in the form of a timeline in Fig. 3–1.

11 March

- 14:46 | Great East Japan Earthquake, loss of off-site power, all operating reactors automatically shut down
- 15:36 | Second tsunami wave started flooding site (estimated inundation height: Onahama Port (OP) +14.5 m)
- 15:42 | Fukushima Daiichi NPP reported a specific event (station blackout) to national and local governments under Article 10 of the Act on Special Measures Concerning Nuclear Emergency Preparedness (Nuclear Emergency Act)
- 16:45 | Fukushima Daiichi NPP reported an event classified as a nuclear emergency (inability of water injection of the emergency core cooling system for Units 1 and 2) under Article 15 of the Nuclear Emergency Act to national and local governments
- 19:03 | Declaration of a nuclear emergency by the national Government and establishment of Nuclear Emergency Response Headquarters (NERHQ)
- 20:50 | Fukushima Prefecture issued an evacuation order for an area of 2 km radius around Fukushima Daiichi NPP
- 21:23 | National Government issued an evacuation order for an area of 3 km radius and sheltering order for a 3–10 km radius around Fukushima Daiichi NPP

12 March

- Fukushima Prefectural Government began monitoring evacuees using criterion of 13 000 counts/min
- 03:20 | Off-site Centre (OFC) became partially operational
- 05:44 | National Government issued an evacuation order for an area of 10 km radius around Fukushima Daiichi NPP
- 13:15 | Local Nuclear Emergency Response Headquarters (Local NERHQ) issued an order to local government that, if a decision is taken to implement iodine thyroid blocking (ITB), stable iodine tablets would need to be distributed to evacuation facilities
- 15:36 | Explosion in Unit 1: destruction of water and power provisions, degrading site radiological conditions
- 18:25 | National Government issued an evacuation order for an area of 20 km radius around Fukushima Daiichi NPP
- 19:04 | Seawater injection into the core of Unit 1 started

13 March

- 05:58 | Fukushima Daiichi NPP reported an event classified as a nuclear emergency (loss of reactor cooling function at Unit 3) under Article 15 of the Nuclear Emergency Act to national and local governments

14 March

- Monitoring criterion for full decontamination of the public increased from 13 000 counts/min to 100 000 counts/min
- 11:01 | Explosion in Unit 3 and destruction of alternative water injection equipment for Units 1 and 3
- 13:38 | Fukushima Daiichi NPP reported an event classified as a nuclear emergency (loss of reactor cooling function at Unit 2) under Article 15 of the Nuclear Emergency Act to national and local governments

15 March

- Dose criterion for emergency workers increased from 100–250 mSv (with retroactive effect from 14 March)
- 05:30 | Government-TEPCO Integrated Response Office established in Tokyo
- 06:14 | Sound in Unit 2 primary containment vessel, explosion in Unit 4 reactor building
- 09:00 | Maximum radiation level at main gate (c. 12 mSv/h)
- 11:00 | National Government issued an order to shelter for residents within a 20–30 km radius of Fukushima Daiichi NPP
  | Relocation began of OFC to Fukushima Prefectural Public Hall

FIG.3–1. Timeline of key events relevant to EPR and actions in response to the emergency at the Fukushima Daiichi NPP.

20:40–50 Dose rates in the order of a few hundred μSv/h measured in some locations beyond the 20 km evacuation zone

17 March

Provisional Regulation Values to restrict food and drinking water established

20 March

National Government received aerial monitoring data from the United States of America

21 March

National Government began to issue restrictions on the distribution of specific food

25 March

National Government recommended voluntary evacuation for residents within the 20–30 km radius of the Fukushima Daiichi NPP

11 April

National Government announced criterion of 20 mSv dose to determine areas beyond the 20 km evacuation zone from which people might need to be relocated

17 April

TEPCO issued a Roadmap that outlined the steps toward recovery on the site

19 April

National Government established criterion of 20mSv/y to determine reopening of schools (the criterion of 20 mSv/y was later reduced to 1 mSv/y)

22 April

Deliberate Evacuation Area, Evacuation Prepared Area in Case of Emergency and Restricted Area established

25 April

Joint press conferences between various organizations involved in the response held from this day onward

15 May

Commencement of relocation from the Deliberate Evacuation Area

17 May

National Government issued Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers

30 June onwards

National Government began to designate locations for relocation, identified as Specific Spots Recommended for Evacuation

30 September

Evacuation Prepared Area in Case of Emergency lifted

16 December

Conditions for a cold shutdown state achieved in Units 1–3

1 April 2012

Standard limits established with activity concentrations for radionuclides in food and drinking water on the basis of 1 mSv/y criterion

FIG.3–1. Timeline of key events relevant to EPR and actions in response to the emergency at the Fukushima Daiichi NPP. (cont.). [1]

[1] Throughout this volume, Japan Standard Time (JST) is used, except for Section 3.5, which uses Universal Time Coordinated (UTC) when describing activities at the international level. JST is nine hours ahead of UTC.

3.1. INITIAL RESPONSE IN JAPAN TO THE ACCIDENT

3.1.1. Relevant EPR arrangements in Japan prior to the accident

Before the accident at the Fukushima Daiichi NPP, separate arrangements were in place for responding to nuclear emergencies and natural disasters at the national and local levels. These arrangements did not envisage the need to respond to a nuclear emergency and a natural disaster occurring simultaneously [1, 2] (see Appendix I for more details). Lessons identified from the response to the Japan Nuclear Fuel Conversion Co. (JCO) Tokaimura criticality accident in 1999 [3, 4] resulted in an increased role of the national Government in managing the response to a nuclear emergency [5].

It was planned that the core entities in managing a nuclear emergency would be the Nuclear Emergency Response Headquarters (NERHQ)[2] and its Secretariat[3], as well as the Local Nuclear Emergency Response Headquarters (Local NERHQ)[4] (see Appendix I). The NERHQ would direct and coordinate the national response, which was to include preparing and issuing orders[5] and/or recommendations on evacuation to the local government [5].

The overall management of the national response to a nuclear emergency was to be coordinated at the local level, as soon as possible, by the Local NERHQ at the Off-site Centre (OFC). The OFC was to be established within a 20 km radius of an NPP [7]. For the Fukushima Daiichi and Fukushima Daini NPPs, the OFC was to be established within 5 km of the Fukushima Daiichi NPP. Each OFC had the necessary facilities and equipment to communicate with the Prime Minister's Office, the Cabinet Office and other relevant national and local authorities. It also allowed easy communication with the Emergency Response Centre established by the Ministry of Economy, Trade and Industry (METI) and the Nuclear and Industrial Safety Agency (NISA), which was part of the ministry (METI/NISA-ERC). The Local Prefectural Nuclear Emergency Response Headquarters and the Joint Council for Nuclear Emergency Response (JCNER) were also planned to be located in the Off-site Centre [1, 2, 8].

For the prefectural response to a nuclear emergency, it was planned that the Local Prefectural Nuclear Emergency Response Headquarters and the Prefecture Headquarters for Disaster Control would coordinate activities at the prefectural level. The JCNER would coordinate between the national response at the local level and the prefectural response [1, 5, 8].

Notification from the NPP to local and national governments was required under Article 10 of the Act on Special Measures Concerning Nuclear Emergency Preparedness (hereafter referred to as Nuclear Emergency Act) [5] when certain 'specific events' occurred, such as failure of all AC power supplies for more than five minutes [9]. Under Article 15 of the Nuclear Emergency Act [5], a report of a nuclear emergency would be sent when certain predefined criteria were met or exceeded, such as the loss of all capabilities to cool the reactor [5, 7, 10].

---

[2] The NERHQ, which was planned to be located in the Prime Minister's Office, was to be composed of those appointed by the Prime Minister from among the officials of the Cabinet Secretariat and designated administrative organs [5]. The Prime Minister was to serve as the Director General of the NERHQ.

[3] The NERHQ Secretariat was to be staffed by representatives of key organizations and headed by the Director General of the Nuclear and Industrial Safety Agency (NISA), which was part of the Ministry of Economy, Trade and Industry (METI). It would be located in the METI/NISA Emergency Response Centre (METI/NISA-ERC) in the METI building.

[4] The Local NERHQ was to be staffed by individuals from all relevant organizations, with the METI Senior Vice Minister as Director General. It was planned to be located at the Off-site Centre.

[5] The Nuclear Emergency Act [5] and the Disaster Countermeasures Basic Act [6] use the terms 'instructions' and 'recommendations' for issuing protective actions. An 'instruction' is mandatory and the public is therefore required to adhere to it. A 'recommendation' is only a suggestion and therefore not mandatory. However, for the purposes of clarity, the term 'orders' is used in this report as an equivalent of 'instructions'.

Table 3.1–1 lists the criteria to be used by the operators of the Fukushima Daiichi NPP for notification and reporting, as they were listed on the reporting forms (see Annex I).

TABLE 3.1–1. CRITERIA TO BE USED BY THE OPERATORS OF THE FUKUSHIMA DAIICHI NPP FOR REPORTING AN EMERGENCY

Type of events	Criteria	Type of events	Criteria
Article 10[a] (Specific Event)	(i) Rise in site boundary radiation dose rate	Article 15[a] (Nuclear Emergency)	(i) Abnormal rise in the site boundary radiation dose rate
	(ii) Release of radioactive material (higher than preset levels) through the normal release path		(ii) Abnormal release of radioactive material through the normal release path
	(iii) Release of radioactive materials due to a fire, explosion or other hazard		(iii) Abnormal release of radioactive material due to a fire, explosion or other hazard
	(iv) Scram failure		(iv) Out-of-reactor criticality
	(v) Leakage of reactor coolant		(v) Loss of the reactor shutdown function
	(vi) Loss of reactor feedwater		(vi) Inability of water injection of the emergency core cooling system
	(vii) Loss of reactor heat removal function		(vii) Abnormal rise in containment pressure
	(viii) Station blackout		(viii) Loss of pressure suppression function
	(ix) Loss of DC power supply (partial loss)		(ix) Loss of reactor cooling function
	(x) Drop in the reactor water level at shutdown		(x) Loss of DC power supply (complete loss)
	(xi) Drop in the fuel pool water level		(xi) Core meltdown
	(xii) Unavailability of the control room		(xii) Abnormal drop in reactor water level at shutdown
	(xiii) Possible out-of-reactor criticality		(xiii) Unavailability of the control room

[a] Nuclear Emergency Act [5]

Table 3.1–2 provides additional details from the relevant Cabinet Order and Ministerial Ordinance [7, 9, 10].

These criteria were not used as emergency action levels (EALs)[6] which would trigger implementation of predetermined public protective actions without additional assessment and judgement off-site. There was no emergency classification system in place that would address the need for prompt and informed management of the response to severe emergencies, as per the IAEA safety standards [13, 14].

It was assumed that a report of an event under Article 15 of the Nuclear Emergency Act [5] would follow a notification of a 'specific event' under Article 10 [8]. Notifications under Articles 10 and 15 could also be sent simultaneously as an initial report. However, it was not envisaged that notification under Article 15 only would be submitted as an initial report [15].

The NPP Site Superintendent would establish the on-site Emergency Response Centre (ERC) to direct the on-site Emergency Response Organization (ERO), which would implement different emergency

[6] Emergency action level (EAL) is a specific, predetermined, observable criterion used to detect, recognize and determine the emergency class of an event, which, if met or exceeded, would trigger declaration of the appropriate emergency class and initiation of the predefined response actions for that emergency class [11-13].

response functions to prevent progression of the accident and to mitigate its consequences, to protect plant personnel and to address any other site related issues in accordance with established plans and procedures (see Appendix I for background information).

TABLE 3.1–2. CRITERIA FOR A SPECIFIC EVENT AND FOR A NUCLEAR EMERGENCY AS SPECIFIED IN THE RELEVANT NATIONAL LAW [9]

Events	Criteria for a Specific Event	Criteria for a Nuclear Emergency
a) Radiation dose near the site boundary	5 μSv/h or more at one point for more than consecutive 10 minutes	500 μSv/h or more at one point for more than consecutive 10 minutes
	5 μSv/h or more at two or more points simultaneously	500 μSv/h or more at two or more points simultaneously
b) Detection of radioactive materials in usual release points such as exhaust pipes	When the concentration of radioactive materials equivalent to 5 μSv/h or more continues for 10 minutes or more, or radioactive materials equivalent to 50 μSv/h or more are released	When the concentration of radioactive materials equivalent to 500 μSv/h or more continues for 10 minutes or more, or radioactive materials equivalent to 5 mSv/h or more are released
c) Detection of radiation or radioactive materials by fire, explosion, etc. (outside the control zone)	Radiation dose of 50 μSv/h or more	Radiation dose of 5 mSv/h or more
	Release of radioactive materials equivalent to 5 μSv/h or more	Release of radioactive materials equivalent to 500 μSv/h or more
d) Individual events of each nuclear installation:		
Failure of reactor scram	When the nuclear reactor shutdown cannot be performed by usual neutron absorbers	When all reactor shutdown functions are lost in a case where emergency reactor shutdown is necessary
Loss of reactor coolant	When leakage of nuclear reactor coolant occurs, which needs operation of the emergency core cooling system	When water cannot be injected into the nuclear reactor by any emergency core cooling system
Loss of all AC power supplies	When power supply from all AC power supplies fails for 5 minutes or more	When all functions for cooling a reactor are lost with loss of all AC power supplies
Decrease in water level of the spent fuel pool at reprocessing facilities	When water level is decreased to the point where a fuel assembly is exposed	—

In the case of the Fukushima Daiichi NPP, for example, the on-site ERC, if necessary, would send a request for support to TEPCO Headquarters, using TEPCO's capabilities or resources gathered from other nuclear operating organizations, through the Agreement on Cooperation between Japanese Nuclear Operators [16, 17]. A clearly established procedure for requesting such assistance was included in the Fukushima Daiichi NPP Nuclear Operator Emergency Action Plan [16].

The provision of resources to the NPP by the national Government was not clearly described in the other emergency plans existing at the different levels [1, 2, 8].

Off-site response would start from a notification on a reportable event under Article 10 of the Nuclear Emegency Act [5] sent by an NPP to national and local governments. Key actions to be taken if an event fell under Article 10 and/or Article 15 of the Nuclear Emergency Act are summarized in Fig. 3.1–1 [1, 5, 6, 8, 16].

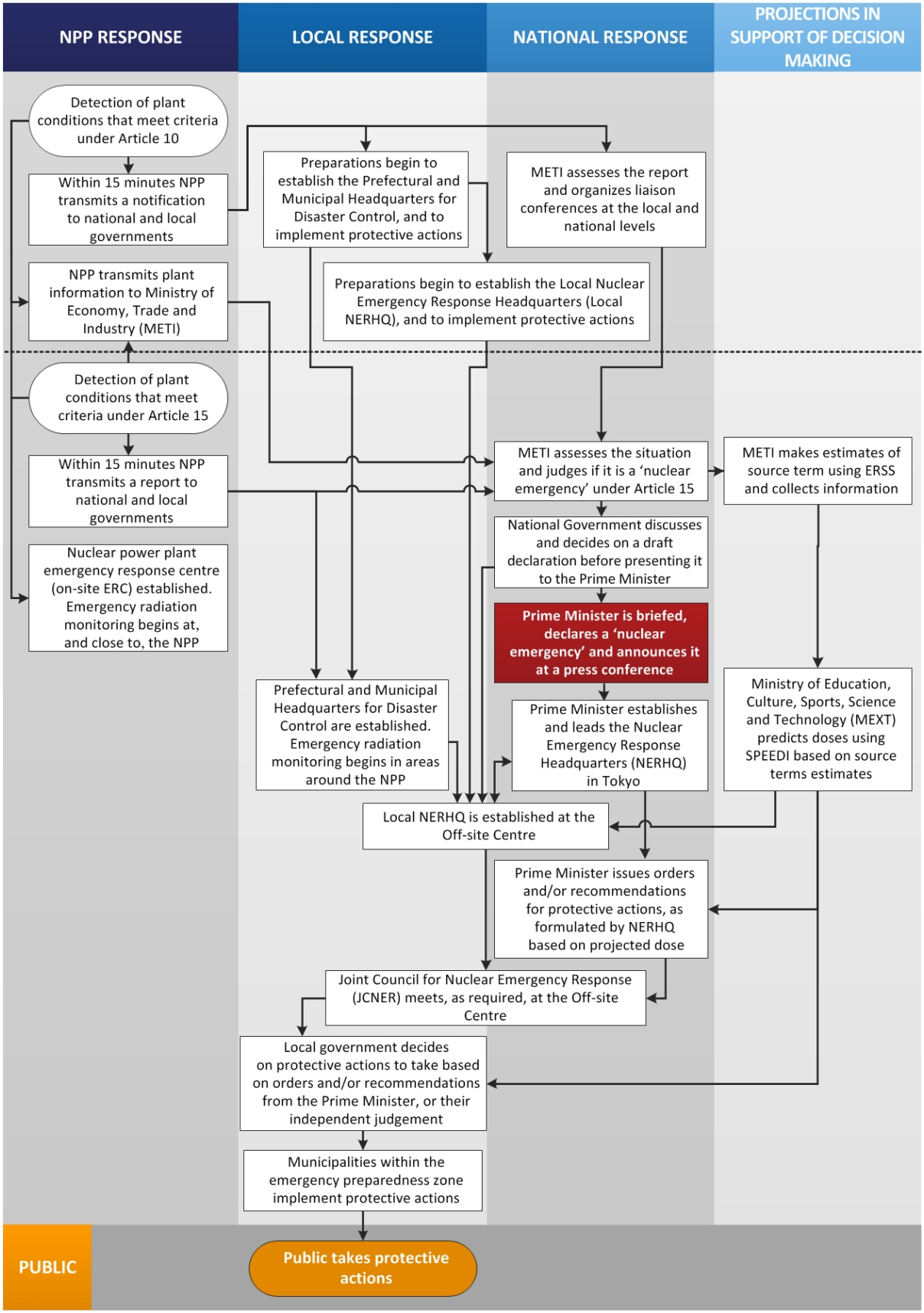


FIG. 3.1–1. Key actions to be taken if an event falls under Article 10 and/or Article 15 of the Nuclear Emergency Act [5], as planned prior to the Fukushima Daiichi accident (based on Refs [1, 5, 6, 8, 16]).

After receiving a notification, national officials in Tokyo (METI/NISA) would assess the event report [8] and a liaison conference of relevant ministries and agencies on accident management would be convened in Tokyo, along with a local liaison conference on accident management at the respective OFC to assess the situation and coordinate the initial response. If it was judged that the event fell under the classification of a nuclear emergency as set forth in Article 15 of the Nuclear Emegency Act [5], the response would proceed as described below without establishing these conferences, or closing them if they had already began.

If NISA assessed a declaration of a Nuclear Emergency to be warranted (as per Article 15), it would prepare a draft public notice of a declaration of a Nuclear Emergency and a draft of orders and/or recommendations for the heads of local governments, which would be sent to the Cabinet Secretariat located in the Prime Minister's Office and the Cabinet Office [2].

The Deputy Chief Cabinet Secretary for Crisis Management, the Director General of the government office responsible for safety regulation (NISA) and the Director General of the Cabinet Office for Disaster Preparedness would then promptly discuss and decide on these drafts, while incorporating inputs from local governments, as necessary, to be presented to the Prime Minister. If there was no time to complete this procedure, then verbal consent would be obtained [8].

The Prime Minister would be briefed on the event, and if he/she concurred with the draft, the declaration of a Nuclear Emergency would be issued.

The Prime Minister would establish and direct (as Director General) the NERHQ and NERHQ Secretariat located in the METI/NISA-ERC to coordinate the emergency response. The NERHQ would monitor conditions at the nuclear facilities and coordinate with local governments.

The Prime Minister would also direct the establishment of the Local NERHQ at the OFC. Nuclear safety inspectors at the site would immediately go to the OFC[7], and a Senior Specialist for Nuclear Emergency Preparedness would start the process of activating the Local NERHQ. The Vice Minister of METI (who would act as the Director General of the Local NERHQ), along with representatives of relevant national organizations (e.g. the Nuclear Safety Commission of Japan (NSC)) from Tokyo and representatives from the local government, would also go to the OFC.

The NPP Site Superintendent would provide the relevant off-site organizations (e.g. METI) with timely information of the accident progression. In parallel with the assessment of the event and activation of the national response described above, METI, as soon as the notification was received (as shown on the right hand side of Fig. 3.1–1), would monitor conditions at the NPP. It would attempt to make predictions of the accident evolution, including predictions of timing, rate and composition of possible releases (i.e. the source term) of radioactive material from the NPP based on plant conditions provided by the operator and using the Emergency Response Support System (ERSS)[8].

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) would use the source term predictions by METI to predict off-site consequences (e.g. projected doses to the public) from the possible release of radioactive material using the System for Prediction of Environmental Emergency Dose Information (SPEEDI). Doses that were predicted by using SPEEDI would be compared with predetermined criteria for taking protective actions [19] to determine where and what

[7] Some nuclear safety inspectors would remain at the site to monitor the plant situation for reporting to METI/NISA.

[8] The ERSS is a computer-aided tool to assess the status at the nuclear power plant and predict the progression of an accident [18].

protective action(s) should be taken (see Section 3.3 for details). MEXT would transmit the predictions to terminals in the NERHQ, Local NERHQ, NSC, Prefecture Headquarters for Disaster Control and elsewhere. Within the NERHQ, protective action recommendations would be drafted for issuance by the Prime Minister, who would be responsible for issuing orders and/or recommendations for protective actions to the public [8].

Thus, determination of the protective actions was to be based on the projections performed in real time. There was no system in place to recommend urgent protective actions for the public based on pre-defined plant conditions which, if met, would correspond to a specific emergency class and would trigger a decision on urgent protective actions for the public without additional assessment and judgement [11, 13].

The Prime Minster would provide orders and/or recommendations to the local government on the implementation of protective actions. The local governments (prefecture/town/city/village) would decide on the protective actions to be taken based on: (a) the orders and/or recommendations given by the Prime Minister (or NERHQ Director General); (b) decisions taken within the JCNER (if there was enough time); or (c) their own independent judgement [2, 6].

Local authorities would make preparations to establish the Prefecture Headquarters for Disaster Control[9], in order to coordinate the response to a nuclear emergency at the prefectural level, and the Local Prefectural NERHQ at the OFC [1].

The prefecture and municipalities would send representatives to the OFC to staff the Local NERHQ and JCNER. The Local NERHQ would organize the JCNER, consisting of representatives of national and local governments and the NPP. The representatives of the JCNER would share information and coordinate protective actions and information to be provided to the media. The policies concerning key issues associated with protective action recommendations would be discussed and decided through the Emergency Response Policy Meeting of the JCNER. The Local NERHQ at the OFC would have the capability to make predictions on the impact of releases using SPEEDI (operated by MEXT), based on data obtained from ERSS (operated by METI), and to monitor environmental radiation levels in real time using monitoring posts located in the vicinity.

Once the Local NERHQ at the OFC was operational, the Prime Minister would delegate to the Director General of the Local NERHQ part of his/her authority. This would include responsibilities that are best assumed locally (concerning orders and/or recommendations to evacuate residents, restrict the intake of beverages and food, and implement iodine thyroid blocking (ITB)).

Close coordination between the NERHQ, Local NERHQ and others would be accomplished by using the on-line Integrated Nuclear Emergency Preparedness Network and a videoconference system.

The prefecture and the local municipalities would start preparations for sheltering or evacuation, such as setting up shelters, making vehicles available to transport local residents and arranging sound trucks (see Section 3.3.2.1) [1]. The logistics of sheltering and evacuations would be carried out according to predetermined plans.

A disaster wireless system and sound trucks would be used to warn and inform the residents. For example, evacuees gathered at assembly points would be evacuated using vehicles provided by the Government or, if necessary, by vehicles provided by their owners. Special consideration would be

[9] Within the arrangements for Fukushima Prefecture, the Prefecture Headquarters for Disaster Control would be located in the Fukushima Prefectural Office.

given to vulnerable people such as elderly persons, infants, pregnant women and injured or sick persons. If stable iodine tablets for ITB were to be prescribed for the public, the tablets would be distributed by the prefecture at the time of the accident. No pre-distribution of stable iodine tablets to the population living close to an NPP at the preparedness stage was foreseen.

The local governments would implement the protective actions for the public within the 10 km emergency planning zone (EPZ) of an NPP in accordance with their emergency response plans.

Local residents would be monitored (screened) for external contamination and decontaminated if the criteria established were exceeded. If required, exposed and contaminated individuals would be treated at designated radiation emergency medical hospitals as well as at the National Institute of Radiological Sciences (NIRS) located in Chiba (approximately 40 km from Tokyo).

In parallel, the on-site ERO would keep off-site officials informed about the developments on-site. Radiation monitoring in the wider area would be conducted by the national Government and the prefecture[10], while the operator would conduct monitoring at and near the NPP site.

3.1.2. Identification, notification and activation in response to the accident

As a result of the Great East Japan Earthquake that occurred at 14:46 on 11 March 2011 off the north-eastern coast of Japan, the Fukushima Daiichi NPP lost off-site electrical power, the emergency diesel generators (EDGs) were automatically activated and the reactor protection systems were initiated in accordance with the design of the NPP [17].[11] In addition to causing strong ground motion and infrastructure damage, the earthquake generated a series of large tsunami waves. When the second of these waves arrived at the Fukushima Daiichi NPP at 15:36, it overwhelmed the tsunami barrier seawalls, flooded the main buildings and caused extensive damage to the structures and equipment necessary for keeping the plant in safe shutdown [20]. As a consequence, the Fukushima Daiichi NPP entered into a condition in which the Nuclear Operator Emergency Action Plan [16] was to be fully activated. This triggered actions to set up the on-site ERC and on-site ERO.

The flooding caused a loss of all AC power in Units 1–5, creating a situation referred to as ‘station blackout’. Within the next 10–15 minutes, DC power, too, was lost in Units 1, 2 and 4. This resulted in the loss of monitoring and operating functions in the main control rooms, the loss of tools for communication with workers in the field, the loss of lights and the loss of all motor operated systems (i.e. safety systems and cooling facilities).

The loss of AC/DC power shortly after the tsunami also resulted in the loss of core cooling in Units 1–3, leading to severe damage to the fuel in the core [12].

Notification of a ‘specific event’ for Units 1[13] to 5 under Article 10 of the Nuclear Emergency Act [5] due to a station blackout was communicated by the plant by telephone to NISA and by fax to TEPCO

---

[10] For Fukushima Prefecture, radiation levels would be monitored in real-time at 23 locations in the vicinity of the local Environmental Radioactivity Monitoring Centre located next to the OFC. In addition, the Centre would deploy monitoring teams.

[11] For a detailed description of the onset and progression of the accident, see Technical Volume 1, Sections 1.1 and 1.3.

[12] According to IAEA safety standards [11, 13, 14], the loss of core cooling warranted the classification of the event as a General Emergency and the implementation of urgent protective actions for the public off the site, since it would result in severe damage to the fuel in the core and could potentially result in a large release of radioactive material.

[13] In the following account, the evolution of the situation at Unit 1 is described in detail, because progression of the situation at this unit was most important for decisions on public protective actions, as it was the first unit to experience severe damage to the fuel in the core.

Headquarters, METI, the Governor of Fukushima Prefecture and the mayors of Okuma Town and Futaba Town (Fig. 3.1–2) (Fax 1, Annex I).[14]

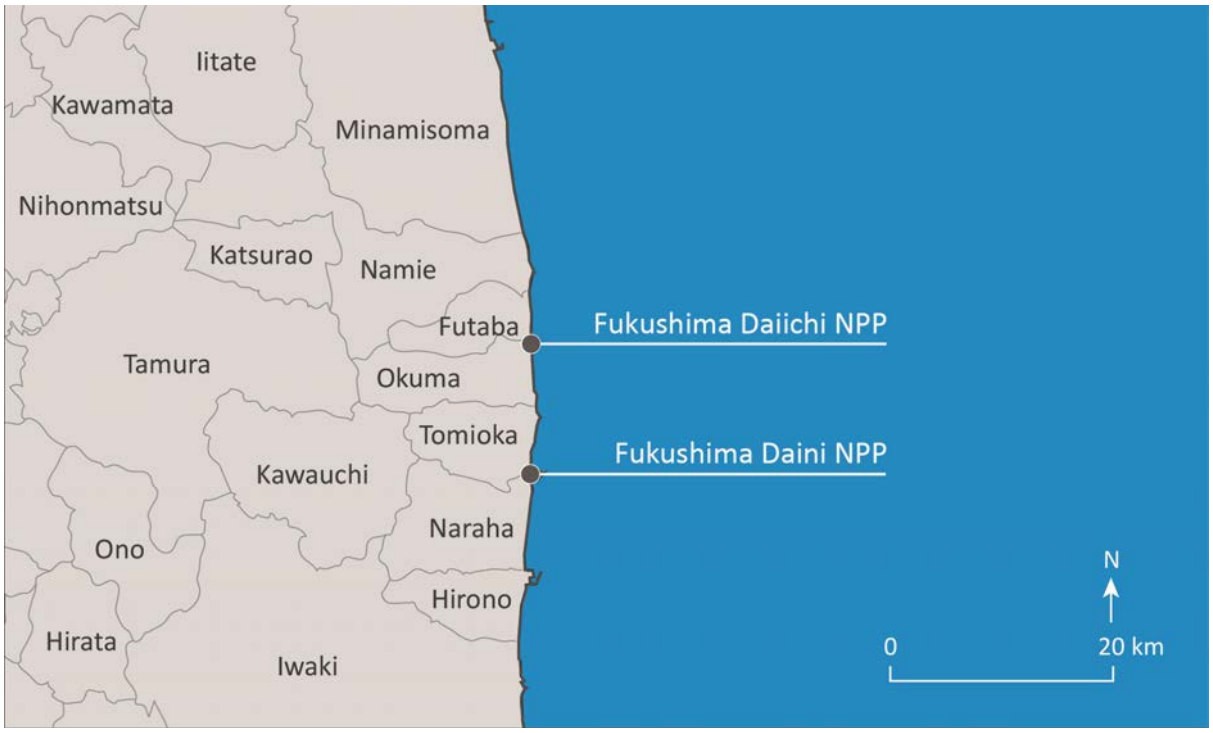


FIG. 3.1–2. Municipalities near the Fukushima Daiichi and Fukushima Daini NPPs [21].

After trying to send a fax message to Namie Town (receipt of which could not be acknowledged), repeated attempts were made to communicate by telephone, disaster priority mobile phone, satellite mobile phone and hotline. However, since all the means of communication were out of order, no phone contact could be established [17].

On 11 March, TEPCO staff, in order to explain the conditions at the relevant NPPs, personally went to the four municipalities in which the NPPs are located (Okuma Town and Futaba Town for Fukushima Daiichi, and Naraha Town and Tomioka Town for Fukushima Daini). In addition, TEPCO staff visited Namie Town on 13 March to explain the situation [9].

At 16:25, the shift supervisor reported to the on-site ERC on the occurrence of a situation falling under Article 15 of the Nuclear Emergency Act [5]. At 16:36, the Site Superintendent confirmed that, due to the loss of the water injection function of the emergency core cooling system (ECCS), Article 15 of the Nuclear Emergency Act was applicable [5, 17].

At 16:45, the Fukushima Daiichi NPP reported to off-site officials (Fax 2, Annex I) an event at Units 1 and 2 classified as a nuclear emergency (under Article 15 of the Nuclear Emergency Act [5]) [17, 22-24], based on the inability of the ECCS to inject water into the reactors of Units 1 and 2 [24].

[14] TEPCO notified NISA of a ''specific event' for Units 1–5 under Article 10 of the Nuclear Emergency Act [5] by telephone at 15:42. According to the fax sheet received by the NISA from TEPCO, the received time was recorded as 16:00. The delay in the receipt of the fax might have been caused by technical difficulties [21].

This notification indicated that the NPP staff could no longer maintain core cooling in the reactors of Units 1 and 2 and thus could no longer prevent the fuel in the cores from being damaged.

At 22:10 (Fax 8, Annex I), based on displays in the control room, it was reported to off-site officials that the reactor water level in Unit 1 was above top of active fuel (TAF). However, as shown in Fig. 3.1–3 [17, 25], the water level was, in fact, below TAF at this time.

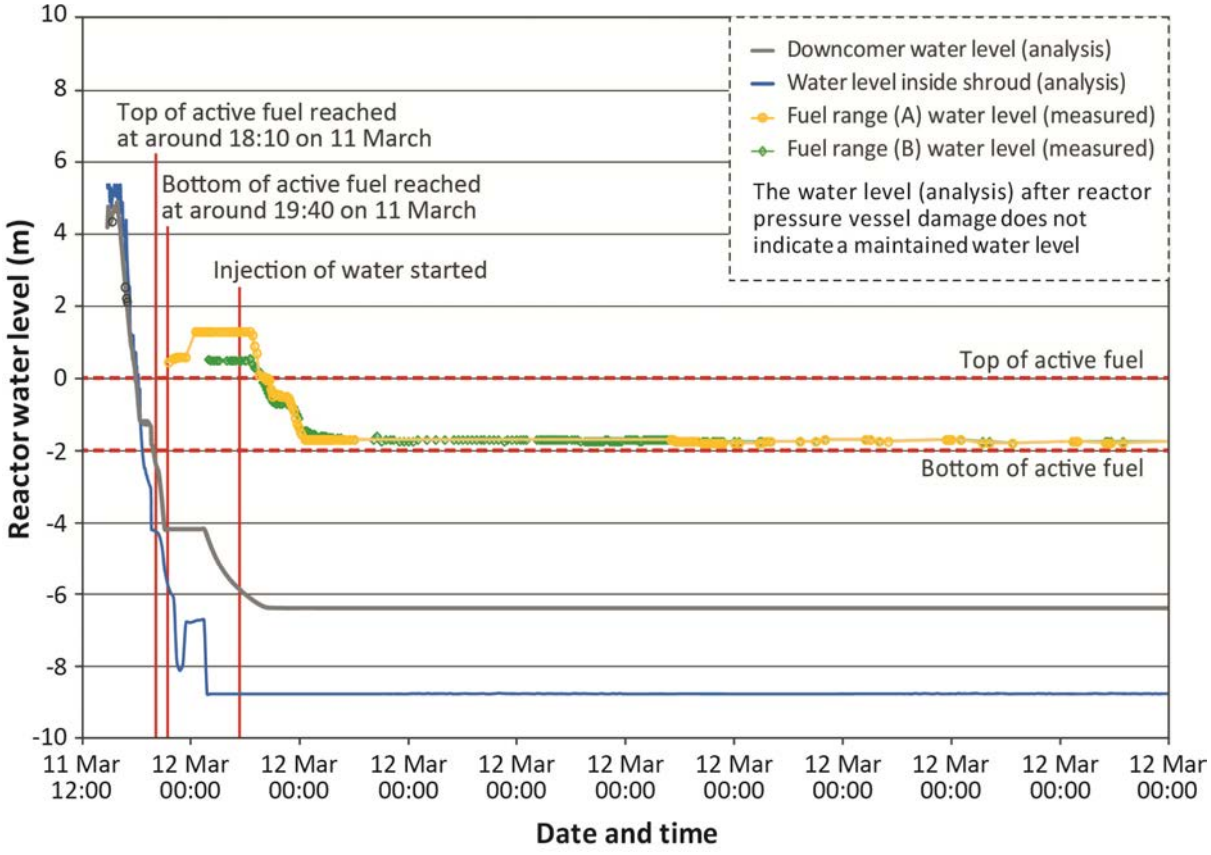


FIG. 3.1–3. Water level in Unit 1 as a function of time [17].

This error occurred because the water level instrumentation was not designed to function under emergency conditions [17, 21].[15]

[15] According to IAEA safety standards [11], the response of control room instrumentation under accident conditions needs to be considered in the development of the EPR arrangements.

3.1.3. Mitigatory actions

Figure 3.1–4 presents a timeline of key events relevant to the mitigatory actions[16] taken after the onset of the accident[17].

3.1.3.1. Management and implementation

The initial mitigatory actions after the earthquake took place in accordance with TEPCO's abnormal operating procedures[18]. An ERC, headed by the Site Superintendent, was established at the Fukushima Daiichi NPP around 15 minutes after the earthquake [17, 27]. It was located in the seismically isolated building, which was fitted with special features, including an autonomous electrical power supply and ventilation systems with filtration devices. This building had been constructed[19] as a result of lessons learned from the experience of the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and its use enabled mitigatory actions to continue at the site during the response to the accident [17]. All safety systems behaved as expected.

The situation changed dramatically when the tsunami wave hit the NPP. As most of the cooling systems of all the three operating reactors (Units 1, 2 and 3) became inoperative, the overriding priority was to take mitigatory actions to restore core and containment cooling in these reactors in order to prevent radioactive releases, or reduce the size of such releases. At Units 4, 5 and 6 (which were undergoing planned refuelling and/or maintenance outages), the critical parts that needed to be cooled were the spent fuel pools [17]. Accordingly, the NPP staff started to implement the Fukushima Daiichi NPP Nuclear Operator Emergency Action Plan[20].

The mitigatory actions were conducted in a complicated and stressful environment marked by: damage to the plant's infrastructure caused by the tsunami (e.g. presence of a huge amount of debris); occurrence of aftershocks, which triggered the tsunami alerts; lack of electricity supply, which disabled most of the plant's equipment and lighting inside the buildings; difficulties in communication, both on-site and off-site; failure of the safety systems needed for core cooling; and other challenging conditions (hydrogen explosions, increased radiation levels, etc.). Workers at the site carried out mitigatory actions under very difficult conditions; they worked longer hours under far more tiring circumstances than would normally be expected [17].

The simultaneous occurrence of these circumstances had not been considered in the emergency plans. Consequently, the ERO became overwhelmed, and many mitigatory actions could not be carried out in a timely manner [17].

---

[16] Mitigatory actions are immediate actions to reduce the potential for conditions to develop that would result in exposure or a release of radioactive material requiring emergency actions on or off the site, or to mitigate source conditions that could result in exposure or a release of radioactive material requiring emergency actions on or off the site [12, 26].

[17] Mitigatory actions are also discussed as part of the overall description of the onset and progression of the accident in Technical Volume 1, Sections 1.1 and 1.3. They are addressed in Technical Volume 2, Section 2.4, from the nuclear safety perspective, e.g. assessing the accident management actions and procedures and the implementation of severe accident management criteria and guidelines during the accident. This section describes mitigatory actions from the perspective of emergency preparedness and response on the site, e.g. actions undertaken by the on-site ERO, as described in the Nuclear Operator Emergency Action Plan [16].

[18] The abnormal operating procedures were implemented for a 'natural event' and a 'turbine and electrical incident' as described in more detail in Technical Volume 1, Section 1.1.[19] Construction of the seismically isolated building started in March 2009 and the building was put into operation in July 2010.

[19] Construction of the seismically isolated building started in March 2009 and the building was put into operation in July 2010.

[20] This plan provided the basis for organizational and material resources and emergency actions to be carried out on-site and for liaison with off-site entities (e.g. TEPCO, NERHQ and Local NERHQ) [16].

11 March

- 14:46 | Great East Japan Earthquake, loss of off-site power, all operating reactors automatically shut down
- 15:36 | Second tsunami wave started flooding site (estimated inundation height: OP+14.5 m)

12 March

- 00:06 | Site Superintendent ordered preparations for venting of Unit 1
- 01:30 | Prime Minister and METI approved implementation of venting of Units 1 and 2
- 03:30 | Attempts to vent Unit 1 failed
- 06:50 | Minister of METI ordered venting to be carried out
- 07:11 | Prime Minister and NSC Chairman met NPP Site Superintendent to discuss conditions at the plant and status of venting
- approx. 12:00 | Site Superintendent ordered preparation for seawater injection
- 14:00 | Operators opened venting line of Unit 1 and received confirmation of venting at 14:30
- 15:20 | TEPCO notified NERHQ that, following preparations, seawater injection would begin for Unit 1
- 15:36 | Explosion in Unit 1: destruction of water and power provisions, degrading site radiological conditions
- 17:55 | METI issued an order to TEPCO to inject sea water into Unit 1
- 18:05 | Prime Minister received report from METI about the order to inject sea water into Unit 1
- 19:04 | Seawater injection into the core of Unit 1 started
- 19:25 | Site Superintendent instructed to delay seawater injection; seawater injection continued
- 19:55 | Explanation about seawater injection provided to Prime Minister; Prime Minister authorized seawater injection

13 March

- 06:20 | Direct telephone line installed connecting Prime Minister's Office to the plant

14 March

- 11:01 | Explosion in Unit 3 and destruction of alternative water injection equipment for Units 1 and 3
- 19:45 | TEPCO began to prepare evacuation guidelines for non-essential staff located on-site

15 March

- J-Village started to be used as a general logistical support base
- 03:00 | Prime Minister informed by METI of full withdrawal of on-site staff
- 04:17 | Prime Minister asked TEPCO President about full withdrawal of staff and was subsequently informed it was not planned
- 05:30 | Government-TEPCO Integrated Response Office established in Tokyo
- 06:14 | Sound in Unit 2 primary containment vessel, explosion in Unit 4 reactor building
- 09:00 | Maximum radiation level at main gate (ca. 12 mSv/h)

FIG. 3.1–4. Timeline of key events relevant to mitigatory actions on-site.

The national Government became involved in decisions concerning mitigatory actions, such as the injection of seawater for fuel cooling [25, 27]. Roles, responsibilities and authorities in this regard had not been clearly assigned at the preparedness stage.

Insights of this situation can be illustrated by the following examples concerning: venting of the Unit 1 reactor; seawater injection; and evacuation of personnel from the NPP site.

Venting of the reactor

Once clear symptoms of core damage in Unit 1 were detected on the evening of 11 March, primary containment venting became the overriding priority[21], together with the resumption of water injection into the reactor core [17]. At approximately 00:55 on 12 March, TEPCO reported to the relevant authorities an abnormal increase in the containment pressure as defined in Article 15 of Nuclear Emergency Act [5, 27]. The containment pressure built up before venting took place, leading to an increase in the leakage of hydrogen into the reactor building, which subsequently led to a hydrogen explosion on 12 March. On 11 March, the Chairman of the Nuclear Safety Commission of Japan (NSC), upon hearing that the DC power supply at the Fukushima Daiichi NPP had been lost, believed that "[t]he only thing to do is to depressurize, inject water, and vent the unit" [25]. He therefore urged TEPCO to "quickly start venting".

The Prime Minister's Office[22] became aware of the necessity of containment venting at 01:30 on 12 March and obtained the Prime Minister's approval to conduct the venting. At 03:06, the Minister of METI and TEPCO's Managing Director held a joint press conference, in which they announced the venting. As the scheduled time passed, and the venting had yet to be carried out, the Office on the fifth floor of the Prime Minister's Office requested an explanation for the delay. In response, it was explained that venting required manual action to be carried out in the plant under very difficult conditions, including working in an environment of increased radiation levels (e.g. an estimated dose rate of 300 mSv/h in the valve area) [28].

TEPCO reported the details about the ongoing preparations for the implementation of the containment venting to METI/NISA-ERC through a TEPCO liaison in NISA. At approximately 06:50 on March 12, the Minister of METI issued an order under paragraph 3, Article 64 of the Reactor Regulation Act, to implement containment venting [29]. Although the Fukushima Daiichi NPP was informed of the implementation order, NPP staff did not proceed with the preparation, as scheduled, due to the difficult on-site conditions (e.g. the absence of lighting, increased radiation levels and frequent aftershocks) [27]. Since the Prime Minister could not obtain consistent information from TEPCO regarding containment venting and other actions, he decided to visit the Fukushima Daiichi NPP site to directly review the situation [25].

Seawater injection

Seawater injection was considered to be very important to prevent further deterioration of the conditions inside primary containment [17, 25]. At around 15:20 on 12 March, TEPCO notified the NERHQ that, as soon as preparations were complete, sea water would be injected into Unit 1 by the use of firefighting equipment [25]. However, NISA officials who were stationed in the METI/NISA-

[21] For a detailed discussion, see also Technical Volume 1, Section 1.3.

[22] The Prime Minister and his support staff were located on the fifth floor of the Prime Minister's Office (in the Prime Minister's working office and reception rooms), while the Crisis Management Centre was located in the basement of the building. This decision making group was separate from the NERHQ. This set-up was not in accordance with the decision making process that was specified in the Nuclear Emergency Response Manual [8] and had been exercised prior to the accident.

ERC and the Prime Minister's Office could obtain only fragmentary information[23], and they could not fully appreciate the difficulty of the seawater injection operation [27]. At 17:55, an order was issued by METI to TEPCO to inject sea water into the reactor of Unit 1. At about 18:00, the Prime Minister was briefed by staff in the fifth floor Office of the Prime Minister's Office on the plan for the injection of sea water. He raised concerns regarding criticality, which were considered as not having been sufficiently answered, and, consequently, he did not approve the seawater injection.

There was no indication of efforts being made at the time to tell the Prime Minister that the Fukushima Daiichi NPP was already working toward seawater injection or that METI had already issued an order to carry it out. Seawater injection at the Fukushima Daiichi NPP Unit 1 started at 19:04, but this fact was not conveyed to the Office on the fifth floor of the Prime Minister's Office. At around 19:25, the fifth floor Office instructed the Fukushima Daiichi NPP Site Superintendent to delay the seawater injection, as it was still being deliberated at the Prime Minister's Office. At around 19:55, after further explanation, the Prime Minister approved the injection [25, 27].

TEPCO was notified by personnel dispatched to the Prime Minister's Office that "the Prime Minister has not approved seawater injection," leading to deliberation between the on-site ERC and the ERC at TEPCO Headquarters [17]. A decision was taken to temporarily suspend the injection. However, the Site Superintendent continued seawater injection, as he believed that this was vital in order to prevent accident progression [17].

Evacuation of plant personnel

On the night of 14 March, the President of TEPCO was informed that evacuation of all non-essential on-site personnel from the Fukushima Daiichi NPP was being considered if the circumstances were to deteriorate [21]. Before dawn of 15 March, the President contacted NISA and reported that the situation at Unit 2 was grave, that he would not rule out an evacuation of non-essential personnel, and that he was seeking NISA's approval. He did not clearly state that essential personnel would remain at the NPP site. Discussions were carried by the Prime Minister's Office until around 03:00 on 15 March. At about 03:00, the Prime Minister [21] was informed of the request, and he immediately responded that evacuation of all personnel was unacceptable. The TEPCO President was called to the Prime Minister's Office to confirm TEPCO's intentions on the matter. The TEPCO President confirmed that the company was not planning to evacuate all personnel from the plant [17]. The Prime Minister proposed that the rapid sharing of information and good communication between the parties be ensured in the future, and that the national Government and TEPCO establish an integrated response headquarters at TEPCO's Headquarters.

3.1.3.2. Off-site support

Shortly after the beginning of the accident, the on-site ERC requested, through the ERC at TEPCO Headquarters[24], additional human resources and equipment to be sent to the Fukushima Daiichi NPP. With the establishment of the integrated response headquarters between the national Government and TEPCO, a clear process for addressing needs to support on-site mitigation and recovery actions had been put in place [17, 25].

[23] At this time, the nuclear safety inspectors at the Fukushima Daiichi NPP had already evacuated to the OFC.

[24] One of the tasks of this ERC was to provide support to the on-site ERC at the Fukushima Daiichi NPP with regard to human resources and equipment.

Human resources

Personnel from TEPCO, from contractors and from other Japanese NPPs (not operated by TEPCO) were dispatched to the Fukushima Daiichi site to assist with various tasks, including restoring power and monitoring instruments, injecting cooling water into the reactors, removing rubble and monitoring radiation levels [17]. Personnel from national government agencies and organizations — such as the Japan Self-Defense Force (SDF), police and firefighters — were also dispatched to the site. They helped with activities including operating the large equipment needed to pour or spray water onto the spent fuel pools in Units 1, 3 and 4 and providing helicopter surveillance of the spent fuel pools [17, 22, 27].

During the first days of the emergency, about 400 people on average were dispatched to the Fukushima Daiichi NPP site every day [17]. In many cases, operations were performed by specialized personnel from TEPCO owing to the extremely demanding conditions prevailing on the site [17].

As the accident progressed, more human resources became available on the site, which made it possible to cope more effectively with serious unforeseen problems (e.g. uncontrolled releases of highly contaminated water to the sea, which occurred in the first days of April 2011) [17].

Equipment

Following the tsunami, there were multiple equipment failures on-site, and a range of portable equipment and heavy machinery was necessary to cope with the situation. The first equipment provided to assist in on-site mitigation activities was collected in the evening of 11 March and reached the site in the morning of 12 March. Some of this equipment was supplied by TEPCO and some by the Japanese official authorities (e.g. the SDF). Many types of portable equipment were delivered, such as: mobile AC power generators; equipment for power restoration (mainly cables and transformers); mobile pumps (engine driven), such as fire engines with all of the associated fittings and equipment; mobile air compressors; radiation monitoring vehicles; batteries of different types, voltages and sizes; and portable lighting equipment. In some cases (especially for batteries and equipment to restore electric power supply), a logistical procurement team was established near the Fukushima Daiichi site to manage the request and/or procurement of the equipment needed [17].

Extensive damage of the transport infrastructure due to the earthquake and tsunami, in addition to insufficient pre-planning, impaired the effectiveness of this support. For example, when the request for equipment did not contain an adequate specification of what was required, it led to the procurement of equipment that was incompatible with existing plant equipment (due to mismatched fittings, connectors, etc.) [17].

The delivery of equipment was hampered by multiple problems. Fear of contamination from radioactive material deposited on vehicles impeded the transport of supplies necessary for the response [17]. On-site emergency workers encountered difficulties in obtaining authorization from the police to travel on roads leading to and from the site [17]. Truck drivers abandoned deliveries or retreated, requiring on-site emergency workers with driving licences to replace them [17]. Receiving, managing and organizing the arrival of deliveries was logistically very challenging [17].

In addition to portable equipment, some heavy equipment was provided to the Fukushima Daiichi NPP by different national organizations (e.g. the SDF) and also by local and prefectural organizations (e.g. firefighting brigades) [17, 30].

To manage and streamline the support, some logistical points were established, mainly for administrative and radiation control of personnel coming to the site. These points were established at the J-Village[25] and the TEPCO Onahama Coal Center [17].

3.1.4. Management of the off-site response

Figure 3.1–5 presents a timeline of key events relevant to management of the off-site response to the accident.

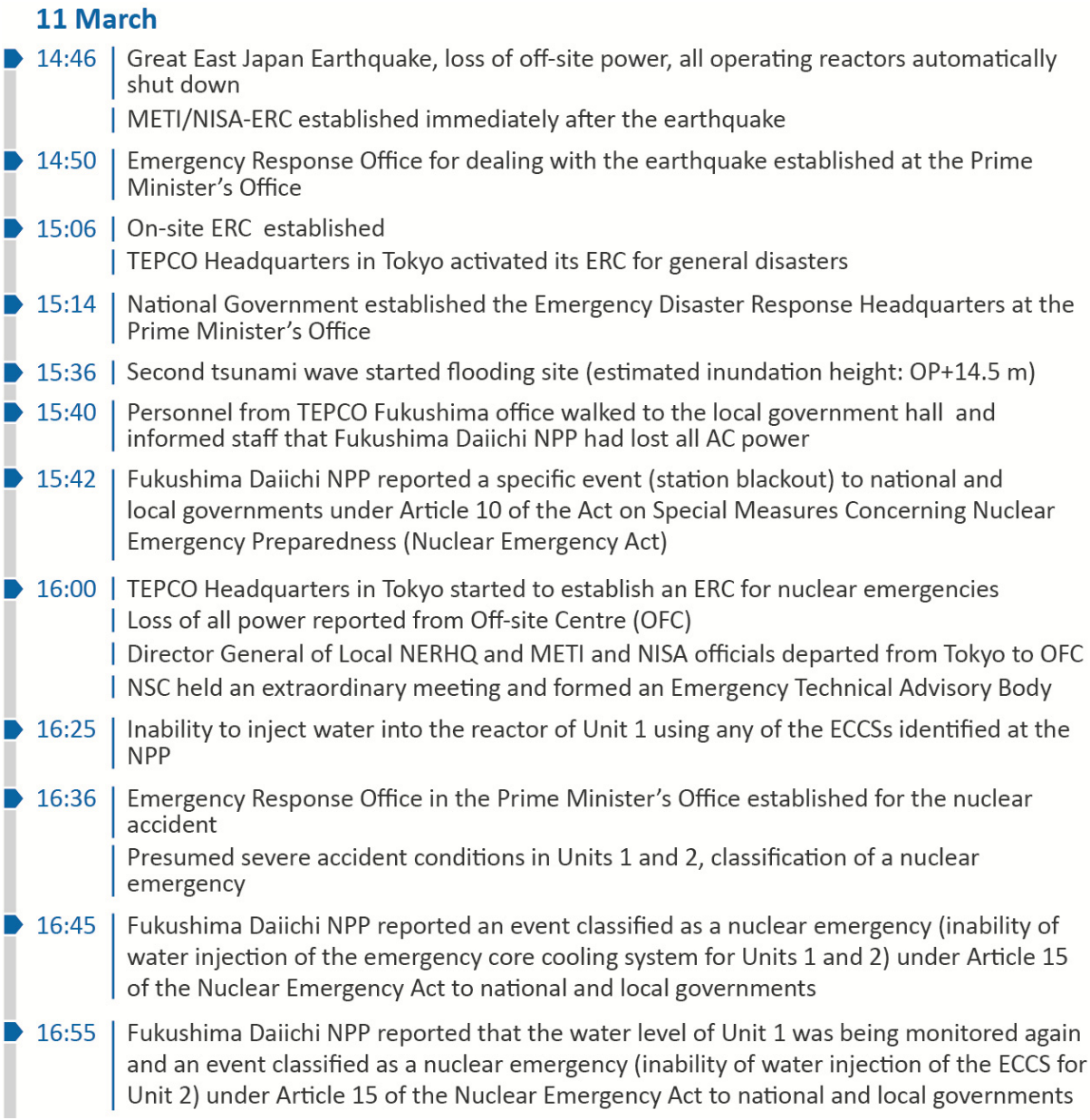


FIG. 3.1–5. Timeline of key events relevant to the management of the off-site response.

[25] J-Village is located about 20 km south of the Fukushima Daiichi NPP. Prior to the accident, it was a football training facility. After the accident, it was utilized as a general logistical support base, e.g. for preparing workers for assigned tasks, for monitoring and decontamination, as necessary, after completion of the assigned tasks, for triage, etc. [22].

17:12 | Fukushima Daiichi NPP reported an event classified as a nuclear emergency (inability of water injection of the ECCS for Unit 1) under Article 15 of the Nuclear Emergency Act to national and local governments

17:37 | Fukushima Daiichi NPP reported to national and local governments that radiation levels were within normal range in the area surrounding the plant

17:42 | Minister of METI informed Prime Minister and requested approval for declaration of a nuclear emergency

18:30 | Prime Minister approved declaration of a nuclear emergency under Article 15 of the Nuclear Emergency Act

19:03 | Declaration of a nuclear emergency by the national Government and establishment of Nuclear Emergency Response Headquarters (NERHQ)

20:30 | Prime Minister took charge of the Crisis Management Centre and subsequently relocated to the fifth floor of the Prime Minister's Office

21:01 | Fukushima Daiichi NPP reported the inability of the reactor core isolation cooling system to inject water into Unit 2; reactor water level may reach the top of active fuel (Unit 2); preparing to request local governments to evacuate residents; radiation exposure of workers unknown to national and local governments

12 March

03:20 | Off-site Centre (OFC) became partially operational

10:30 | First meeting of JCNER

15 March

05:30 | Government-TEPCO Integrated Response Office established in Tokyo

11:00 | Relocation began of OFC to Fukushima Prefectural Public Hall

FIG. 3.1–5. Timeline of key events relevant to management of the off-site response (cont.).

The locations of the core entities involved in the management of the off-site responses to the Fukushima Daiichi accident are presented in Fig. 3.1–6.

At 14:50 on 11 March 2011, an Emergency Response Office for dealing with the earthquake was established in the Prime Minister's Office by the Deputy Chief Cabinet Secretary for Crisis Management, and members of the Emergency Operations Team were convened there [31].

After the earthquake, METI/NISA immediately established its ERC and began gathering information about the state of the NPPs in the affected areas.

At 15:06, an ERC for general disasters was established at the TEPCO Headquarters office in Tokyo. Efforts then began to identify and evaluate possible earthquake damage to all NPPs operated by TEPCO and to restore power to those places experiencing a blackout [17, 27].

At 15:14, the national Government established the Emergency Disaster Response Headquarters in the Prime Minister's Office, with the Prime Minister as the Headquarters' Director General; the Headquarters' Secretariat was set up in the Prime Minister's Cabinet Office. At 15:37, the first meeting of the headquarters was held [27].

At 15:42, the Fukushima Daiichi NPP Site Superintendent made an Article 10 notification ('specific event') to the national Government (METI/NISA) and local governments (see Fax 1, Annex I).

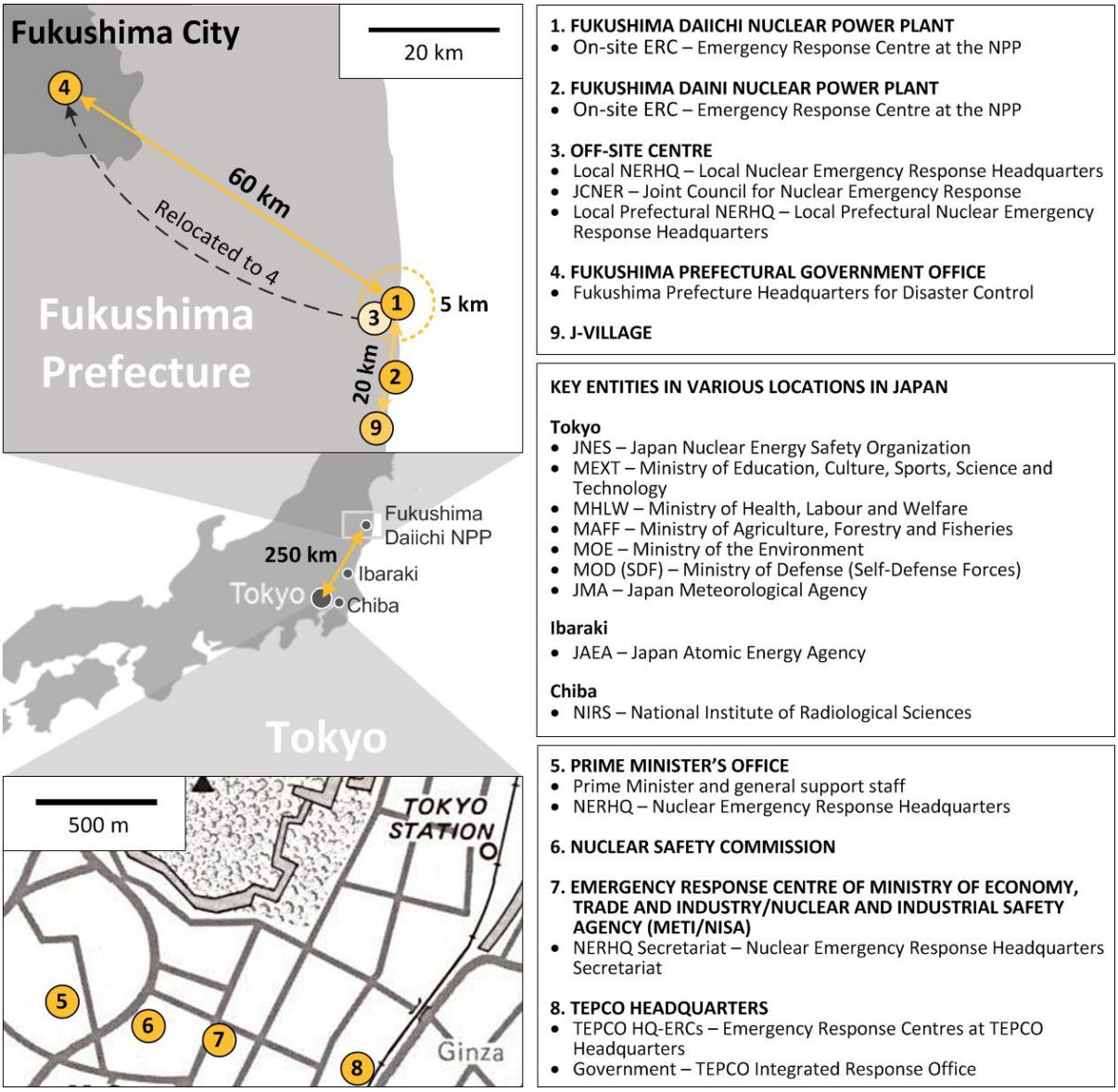


FIG. 3.1–6. Location of core entities involved in the management of off-site responses during the Fukushima Daiichi accident [1, 8, 17, 25, 32-44].

Upon receiving the fax notification from the Fukushima Daiichi NPP regarding the occurrence of a 'specific event' under Article 10 of the Nuclear Emegency Act [5], TEPCO also established an ERC for nuclear emergencies at its headquarters in Tokyo. Since then, both of TEPCO's ERCs (for general disasters and for nuclear emergencies) operated as a joint ERC (hereafter referred as TEPCO HQ-ERC) [17]. In the early stages of the accident, the person meant to assume the role of Head of the TEPCO HQ-ERC was unavailable[26]. Staff from the TEPCO Headquarters office were dispatched

[26] It was planned that in a nuclear emergency the President of TEPCO would be the head of the TEPCO HQ-ERC. However, when the accident at the Fukushima Daiichi NPP occurred, he was away on a business trip. The President returned to Tokyo around 09:00 on 12 March. When the earthquake occurred, the TEPCO Chairman was on a business trip to China, but returned to Tokyo at around 16:00 on 12 March [17]. Until the arrival of the TEPCO President, the company's Managing Executive Officer acted as the head of the TEPCO HQ-ERC, although this authority should have been delegated to the TEPCO Vice-President in the absence of the President. This decision was based on the specific conditions of the event [17].

almost immediately after the earthquake to the ERC at METI/NISA to function as a liaison with the TEPCO HQ-ERC [17].

The TEPCO HQ-ERC dealt simultaneously with the Fukushima Daiichi accident, the situation at the Fukushima Daini NPP and the impact of the earthquake on the large distribution and generation grid network operated by the company. This challenged the ability of the TEPCO HQ-ERC and the ERC at the Fukushima Daiichi NPP to understand the progression of the nuclear accident and define response strategies at the very beginning of the accident. Nevertheless, after these initial challenges, the TEPCO HQ-ERC assumed a key role by providing both human and material resources (e.g. portable equipment) for the on-site response [17].

The NSC, after receiving a message from NISA about the Article 10 notification, held an extraordinary meeting and formed an Emergency Technical Advisory Body [27].

At 16:36, the Deputy Chief Cabinet Secretary for Crisis Management established an Emergency Response Office for the nuclear accident in the Prime Minister's Office and expanded the Emergency Operations Team to handle both the natural disaster and the emergency at the Fukushima Daiichi NPP [21, 22].

At 16:45, the Fukushima Daiichi NPP Site Superintendent sent a report of an event classified as a nuclear emergency under Article 15 of the Nuclear Emergency Act [5] to the national Government (METI (NISA)) and to local governments (see Fax 2, Annex I).

At around 17:00, the Prime Minister asked the NISA Director General for an explanation of the Article 10 notification, but the latter could not provide any details; neither could the TEPCO staff members who were sent to the Prime Minister's Office. However, they gave some general information on the consequences that would ensue if the AC power at the Fukushima Daiichi NPP was not re-established [21].

After receiving the report from the Fukushima Daiichi NPP of an event classified as a nuclear emergency, NISA conducted technical verifications and judged the situation to be indeed a nuclear emergency under Article 15. At around 17:42, after giving his consent to the results of this assessment, the Minister of METI went to the Prime Minister to obtain his approval for a declaration of a nuclear emergency [25]. Their discussions were interrupted for about five minutes [21] when the Prime Minister met with the heads of the ruling and opposition parties. The Prime Minister gave his approval for the declaration of a Nuclear Emergency at about 18:30 [21].

The Prime Minister issued a declaration of a nuclear emergency at 19:03 on 11 March 2011 and established the NERHQ and Local NERHQ [22]. This was more than two hours after having been notified by the Fukushima Daiichi NPP of an event at Units 1 and 2 classified as a nuclear emergency under Article 15 of the Nuclear Emergency Act [5, 22].

The first meeting of the NERHQ took place at 19:03 on 11 March. Eight meetings were held by the NERHQ between 11 and 15 March 2011.

At 19:45, a press conference was held announcing the declaration of a nuclear emergency and the establishment of the NERHQ. No orders or recommendations for protective actions were issued at that time [25].

At about 20:30, the Prime Minister went to the Crisis Management Centre to take charge of the Government's response to the natural disaster and nuclear emergency [21]. Soon afterwards, he moved to his working office at the fifth floor of the Prime Minister's Office.

Deliberations concerning the off-site protective actions were conducted at the fifth floor of the Prime Minister's Office, including evacuation [27] and mitigatory actions[27] to be taken at the Fukushima Daiichi NPP. The discussions were based on information collected by the Emergency Response Office and the opinions of the Minister of METI, other relevant ministers, the Chief Cabinet Secretary, TEPCO staff members who were present or on the telephone, NISA officials, the Chairman of the NSC and other parties concerned (advisors, secretaries, Prime Minister's Office officials and personnel). This information was not always exchanged with the NERHQ [25]. As a result, multiple unplanned and uncoordinated communications routes were used, which had an impact on the coordination between individual organizations.

In accordance with the arrangements prior to the accident, the NERHQ was supposed to direct and provide comprehensive coordination of the national response to a nuclear emergency. The NERHQ Secretariat collected information through faxes sent from TEPCO and enquiries made to the TEPCO HQ-ERC. However, this was found to be an ineffective and slow method of obtaining information.

As the accident evolved so quickly, there was no time for detailed discussions during meetings of the NERHQ. The core group for the emergency response became the Prime Minister and senior officials, located at the Prime Minister's Office. The Prime Minister issued evacuation orders to local governments without the involvement of the secretariat of the NERHQ [25].The Government–TEPCO Integrated Response Office, an integrated headquarters of the operating organization and the government response organization, was established on 15 March 2011 at TEPCO Headquarters in Tokyo [27] to ensure the timely sharing of information at the national level. This was a new entity, the creation of which was not anticipated in the emergency plans.

METI (NISA) dispatched staff to the Local NERHQ at the OFC at about 16:00 on 11 March. However, the OFC staff reported to NISA at about the same time that they had lost all power, phones, fax and other systems, which led to difficulties in initiating operations in the OFC [25, 45].

The METI Senior Vice Minister (who was to serve as the Director General of the Local NERHQ) departed from Tokyo to the OFC (a distance of about 250 km), along with seven others (e.g. NSC and MEXT representatives) at around 16:00 on 11 March, but did not arrive until about midnight due to the damaged transport infrastructure. They found that the OFC had no AC power [45]. It began partial operation at 03:20 on 12 March 2011, once power had been re-established [45].

The Vice Governor of Fukushima Prefecture arrived at the OFC at around 23:00 on 11 March. Only one of the six nearby towns sent representatives to the OFC, because they were involved in the implementation of evacuation orders [27]. Numerous national level organizations were expected to send representatives to the OFC, but only NISA, MEXT, the NSC, and the Ministry of Defense (SDF) did so immediately [27]. The Ministry of Health, Labour and Welfare (MHLW) did not send a staff member to serve as the chief of the medical squad of the Local NERHQ until 21 March.

The first meeting of the JCNER was held on 12 March at 10:30 [45], at which point the implementation of protective actions, including evacuation, shelter and ITB, was discussed.

The Local NERHQ and other entities, which were supposed to operate from the Off-site Centre (JCNER and Local Prefectural NERHQ), could not fulfil their roles fully, especially during the first days of the emergency. This was due to the damage caused by the earthquake and tsunami, which included: damage to communication systems, the inability to obtain and analyse plant and environmental data, and the limited participation of relevant organizations. In addition, although the

[27] Mitigatory actions that were discussed at the time included whether or not to inject sea water into the reactors.

Local NERHQ was expected to regularly report on its consolidated information at press conferences at the OFC, these did not take place because, from the morning of 12 March[28], the OFC was located in the evacuation area to which access was restricted.

As the OFC was located within 5 km of the Fukushima Daiichi NPP, this resulted in a number of additional difficulties [27]. For example, after 13 March, shortages of food, water and fuel occurred, because normal deliveries within the evacuation zone were suspended.

On 15 March 2011, it became necessary to evacuate the Off-site Centre, due to the worsening radiological conditions[29] (>1 mSv/h), and to relocate it to the Fukushima Prefectural Public Hall, located approximately 60 km from the Fukushima Daiichi NPP (see Fig. 3.1–6) [27, 45]. This was where the Prefecture Headquarters for Disaster Control conducted its operations after moving from their originally planned location, the Fukushima Prefectural Government Office, which had been damaged by the earthquake [25][30]. This facility did not have capabilities equivalent to those of the Off-site Centre, which led to difficulties, for example, in sharing information in real time among the relevant authorities.

The OFC was planned to be the location where monitoring was to be coordinated, as it had direct connections with local monitoring stations. Relocation to the Fukushima Prefectural Public Hall complicated the fulfilment of this task [22, 27].

The OFC was also planned to be the location where announcements to the media would be made at the local level. However, once operations began, its location within the evacuation zone rendered it inaccessible to journalists. Following the relocation of operations from the OFC, press conferences were held from 15 March onwards at the Fukushima Prefectural Public Hall [21] by spokespersons of the Local NERHQ. A further difficulty was that enquiries from residents could not be addressed at the OFC, as had been planned [1], owing to power cuts that caused failures in communication lines [45].

After the start of the nuclear emergency, a large number of staff was already working on the various functional squads of the Fukushima Prefecture Headquarters for Disaster Control, responding to the earthquake and tsunami. Hence, the personnel available to respond to the nuclear emergency was significantly limited, making it impossible to implement the structure laid out in the nuclear response section of the Fukushima Prefecture Disaster Management Plan [1, 25].

To address this need, a new 'nuclear squad'[31] was formed in the Fukushima Prefecture Headquarters for Disaster Control, as part of the organizational structure set-up to respond to the earthquake and tsunami, in order to coordinate emergency response activities at the prefectural level (see Fig. 3.1–7) [25].

---

[28] At 05:44 on 12 March evacuation was ordered for the 3–10 km zone around the Fukushima Daiichi NPP.

[29] The Off-site Centre had not been designed to withstand the increasing radiation levels.

[30] Fukushima Prefecture established its Prefecture Headquarters for Disaster Control at 14:46 on 11 March. Around 15:00, it was decided to move the location from the Fukushima Prefectural Government Office, which was unusable due to damage, to the Fukushima Prefectural Public Hall, which was located only a few minutes walk from the Fukushima Prefectural Government Office. The movement was completed by around 15:30 [46].

[31] A new nuclear squad was formed because the existing nine functional squads, as specified in the Fukushima Prefecture Disaster Management Plan [1] were engaged in response to the earthquake and tsunami [25].

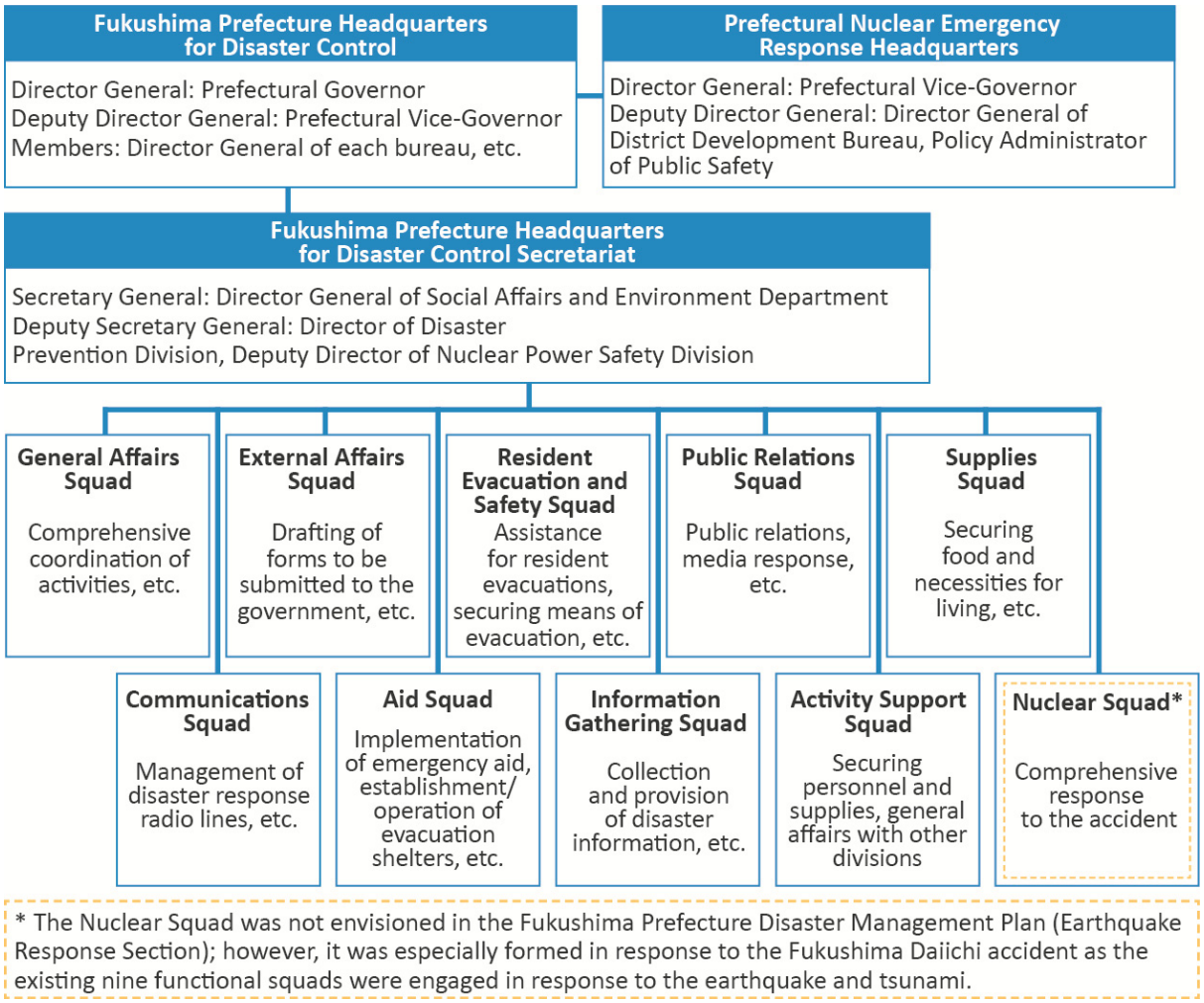


FIG. 3.1–7. Organizational structure of the Fukushima Prefecture Headquarters for Disaster Control [25].

However, the squad's staffing was limited, and there was no clearly defined scope of operations to address the issues of a nuclear emergency. Officials in the nuclear squad were under the impression that the response to the nuclear emergency was to be carried out mainly at the OFC [25].

In addition to the problems described above, there were also logistical difficulties. As a result of the move to the Fukushima Prefectural Public Hall, the Prefecture Headquarters for Disaster Control had only two municipal disaster management radio communication lines in operation, whereas the main conference room of its original location, in the Fukushima Prefectural Government Office, was equipped with 47 lines [25].

3.1.5. Summary

At the time of the accident, separate arrangements were in place to respond to nuclear emergencies and natural disasters at the national and local levels. There were no coordinated arrangements for responding to a nuclear emergency and a natural disaster occurring simultaneously. Consequently, this was also not addressed in relevant training and exercise programmes.

The arrangements to respond to nuclear emergencies envisaged that, following the detection of relevant adverse conditions at an NPP (e.g. loss of all AC power supplies for more than five minutes or loss of all capabilities to cool the reactor), a notification would be sent from the plant to local and national governments. The national Government would then assess and determine whether the

situation was to be categorized as a nuclear emergency. If the situation was categorized as a nuclear emergency, a declaration to that effect would be issued at the national level, and decisions about necessary protective actions would be taken on the basis of dose projections. Arrangements did not foresee the recommendation of public protective actions based on plant conditions without additional assessment and judgement by the off-site authorities.

After the onset of the accident, NPP personnel promptly activated the on-site ERC and notified off-site officials of conditions under Article 10 of the Nuclear Emergency Act [5] and subsequently of the conditions under Article 15 of the Act. The seismically isolated building provided an adequate environment for the work of the on-site ERO early in the response.

Based on a report from the Fukushima Daiichi NPP, the national Government declared a nuclear emergency in the evening of 11 March, more than two hours after having been notified by the Fukushima Daiichi NPP of an event at Units 1 and 2 classified as a nuclear emergency under Article 15 of the Nuclear Emergency Act [5, 22].

The on-site response was marked by the extreme difficulties resulting from the effects of the earthquake and tsunami, such as the lack of electric power supply (causing failure of multiple pieces of equipment and impeding access to, and habitability of, plant buildings) and the presence of rubble that obstructed on-site activities. In addition, the evolution of the accident (several large hydrogen explosions, harsh radiological conditions, etc.) challenged the capabilities of the on-site responders.

This meant that many mitigatory actions could not be carried out in a timely manner. In addition, the national Government was directly involved in decisions concerning mitigatory action on the site.

At the request of the operator, TEPCO, off-site resources (staff and equipment) were mobilized to support the on-site ERO. Extensive damage of the transport infrastructure due to the earthquake and tsunami, in addition to insufficient pre-planning, impaired the effectiveness of off-site support. For example, some equipment that was delivered was not compatible with equipment that was already in operation.

The response at the national level was led by the Prime Minister and senior officials at the Prime Minister's Office in Tokyo. At TEPCO Headquarters in Tokyo, a joint response organization between the operator and the Government was also established.

The activation of the emergency Off-site Centre, located 5 km from the Fukushima Daiichi NPP, was difficult because of extensive infrastructure damage caused by the earthquake and tsunami. Within a few days, it became necessary to evacuate the Off-site Centre due to adverse radiological conditions. Thus, the Local NERHQ that was planned to run operations from the OFC could not fulfil its role fully, especially during the first days of the emergency.

3.1.6. Observations and lessons

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**
Consideration needs to be given to the possibility of a severe nuclear accident, irrespective of the cause, possibly involving more than one unit at a site and occurring simultaneously with a natural disaster, which could result in disruption at the site and of the local infrastructure. Systems, communications and monitoring equipment for providing essential information for both on-site and off-site responses need to be able to function under such circumstances.

Facilities where the response will be managed (e.g. on-site and off-site emergency response centres) need to be selected or designed to be operational under a full range of emergency conditions (radiological, working and environmental conditions), and need to be suitably located and/or protected so as to ensure their operability and habitability under such conditions.

— **The emergency management system for response to a nuclear emergency needs to include clearly defined roles and responsibilities for the operating organization and for local and national authorities. The system, including the interactions between the operating organization and the authorities, needs to be regularly tested in exercises.**
Arrangements are needed that integrate the response to a nuclear emergency with the response to natural disasters and human-made disasters (e.g. earthquakes, floods and fires).
The on-site response needs to be managed by personnel located at the site who have knowledge of the plant and of the situation. The on-site and off-site responses need to be coordinated based on pre-planned arrangements.

— **There is a need for arrangements to conduct mitigatory actions for the full range of postulated emergencies, including emergencies not considered in the design basis (e.g. severe fuel damage) and those involving several units at a multi-unit plant.**
In developing these arrangements, there is a need to consider the response of the personnel, instrumentation and systems of the facility under different emergency conditions. This includes the development, maintenance and testing of plans and procedures for responding to severe reactor accidents, including immediate response actions and those for staffing emergency response positions, particularly in the case of long lasting emergencies involving multiple units. The mitigatory actions need to be agreed on at the preparedness stage and then implemented on-site in an emergency response without consultation with, and/or request for approval by, off-site officials.

— **Arrangements are needed to enable the on-site emergency response organization (ERO) to provide and receive assistance (including heavy equipment) for performing mitigatory actions in an emergency, particularly in the case of long lasting emergencies and emergencies involving several units at a multi-unit plant.**
These arrangements need to ensure that the assistance received (e.g. equipment) is compatible with existing on-site capabilities under different emergency conditions.

3.2. PROTECTING EMERGENCY WORKERS

This section describes the protection of personnel involved in the emergency response at the site, referred to as on-site emergency workers, and the protection of emergency workers and 'helpers' from the public involved in the emergency response off the site, referred to as off-site emergency workers and helpers, respectively.[32] The term helpers refers to members of the public who willingly and voluntarily were involved in the off-site emergency response and, therefore, did not have the status of worker for an employer at the time of this involvement. On-site emergency workers include NPP personnel, either directly employed by TEPCO or subcontracted, as well as personnel from the SDF, firefighting services and police engaged in emergency work on-site. Off-site emergency workers include personnel from different organizations and services (governmental and non-governmental) involved in the emergency response off-site due to their engagement in evacuating the public and special facilities, providing support to evacuees, providing medical care and carrying out monitoring and sampling, etc.

The timeline of events that are important for the protection of emergency workers during the response to the Fukushima Daiichi accident are shown in Fig. 3.2–1.

[32] The focus of this section is on the initial phase of the emergency, when the major challenges of ensuring adequate protection for emergency workers were faced.

11 March

- Four on-site workers injured as a result of the tsunami and two workers died
- Plant personnel not considered essential for the emergency response evacuated from the NPP site
- 320 electronic personal dosimeters (EPDs) located in the seismically isolated building and several other controlled areas of the plant were functioning
- Radiation monitoring activities started, including radiation surveys around the site
- Relief teams from the Japanese Red Cross Society engaged in the response off-site
- Evening | High dose rates detected in the reactor building of Unit 1; protection measures were implemented

12 March

- Monitoring performed off-site until 14 March within the 20 km zone that had been ordered to evacuate
- 04:20 | High radiation levels near the turbine building of Unit 1
  Contract workers temporarily returned to seismically isolated building without injecting water from the fire engine into the reactor core of Unit 1
- 05:00 | Contracting company authorized staff to assist with water injection
- 15:36 | Five on-site emergency workers sustained conventional injuries as a result of the explosion in Unit 1

13 March

- ITB implemented as a protective measure for emergency workers on-site

14 March

- Evacuation of non-essential plant personnel on-site completed
- Relief teams dispatched from Japanese Red Cross Society departed from Fukushima Prefecture. Fukushima Red Cross Hospital remained to provide relief activities off-site
- 11:01 | Four SDF personnel and seven TEPCO workers sustained conventional injuries on-site after explosion in Unit 3

15 March

- Dose criterion for emergency workers increased from 100–250 mSv (retroactive effect to 14 March)
- New radiation protection contingency provisions adopted on-site (e.g. group-assigned EPDs)
- J-Village starts to be used as a general logistical support base
- Off-site rescue team suspended mission (dose criterion of 5 mSv reached) before completing rescue of patients at a hospital located within 5 km of Fukushima Daiichi NPP

17 March

- Revised dose criterion of 250 mSv also implemented for national Government employees engaged in emergency work on and off-site, excluding those from firefighting services

19 March

- First occupational physicians present at seismically isolated building for medical management of on-site emergency workers

23 March

- Remaining female on-site emergency workers evacuated

24 March

- Two on-site workers exposed to high levels of contaminated water at their feet

FIG. 3.2–1. Timeline of key events important for the protection of emergency workers.

26 March

- Measures implemented for on-site areas to improve the situation at the seismically isolated building due to buildup of radioactive contamination (between 26 March and 8 April)

30 March

- One doctor and two nurses from TEPCO hospital in Tokyo stationed at J-Village to provide first aid treatment for workers

31 March

- Every emergency worker on-site provided with an EPD

Early April

- Medical clinic at J-Village renovated and designated as a primary radiation emergency medicine facility
- Medical headquarters established at Local NERHQ in Fukushima City. First comprehensive medical response plan for medical management of on-site emergency workers developed

15 April

- Initial triage and first aid started to be provided during the day by occupational health physicians at the Fukushima Daiichi NPP

Late April

- Increased number of hospitals in Fukushima and nearby prefectures agreed to accept injured on-site emergency workers

May

- On-site worker died due to a heart attack. Arrangements made for doctors to be available at seismically isolated building on a 24 hour a day, 7 days a week basis

1 July

- Twenty-four hour medical emergency care facility established at Fukushima Daiichi NPP

2 August

- ITB was implemented only for emergency workers on-site carrying out emergency work in designated buildings

26 August

- Ministry of Health, Labour and Welfare (MHLW) issued a notification and guidelines for ensuring radiation protection of emergency workers involved in decontamination work off-site

1 November

- 100 mSv effective dose criterion re-established for new emergency workers engaged in emergency work

21 November

- Administration of ITB stopped for emergency workers on-site

16 December

- 100 mSv effective dose criterion re-established for the majority of emergency workers (on-site and off-site) engaged in emergency work, except approximately 50 TEPCO employees working on-site

30 April 2012

- 100 mSv effective dose criterion re-established for the remaining 50 TEPCO employees

FIG. 3.2–1. Timeline of key events important for the protection of emergency workers (cont.).

3.2.1. Relevant arrangements in Japan prior to the accident

The national legislation and guidance in Japan prior to the accident addressed measures to be taken for the protection of emergency workers[33]. However, the arrangements that were in place addressed these measures only in a general way and not in sufficient detail.

The NSC's Nuclear Emergency Preparedness Guide specified the following protective measures to be applied for emergency workers involved in the emergency response and recovery activities: distribution of direct reading personal dosimeters (e.g. pocket dosimeters, alarm dosimeters), distribution of protective masks for reducing inhalation of contaminated air (depending on the emergency tasks) and administration of stable iodine (i.e. ITB). In addition, this guide addressed the importance and need for a continuous programme of education and training of emergency workers to provide for smooth and effective implementation of various emergency response activities [19].

The Basic Disaster Management Plan [2] required that the operator and the different prefectural and local authorities involved in the emergency response would provide the relevant staff. The plan also assigned the national Government the role of providing specialized personnel from various governmental bodies (e.g. the SDF, National Police Agency, Fire and Disaster Management Agency, Japanese Coast Guard).

The Fukushima Daiichi NPP Nuclear Operator Emergency Action Plan [16] defined protective measures for emergency workers in a generic way, covering the following areas: defining responsibilities; assigning generic duties in emergency preparedness and response; and listing an inventory of available instrumentation (e.g. survey meters and electronic dosimeters) as prescribed in the Ordinance on Prevention of Ionizing Radiation Hazards [47] and elaborated in the Regulatory Guide on Emergency Preparedness for Nuclear Facilities (hereafter referred to as the Nuclear Emergency Preparedness Guide) [19].

The dose limits for all emergency workers were set in the national legal framework and were derived from the report of the Radiation Council, issued in 1998 [48], which considered the IAEA safety standards [49]. These dose limits were incorporated into relevant legal instruments, such as the Ordinance on Prevention of Ionizing Radiation Hazards [47], the Nuclear Emergency Act [5], the National Personnel Authority Rules [50] and the Nuclear Emergency Preparedness Guide [19], addressing emergency workers from different organizations and services. Dose limits for emergency workers were specified according to the intended tasks. The upper dose limit was set at 100 mSv for life saving actions and activities to prevent the development of catastrophic conditions. Efforts to minimize the exposure to emergency workers continued to be required under these circumstances [19, 47] (see Table 3.2–1).

[33] The IAEA uses the term 'emergency workers' to cover those with specified duties as a worker (any person who works, whether full time, part time or temporarily, for an employer and who has recognized rights and duties in relation to occupational radiation protection) in response to an emergency, including workers employed, both directly and indirectly, by registrants and licensees as well as personnel of responding organizations, such as police officers, firefighters, medical personnel, and drivers and crews of evacuation vehicles [14, 26]. In Japan the term 'emergency preparedness personnel' is used to cover all those who perform emergency response activities in a nuclear emergency, such as "… communication of public information and instructions to residents in the vicinity, guidance of residents in the vicinity for evacuation, traffic control, radiation monitoring, medical treatment provision, and actions to prevent a situation from developing into a disaster in a nuclear facility, and those who perform disaster recovery activities such as removal of radioactive contaminants" [19].

TABLE 3.2–1. DOSE CRITERIA FOR EMERGENCY WORKERS [19]

Effective dose	Equivalent dose to the eye	Equivalent dose to the skin	Tasks
100 mSv	300 mSv	1 Sv	Performing inevitable emergency activities, such as saving lives and preventing the development of catastrophic conditions
50 mSv	—	—	Performing disaster emergency response activities and disaster recovery activities

These dose limits were the maximum doses that were permissible to be received, but only by male emergency workers and female emergency workers who could not become pregnant [47]. Female workers who could become pregnant were not to be engaged in emergency work which might lead to doses exceeding these dose criteria. However, in cases where they were designated as radiation workers (and not as emergency workers), they may have been given some tasks in response to an emergency and the dose limits for occupation exposure of 5 mSv quarterly were to be applied.

Although the above mentioned report of the Radiation Council considered the IAEA safety standards, the dose criteria to be applied for emergency workers included in the report and subsequently transposed in the legal framework in Japan were lower than those provided in the IAEA safety standards (i.e. para. I-1 of IAEA Safety Standards Series No. GS-R-2, and para. V.27 of the Basic Safety Standards) [11, 49].

3.2.2. Protection of personnel at the NPP following the earthquake and tsunami

Following the tsunami alert, efforts were made to protect plant personnel (about 6000 people) from the expected impact of the tsunami. Tsunami alerts were broadcast using the on-site public address system, advising personnel to evacuate and to relocate to designated locations at higher levels. While in most cases, these efforts were successful, not all personnel received the tsunami alert and evacuation orders [17, 25]. Two workers who were checking equipment after the earthquake on the underground floor of the Unit 4 turbine building were drowned in the flooding caused by the tsunami [17].

The protection of plant personnel from the effects of the tsunami was successful largely due to lessons learned from the experience at the Kashiwazaki-Kariwa NPP following the Niigata-Chuetsu-Oki earthquake in 2007, and efforts made afterwards in developing procedures for exiting in an emergency [17].

From 11 to 14 March 2011, plant personnel not considered essential for emergency activities — including female workers and most of the employees of subcontractors — were evacuated from the site. In the morning of 15 March, an evacuation of additional plant personnel took place because of worsening conditions at the site. An estimated 50–70 staff remained on the site, while approximately 650 people were temporarily evacuated to the Fukushima Daini NPP using buses or private vehicles. They began to return to the Fukushima Daiichi NPP from noon on the same day [17].

3.2.3. Protective measures for emergency workers

During the accident, a range of impromptu measures were adopted to maintain an acceptable level of protection for on-site emergency workers under the extreme conditions.

3.2.3.1. Management of doses

In the initial phase of the accident, the system for providing radiation protection at the Fukushima Daiichi NPP was severely affected. Almost all of the 5000 electronic personal dosimeters (EPDs) and associated readers and chargers became inoperable, because the controlled area access points where EPDs were kept, were flooded. Only about 320 EPDs remained operable, some of them located in the seismically isolated building, others located in different controlled areas of the plant [17].

As of the evening of 11 March, dose rates exceeding 1 mSv/h were detected in the reactor building of Unit 1 [17]. As a consequence, the following protection measures were put in place by the ERO [17, 51]:

— Strict control of access to buildings where high radiation levels were detected or suspected;
— Use of protective clothing and respiratory protection for emergency workers working outdoors or performing continuous work in the vicinity of the reactors, for example in the plant control rooms. Emergency workers needed to wear protective equipment before they left the seismically isolated building to carry out their assigned tasks. Where possible, the protective equipment consisted of a full mask fitted with a mixed charcoal and particulate filter or a particulate filter. When no filters were available, dust masks were provided instead.

New radiation protection contingency provisions were adopted from 15 March 2011, in view of the progression of the accident and the worsening radiological conditions on-site resulting from the radioactive releases [17, 30]. Since there were insufficient EPDs available for all the emergency workers on-site, an instruction was issued to share a single EPD for groups of emergency workers devoted to work that could be expected to have homogeneous radiological conditions (group assigned EPD). The doses received by emergency workers in the seismically isolated building were controlled by area dose rate monitoring and time spent in the area. This situation continued until the end of March 2011, by which time a sufficient number of dosimeters had been received from other NPPs [17, 27] to equip every emergency worker on-site with an EPD [17, 30, 53, 54].

Owing to the extreme circumstances associated with the accident, the radiological conditions in the seismically isolated building began to degrade. The release of fission products led to a buildup of radioactive contamination at the entrance and check points within the building and an increase in radiation dose rates at windows that had the lowest shielding properties. Several measures were taken between 26 March and 8 April 2011 to improve the situation, including: use of portable fans and filters to supply filtered air from outside and extraction of air from the affected building; installation of floor pads made with materials that were easy to decontaminate; modifications to the building entrance points to separate personnel checking activities from the outside and the inhabited spaces; and installation of lead shielding on windows [17, 30].

There was also a buildup of radioactive contamination in the three main reactor control rooms (MCRs). Although these areas had been fitted with dedicated habitability systems, they had become inoperable due to the loss of electrical power. Portable fans were used to increase the exhaust of the contaminated atmosphere in the MCR enclosures a few weeks after the onset of the accident [17].

Radiation monitoring, including radiation surveys around the site, notably at the boundaries of the site and in the area around Units 1–4, were performed from the first days of the accident. These activities were important for providing a broad overview of the accident's evolution and the radiological conditions at the site. They also contributed to improving the protection of emergency workers. Maps of the radiological conditions at different areas of the plant were drawn up, paying particular attention to areas where emergency activities were taking place and to the access routes between different working points where significant doses could be received [17, 53, 55]. During the weeks when there was a shortage of EPDs, the tracking of individual doses to emergency workers was difficult. Some

workers left the site without returning their EPD or without providing information required to track the work group to which the emergency worker had been assigned. Consequently, entrance check points were established at the seismically isolated building, at J-Village (where entrance and exit check points were installed) and at the Onohama Coal Centre, which served as the base for exit check points. Those emergency workers gaining access to the controlled area were recorded and EPDs were assigned at the entry points, and were then retrieved at the exit points. Personal records of the emergency workers entering and leaving the area were maintained. Whole body counters (WBCs) were also installed in J-Village and at the Okahama Coal Centre (mobile WBCs). These WBCs were used for internal contamination checks, which were performed mainly for workers suspected of being internally contaminated and for female workers [17, 53, 55].

Recognizing the problems encountered in tracking individual doses, a campaign to recover individual dose data for all the emergency workers was undertaken. This included thorough cross-checking of records, personal surveys to gather information on all relevant aspects of the emergency workers' activities to retrieve sufficient data to estimate doses (including the dose rates to which they were exposed and the duration of exposure). After this campaign, there were ten cases for which the doses were unknown or for which insufficient data existed for assessing the doses [17, 51, 53, 55]. This required an additional investigation, primarily to determine the identity of the workers and, thereafter, to reconstruct their doses. While the investigation was successful in the recovery of contact information for three of these ten workers, seven remained unidentified, with no entry in any of TEPCO's contractors' records. However, the three workers for whom the contact information was found could, for various reasons, not be contacted (for example, they had left their job or had moved) [17].

Emergency workers from off-site services, primarily from the firefighting services and the SDF, were engaged in activities associated with the cooling of spent fuel pools at the Fukushima Daiichi NPP. Their employers were made responsible for ensuring their protection while working on the site. These emergency workers wore protective clothing and respiratory protection. In an effort to manage their doses received during these activities, they were also provided with personal dosimeters and survey meters [56]. However, some issues emerged with TEPCO's subcontractors, particularly the firefighting services, when they were called upon to respond on the site. The lack of proper knowledge of the contract conditions and questions as to whether they covered the response to an emergency of this type, initially resulted in a refusal to respond by the firefighting service subcontracted by TEPCO. As none of the TEPCO employees were capable of using the fire engines, the ERO, in cooperation with the Local NERHQ, arranged for a local firefighting team, which was to be supported by a limited number of personnel from the subcontracted firefighting service. Eventually, the subcontracted firefighting service agreed to take on the assignment [27, 57]. For the off-site emergency workers, particularly those intervening in the emergency for the first time, TEPCO provided brief training in the form of 30 minute explanation sessions[34] before they entered the NPP. This training did not include all emergency workers, and it was not considered by national authorities as being sufficient. Training was conducted in J-Village and covered topics such as the use of protective clothing and masks, dose management aspects and effects from radiation exposure [25, 51, 53, 54]. Insufficient training in the use of respiratory protection was considered to be one of the contributing factors of the internal contamination among emergency workers on the site even as late as June 2011 [53, 54, 57, 58].

The accident also presented TEPCO with challenges in ensuring the well-being of on-site emergency workers, for example in providing adequate facilities and conditions for resting, sleeping, eating,

[34] The brief explanatory training sessions were conducted until about May 2011.

sanitation, etc. In the absence of arrangements in this regard prior to the accident, it took several months for TEPCO to address these challenges [57, 59-63].

Before any emergency work was performed within the 30 km zone around the Fukushima Daiichi NPP, the SDF made a preliminary dose assessment based on the duration estimated for the intended emergency work and the latest monitoring results from the working area or from its neighbourhood. The emergency tasks were always carried out wearing simple protective clothing. Individual dosimeters were used by SDF members to monitor their exposure and to confirm their cumulative dose during the work. Initially, the SDF set and successfully implemented the upper limit of the cumulative exposure dose for an individual member from its teams to be 50 mSv for male and 5 mSv for female emergency workers. In order to ensure compliance with these criteria during the actual implementation of emergency work, lower levels (30 mSv for male or 3 mSv for female emergency workers) were used as turn-back doses. Thereafter, SDF emergency workers were subject to the increased dose criterion of 250 mSv effective dose for specific tasks (see Section 3.2.3.2); however, no SDF member received exposure exceeding this criterion [22].

While performing emergency tasks within 20 km of the Fukushima Daiichi NPP, the firefighting teams also used simple protective clothing and were measuring the dose rate and cumulative dose during their tasks for compliance with the criteria applicable for emergency workers. The upper dose criterion for emergency work was decided by the individual firefighters' headquarters, with account taken of the values set in the manual for firefighting activities at nuclear power facilities prepared by the Fire and Disaster Management Agency in March 2001. After each operation, firefighters had their doses measured and recorded; these measurements showed that none of the firefighters exceeded the set criterion of 100 mSv effective dose during the performance of their tasks [22].

Emergency workers also included police who were engaged off-site within the 20 km area. They were provided with protective clothing and respiratory protection. Their doses were managed by individual dosimeters and survey meters. Although stable iodine tablets were distributed to a total of 552 police officers, none of them took the tablets [64].

In order to provide for adequate rescue and transport of patients in hospitals and nursing homes within the 20 km zone around the Fukushima Daiichi NPP, medical staff teams were engaged as emergency workers and were provided with individual dosimeters to monitor their doses throughout the intervention. For female nurses, the dose criterion of 5 mSv was applied. In some cases, such as the one at Futaba Hospital on 15 March, the dosimeters of five female nurses sounded an alarm, as the dose criterion of 5 mSv was approached, resulting in the team suspending its mission before completing the rescue of all the patients at the hospital. The rescue and transportation operation had to be finished later by other teams [27].

Although an evacuation order was issued within the 20 km zone on 12 March, monitoring continued to be performed within this area until 14 March [27].

Early on in the response, by 13 March, relief teams of the Japanese Red Cross Society (JRCS) contributed to the emergency response following the earthquake and tsunami, as well as the subsequent nuclear emergency, by providing medical care and support to members of the public. However, due to the lack of preparedness for responding to a nuclear emergency, a lack of relevant knowledge about radiation emergency medical response and the lack of protective and monitoring equipment, all the relief teams dispatched from JRCS chapters left Fukushima on 14 March. The Fukushima Red Cross Hospital remained to provide relief activities [65].

3.2.3.2. Dose limits

Despite the various measures to improve the radiological conditions in which emergency workers were performing their tasks, it became clear that, within a few days, the cumulative doses of many emergency workers who had been working on-site since the onset of the accident were approaching the prescribed dose criterion for inevitable emergency work (100 mSv effective dose) in the Ordinance on Prevention of Ionizing Radiation Hazards [47].

On 14 March 2011, the dose limit for emergency workers undertaking specific emergency work was temporarily increased to 250 mSv[35] to allow the necessary activities to continue on-site and within a 30 km radius of the Fukushima Daiichi NPP [67, 68]. This change was implemented by means of an exemption to the Ordinance on Prevention of Ionizing Radiation Hazards, published on 15 March 2011, with retroactive effect from 14 March 2011 [67, 68].

The dose criterion of 250 mSv was not to be applied to female emergency workers who could become pregnant, because the exemption [67] was specifically issued in relation to Article 7, paragraph 2, of the Ordinance [47], which applied only to male emergency workers and to female emergency workers who could not become pregnant. For those females who could become pregnant and who were designated as radiation workers prior to the accident, the dose limit of an effective dose of 5 mSv per quarter was applied (see also Section 3.2.1). The dose limits for a member of the public (1 mSv effective dose in a year) were applied to female personnel who were not designated or registered as either radiation workers or emergency workers prior to the accident but remained at the site after its onset performing auxiliary tasks in the seismically isolated building. Due to the worsening situation at the site, all female emergency workers were evacuated from the site between 14 and 23 March [17, 30]. Eventually, all female workers who stayed in the building were designated as radiation workers and a relevant dose limit of an effective dose of 5 mSv per quarter was applied to them. Two female workers exceeded this dose limit [53].

The temporary increase in the dose limit to 250 mSv was withdrawn on 1 November 2011 for on-site emergency workers who began working from this date onwards. On 16 December 2011 this dose limit was withdrawn for the majority of the remaining emergency workers, and on 30 April 2012 it was withdrawn for a group of approximately 50 TEPCO employees with accumulated doses exceeding 100 mSv who had specialized knowledge and experience in operating the reactor cooling systems and in maintaining the facilities and equipment for suppressing the emission of radioactive materials [57, 68, 69].

Three days after the decision to increase the dose criterion for emergency workers (on 17 March), discussions were held within the Government regarding further increasing this dose criterion to 500 mSv. Some preparatory arrangements were undertaken, but no final decision was made for doing so [27].

Article 4, paragraph 3, of the National Personnel Authority Rule 10-5 on Radiation Injury Prevention for Employees specifies the application of the dose criteria for governmental employees engaged in emergency response, such as nuclear safety inspectors [27, 50]. Because this requirement for national government employees engaged in emergency response was specified in a document other than the Ordinance on Prevention of Ionizing Radiation Hazards [47] to which the exemption was issued, the revision of the criteria stipulated on 15 March did not apply immediately to this group of emergency

[35] It was reported in Ref. [66] that the increase to 250 mSv resulted in confusion as to why this was being done and whether it resulted in a substantial increase in health risks.

workers, while it did apply to local government employees[36] engaged in emergency work. However, the National Personnel Authority of Japan followed the publicly announced increase in the dose criteria for emergency workers and, on 17 March, issued a revision to the National Personnel Authority Rule 10-5 on Radiation Injury Prevention for Employees for the increased dose criterion to also be applied to national government employees under the same circumstances [27, 58].

Although the staff of the Ministry of Defense, including the SDF personnel, were in governmental service, they were not considered national government employees. Nevertheless, the revised criteria for emergency work came into force on 14 March for the SDF personnel because the rules of the National Personnel Authority were applicable.

Dose criteria to be applied for emergency workers from the firefighting services as local government employees engaged in emergency response on-site were additionally specified in the manual for firefighting activities at nuclear power facilities, which was prepared by the Fire and Disaster Management Agency in March 2001. The manual stipulates an effective dose limitation of 100 mSv for emergency work to save lives. There was no change in this dose criterion, which applied to emergency workers from the firefighting services [27].

Using the legal basis explained above that existed prior to the accident, the Fukushima Prefecture Disaster Management Plan [1] provided the dose criteria to be applied for personnel of Fukushima Prefecture engaged in performing general emergency tasks. These criteria were 50 mSv effective dose and 100 mSv effective dose for emergency tasks such as mitigatory actions and rescue activities.

Despite the difficulties, the protective measures taken for on-site emergency workers were generally successful in controlling radiation exposures and limiting them to levels far below those at which acute radiation syndrome might be expected to occur. This applies to all on-site emergency workers, including TEPCO employees and subcontractors, SDF personnel and firefighters. Of the latter category, none of those who were engaged in taking on-site mitigatory actions, such as injecting water into a spent fuel pool, were exposed to radiation doses exceeding 100 mSv [27].

However, there were six cases in which emergency workers incurred doses in excess of the dose limit of 250 mSv. These ranged from the highest dose of 678 mSv (of which 590 mSv was from internal contamination) to the lowest dose of 308 mSv (of which 260 mSv was from internal contamination). Successive follow-up checks revealed several causes for this: unavailability of adequate respiratory protection against volatile iodine for the emergency workers in the control room early after the onset of the accident (11–12 March); ITB not being implemented until the evening of 13 March; respiratory protection not worn for different reasons (e.g. too tight, fogging of the mask's glass while breathing); taking individual actions leading to inadvertent ingestion (e.g. smoking, eating and drinking in the contaminated environment); and repeated exposure to the severe working conditions in which the assigned tasks were performed. In addition, unexpected high external doses of about 180 mSv were received by two workers due to the unanticipated presence of highly contaminated water in the working area [17, 27, 30].

In an effort to comply with the 250 mSv dose limit, TEPCO subsequently issued a rule that applied from 11 March to 15 December 2011 to exempt emergency workers who had received doses exceeding 200 mSv from further emergency work at the Fukushima Daiichi NPP [30, 70]. On 28 April 2011, a notice was issued by the Ministry of Health, Labour and Welfare [70]. In this rule, a compliance with the dose limit of 100 mSv for five consecutive years was requested to be applied by all employers of radiation workers involved in emergency work at the Fukushima Daiichi NPP with

[36] Who were subject to the Industrial Safety and Health Act [52], under which the above mentioned Ordinance is set.

regard to further work involving occupational exposure that was not associated with the Fukushima Daiichi NPP[37] [71].

The difficulties in providing radiation protection at the plant also resulted in delays in the communication to emergency workers of the doses received and the unavailability of cumulative doses for emergency workers in time for consideration of restrictions to prevent further exposures. It took several months for TEPCO to adequately manage the notification system for this purpose [25, 53, 55, 57].

3.2.3.3. Iodine thyroid blocking

Iodine thyroid blocking (ITB)[38] was implemented as a protective measure for emergency workers from 13 March 2011. The initial advice to take stable iodine tablets was sent (as a fax message) from the Tokyo headquarters of TEPCO to the Fukushima Daiichi NPP at around noon on 12 March. However, this message did not reach the medical team of the on-site ERO.

On 13 March, the general manager of the on-site ERO advised the on-site medical team leader to make an internal announcement. The on-site medical team leader gave instructions for the administration of stable iodine tablets and dosage. Notices about the distribution of stable iodine tablets were put up around the site. This measure applied to emergency workers under 40 years of age and, to those over 40 years who wished it, who were engaged in emergency work that could result in a projected thyroid equivalent dose of 100 mSv. For the first few days, the on-site medical team gave instructions about the administration of stable iodine during the morning and evening on-site ERO meetings. Thereafter, information about administration was disseminated within the seismically isolated building, as changes were made to the advice. From 2 August 2011, ITB was implemented only for emergency workers carrying out emergency work in designated buildings on the site, and, on 21 November 2011, this measure was terminated [17].

There were a total of approximately 30 000 stable iodine tablets in stock in the main office building at the Fukushima Daiichi NPP. At the time of the accident, stable iodine tablets were distributed to the seismically isolated building; however, the stable iodine tablets were not available and ready for use in the MCRs and they could not be distributed in a timely manner to the MCRs due to the devastation caused by the earthquake and the tsunami.

The on-site medical team initially distributed the stable iodine tablets to the managers of the workers for further distribution. Subsequently, tablets were distributed at a designated place at the plant. In each case, a list of workers was made available to be signed by emergency workers (and sometimes by the manager) on receipt of the tablets. However, in some cases, these lists were incomplete or lost. For example, one of three emergency workers who stayed in the MCR of Units 3 and 4 between 11 March and the evening of 13 March remembered taking stable iodine tablets, but no record of the intake could be found [27].

During the entire period of on-site implementation of ITB, approximately 17 500 tablets were administered to 2000 emergency workers. About 75% of the emergency workers received fewer than ten tablets per individual, although one individual received as many as 87. Emergency workers who took more than 20 tablets or who were continually taking the tablets for more than 14 days were given

[37] According to the IAEA safety standards, "[w]orkers shall not normally be precluded from incurring further occupational exposure because of doses received in an emergency exposure situation." [11].

[38] 'Iodine thyroid blocking' is an urgent protective action to be taken in an emergency involving radioactive iodine. Iodine thyroid blocking involves the administration of a compound of stable iodine (usually potassium iodide) to prevent or reduce the uptake of radioactive isotopes of iodine by the thyroid gland [12].

a medical examination. In total, 178 emergency workers were estimated to have incurred thyroid equivalent doses of over 100 mSv, and 25 emergency workers under the age of 40 were found not to have taken stable iodine tablets [17].

3.2.3.4. Planning the emergency work for decontamination activities

The planning of decontamination work started after the urgency associated with the implementation of protective actions for the public abated and when sufficient information from field monitoring was obtained. It was based on the Basic Policy for Emergency Response on Decontamination Work [72] and the Guidelines for Municipal Decontamination Work [73] issued on 26 August 2011. Following this policy and guidelines, the Ministry of Health, Labour and Welfare issued a notification in accordance with this policy, and guidelines for ensuring the radiation protection of emergency workers involved in the decontamination activities [74]. Every employer had the responsibility to ensure the protection for each worker engaged in decontamination work by taking measures that included:

— Using personal dosimeters to control the dose due to external exposure while performing decontamination work, recording the data and informing the worker on the dose incurred on a daily basis and on cumulative dose once a month;
— Keeping the dose below 20 mSv per year for male workers and female workers who were not pregnant or were not expected to be pregnant, or under 5 mSv per three months for female workers who were or were expected to be pregnant;
— Wearing of respiratory protection, when required, and adequate personal protective equipment when the work was carried out;
— Instructing workers not to smoke, eat or drink at the workplace;
— Providing workers with instruction and training adequate for their expected duties before starting the decontamination work;
— Provision of periodical health examinations, at least once every six months for full time workers engaged in the decontamination work.

Following this notification, policy and guidelines, a Ministerial Ordinance on Prevention of Ionizing Radiation Hazards at Work to Decontaminate Soil and Wastes Contamined by Radioactive Materials Resulting from the Great East Japan Earthquake and Related Works and its guidelines were published on 22 December 2011, with 1 January 2012 as the date of entry into force [75-77].

Activities to be undertaken in the weeks and months following the onset of the accident had been carefully planned so that adequate attention was given to the protection of those engaged in the decontamination work within the framework for occupational exposure for normal operations consistent with the IAEA safety standards [11, 49].

3.2.3.5. Designation of emergency workers

Many different types of emergency workers were needed to support the on-site and off-site emergency response. On-site emergency workers included NPP personnel, either directly employed by TEPCO or subcontracted, as well as personnel from the SDF, the firefighting services and police engaged in emergency work on the site [17]. Off-site emergency workers included personnel from different organizations and services (governmental and non-governmental). Their tasks included evacuation of the public and of special facilities, offering support to evacuees, providing medical care, and carrying out monitoring and sampling [27, 57, 65, 78].

Not all of the emergency workers had been designated as such prior to the emergency (e.g. some TEPCO employees and employees of subcontractors who served as emergency workers), and arrangements were not in place to integrate them into the response after their designation as

emergency workers. Additionally, many of those who had not been designated prior to the emergency had not been trained to work under nuclear emergency conditions. For example, they had not been trained in radiation protection aspects, informed of the potential health risks from radiation exposure, or trained in the use of respiratory protection or in dealing with patients potentially contaminated with radioactive material [79]. This resulted in some delay in the implementation of mitigatory actions early in the response [27].

3.2.4. Medical management of emergency workers

Obtaining the necessary medical treatment for emergency workers with conventional injuries was difficult, because several hospitals were closed as a result of the evacuation or sheltering, and some were not prepared to treat patients possibly contaminated with radioactive material [79, 80]. Until primary medical care was provided on the site, emergency workers with conventional injuries were transported to one of two local hospitals for treatment[39] [63, 80]. As a consequence of the earthquake and tsunami, two workers were slightly injured, two required treatment in the hospital and two workers died on 11 March. One worker was treated at the designated radiation emergency hospital in Okuma Town. Another worker who required surgical treatment was transported to a hospital in Koriyama City due to the disruption of the water supply at the hospital in Okuma Town. Overall, 30 emergency workers from Fukushima Daiichi NPP visited hospitals for treatment of trauma and/or other illnesses not related to radiation exposure in March 2011 [81].

About 17 hours after the earthquake, the NIRS dispatched the Radiation Emergency Medical Assistance Team (REMAT), consisting initially of a physician, a nurse, and a health physicist, to the Local NERHQ (in the Off-site Centre) to perform assessments of the contamination and decontamination of emergency workers[40] [79].

On 12 March, five workers sustained conventional injuries without suffering contamination as a result of the first hydrogen explosion at the Unit 1 reactor building. No triage was performed for them at the site [80]. Four of the injured workers were transported using facility vehicles to a non-designated medical clinic, while one worker, with injuries requiring surgical treatment, was referred to a hospital in Koriyama City.

No medical doctors were available at the Fukushima Daiichi NPP for the first week after the accident [80]. From 19 March, occupational health doctors began to provide primary care for on-site emergency workers at the ERC in the seismically isolated building, if this was required [17, 63, 80].

At the Fukushima Daini NPP, an occupational physician and two nurses were present 24 hours a day, seven days a week, to provide first aid and general medical management for on-site emergency workers, if required. This service was provided from 11 March onward at the health management office. In addition, on 16 March, three medical doctors, two nurses and a general assistant were dispatched from Toden Hospital and other hospitals to assist them.

On 14 March, four SDF personnel and seven TEPCO workers sustained conventional injuries after the second hydrogen explosion, which took place at Unit 3. Four SDF personnel were brought to the Local NERHQ, where the initial triage was performed. All of them showed contamination on their protective gear (above 1 mSv/h at 10 cm from the surface). After removal of their protective gear and decontamination (e.g. taking a shower), the remaining contamination on the face was measured. One

[39] Radiation and disaster emergency medical systems in Japan prior to the accident are described in Appendix II.

[40] Later on, many experts, including physicians, nurses, radiation protection experts, health physicists and logisticians, were sent to Fukushima Prefecture from the NIRS.

SDF member was transferred by ambulance to the Fukushima Medical University (FMU) Hospital in Fukushima City. He was diagnosed with a conventional injury to the shoulder and arm. One of the other patients had a contaminated wound on a thigh and was transferred to the NIRS by a SDF helicopter [82].

Three of the seven TEPCO workers were transferred by ambulance to the FMU Hospital, accompanied by a nurse and a radiation protection expert from the NIRS, since the primary hospitals for a radiation emergency were either located within the evacuation zone or did not function. However, even hospitals located outside of the evacuation area could not receive contaminated patients due to the lack of knowledge about medical response to a radiation emergency. The doses of experts who took care of patients with contamination were a few tens of μSv [79, 83].

For the medical management of multiple casualties during the Fukushima Daiichi accident, a triage process that incorporated elements of medical and radiological triage was developed [84]. Following initial triage on the site, all injured workers were transported for medical and radiological triage at J-Village [17, 22, 63, 80].

Screening facilities and decontamination tents provided by the SDF and fire departments from other prefectures were set up at J-Village, which was established on 15 March as the only access point to the NPP. On 18 March, an emergency physician arrived at J-Village, accompanying the fire brigades which were engaged in emergency cooling operations for the spent fuel pool of Unit 3. In addition, one SDF doctor and two to three SDF nurses were deployed at J-Village from 17 March onward [21] [17].

On 24 March, two workers received high doses to their feet from the contaminated water in the basement of the Unit 3 reactor building. They were initially evaluated and decontaminated by a part-time occupational health doctor at the seismically isolated building of the Fukushima Daiichi NPP and transported by a facility vehicle to J-Village where an emergency physician carried out a second evaluation before final transportation to the FMU Hospital. A medical doctor from the NIRS was dispatched to the FMU Hospital to support treatment and decontamination. The two workers were transported to the NIRS for dose assessment, the results of which were as follows: equivalent dose to the skin of 466 mSv for each worker and committed effective dose of 39 mSv and 35 mSv, respectively. As of 30 March, one doctor and two nurses from the TEPCO hospital in Tokyo were located at J-Village to provide first aid treatment for workers.

In early April 2011, a medical clinic at J-Village (which had served as a sport clinic prior to the accident) was renovated and designated for the medical management of affected on-site emergency workers as a primary radiation emergency medical facility. Emergency physicians, nurses and radiation specialists were located at this facility with the support of the Japanese Association for Acute Medicine, Hiroshima University and the NIRS [63, 80]. In early April 2011, the medical headquarters were established at the Local NERHQ in Fukushima City and the first comprehensive medical response plan for the medical management of on-site emergency workers was developed by the Local NERHQ (see Fig. 3.2–2) [84].

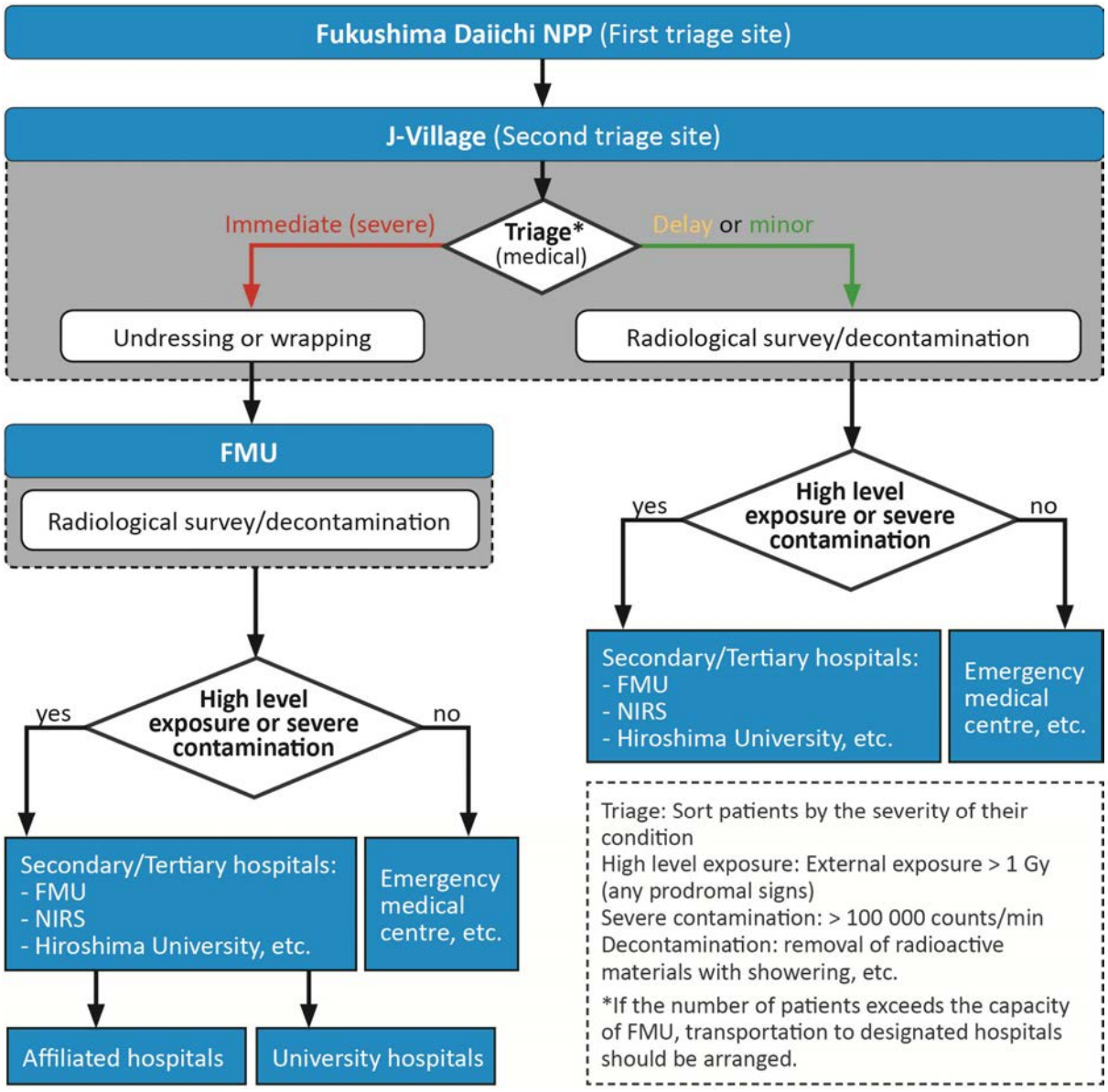


FIG. 3.2–2. Triage arrangements and roles of hospitals as of 22 April 2011 [84].

In the case of a mass casualty event, the first triage was to be performed on-site; the second triage and life-saving actions were to be provided by the emergency physicians at J-Village. Since vehicles were not allowed to enter the 20 km restricted zone, the injured workers were transported by TEPCO or SDF vehicles from the site to J-Village before transportation to referral hospitals by fire department ambulances or SDF helicopters. Severely injured personnel with contamination were to be transported by SDF aircraft to the designated radiation emergency hospitals outside Fukushima Prefecture, such as the NIRS, affiliated hospitals in the Kanto region and Hiroshima University [85].

In late April 2011, more hospitals, including disaster medical centres in Fukushima and nearby prefectures, were requested to accept on-site emergency workers in the case of injury [84].

As was mentioned earlier, initial triage and first aid was provided at the Fukushima Daiichi NPP by occupational health physicians during the day from 15 April [86]. Following an event in May 2011, when a worker died from a heart attack, arrangements were made for doctors to be available around the clock at the seismically isolated building of the Fukushima Daiichi NPP. This was arranged with

the involvement of the University of Occupational and Environmental Health and the Japan Labour Health and Welfare Organization [17, 87, 88]. During this time, the medical doctors treated emergency workers for the consequences of the excessive heat that was caused by the use of personal protective equipment. Actions were implemented to reduce the health effects induced by the heat, such as compulsory rest, use of cooling jackets and rehydration measures [89].

A 24 hour medical emergency care facility at the Fukushima Daiichi NPP was established on 1 July 2011 on the first floor of the Unit 5–6 reactor management building (located 650 m north of the Unit 1 reactor building), which became known as the '5/6 ER'. Emergency physicians, nurses and radiological technicians experienced in the medical management of nuclear emergencies were recruited from emergency medical services all over Japan. This was done through the efforts of the Ministry of Health, Labour and Welfare (MHLW) in cooperation with the Japan Association of Acute Medicine, following guidance given by the Prime Minister's Office. The facility was located in the middle of the Restricted Area, where only authorized personnel and vehicles were allowed to enter [80, 88].

However, despite the establishment of temporary medical facilities (5/6 ER and the J-Village clinic), significant delays continued in the provision of medical care by emergency hospitals because of the distance of J-Village and hospitals from the Fukushima Daiichi NPP. This situation was exacerbated by the fact that the roads surrounding the Fukushima Daiichi NPP remained disrupted and by the establishment of a no fly zone in the 20 km Restricted Area.

Figure 3.2–3 presents an overview of the medical conditions managed at the Fukushima Daiichi NPP from March 2011 until June 2012 [80, 90].

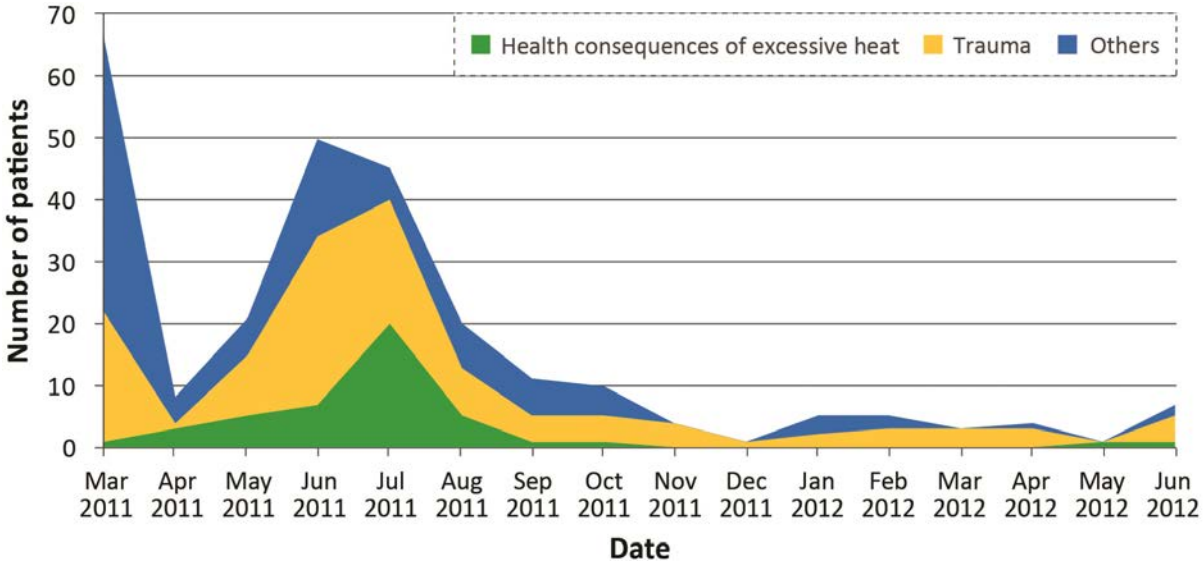


FIG. 3.2–3. Injuries and illnesses treated at the Fukushima Daiichi NPP (from March 2011 to June 2012)[41] [80, 90].

During this period, three deaths occurred, primarily due to cardiac arrest and none of them related to radiation.

[41] Among the reasons specified as 'others' are medical problems such as headache, sickness, etc.

3.2.5. Voluntary involvement of members of the public in the emergency response

In the aftermath of the accident, people from the affected areas, as well as from all over Japan, and from a number of non-governmental organizations (helpers) volunteered to assist in such activities as the provision of food, water and necessities, and later in decontamination and monitoring activities.

This demonstrates the need to identify, at the preparedness stage, when and how such helpers may be involved in the aftermath of an accident, and how they will be integrated in the emergency response organization and afforded an adequate level of protection. National authorities issued guidance on the type of activities helpers could carry out and on measures to be taken for their protection [78, 91, 92].

Self-employed workers, residents and volunteers who performed decontamination works in their local area were asked to follow the applicable sections of the MHLW's Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works [78, 93].

There were a number of NGOs that recruited volunteers from all over Japan who participated in decontamination works, environmental radiation monitoring, etc., in Fukushima Prefecture. The Ministry of the Environment and the Fukushima Prefectural Government supported such initiatives of NGOs by distributing information through governmental web sites [78, 91].

With regard to the assignment of specific tasks undertaken in decontamination areas and the responsibility of coordination and supervision, the MHLW's Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works [93] stipulated the following:

— Residents and self-employed workers were expected to conduct decontamination activities, etc., as a communal group when they needed to decontaminate the soil of their residences, offices, farmland and so forth in areas where the average ambient dose rate might exceed 2.5 μSv/h. In such cases, the frequency of the work should be less than dozens of times (days) per year, to prevent individuals from receiving effective doses higher than 1 mSv/y through the work.
— In the case of recruiting volunteers from outside the special decontamination areas, the volunteer organizers should note that the exposure dose limit to the public from the radiation source was specified as 1 mSv/y under the planned exposure situation defined by the International Commission on Radiological Protection (ICRP).

This information was also provided on the web site of the Ministry of the Environment and in its leaflet for volunteers [78, 92-94].

3.2.6. Summary

At the time of the accident, the national legislation and guidance in Japan addressed the requirements and the measures to be taken for the protection of emergency workers, but only in general terms and not in sufficient detail. Practical arrangements, such as the Nuclear Operator Emergency Action Plan at the Fukushima Daiichi NPP [16] or the Fukushima Prefecture Disaster Management Plan [1], were generic and did not contain sufficient guidance on how measures were to be implemented in the event of a nuclear accident.

Implementation of the arrangements for ensuring the protection of workers against radiation exposure was severely affected by the extreme conditions at the site. In order to maintain an acceptable level of protection for on-site emergency workers, a range of impromptu measures was implemented. These measures resulted in doses far below those that could have resulted in acute radiation syndrome and, in most cases, below the legally set national dose limit for emergency workers. Nevertheless, a few emergency workers received doses in excess of these levels, mainly due to a lack of training and incorrect implementation of protective measures (e.g. improper use of respiratory protection, late

implementation of ITB measures or taking actions that resulted in inadvertent ingestion of radionuclides).

Many emergency workers from different professions were needed to support the emergency response. Emergency workers came from various organizations and public services. Not all had been designated prior to the emergency as emergency workers (e.g. some TEPCO employees and subcontractors). There were no arrangements in place to integrate into the response those emergency workers who had not been designated prior to the accident.

Contact details and doses for some of emergency workers were not adequately tracked and/or recorded at the time. In addition, many of those who had not been identified as emergency workers prior to the emergency (e.g. some medical staff and members of the Japanese Red Cross Society) lacked adequate training and guidance to work under emergency conditions. Some of the rescue teams that supported the evacuation process were not provided with adequate training in radiation protection and were not given information on the potential health risks from radiation exposure, or information dealing with possibly contaminated patients.

During the response, the dose limit for emergency workers undertaking specific emergency work was temporarily increased to 250 mSv, to allow the necessary activities to continue. These dose criteria were not always applied consistently to all emergency workers, considering their expected duties. For example, the dose limit of 250 mSv was not applicable to emergency workers from the firefighting service.

Medical management of emergency workers was also severely affected and major efforts were required to meet the needs of on-site emergency workers. Difficulties were encountered in seeking required medical treatment for on-site emergency workers because several hospitals were closed as a result of the evacuation or sheltering orders, while others were not prepared to treat patients with possible contamination. Detailed arrangements for the medical management of emergency workers had not been developed at the preparedness stage. Occupational health doctors started to provide primary care for on-site emergency workers at the on-site ERC in the seismically isolated building eight days after the beginning of the accident. Two triage centres were established, one on-site and the other in J-Village, which also served as a base facility for emergency workers and for their decontamination, if required.

As of 1 July 2011, an emergency care facility was established at the Fukushima Daiichi NPP. For this facility, medical staff trained to deal with radiation emergencies had been recruited from all over Japan. However, significant delays continued in the provision of medical care to emergency workers for various reasons, including the distance of hospitals from the Fukushima Daiichi NPP, roads being disrupted and a no fly zone being established within the 20 km zone.

Members of the public, referred to as helpers, volunteered to assist in the off-site emergency response. National authorities issued guidance on the type of activities that helpers could carry out and on measures to be taken for their protection.

3.2.7. Observations and lessons

— **Emergency workers need to be designated, assigned clearly specified duties, regardless of which organization they work for, given adequate training, and be properly protected during an emergency. Arrangements need to be in place to integrate into the response those emergency workers who had not been designated prior to the emergency.**
Account needs to be taken of those who may not have been designated as emergency workers at the preparedness stage. Dose criteria for emergency workers need to be set in advance and applied in a consistent manner for the assigned emergency duties.

— **Arrangements need to be pre-planned for members of the public (referred to as helpers) who volunteer to assist in response actions to be integrated into the emergency response organization and to be afforded an adequate level of radiation protection.**
The arrangements need to include measures for their safety, including dose criteria to be applied, registration and integration within the emergency response organization and training ('just-in-time' instructions before undertaking the assigned duties) prior to the start of their work.
— **There is a need to involve non-governmental organizations in establishing adequate emergency arrangements at the preparedness stage to facilitate their effective support to the overall emergency response.**
This needs to cover the identification of their roles, the development of procedures and the provision of training.
— **Arrangements for the protection of emergency workers need to be elaborated in detail in the relevant emergency plans and procedures.**
These plans and procedures need to be routinely tested to ensure their effective implementation. The arrangements need to include: those for ensuring the operability and habitability of emergency response facilities under a range of hazardous conditions; those for ensuring the well-being of emergency workers; and those for timely communication of doses incurred and associated health risks to emergency workers.
— **There is a need for the training of emergency workers in the implementation of measures and actions for their protection in an emergency, with specific emphasis on severe environmental and radiological conditions.**
Training programmes, including drills and exercises, need to cover the use of personal protective equipment, self-protective measures and actions to prevent inadvertent ingestion.
— **Arrangements for medical preparedness and response in relation to emergency workers need to be detailed and integrated in the overall emergency planning.**
These arrangements need to take into account the necessity to promptly provide medical care to emergency workers and to function under severe environmental and radiological conditions.

3.3. PROTECTING THE PUBLIC

3.3.1. Arrangements for protecting the public in Japan prior to the accident

Prior to the accident, 10 km EPZs, in which emergency preparedness was to be significantly enhanced, had been established around the Fukushima Daiichi and Fukushima Daini plant sites (Fig. 3.3–1). There were plans to implement protective actions within these zones [1].

The emergency response plans envisaged that decisions on protective actions would be based on dose projections performed at the time when a decision was necessary (see Appendix I for more details). Doses were to be projected by using a dose projection model, the System for Prediction of Environmental Emergency Dose Information (SPEEDI) after the onset of the accident and to be compared with predetermined dose criteria to determine what protective actions were needed and where they were to be applied [8, 19]. This approach was not in line with IAEA safety standards, which stipulate that the initial decisions on urgent protective actions[42] for the public need to be based on plant conditions [11, 13].

[42] Urgent protective actions are actions that must be taken promptly (normally within hours) in order to be effective. The most common urgent protective actions in a nuclear emergency are evacuation, sheltering, ITB, restriction of the consumption of potentially contaminated food and decontamination of individuals.

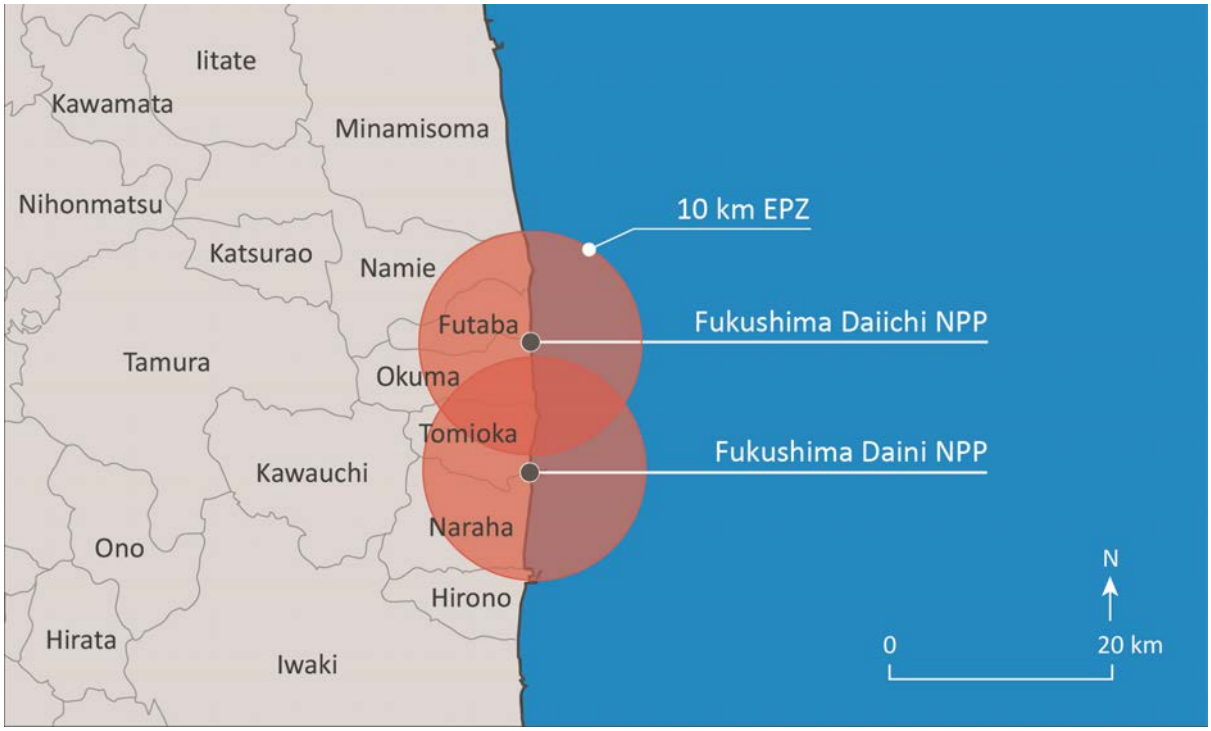


FIG. 3.3–1. Emergency planning zones (EPZs) for the Fukushima Daiichi and Fukushima Daini NPPs established prior to the accident [1].

Predetermined criteria were available for sheltering[43], evacuation[44] and ITB in terms of projected dose (see Table 3.3–1). There were no predetermined criteria in terms of measurable quantities, such as operational intervention levels (OIL[45]). The dose criteria for sheltering, evacuation and ITB were consistent with the guidelines for generic intervention levels for these protective actions that have been established in the IAEA safety standards [11].

There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation[46] [19].

It was envisaged that METI, as soon as notification was received from the operator of the NPP, would monitor conditions at the plant and attempt to predict the timing, rate and composition of possible releases of radioactive material from the NPP, based on plant conditions provided by the operator and using the Emergency Response Support System (ERSS). MEXT would then use the outcome of these predictions from METI to perform a projection of doses to the public from the possible releases of radioactive material using SPEEDI.

---

[43] Sheltering is the short term use of a structure for protection from an airborne plume and/or deposited radioactive material [12].

[44] Evacuation is the rapid, temporary removal of people from an area to avoid or reduce short term radiation exposure in an emergency. Evacuation may be performed as a precautionary action based on plant conditions [12].

[45] An OIL is a type of action level that is used immediately and directly (without further assessment) to determine the appropriate protective actions or other response actions on the basis of an environmental measurement or laboratory analysis [11]. It is a calculated level, measured by instruments or determined by laboratory analysis, that corresponds to generic criteria, expressed in terms of dose. OIL is typically expressed in terms of dose rate, ground or surface concentration, or activity concentration of radionuclides in the environment, food, or drinking water samples [11].

[46] Relocation is the non-urgent removal of people to avoid longer term exposure (e.g. within one year) from deposited radioactive material [12].

MEXT would transmit the predictions to terminals in the NERHQ, Local NERHQ, NSC, Prefecture Headquarters for Disaster Control, and elsewhere, in order to support decisions on, and implementation of, protective actions. Within the NERHQ, protective action orders/recommendations would be drafted for issuance by the Prime Minister based on the dose projection of SPEEDI and the criteria for taking actions in the NSC's Nuclear Emergency Preparedness Guide [19]. The Local NERHQ would have the capability to make predictions of the impact of releases using SPEEDI, based on data obtained from the ERSS, and to monitor environmental radiation levels in real time, using monitoring posts located in the vicinity.

The importance of initiating protective actions upon detection of conditions in the power plant that can result in core damage has been recognized for many years [95] and supported by numerous studies. The most recent study by the United States Nuclear Regulatory Commission [96] shows that initiating protective actions upon detection of conditions that will result in core damage can be very effective in reducing the risk of detectable radiation induced health effects.

The NSC's Nuclear Emergency Preparedness Guide [19] provided guidance for the establishment of EPZs. According to the Guide, the analysis used to establish the size of the EPZ showed that protective actions such as sheltering and evacuation should be unnecessary outside of the EPZ. Within the EPZ, arrangements needed to be made for: communicating information to the residents; establishing an environmental monitoring system; and implementing urgent protective actions, etc.

As indicated in the Guide [19], the amount of release was inversely estimated from the levels of dose, as criteria for protective actions (see Table 3.3–1), namely 10 mSv effective dose due to external exposure and 100 mSv equivalent dose to childhood thyroid at distances of 8 km and 10 km from an NPP [15]. Thus, release characteristics consistent with those postulated for severe reactor accidents were not considered.

TABLE 3.3–1. CRITERIA FOR THE IMPLEMENTATION OF SHELTERING, EVACUATION AND IODINE THYROID BLOCKING[47]

Projected dose (mSv)[a]		Protective measure
Effective dose due to external exposure	Equivalent dose due to internal exposure: Of childhood thyroid due to radioactive iodine; Of the bone surface or lung due to uranium of the bone surface or lung due to plutonium	
10–50	100–500	Residents must seek shelter indoors, such as their houses. Windows, etc., should be closed to ensure airtightness. However, seek shelter in a concrete building or evacuate as instructed, if there is a release of neutron beams or gamma rays directly from the facility.
50 or more	500 or more	Residents must seek shelter in a concrete building or evacuate as instructed.
Equivalent dose of childhood thyroid due to radioactive iodine (mSv)[a]		Protective measure
100		Iodine thyroid blocking for individuals of less than 40 years of age, if needed, and considering the implementation of other protective measures.

[a] The projected dose is a dose that an individual would receive if he/she stayed outdoors and no actions were taken during the release of radioactive material or radiation.

[47] The contents of the table are taken from the Regulatory Guide on Emergency Preparedness for Nuclear Facilities, developed by the NSC of Japan, as translated into English [19].

There were no provisions for a precautionary action zone (PAZ) to plan for prompt protection of those at greatest risk (i.e. in the immediate vicinity of the site).

The dose criteria in the NSC's Nuclear Emergency Preparedness Guide [19] for sheltering, evacuation and ITB were consistent with the guidelines for generic intervention levels and generic action levels for protective actions in an emergency established in the IAEA safety standards [11].

The criteria of activity concentrations of specific radionuclides to be used in the case of a nuclear emergency for restrictions on food and drink produced in Japan had been developed before the accident[48] (Table 3.3–2) [19]. However, these values had not been adopted for use in an emergency as specific regulatory limits[49] [21, 25].

TABLE 3.3–2. CRITERIA FOR RESTRICTIONS ON THE INTAKE OF FOOD AND DRINK[50] (NUCLEAR EMERGENCY PREPAREDNESS GUIDE)

Food and drink	Radionuclide
	Radioactive iodine (representative nuclide of mixed nuclides: I-131)
Drinking water Milk/dairy products	3×10^2 Bq/kg or more
Vegetables (excluding root vegetables and potatoes)	2×10^3 Bq/kg or more
	Radioactive caesium
Drinking water Milk/dairy products	2×10^2 Bq/kg or more
Vegetables Grain Meat, eggs, fish, other	5×10^2 Bq/kg or more
	Uranium[a]
Drinking water Milk/dairy products	20 Bq/kg or more
Vegetables Grain Meat, eggs, fish, other	1×10^2 Bq/kg or more
	Alpha nuclides of plutonium and transuranic elements[a] (total of radiation concentrations of Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Cm-242, Cm-243 and Cm-244)
Drinking water Milk/dairy products	1 Bq/kg or more
Vegetables Grain Meat, eggs, fish, other	10 Bq/kg or more

[a] As the indices of restrictions on intake of food products marketed for infants, 20 Bq/kg was to be applied for uranium, and 1 Bq/kg for alpha nuclides of plutonium and transuranic elements. However, this criterion was to be applied to those products cooked and served for meals.

[48] The MHLW is responsible for food and water safety in Japan.

[49] Criteria for food imported into Japan (370 Bq/kg of radioactive caesium — ^{137}Cs and ^{134}Cs) were established as a regulatory limit following the accident at the Chernobyl NPP in the former Soviet Union in 1986 [25].

[50] The contents of the table are taken from the Regulatory Guide on Emergency Preparedness for Nuclear Facilities, developed by the NSC of Japan, as translated into English [19].

3.3.2. Urgent protective actions

The timeline of events that were important for urgent protective actions during the response to the Fukushima Daiichi accident are shown in Fig. 3.3–2. Owing to the overlap in the EPZs of the Fukushima Daiichi and Daini NPPs (see Fig. 3.3–1), decisions on the urgent protective actions for the Fukushima Daini NPP are also described.

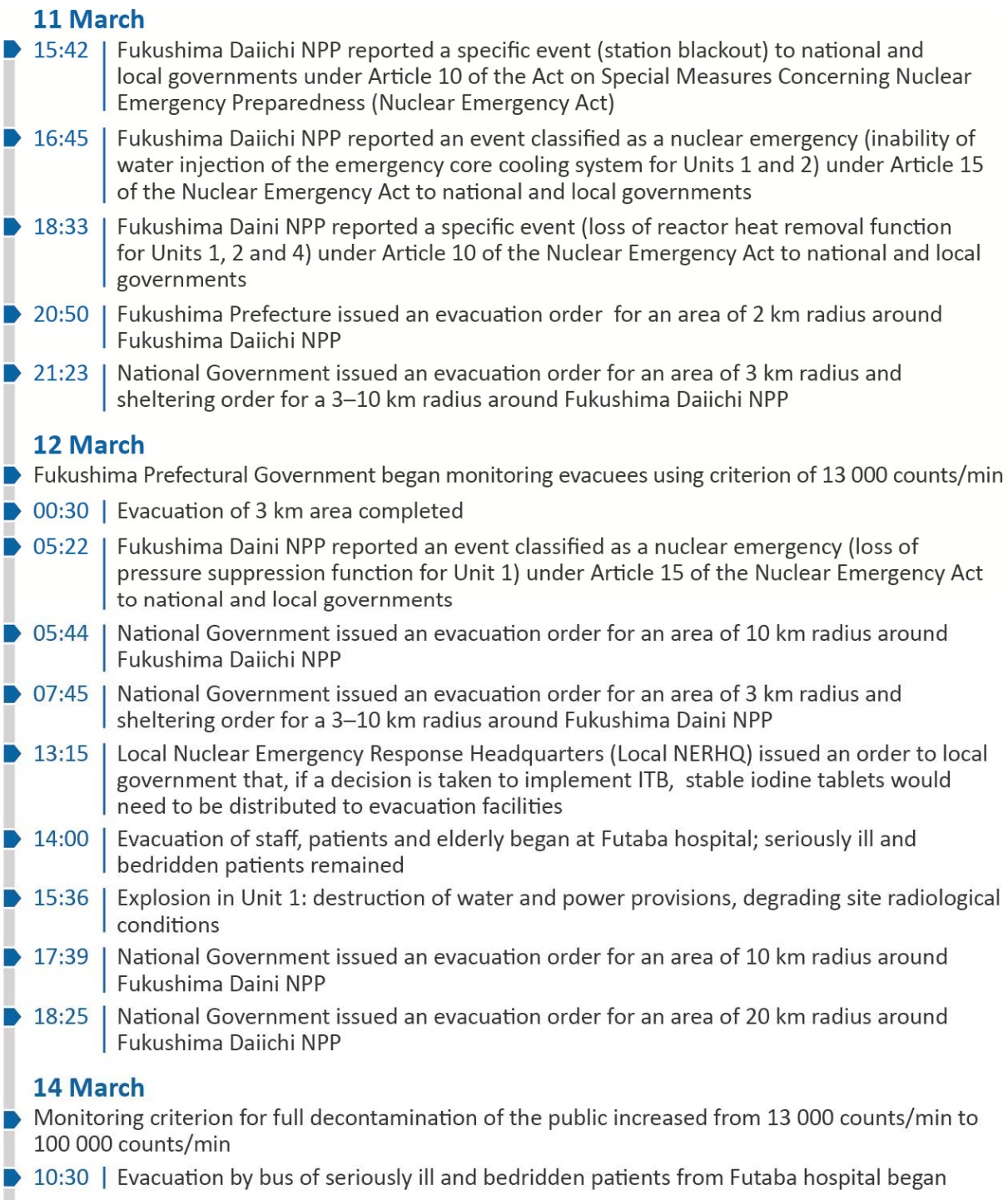


FIG. 3.3–2. Timeline of key events important for urgent protective actions.

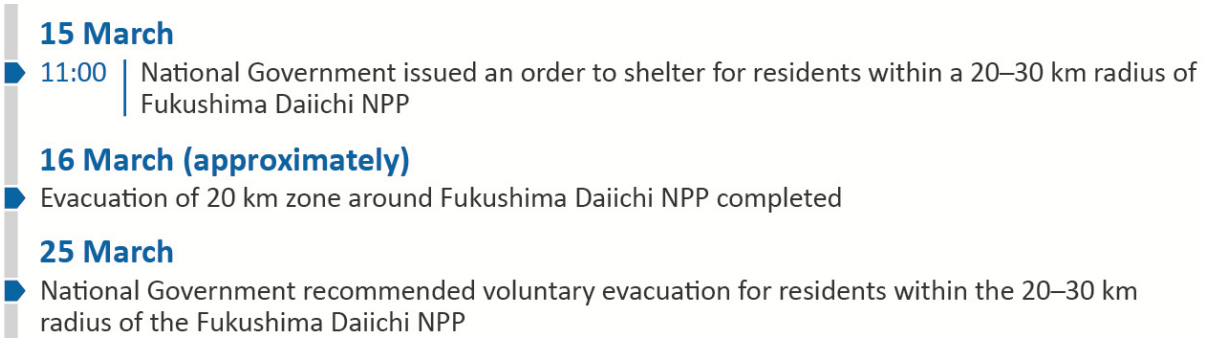


FIG. 3.3–2. Timeline of key events important for urgent protective actions (cont.).

3.3.2.1. Evacuation and sheltering

During the response to the accident, 'source term' estimates[51] from the ERSS could not be provided as an input to SPEEDI owing to the loss of on-site power. Decisions on evacuation and sheltering were taken on the basis of plant conditions (i.e. loss of core cooling), rather than on dose projections as had been planned [22, 25].

Decisions based on events at the Fukushima Daiichi NPP

At 20:50 on 11 March 2011, Fukushima Prefecture issued an evacuation order for residents within a radius of 2 km of the Fukushima Daiichi NPP on the basis of information received directly from TEPCO personnel who visited the Fukushima Prefectural Government Office (this was done in addition to receiving the Article 15 notification from the Fukushima Daiichi NPP) [6, 22, 25, 27].

The 2 km evacuation zone was determined based on experience gained in past emergency preparedness exercises [25].The Fukushima Prefectural Government was not aware that, at that time, the national Government was also considering the need to evacuate the population from the vicinity of the Fukushima Daiichi NPP [25].

The decisions of the national and local governments on protective actions were not always coordinated, mainly as a result of the severe communication problems and partly due to the difficulties in activating the Off-site Centre [45]. At 21:23 on 11 March, the national Government issued an evacuation order for an area within a radius of 3 km of the plant, and sheltering for an area within a radius of 3–10 km.[52] The national Government decided on the 3 km radius based on the recommendation in the IAEA safety standards [13] for the PAZ and because it was thought to be sufficient even if venting was required [21][53]. When the national Government issued its order for a 3 km radius evacuation, it was not aware that local government had already issued an order for a 2 km radius evacuation [27].

At 05:44 on 12 March 2011, the national Government issued an order for the evacuation of an area with a radius of 3–10 km, and at 18:25 it extended it to an area within a radius of 20 km of the plant [22, 25]. As a result of the plant conditions, difficulties in coordination and insufficient pre-planning, orders for evacuation and sheltering were modified several times within 24 hours.

---

[51] That is, estimates of the timing, rate and composition of the releases.

[52] The national Government issued an order for evacuation about 4½ hours after the Fukushima Daiichi NPP notified off-site officials at 16:45 of an event under Article 15 of the Nuclear Emergency Act [5] (Fax 2, Annex I).

[53] However, it should be noted that IAEA guidance for the radius of the PAZ is not based on venting.

This new order was explained by the Prime Minister at 20:32 on 12 March to the media [27]. No descriptions were found in the report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations[54] that the Chief of the Nuclear Emergency Response Headquarters instructed the population within a 10–20 km radius to shelter while waiting to evacuate [21, 27, 97].

Decisions based on events at the Fukushima Daini NPP

Cooling of reactor Units 1, 2 and 4 of the Fukushima Daini NPP was lost at 18:33 on 11 March. A notification based on Article 10 of the Nuclear Emergency Act [5] was sent to the national Government and local governments. On 12 March, between 05:22 and 06:07, pressure suppression functions were also lost, resulting in a submission by the NPP of a report pursuant of the provisions of Article 15 of the Nuclear Emergency Act [5].

At 07:45, METI declared a nuclear emergency, after having received approval from the Prime Minister. An evacuation order to citizens within a radius of 3 km and an order for sheltering within a 3–10 km radius of the Fukushima Daini NPP was issued at 07:45 on 12 March 2011 [27].

Following the hydrogen explosion in Unit 1 of the Fukushima Daiichi NPP (at 15:36 on 12 March), a decision was taken at 17:39 on 12 March to evacuate residents within a 10 km radius around the Fukushima Daini NPP as a precaution in case of a similar hydrogen explosion at this plant [27]. As this 10 km evacuation zone was within the 20 km evacuation zone around the Fukushima Daiichi NPP, no further protective actions were needed in relation to the Fukushima Daini NPP.

Implementation of evacuation of the public

At the time of the accident at the Fukushima Daiichi NPP, about 1900 residents lived in the 2 km zone; about 6000 residents in the 3 km zone, about 51 000 residents in the 10 km zone and about 78 000 residents in the 20 km zone. Evacuations[55] also affected those working in these areas [25].

There were major problems in communicating evacuation orders from the national Government to the local government: only three municipalities within the evacuation zone (Futaba Town, Okuma Town and Tamura City) received these orders; the other seven municipalities in the evacuation areas were unable to receive the orders due to problems in telephone communication caused by the earthquake [25]. However, before the national evacuation order was received, municipalities had already issued evacuation orders to residents based either on their independent judgement of the situation or on information obtained via the media [27].

The communication of evacuation orders to the public in municipalities was arranged by using the local disaster management radio communication network, sound trucks, police cars and door-to-door visits [27]. Also, some citizens learned from the media about the need for evacuation and started to leave the area voluntarily [25, 27]. For instance, when evacuation orders were issued for residents in the 3 km zone around the Fukushima Daiichi NPP, nearly all of the residents had already moved to locations outside of this zone. Evacuation of the 3 km zone was completed by about 00:30 on 12 March [27].

---

[54] The Investigation Committee on the Accident at the Fukushima Nuclear Power Station was established by the Cabinet decision of 24 May 2011 with the aim of making policy proposals on measures to prevent further spread of the damage caused by the accident and a recurrence of similar accidents in the future. The members of the Committee, with academic and various other backgrounds, were appointed by the Prime Minister [21].

[55] The evacuation of hospitals and nursing care facilities is dealt with in Section 3.3.2.3.

There were difficulties in evacuation due to infrastructure damage and communication and transportation problems resulting from the earthquake and tsunami. In spite of damaged roads and traffic jams, most residents not requiring medical support began to leave the evacuation area within a few hours after the orders for evacuation had been issued [25].

Figure 3.3–3 shows the percentage of evacuated residents in various locations as a function of time and with respect to the timing of the evacuation orders.

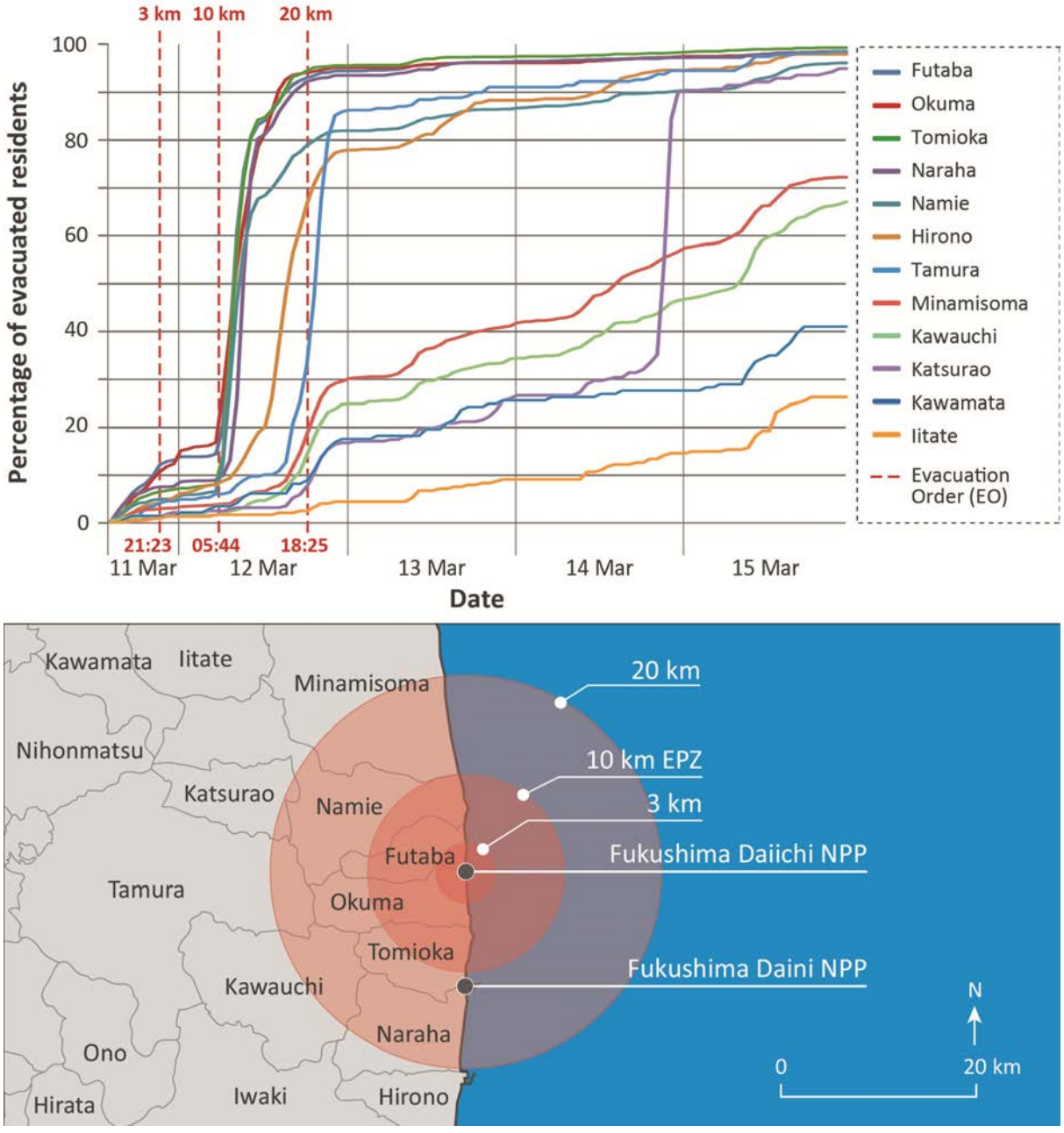


FIG. 3.3–3. Percentage of evacuated residents in various locations [25].

This figure demonstrates that, once evacuation orders had been issued, implementation was rapid. In Futaba Town, Okuma Town and Tomioka Town, which had many areas within the 10 km zone from the Fukushima Daiichi NPP, 80–90% of the residents had left the area within a few hours after the

evacuation order [25]. In areas where no orders for protective actions were issued, e.g. in Iitate Village, residents started to voluntarily leave the area, and by 15 March more than 20% of the population had moved.

According to the Fukushima Prefecture Disaster Management Plan [1], each city/town/village was primarily responsible for implementing protective actions, but in the event of an emergency across the borders of cities, towns and villages, Fukushima Prefecture had the responsibility of formulating an evacuation plan. Shelters to receive evacuees from Fukushima Prefecture were also designated outside the EPZ for the Fukushima Daiichi and Fukushima Daini NPPs (in Iwaki City and Minamisoma City). Fukushima Prefecture also had the possibility to request other municipalities to receive the evacuees [1].

The prefecture coordinated the evacuation of Futaba Town and Okuma Town when evacuation of the 10 km zone was ordered [25]. In other cases, the towns in the evacuation zones made their own arrangements bilaterally with the recipient towns for the destination of their evacuated citizens. In some municipalities, residents were initially advised to go to shelters which were located in the same town or village [25]. Many evacuees were evacuated to locations within 20 km of the nuclear power plant and, each time the evacuation zone was expanded, some of those who had already been evacuated were required to move again. For example, Tomioka Town evacuated its residents to Kawauchi Village, which itself was subject to evacuation according to a decision made by the Government four days later [27]. Some residents were evacuated to areas which were later designated to be within the 'Deliberate Evacuation Area'[56], and thus had to be evacuated more than once: approximately 50% of the residents from Namie Town, 30% from Futaba Town and 25% from Tomioka Town. For other municipalities, it was about 10% of residents who had to be evacuated more than once [25].

More than 20% of the evacuees from towns in the vicinity of the Fukushima Daiichi NPP (Futaba Town, Okuma Town, Tomioka Town, Naraha Town, Hirono Town and Namie Town) were required to move more than six times [25].

The majority of the municipalities located in the 20 km zone learned of the national Government's decision to expand evacuation out to this distance via the media. The pattern of evacuation within municipalities varied. For example, part of Kawauchi Village fell within the 20 km zone and was ordered to evacuate by the national Government at 18:25 on 12 March. Approximately 20–30% of the residents were evacuated on that day. The local government then issued an order for evacuation of those residents of Kawauchi Village located within the 20 km radius on 13 March. Two days later, on 15 March, the local government issued a recommendation for voluntary evacuation of the entire population of Kawauchi Village, which was revised to a full evacuation on 16 March [25].

The completion of the evacuation of the 20 km zone took about three days. There was a need for information[57] to be provided to evacuees, such as how to prepare for an evacuation, how long the evacuation could last [25] and what actions to take while awaiting evacuation.

When the evacuation zone was expanded to 20 km, there were also difficulties in defining which areas were included in this zone. Due to the earthquake, only a limited number of communication channels were available locally. In addition, the OFC had maps only for areas within the 10 km radius, i.e. the

[56] An area established on 22 April 2011 from which residents were encouraged to relocate within roughly one month (see Section 3.3.3.1).

[57] Prior to the accident, leaflets had been distributed to residents located in the EPZ that provided instructions on how to evacuate, including the need to close ventilation systems in houses prior to leaving.

EPZ areas of the Fukushima Daiichi and Fukushima Daini NPPs. Thus, municipalities did not receive detailed instructions from the Local NERHQ at the OFC [27].

Implementation of sheltering of the public

Sheltering is a short term protective action and is used typically for a few days. It is usually used as a temporary measure whenever immediate and safe evacuation is not possible (e.g. for special facilities[58] for which immediate evacuation would create additional risk), and whenever conditions make immediate evacuation impossible or hazardous (e.g. in severe weather). Sheltering, by itself, is not considered to be adequate protection against a release from a damaged reactor core and, if possible, needs to be undertaken in conjunction with ITB.

The order for the sheltering of residents living within a radius of 20–30 km area from the Fukushima Daiichi NPP was given at 11:00 on 15 March and remained in force until 25 March [22, 25]. The residents were not told how long they could expect to have to shelter [25], nor were instructions given on how to minimize indoor contamination while sheltering [98].

This extended time of sheltering and the breakdown of the local infrastructure resulted in serious disruptions to people's lives [7]. For example, in Iwaki City, there was a misunderstanding of the extent of the order to shelter: stores and supermarkets were closed throughout the city, while the order applied only for one area in the northern part of the city [27]. While, by 21 March, the Government supplied the sheltered residents with gas, food and medicine, the level of support proved to be insufficient [25].

Sheltering was not extended to five towns and villages due to their own initiatives:

— Naraha Town received an evacuation order for residents residing within a 3 km zone but decided to evacuate all residents on 12 March;
— Hirono Town, which received an evacuation order for residents residing within a 10 km zone, recommended voluntary evacuation of all residents on 12 March, although a majority of the town's area was located beyond the 10 km zone;
— Katsurao Village decided to evacuate its residents on 14 March;
— Namie Town decided to evacuate its residents on 15 March;
— Kawauchi Village decided to evacuate its residents on 16 March [25].

On 25 March 2011, a recommendation for voluntary evacuation was issued by the national Government to residents within the 20–30 km zone [22, 25], in part because of the difficulties caused by prolonged sheltering [25, 27]. Many residents, however, had already voluntarily left the area. Voluntary evacuation started during the early days of the accident. NERHQ also informed Fukushima Prefecture about lodging facilities and transportation, but the decision whether or not to choose voluntary evacuation after the Government's recommendation was left to the citizens themselves [25]. In Minamisoma City, residents started to evacuate voluntarily as early as 12 March, and about 70% had left the city by 15 March with the help of officials (see Fig. 3.3–3). In addition, charter buses were made available for residents in Minamisoma City between 18 and 20 March, and again on 25 March.

On 22 April, the advisory to shelter for areas located within a radius of 20–30 km from the NPP was lifted [27]. Yet, the recommendation for voluntary evacuation was still valid.

[58] Special facilities include telecommunications centres that need to be staffed, chemical plants that cannot be evacuated until certain actions have been taken to prevent fire or explosions, hospitals with patients who cannot be immediately evacuated and prisons whose inmates have to continue to be managed [11].

Access control to the 20 km zone around the Fukushima Daiichi NPP

On 28 March, a decision was taken to prohibit access to the evacuated areas, and evacuees were informed about this decision on 30 March [27]. Before full access controls were established, some evacuees had returned to their homes in the evacuated areas to collect belongings [27], and no monitoring of the public had been conducted when they exited the area.

On 22 April[59], the existing 20 km evacuation zone around the Fukushima Daiichi NPP was established as a Restricted Area[60], with controlled re-entry and conditions for temporary access. This decision was made in consideration of the rights of residents and was based on consultation with local governments [99]. On 9 May, the NSC provided advice on the implementation of temporary access.

The following conditions were specified for temporary access to the 3–20 km radius: an external dose rate of less than 200 μSv/h; and the time spent in the Restricted Area limited to a maximum of five hours [27].

Safety instructions were given to residents entering the Restricted Area, requiring them to wear protective clothing, carry a dosimeter and a walkie-talkie to ensure a means of communication in case of an emergency, and to bring only small items back from the Restricted Area. In addition, residents were required to be monitored for possible contamination when returning from the Restricted Area, and to undergo decontamination, if necessary [22].

In May 2011, short term temporary access was granted sequentially after coordination with the relevant local governments, with arrangements in place, including specific instructions and monitoring for contamination [27, 99, 100]: access to Kawauchi Village (on 10 and 12 May), Katsurao Village (12 May), Tamura City (22 May), Minamisoma City (25 and 27 May), Tomioka Town (25 May), Futaba Town (26 and 27 May) and Namie Town (26 and 27 May) [22, 100].

Between 13 May and 30 June, almost 20 000 residents, accompanied by staff of the respective municipalities, went to the Restricted Area (see Fig. 3.3–4).

From the end of May, private vehicles were allowed to be transferred from the Restricted Area and, when necessary, contamination monitoring was arranged for these vehicles. Private companies were given temporary access to the Restricted Area if their business would be considerably affected without such access [22].

[59] At 11:00 on 21 April, the NERHQ issued a directive to the heads of all concerned municipalities that restricted areas should be established within the specified radius. The official establishment date was 00:00 on 22 April.

[60] Restricted Areas, established pursuant to the provisions of Article 63, Paragraph (1), of the Disaster Countermeasures Basic Act, applied by replacing the terms and phrases pursuant to Article 28, Paragraph (2), of the Nuclear Emergency Act [5].

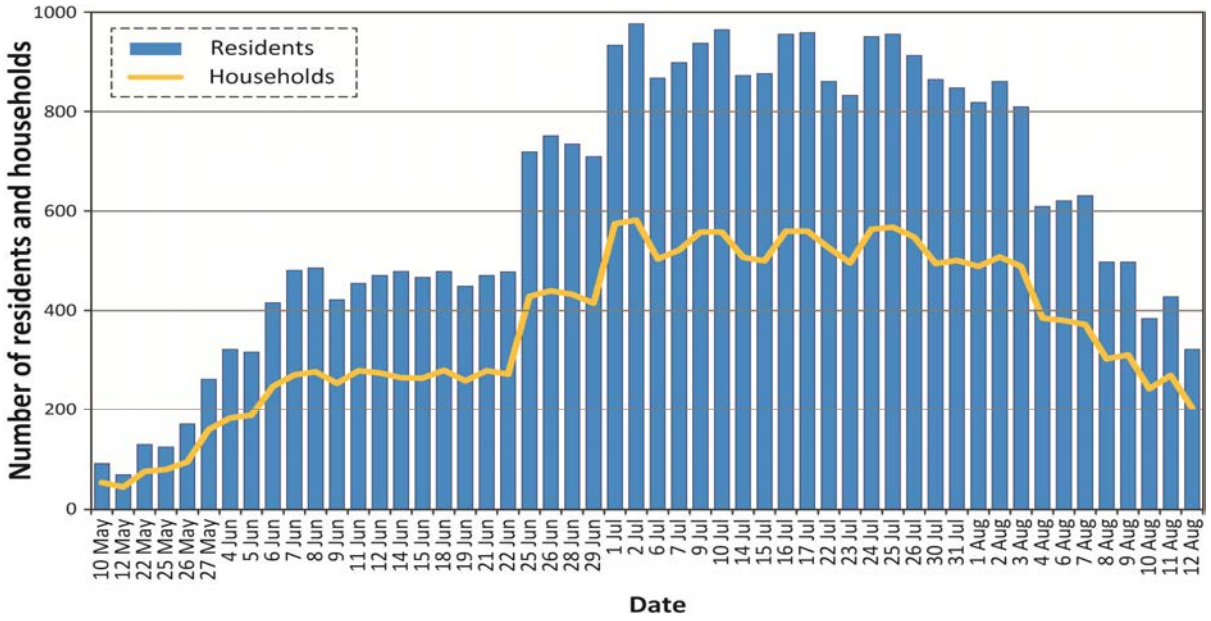


FIG. 3.3–4. Trends in the number of evacuated residents and households temporarily accessing the Restricted Area between May and August 2011 [30].[61] *Evacuation of hospitals and nursing care facilities.*

From 12 March, all hospitals within 20 km (including the designated radiation emergency hospitals) began to close to the public as a consequence of the evacuation order. Three hospitals were completely closed on 13 March and, from 15 March, only one — Fukushima Rosai hospital, located in Iwaki City, approximately 44 km south of the Fukushima Daiichi NPP — of the five primary radiation emergency hospitals in Fukushima Prefecture was functioning (see Appendix II for more details of the emergency medical systems prior to the accident). However, it suffered from severe shortage of medical personnel, who left because of a fear of radiation, among other factors. The only designated radiation emergency hospital in Fukushima Prefecture with sufficient functional capacity was the Fukushima Medical University (FMU) Hospital, which was located 60 km north-west of the plant [80].

In accordance with the Basic Disaster Management Plan [2], the local government needed to give adequate consideration to vulnerable people, such as the elderly and people with disabilities, and to try to evaluate their health conditions in the evacuation area. Prior to the accident, it was planned that evacuation of hospitals within the 10 km EPZ was to be undertaken following the emergency plans, which had been prepared by the hospitals for response to conventional hazards (e.g. fire) [1]. Only one hospital had prepared an evacuation manual for a nuclear emergency [25]. The assumption was that a nuclear emergency would be on the same scale as the JCO Tokaimura criticality accident of 1999 [25], which had only limited impact off-site. Thus, the evacuation of all patients from hospitals and nursing homes located within or beyond the EPZ was not anticipated [25]. During the investigation performed by the National Diet of Japan after the accident [25], medical staff explained that: "[i]t was impossible for us to find, by ourselves, transportation for all the hospitalized patients and hospitals to which all of them could be transferred, unless the number of hospitalized patients was around ten". They further pointed out that "[n]either the earthquake evacuation drills nor the nuclear accident drills were implemented based upon a prior anticipation of having to evacuate all hospitalized patients" [25].

[61] The dates in this figure are not in a linear sequence; the slope and area defined by the histogram and line should therefore be interpreted with caution.

According to Tanigawa et al. [101], approximately 2220 patients and elderly people stayed in seven hospitals and 17 nursing homes within the 20 km evacuation zone. Significant challenges were encountered when evacuating patients from these hospitals and nursing homes (e.g. providing appropriate transport and evacuation shelters with medical supplies). There were seriously ill patients (e.g. terminally ill patients, patients requiring dialysis) whose conditions made it difficult to transport them without potentially causing harm or injury. During the evacuation of hospitals and nursing homes, some fatalities did occur [25]. Official sources have attributed 51 deaths (as of April 2011) to the evacuation of patients and residents from hospitals and nursing homes located within 20 km of the Fukushima Daiichi NPP [102].

Evacuation of the public within a 3 km radius was completed at 00:30 on 12 March [27]. On the morning of 13 March, lists were compiled by the Prefectural Headquarters for Disaster Control of hospitals located within the evacuation zone that had been evacuated only partially [21]. It was estimated initially that the number of patients and elderly people remaining amounted to approximately 700. However, no accurate data were available at that time [103]. The condition of the patients was also unknown. For example, the need to provide continual medical care for mentally ill patients from a psychiatric hospital was not anticipated [21].

In the morning of 13 March, the Prefecture Headquarters for Disaster Control received a request from the Local NERHQ to take care of patients at Futaba Hospital and other places. Upon receiving this request, lists of hospitals and people remaining within 20 km of the NPP were prepared and completed by around 21:40 on 13 March. Based on these lists, the rescue team of the Local Prefectural NERHQ began managing the locations of screening sites and evacuation shelters and assigning people to specific locations. The staff at these shelters informed the Local Prefectural NERHQ that, as a condition for accepting the evacuees, they would have to be monitored and decontaminated [21]. None of the hospitals in Fukushima Prefecture were able to accept the hospitalized patients that were evacuated. Arrangements were made for the evacuated patients to be monitored at a location 30 km away, at the Soso Public Health Centre in Minamisoma City.

The largest number of patients and elderly people (339) evacuated was from Futaba Hospital, located within 5 km from the Fukushima Daiichi NPP. The Prefectural Headquarters for Disaster Control was unaware that many of the patients at the hospital were bedridden (e.g. requiring dialysis, suffering from dementia or in a terminal condition) [21]. It was assumed that, since Futaba Hospital treated patients with mental health problems, only a few of them would have physical problems [21].

Patients from this hospital were transported on 14 March “over a long distance (approximately 230 km) and over a long period of time (over ten hours), with the result that some patients lost their physical strength and others died” [25] (see Fig. 3.3–5). Three patients died in the vehicle during the evacuation, and an additional 11 patients died by early morning of the following day at the evacuation shelter (a high school), at which no medical facilities were available to the patients [25]. Some of the patients and elderly people were not accompanied by the appropriate medical staff when they were evacuated. It was also reported that, during transportation, some bedridden patients were laid on bus seats and suffered traumas when they fell off the seats; in other cases, patients were placed in an unheated room at an evacuation shelter [101].

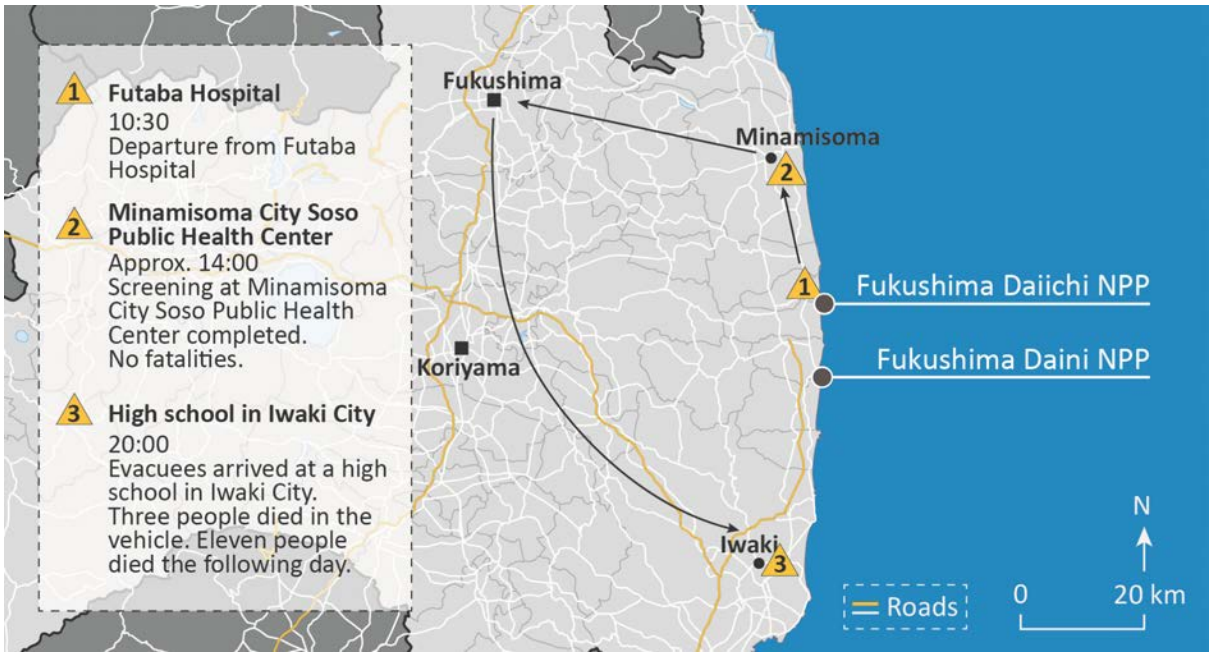


FIG. 3.3–5. The 230 km route of the journey taken by patients evacuated from Futaba Hospital to the high school in Iwaki City [25].

Several rescue teams were dispatched to Futaba Hospital. However, the failure of communication systems meant that the rescue teams were unable to coordinate their missions. One team suspended its mission due to its adherence to the occupational dose limit for females (5 mSv) [21]. The second rescue team did not confirm, prior to leaving, that all patients had been evacuated from all buildings of the hospital. Consequently, some patients were left behind. Four of the remaining 130 patients died at the hospital — two on 13 March and two on 14 March — and another patient left the hospital and went missing [21].

On 15 March 2011, the national Government ordered sheltering in a radius of 20–30 km from the Fukushima Daiichi NPP. On 17 March, the evacuation of all hospitalized patients and elderly people in care facilities within the sheltering zone was initiated because of a shortage of medical supplies and commodities in the area. At this time, the Disaster Medical Assistance Team (DMAT)[62] headquarters, located at the MHLW, planned and arranged the evacuation of more than 400 patients with the support of DMATs [105]. It took two days to obtain permission from the Government to dispatch DMATs to Fukushima Prefecture, largely due to the need for inter-ministerial coordination[63]. Many ambulances and SDF vehicles were mobilized at this time, and DMATs were engaged in performing triage of the patients at collection sites and in providing medical care before and during evacuation. Although it took four days to complete, the evacuation was performed safely without any casualties.

3.3.2.2. Iodine thyroid blocking

Radioactive iodine can be released when the fuel in the reactor core or fuel recently removed from the core overheats. People near the NPP (within about 10–30 km), even those being sheltered, may then

[62] A DMAT is a specially trained medical team for dealing with disasters, consisting of one doctor, two nurses and a logistics specialist [104].

[63] The radiation emergency medical system had been developed under the direction of MEXT, whereas DMATs were under the MHLW.

inhale radioactive iodine, which would concentrate in the thyroid gland causing exposure. Inhalation of radioactive iodine by pregnant women may also lead to exposure of the foetus. The uptake of radioactive iodine by the thyroid gland can be reduced by increasing the intake of stable iodine, which diminishes the impact of radioactive iodine on the thyroid gland (and the foetus). This process is known as iodine thyroid blocking (ITB). To be effective, stable iodine must be administered before or shortly after inhalation or ingestion of the radioactive iodine (i.e. within about two to six hours) [106].

At 13:15 on 12 March, the Local NERHQ issued an order to the Prefectural Government and the respective towns (Okuma Town, Futaba Town, Tomioka Town and Namie Town) that, if a decision was taken to implement ITB, then stable iodine tablets would need to be distributed to evacuation centres, and pharmacists and doctors would need to be stationed at these centres [27]. However, implementation of the ITB was not ordered.

From 03:10 on 15 March to 16 March, discussions were held between the NSC and Local NERHQ through the METI-ERC concerning the distribution of stable iodine tablets to the public. Finally, the Local NERHQ issued an order at 10:35 on 16 March to the Fukushima Prefectural Government and municipalities indicating that stable iodine should be administered to those who were being evacuated from within a radius of 20 km of the Fukushima Daiichi NPP. However, the Fukushima Prefectural Government did not follow this order, because it had already confirmed that evacuation of people from within the 20 km zone was complete [27].

On 14 March, the Fukushima Prefectural Government decided to distribute two stable iodine tablets to each resident younger than 40 years old outside the 20 km radius and within an approximate radius of 50 km of the Fukushima Daiichi NPP. By 20 March, the Fukushima Prefectural Government had distributed approximately 1 000 000 stable iodine tablets [27].

Administration of stable iodine for ITB was not implemented uniformly, owing primarily to inadequate pre-planned arrangements. Some local governments distributed stable iodine tablets but did not advise taking them, while others distributed the tablets and advised the public to take them, and still others awaited instructions from the national Government [27].

With regard to the use of ITB based on skin monitoring results, a meeting of the national Government took place at midnight on 12 March to decide whether and when to issue orders on administration of stable iodine. It was decided that stable iodine should be taken when the results of skin monitoring (screening)[64] exceeded 10 000 counts/min, but this was not implemented[65].

3.3.2.3. Monitoring of the public

In general terms, it is very unlikely that, in the event of a severe reactor emergency, radioactive material deposited on the skin or clothing would represent an important health hazard to anyone off-site. Following the accident at the Fukushima Daiichi NPP, radioactive material deposited on the skin and clothing of the public was monitored to determine if protective or other response actions were warranted.

The monitoring teams in Fukushima Prefecture were managed in a structured manner with teams, equipment and activities scheduled and registered. A system was established for sharing information, with meetings held twice a day. At each briefing, radiation protection and safety issues, including an

[64] In some documents describing the response to the Fukushima Daiichi accident, monitoring of the public is called screening.

[65] While the effectiveness of taking stable iodine when the skin is already contaminated above certain criteria would be limited, it is considered a good practice, as it helps reduce some of the dose to the thyroid [107].

explanation of the steps for preventing internal contamination, were emphasized. The members of the monitoring teams wore protective coveralls and face masks. The monitoring teams were composed of personnel with experience conducting monitoring under normal conditions. Since the members of the monitoring teams routinely worked with radiological detection equipment, it was assumed that no special training for conducting monitoring under emergency conditions was required. The monitoring teams used Geiger–Mueller (GM) survey meters held 1 cm from the body of a monitored individual. For each individual, a few minutes were needed to perform the monitoring.

In accordance with its emergency plan, the Fukushima Prefectural Government began monitoring evacuees as of 12 March, using an operational intervention level (OIL) of 13 000 counts/min that was established for personal decontamination prior to the accident (which corresponded to a response to a surface concentration of 40 Bq/cm^2 for the monitoring instruments they were using) [21].

From 14 March [21], the Fukushima Prefectural Government raised the OIL for public monitoring to 100 000 counts/min[66] for personal decontamination and 13 000 counts/min for partial wipe-off decontamination[67] [21]. The OIL for personal decontamination was increased on the recommendation of the radiation emergency medical team in view of the fact that whole body decontamination was unsuitable under the low temperatures prevailing at the time; most evacuees did not have a change of clothes, and no heated shower facilities were available [21].

On 20 March, the Local NERHQ issued an order to raise the OIL level to 100 000 counts/min based on the provisions of Article 20, Paragraph 3, of the Nuclear Emergency Act [5]. This meant that no decontamination would be required for those with count rates of less than 100 000 counts/min. However, the Fukushima Prefectural Government did not change its practice of conducting partial wipe-off decontamination for those with count rates of 13 000 counts/min, in order to avoid confusing those performing the monitoring and to ensure the safety of those with count rates of 13 000 counts/min [21].

Shelters, hospitals, apartments and other facilities, not only in Fukushima Prefecture but also in other prefectures, began to refuse accepting evacuees who did not have evidence that monitoring had been performed. Because of this, a certification process was created, and a certificate was issued if the monitoring did not detect levels above the criteria (100 000 counts/min) during the initial survey or after decontamination. The issuance of certificates caused problems, because shelters refused to accept evacuees without a certificate. In its document issued on 21 March 2011, the Community Health Office of MHLW stated that it was not appropriate for public health centres to issue certifications, because this could lead to an increased workload that may interfere with essential tasks.[68] However, Fukushima Prefecture did not stop issuing the certificates, since they were still in demand [108].

It was also reported that some medical staff at medical facilities refused to treat patients who were possibly contaminated [109].

---

[66] 100 000 counts/min is consistent with the OIL for skin contamination in IAEA safety standards [14] calling for skin decontamination and medical examination.

[67] Partial wipe-off decontamination involves using wet towels or tissues for removing localized contamination.

[68] Article 6 of the Community Health Act (Act No. 101 of 1947) stipulates essential tasks by public health centres. On 18 March 2011, the Community Health Office, General Affairs Division, Health Service Bureau and MHLW, requested community health departments in the prefectural government (a city as prescribed by the Cabinet Order as set forth in Article 5(1) of the Community Health Act) and in a special ward of Tokyo to conduct health consultations related to the health effects of radiation on residents in public health centres and equivalents. The document issued by the Community Health Office on 21 March 2011 additionally requested that public health centres do not issue certifications because of the higher workload this would entail, which would have an impact on essential tasks, including health consultations.

More than 200 000 people, representing over 10% of the population of Fukushima Prefecture, were monitored in total. The measurement results of 901 individuals were between 13 000 and 100 000 counts/min, and these individuals therefore needed partial wipe-off decontamination. The measurement results of 102 individuals were higher than 100 000 counts/min, thus requiring whole body decontamination. The results of measurements for the latter group were below 100 000 counts/min once they had removed their clothing [27].

3.3.2.4. Prevention of inadvertent ingestion

The inadvertent ingestion of radioactive material deposited on the skin or on the ground (e.g. from inadvertent ingestion of dirt on hands) can be a significant source of dose for those living near the NPP (e.g. 10–30 km) in the first few days following a release [110]. Inadvertent ingestion can be reduced by following some simple precautions, such as keeping hands away from the mouth and refraining from eating with possibly contaminated hands or smoking in the potentially contaminated areas. However, no evidence was found that such orders were provided to the public around the Fukushima Daiichi NPP.

3.3.2.5. Restriction on ingestion of local produce, milk from grazing animals, rainwater and wild grown products

The accident at the Chernobyl NPP clearly demonstrated that ingestion of food and water directly contaminated by the release (e.g. leafy vegetables and rainwater) or contaminated through the food chain (e.g. milk from animals grazing on open grass and wild products[69]) can be a major source of dose within the first weeks following a release [111].

Following a radioactive release, the patterns of the deposition are very complex and are constantly changing if there is an ongoing release. These complex and changing deposition patterns may make it impossible to promptly identify areas that warrant restrictions on consumption, solely on the basis of monitoring and sampling, particularly for those items that could be consumed shortly after the radioactive material has been deposited (e.g. within the first week). Therefore, as an urgent protective action, restriction of the consumption of food and water directly contaminated by the release of radionuclides (e.g. leafy vegetables, milk from animals grazing on open grass, rainwater and wild products) needs to be taken immediately after a release and before monitoring is performed. Afterwards, restrictions on food and water consumption need to be based on monitoring results of food and water samples [107, 112].

Within 24 hours of the onset of the accident at the Fukushima Daiichi NPP, the Ministry of Agriculture, Forestry and Fisheries (MAFF) requested the Fukushima Prefectural Government to stop collection of wild mushrooms and wild edible plants and to stop harvesting crops in the event of any releases of radionuclides into the environment [113]. On 15 March, MAFF started providing instructions and guidance on sampling and analysis to the local governments of affected prefectures and cities.

3.3.3. Early protective actions

Early protective actions are those actions that must be taken within days or weeks to be effective. They can be long lasting, even after the termination of the emergency. Unlike urgent protective actions, it is generally possible to base these actions on the results of monitoring that takes account of the specific nature of the release of radioactive material and its dispersion in the environment.

[69] For example, wild mushrooms and game.

Examples of early protective actions include relocation, restrictions on food and drinking water and controls on agriculture [11, 12]. A timeline of events related to the implementation of early protective actions relevant to the Fukuskima Daiichi accident is presented in Fig. 3.3–6.



FIG. 3.3–6. Timeline of key events relevant to early protective actions.

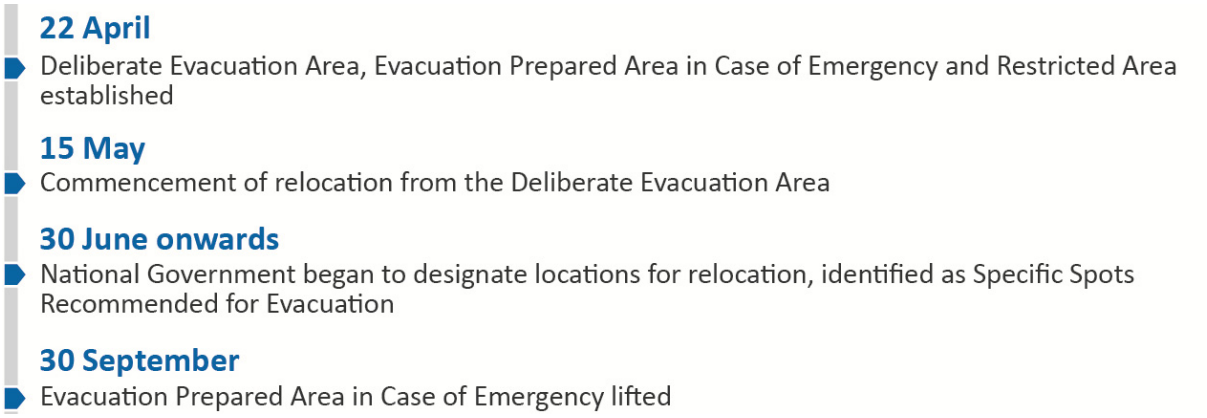


FIG. 3.3–6. Timeline of key events relevant to early protective actions (cont.).

3.3.3.1. Relocation

As discussed in Section 3.3.2.1, on 25 March a recommendation for voluntary evacuation within the 20–30 km zone was announced [25, 27]. A large proportion of residents had already left before the recommendation was issued [25].

On 11 April 2011, the national Government announced that the criterion of 20 mSv dose projected to be received within one year from the date of the accident would be used to determine areas beyond the 20 km evacuation zone from which people might need to be relocated[70] [22]. This criterion was recommended by the NSC on 10 April [25, 27, 114], applying the lowest level in the 20–100 mSv band of reference levels for emergency exposure situations from the ICRP [115][71], at which consideration should be given to reducing doses. According to the ICRP [115], the selection of the criteria also needs to be justified and do more good than harm, considering the overall impact of the actions taken to reduce the dose.

Monitoring results from 15 March and afterwards indicated that there were areas beyond the evacuated areas where the dose to residents would exceed 20 mSv/y [25].

On 22 April 2011, a Deliberate Evacuation Area was established beyond the 20 km evacuation zone to include areas where the projected dose criterion of 20 mSv in one year might be exceeded[72]. This was pursuant to the provision of Article 20, Paragraph 3, of the Nuclear Emergency Act [5]. The boundary of the area was determined in part by using estimated values of the integrated (cumulative) effective dose over one year after the onset of the accident based on measurements [21].

The area covered Katsurao Village, Namie Town and Iitate Village, part of Kawamata Town, and part of Minamisoma City. The national Government issued an order to the effect that relocation of people from this area should be implemented in approximately one month [22, 117].

The delay in establishing a Deliberate Evacuation Area was due to the need to coordinate and consider the opinions of different stakeholders, as there were no existing criteria for relocation prior to

[70] Most of the official Japanese documents describing the response to the Fukushima Daiichi accident do not use the term relocation but refer to the movement of people as ‘evacuation’.

[71] Prior to this decision, on 21 March, a message was issued by the ICRP which contained quotes from generally applicable recommendations of the ICRP (see Annex II).

[72] The recommendation of the ICRP was considered as a reference by the NSC when determining the criteria for establishing the Deliberate Evacuation Area. The criteria for establishing the Deliberate Evacuation Area was authorized by the Japanese Government after reporting its basis to Nuclear Emergency Response Headquarters [116].

the accident. There were also concerns that an expansion of the zone would cause confusion and anxiety among the public [25].

In addition to the Deliberate Evacuation Area, an Evacuation Prepared Area in Case of Emergency (hereafter referred to as Evacuation Prepared Area) was established on 22 April 2011 (see Fig. 3.3–7). Residents of the Evacuation Prepared Area were advised to shelter or evacuate by their own means in the event of possible renewed concerns regarding the Fukushima Daiichi NPP. The designation of the Evacuation Prepared Area was lifted on 30 September 2011 [27].

As a result of the environmental monitoring conducted beyond the Restricted Area (i.e. the 20 km evacuation zone) and the Deliberate Evacuation Area, specific locations were identified with projected doses to residents above 20 mSv within one year after the occurrence of the accident. On 16 June, the national Government announced a guideline which specified that these locations should be designated as Specific Spots Recommended for Evacuation. As of 30 June, the national Government began to designate these locations to be relocated [25, 27].

In order to implement this action, the Local NERHQ was given the task to consult and coordinate with the Fukushima Prefectural Government and the municipalities where the spots recommended for evacuation were located. On 30 June and 25 November, it was recommended that residents living in specific hot spots in Date City should be relocated; on 21 July and 3 August, the same recommendation was made for residents living in Specific Spots of Minamisoma City [27]. As of May 2012, 282 houses were declared to be located in Specific Spots [25]. Residents of these households were offered the choice to relocate; if they decided to do so, they would receive compensation[73]. The implementation of this relocation varied. In some cases, local governments established their own criteria for identifying households to be relocated and also set different criteria to be applied for children and pregnant women [25].

Reopening of schools

Schools in Japan had been closed for spring vacation from the end of March. Local government officials had to decide at an early stage whether to reopen schools and under what conditions. There was a need to set a criterion for reopening schools located in the areas where residents were advised to shelter. At the start of April, Fukushima Prefecture requested the national Government for advice concerning the reopening of schools. Preparation of advice involved consultations between MEXT, which provided air monitoring results, and the NSC. A letter from the ICRP, sent on 21 March 2011, was taken into account.

Initially, on 19 April 2011, a dose criterion of 20 mSv/y was established for this purpose. Based on this dose criterion, an operational criteria of a dose rate of 3.8 μSv/h was calcuated and used in the decision about reopening schools. On 19 April 2011, a decision was also made to restrict outdoor activities at schools and kindergarten grounds with dose rates of more than 3.8 μSv/h [25].

Based on this operational criteria of 3.8 μSv/h, decontamination activities were perfomed for the schools in Fukushima Prefecture. According to the information provided by the Report of National Diet of Japan [25], decontamination activities were also performed for most of the schools in Fukushima Prefecture, including those where the operational criteria were not exceeded. This was done to address public concerns.

The reopening of schools was categorized as action in an existing exposure situation, while the establishment of the Deliberate Evacuation Area was handled as an emergency exposure situation. However, in both cases, the criterion of 20 mSv projected annual dose was used [25].

[73] However, some residents who remained also requested compensation.

The criterion of 20 mSv/y was later reduced to 1 mSv/y. According to the Report by the National Diet, this was done in response to concerns on the part of the public [25]. On 27 May, a notification was issued by MEXT for reducing the dose to children, students and others at schools and other facilities in Fukushima Prefecture. The notification specified a target dose of 1 mSv per year, stipulated that dosimeters should be distributed to schools and stated that financial support for decontamination was to be offered to schools with dose rate measurements higher than 1 μSv/h.

On 26 August, MEXT announced that, after the summer vacation, the criterion of 1 mSv/y would be applied to schools, and the operational criterion of 1 μSv/h would be used [27].

Overview of implemented urgent and early protective actions

The areas and locations for which protective actions were ordered or recommended until 30 September 2011 are shown in Fig. 3.3–7.

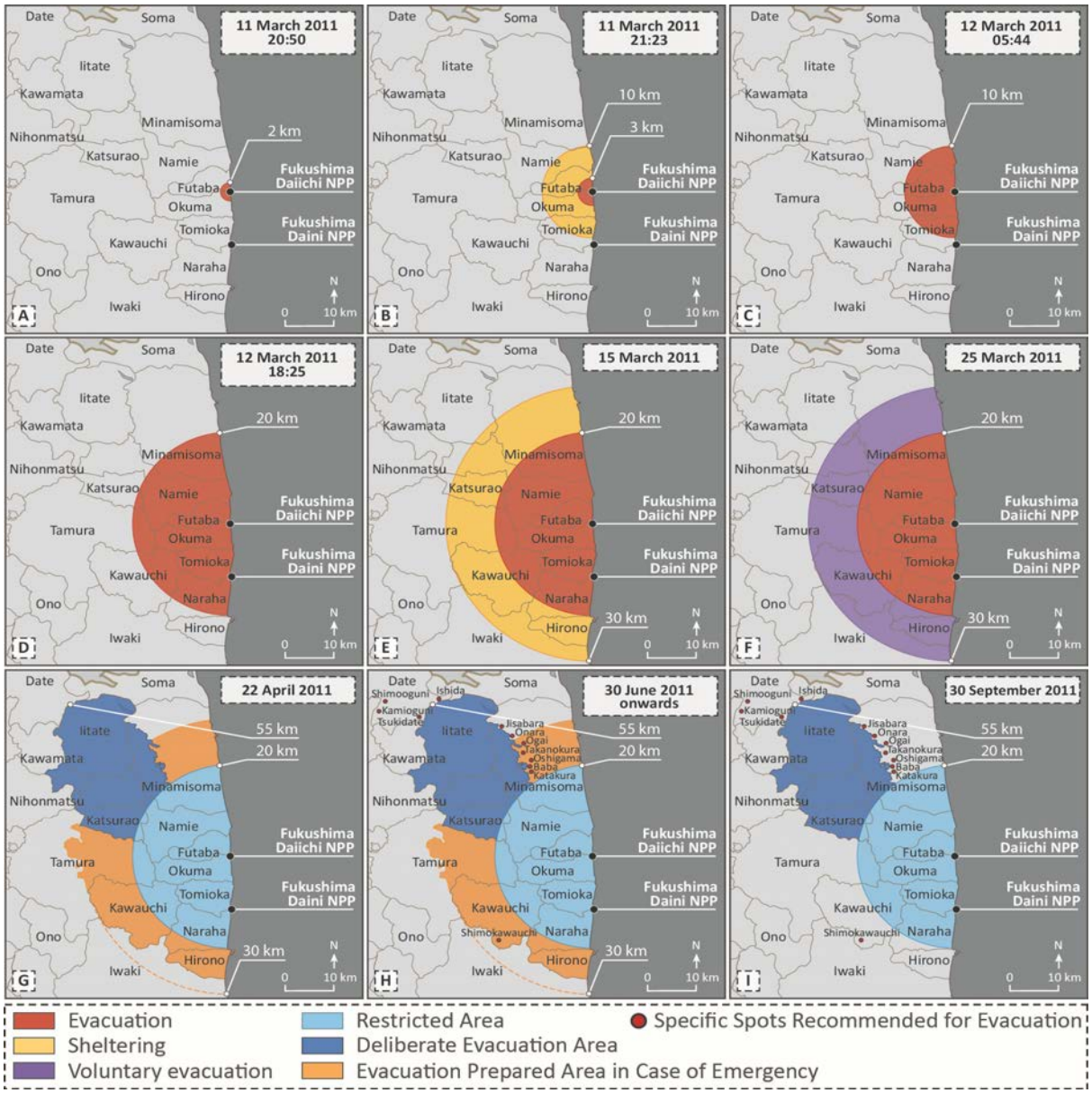


FIG. 3.3–7. Areas and locations where protective actions were ordered or recommended until 30 September 2011 (based on Refs [22, 25, 27, 99]).

3.3.3.2. Protective actions relating to food and drink

Following a release of radioactive material resulting from damage to the fuel in a reactor core, consumption of vegetables grown in the open air, milk from animals grazing on contaminated grass and rainwater can be one of the largest contributors of dose [13].

Authorities in Japan took actions to control the distribution of food, milk and drink from affected areas.

Food and milk

Environmental monitoring was being carried out by the Fukushima Prefectural Government as early as 15 March 2011 and was based on their Prefecture Disaster Management Plan. The results of initial environmental monitoring programmes began to indicate the levels of radionuclides present in vegetation, surface waters and soils in different locations.

On the evening of 15 March, initial results were available indicating ^{131}I at levels ranging from 277 to 1230 kBq/kg and ^{137}Cs in the range of 31.1 to 169 kBq/kg in vegetation (weeds) at four locations, at a distance of 36 km and 46 km from the Fukushima Daiichi NPP [25]. These levels were higher than the provisional regulation values[74] established by MHLW two days later, on 17 March, under the Food Sanitation Act, by adopting into law the criteria in the NSC Nuclear Emergency Preparedness Guide (Table 3.3–3) [118].

As mentioned in Section 3.3.1, criteria for activity concentrations of specific radionuclides for use as the basis for placing restrictions on food and drinking water, in the case of a nuclear emergency, had been developed in Japan before the accident [19]. However, these values had not been adopted for use in an emergency as specific regulatory limits [25, 27]. Therefore, within days of the accident the authorities were deciding on limits related to radionuclides in food and drink. Overnight, from 14 to 15 March, MHLW and MAFF were in discussions about control and regulatory actions relating to radioactivity in food.

Results for activity concentrations of ^{131}I, ^{134}Cs and ^{137}Cs in leafy vegetables, pond water and soil samples, taken on 16 and 17 March 2011, indicated high levels of these radionuclides at various locations [119].

Fukushima Prefecture, the Tokyo Metropolitan Government and Tochigi, Ibaraki and Gunma prefectures commenced monitoring of food items as of March 16 [25]. Results specifically relating to food were published on the MHLW web site from 19 March. For example, food samples reported on 19 March included three raw milk samples taken in Fukushima Prefecture and 12 vegetable samples (spinach and spring onions) taken from Ibaraki Prefecture; these were representative of the food in production at this time of year in Japan.

Subsequently, the NERHQ developed measures aimed at defining the food production and collection areas affected, and restricting the consumption and movement of products exceeding the criteria. Arrangements were made for controlling food and drinking water through directions issued from NERHQ. These arrangements included: (1) radionuclide concentration levels of radioactive caesium and radioactive iodine in food and drinking water established as Provisional Regulation Values under the Food Sanitation Act, above which food and drinking water were restricted; and (2) measurements

[74] These levels also included radionuclides that were not directly relevant to this emergency, for example uranium and alpha emitting radionuclides of plutonium and transuranic elements, that were developed for accident scenarios other than those postulated for an NPP.

of radionuclide concentrations in samples of food and drinking water. Within a few weeks, the levels of ^{131}I had decreased significantly owing to its short half-life (about 8 days), and the food restrictions in the medium to long term were based on concentrations of radioactive caesium only [118].

TABLE 3.3–3. PROVISIONAL REGULATION VALUES FOR RADIONUCLIDE LEVELS IN FOOD AND WATER UNDER THE FOOD SANITATION ACT

Nuclide	Product	Provisional Regulation Value (Bq/kg)
Radioactive iodine (representative radionuclides among mixed radionuclides: I-131)	Drinking water	300
	Milk, dairy products*	
	Vegetables (except root vegetables and tubers)	2000
	[Fishery products, included from 5 April 2011] **	
Radioactive caesium	Drinking water	200
	Milk dairy products	
	Vegetables	500
	Grains	
	Meat, eggs, fish, etc.	
Uranium	Infant food	20
	Drinking water	
	Milk, dairy products	
	Vegetables	100
	Grains	
	Meat, eggs, fish, etc.	
Alpha-emitting nuclides of plutonium and transuranic elements (total radioactive concentration of Pu-238, Pu-239, Pu-240, Pu-242, Am-241, Cm-242, Cm-243, Cm-244)	Infant food	1
	Drinking water	
	Milk, dairy products	
	Vegetables	10
	Grains	
	Meat, eggs, fish, etc.	

* The order was not to use products in excess of 100 Bq/kg for infant formula or for drinking directly (hence the drinking water limit for infants was also effectively 100 Bq/kg).
** On 5 April 2011, based on measured concentrations of ^{131}I in fish samples (sand lance), the Provisional Regulation Values were added for activity concentrations of radioactive iodine (2000 Bq/kg) in fishery products [120].

On 21 March 2011, the national Government began to issue restrictions on the distribution of specific food [121] that evolved with the changing situation. The Director General of the NERHQ directed the governors of Fukushima, Ibaraki, Tochigi and Gunma prefectures to impose restrictions on the distribution of spinach and kakina harvested in these prefectures, and fresh milk produced in Fukushima Prefecture [121]. Food restrictions were formulated on the basis of the results of monitoring of food samples that determined which foods were exceeding the criteria and were used to defined the geographical location(s) affected [122, 123].

On 22 March 2011, food sampling results indicated levels of radionuclides above the Provisional Regulation Values in other types of vegetables and also in fresh milk in other areas. Therefore, in addition to the earlier food restrictions, on 23 March, the Director General of NERHQ directed the

Governor of Fukushima Prefecture to impose restrictions on the consumption and/or distribution of leafy vegetables, any flower head brassicas and turnips produced in Fukushima Prefecture. The Director General of NERHQ also directed the Governor of Ibaraki Prefecture to impose restrictions on the distribution of fresh milk and parsley produced in Ibaraki Prefecture [122]. Separate orders issued by the MHLW on 23 March 2011 instructed governors in the neighbouring prefectures of Miyagi, Yamagata, Saitama, Chiba, Niigata and Nagano to extend the monitoring programme of agricultural and livestock products [123].

Over the following months and years, it was this mechanism of using surveillance monitoring and analytical results to determine which foods exceeded the criteria, and to define the affected geographical location(s) where products were contaminated, that was used to formulate food restrictions.

Food monitoring activities increased to include many different prefectures, with Fukushima Prefecture and neighbouring prefectures taking significantly more samples than those located farther from the site of the accident. From 19 March 2011, and over the first four months following the accident, the average number of food samples per day reported by the MHLW was reasonably constant at around 60. This number increased rapidly from July to a maximum of over 700 sample results reported per day in December 2011 (Fig. 3.3–8) [124].

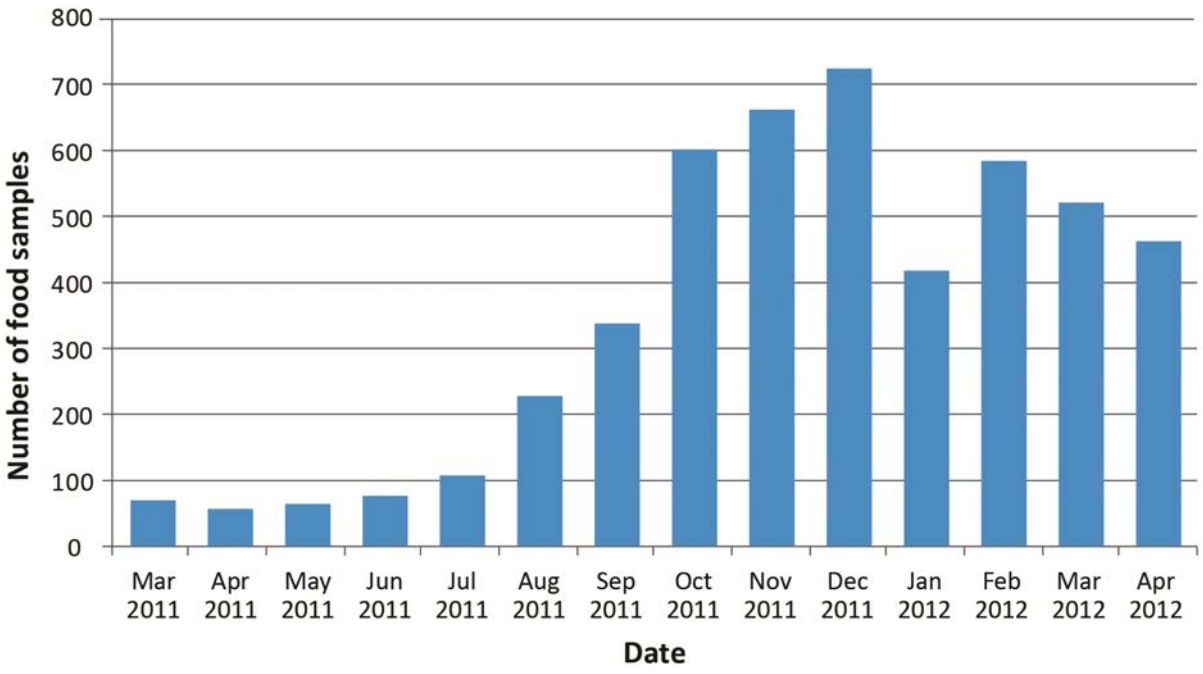


FIG. 3.3–8. Average daily number of food samples reported by MHLW from March 2011 to April 2012 [124].

On 22 March, TEPCO informed MHLW of data indicating radionuclide levels in seawater samples collected at and around a water drain located in the south of the Fukushima Daiichi NPP. MHLW immediately asked Ibaraki and Chiba prefectures to extend their monitoring plans to include seafood available at the coast (due to earthquake and tsunami damage there was no offshore sea fishing) [125].

On 4 April 2011, a policy was established that enabled placement of food restrictions not only in areas defined by prefectural boundaries but also in smaller geographical areas (such as cities, towns and villages), as appropriate. The policy set out a process to establish or lift restrictions on different food products. Prefectures could apply for modifications to restrictions on the condition that the food

monitoring results were below Provisional Regulation Values three consecutive times in weekly monitoring tests [25].

This policy and the legal mechanism of issuing directions under the Nuclear Emergency Act [5] were subsequently used to establish, modify or remove restrictions on different food products. This 'sample and restrict' policy was revised several times to adapt to the situation [27].

The policy revision in June 2011 was necessary because levels of ^{131}I had declined significantly, and levels of caesium radionuclides in food became the main focus of concern. Additional prefectures were also directed to sample food on a regular basis, and additional types of foods were incorporated into the monitoring plans. Samples at that time included foods which were consumed in large quantities in Japan even if the food had not previously been identified as having elevated levels of radionuclides. The revision of 4 August 2011 directed more prefectures to sample foods regularly and emphasized that beef had previously been identified as containing radioactive caesium above the provisional regulatory values [126].

On 1 April 2012, standard limits came into force, which replaced the Provisional Regulation Values (Table 3.3–4).

TABLE 3.3–4. STANDARD LIMITS FOR RADIONUCLIDE LEVELS IN FOOD AND DRINK INTRODUCED ON 1 APRIL 2012

Category	Standard limit for radioactive caesium (Bq/kg)
Drinking water (including beverages)	10
Infant food	50
Cattle milk, including milk based drinks and milk based milk substitutes, but excluding yogurt or yogurt drinks	50
General food	100

These limits specified activity concentrations for radionuclides in food and drinking water on the basis of an effective dose of 1 mSv/y (while the criterion of 5 mSv/y had been used as a basis for the Provisional Regulation Values). The limits took into account the contributions to dose of a range of radionuclides released during the accident by assuming that these additional radionuclides were present in fixed proportions to the concentration of caesium radionuclides. As a consequence, these values were much lower than the Provisional Regulation Values they replaced [127].

Tap water

From 17 March onwards, the concentrations of radionuclides in tap water were measured for each prefecture [22].The MHLW provided regular updates on tap water monitoring data. On 19 March, the MHLW notified local government departments and agencies that the public should avoid consuming tap water if the radionuclide concentration exceeded the Provisional Regulation Values. The MHLW also provided results of water monitoring [22]. On 21 March, the MHLW notified local government departments and agencies that infants should avoid consuming tap water if the radionuclide concentration exceeded the Provisional Regulation Values of 100 Bq/kg of radioiodine [128]. On the same day, the MHLW also announced that radioiodine concentrations (965 Bq/kg of ^{131}I) at a small scale water utility in Iitate Village exceeded the Provisional Regulation Values. Residents were advised of the low health risk and were allowed to continue consuming the water if no alternatives were available. They were also advised that the water could be used for other domestic uses [129, 130].

On 22 March 2011, the MHLW announced the results of drinking water monitoring on the previous day and requested that Date City, Koriyama City, Tamura City, Minamisoma City and Kawamata Town in Fukushima Prefecture inform their residents to refrain from having infants intake tap water (including giving infants formula milk dissolved by tap water, etc.), because radionuclide levels exceeded the Provisional Regulation Value (100 Bq/kg of ^{131}I) that was applicable to infants' drinking water [128]. Similar advice was issued on the following day (23 March) for Iwaki City in Fukushima Prefecture, by the Tokyo Metropolitan Government [131], Tokai Village and Hitachiota City in Ibaraki Prefecture [132]. Thereafter, the MHLW continued the practice of announcing the previous day's drinking water monitoring results and advised the population to refrain from drinking water, as necessary. Advice not to drink tap water was subsequently extended to cover additional prefectures.

On 4 April 2011, the MHLW announced the water monitoring policy, the imposition of restrictions and the cancellation of previous restrictions on drinking water [133]. With regard to the water supply monitoring policy, the MHLW directed regional water suppliers to monitor water by undertaking surveys to measure ^{131}I and caesium radionuclide levels, especially in Fukushima, Miyagi, Yamagata, Niigata, Ibaraki, Tochigi, Gunma, Saitama, Kanagawa, Chiba and Tokyo prefectures. Tap water suppliers were directed to sample water from taps or water filtration plants.

3.3.3.3. Actions to protect agriculture

This part focuses on early actions taken to protect agriculture, specifically in relation to animal feed (primarily to prevent the uptake of caesium radionuclides into dairy and meat products) and actions to minimize the risk of producing rice with caesium radionuclide levels in excess of the Provisional Regulation Values.

Animal feed and contamination of beef

On 19 March 2011, MAFF provided information for cattle farmers as a Notice on Farming Management [27]. This was issued through the prefectural governments in the Tohoku and Kanto districts. This notice was aimed at ensuring that radionuclide levels in livestock were not significantly affected by radionuclides in animal feed. It stated that: cattle raised in regions where dose rates were higher than background must be fed with hay from grass that had been cut, gathered and stored prior to the accident; drinking water for cattle had to be kept in a sealed water tank to prevent contamination; and cattle must not be sent to graze (outdoors on pasture) until further notice.

On 14 April 2011, MAFF provided cattle farmers with a notice via the prefectural governments in the Tohoku and Kanto districts to establish Provisional Permissible Values of concentration levels of radioactive caesium and radioactive iodine in forage for cattle (including hay, pasture grass and straw), in order to prevent or reduce the contamination of beef and milk. This notice stated that the concentrations of radionuclides should be below 70 Bq/kg for radioactive iodine and 300 Bq/kg for radioactive caesium in forage for milking cattle, below 300 Bq/kg for radioactive caesium in forage for beef cattle and below 5000 Bq/kg for radioactive caesium in forage for cattle other than milking and beef cattle [27].

On 8 July 2011, levels of caesium in beef samples exceeding the Provisional Regulation Value (500 Bq/kg) in food were measured in samples collected from Fukushima Prefecture and subsequently in beef from other prefectures. The MAFF Notice on Farming Management was addressed to cattle farmers, but it was not communicated to grain farmers who produced rice straw. It is likely that cattle farmers had fed their cattle with rice straw that had been stored outdoors and had probably been contaminated. A control regime was put in place to prevent such meat from being distributed to consumers [27].

On 1 August 2011, before the rice and wheat harvest, MAFF notified all prefectural governments of maximum Provisional Permissible Values for animal feed (300 Bq/kg of radioactive caesium in feed for cattle, horses, pigs, domestic fowl and other domestic animals, and 100 Bq/kg in feed for farmed fish). Restrictions on the use, production and distribution of feed that exceeded the Provisional Permissible Values were thus established in order to prevent the contamination of animal products with radionuclides via rice bran and wheat bran feed that exceeded the Provisional Permissible Values.

However, on 18 December 2011 and 21 March 2012, beef samples from Fukushima and Iwate prefectures were again identified to have exceeded the Provisional Regulation Values for radioactive caesium [134], possibly due to contaminated feed. Nevertheless, the contaminated meat was detected through routine sampling, and a control regime was put in place to prevent it from being distributed to consumers.

In order to reflect the revision to radionuclide concentration values presented in the standard limits for radionuclide levels in food and drink, the Provisional Permissible Values of radioactive caesium in animal feed were revised prior to the new standard limits for food and drink coming into force on 1 April 2012. New activity concentration levels applicable to caesium radionuclides in feed were established on 3 February 2012 and 23 March 2012 as follows: 100 Bq/kg for horse and cattle feed; 80 Bq/kg for pig feed; 160 Bq/kg for domestic fowl feed; and 40 Bq/kg for farmed fish feed.

Rice production and levels of radionuclides in soil

Protective measures were also put in place to protect the rice harvest in 2011 (see Ref. [27] and Ref. [134]).

On 8 April 2011, the NERHQ issued a policy on restrictions on planting and cultivating rice in agricultural soil that had radioactive caesium levels in excess of 5000 Bq/kg [27]. This level was based on information on the transfer of caesium from soil to rice. Before the accident, the National Institute for Agro-Environmental Sciences had reviewed data relating to radioactive caesium levels in paddy field soil and the rice it produced. These data indicated a transfer coefficient[75] of 0.1 for radioactive caesium from soil to unpolished brown rice. The data also suggested that this transfer coefficient did not depend on the soil type. Polished rice had a lower transfer coefficient, but the more conservative value of 0.1 was used because some Japanese consumers eat brown rice on a daily basis. The upper limit of radioactive caesium in soil in rice production areas (of 5000 Bq/kg) was thus intended to avoid harvesting rice that would exceed the Provisional Regulatory Value of 500 Bq/kg at the end of the growing season [134].

As a precaution, and in view of the fact that rice is a staple food in Japan, the NERHQ, on 22 April 2011, directed the head of the Fukushima Prefectural Government to restrict the cultivation of rice (planting restriction) in 2011 within a 20 km radius of the Fukushima Daiichi NPP as well as in the Deliberate Evacuation Area and the Evacuation Prepared Area, where levels of radioactive caesium in soil exceeding the upper limit were found.

On 30 May 2011, MAFF commenced work in cooperation with MEXT to investigate radionuclide concentrations in agricultural soil. On 30 August 2011, MAFF published a map of radioactive caesium concentration levels in agricultural soils which was based on the results of a survey where soil was sampled from either paddy fields (sampled at 15 cm depth) or other farmland (≤ 30 cm

[75] A transfer coefficient is derived by dividing the concentration of radioactive caesium in the edible portion of the plant (e.g. rice grains) by the radioactive caesium concentration in the soil in which it was grown.

depth) mostly in Fukushima Prefecture but also including samples taken from Miyagi, Tochigi, Gunma, Ibaraki and Chiba Prefectures [30]. In areas where rice cultivation was at that time restricted, the maximum level of radioactive caesium detected in the soil of paddy fields was greater than 30 000 Bq/kg, but in other areas of Fukushima Prefecture it was less than 5000 Bq/kg (upper limit for rice production). MAFF released an updated map of radioactive caesium concentrations in agricultural soils on 23 March 2012 that covered a larger area and included more data points [135].

In August 2011, MAFF also announced that monitoring surveys were to be undertaken to measure radioactive caesium levels in cultivated rice in areas where agricultural products were subject to monitoring surveys, in neighbouring cities, towns and villages, and where radioactive caesium levels in farmland soil exceeded 1000 Bq/kg. Pre-harvest monitoring was to be performed one week prior to harvesting. In rice production areas where the levels of radioactive caesium in rice exceeded 200 Bq/kg as a result of preliminary monitoring, MAFF required one rice sample to be collected per 15 hectares. Where the radioactive caesium in rice was below 200 Bq/kg, MAFF required less intensive sampling (an average of seven rice samples per city, town and village). This rice sampling was undertaken before the rice harvest, and all rice samples collected were found to be below the Provisional Regulation Value [27].

Further monitoring of radionuclide levels in rice was undertaken after the rice harvest as part of the routine monitoring programme. On 29 November 2011, the MHLW announced a restriction on the distribution of rice produced in a specific area of Fukushima Prefecture, because unpolished (brown) rice samples were found to have levels of radioactive caesium above the Provisional Regulation Value [136]. This rice was produced in an area that had not been sampled in the pre-harvest monitoring survey.

3.3.4. Use of the dose projection model SPEEDI as a basis for decisions on protective actions during the accident

As mentioned in Section 3.3.2.1, owing to the loss of power on-site at the Fukushima Daiichi NPP, source term estimates could not be provided by ERSS's subfunction as input data to the SPEEDI system. Thus, it was not possible to project the off-site doses as a basis for decision making on protective actions, using these systems [25]. The alternate projections of doses were performed using other assumptions (predetermined source term of typical severe accidents); however, these projections were not used as a basis for deciding on urgent protective actions [25]. It is extremely difficult to predict the release timing, changes of wind direction and rainfall [25]. During the emergency, it was determined by senior officials and officials in charge that "the accident is not a situation where SPEEDI can be used" [25].

It is also likely that the timing, magnitude, composition and duration of releases would be similarly difficult to predict under many severe reactor accident conditions[76]. For example, severe releases may occur by routes that cannot be monitored by the control room and therefore magnitude, composition or duration of the release may not be known. In addition, severe releases could occur over several days, resulting in very complex deposition patterns off-site, as occurred during the accident at the Chernobyl NPP. The Fukushima Daiichi accident also demonstrated this. The releases during the accident were not predicted, and even a year after the emergency, it was not clear how the releases occurred [17]. In addition, none of the releases from the plant were from release routes that were being monitored. The difficulty in modelling releases for the Fukushima Daiichi accident is illustrated in Figs 3.3–9 and 3.3–10. Figure 3.3–9 shows the ^{137}Cs deposition projected by Japan using a

[76] Examples of causes of containment leakage/failure that are not predicable and that can result in a severe release are: (a) hydrogen explosions; (b) overpressure; (c) by-pass; and (d) failure to isolate. The only release pathway that is predictable is managed venting, and, in most cases, releases by this route would be small [137].

computer model, and Fig. 3.3–10 shows the actual ^{137}Cs deposition concentrations resulting from the accident. The modelling did not reflect the actual situation because of uncertainties in predicting the timing and magnitude of the release, despite having been made on the basis of data available several months after the accident.

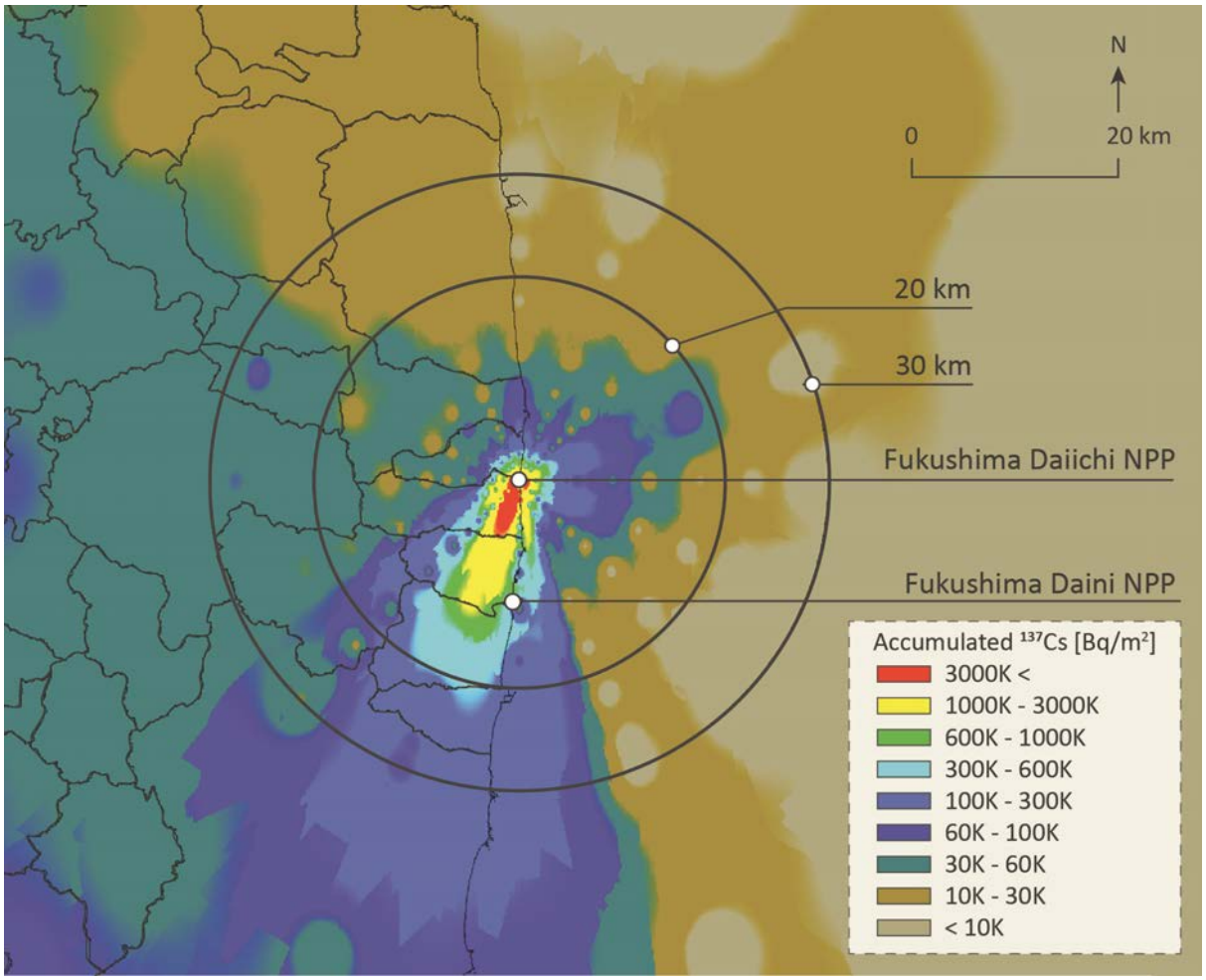


FIG. 3.3–9. ^{137}Cs deposition concentrations based on a model projection [138].

While core damage is sometimes predictable, predictions of containment vessel failure, etc., are extremely difficult to make and, furthermore, it is virtually impossible to make accurate predictions about the amount of released radioactive material and the dose in the early phase when urgent protective actions need to be determined promptly. Hence, it is difficult to make decisions for effective implementation of urgent protective actions based on predictions made in real time [13].

Using the dose projection models for deciding on and communicating the evacuation routes at the time of an accident is likely to cause delays and unnecessary complications. Therefore, deciding and communicating the evacuation route at the time of an accident is not practical [25]. Characteristics of the release, atmospheric dispersion and deposition all may vary significantly, both temporally and spatially, during the evacuation, which may result in the need to change the evacuation routes. Indeed, during the period of the largest overland release from the Fukushima Daiichi NPP (15 March), the wind directions changed by 180 degrees [17]. In addition, failures of communication systems and other problems could make it impossible to effectively implement such changes to evacuation routes. The fundamental concept is to pre-plan and exercise those parts of the response that need to be taken

promptly in order to be effective. Detailed arrangements need to be established in advance and exercised to ensure effective evacuations [139, 140].

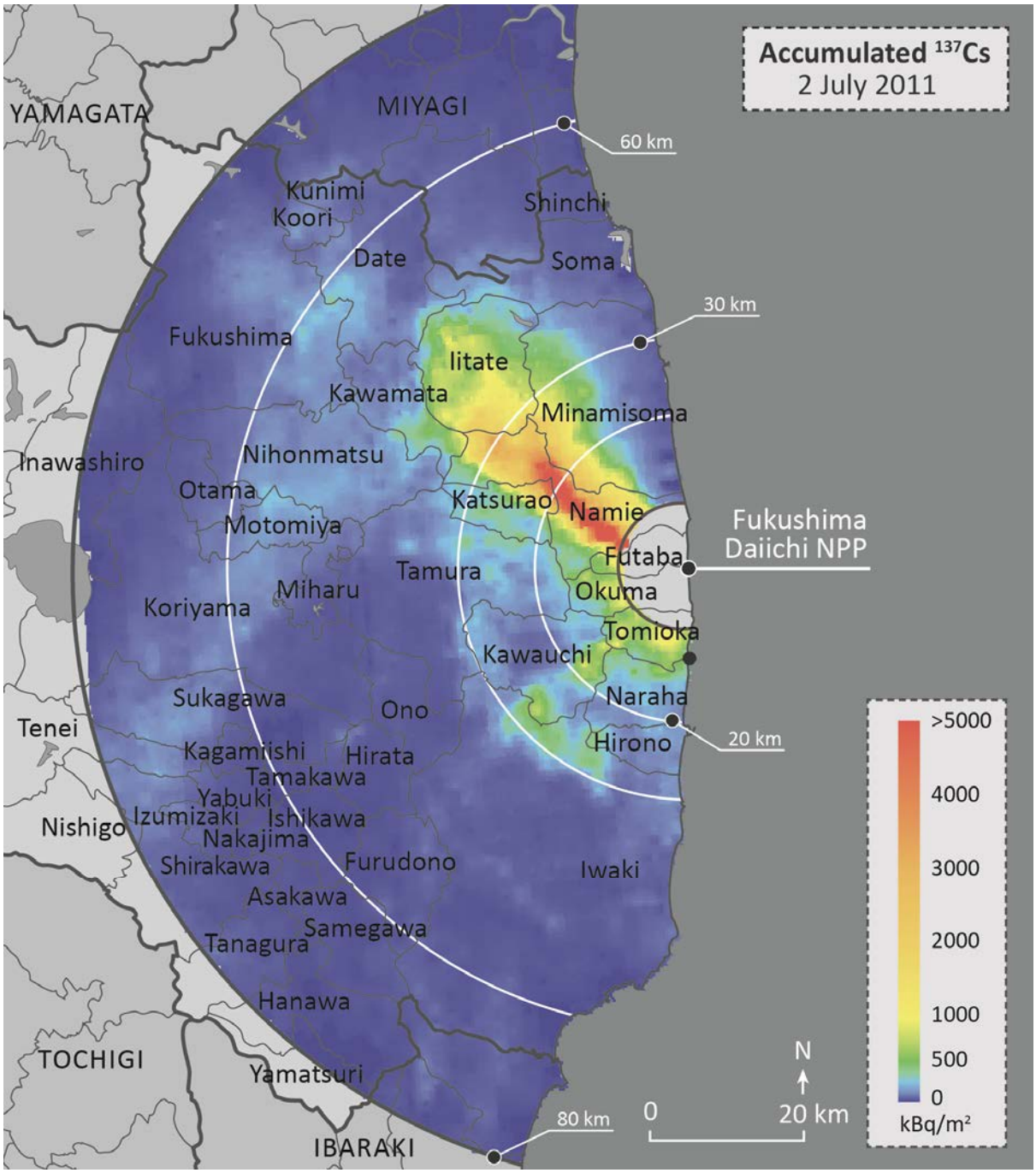


FIG. 3.3–10. Actual ^{137}Cs deposition concentrations [25].

Before the accident [25], EPR experts in Japan began questioning the method of determining protective actions based on projections such as those produced by SPEEDI. Specifically, questions were raised as to the reliability of accident simulation analyses using ERSS, or SPEEDI's radioactivity impact projections that utilized ERSS data. The question whether evacuation orders could really be made by relying on SPEEDI's calculation results, given these uncertainties, was discussed during a meeting conducted by the NSC one month prior to the accident [25].

3.3.5. Environmental monitoring

3.3.5.1. Relevant arrangements in Japan prior to the accident

Under the national EPR arrangements in place prior to the accident [2] in an emergency, the local government would perform environmental monitoring[77] and provide the results to the Local NERHQ [22]. The local government would be supported by teams and equipment provided by MEXT, the NPP operator and designated agencies (e.g. the NIRS and the Japan Atomic Energy Agency (JAEA)) [27].

The three objectives for environmental monitoring were described in the NSC's Regulatory Guide on Emergency Preparedness for Nuclear Facilities (Nuclear Emergency Preparedness Guide) [19] as: (1) Determining the dose rate around the nuclear facility and concentrations of radionuclides in the atmosphere; (2) Determining the concentrations of radionuclides in environmental samples; and (3) Promptly estimating the projected dose in the environment to determine the appropriate protective actions.

Environmental monitoring was to be performed in accordance with the Guideline for Environmental Radiation Monitoring developed by the NSC [141].

The Fukushima Prefecture Disaster Management Plan [1] described the organization and functions of the monitoring and sampling team, including the number of personnel needed to perform functions and the planned flow of information. It also specified that the planning for implementation of monitoring and sampling should be determined at the time of the emergency, with measuring and sampling points to be selected from the locations specified in the Emergency Monitoring Procedure contained in the plan. Detailed lists of available equipment and personnel had been compiled and pre-prepared forms for recording results had been developed (e.g. recording locations and measurements) [1]. The Fukushima Prefecture Disaster Management Plan [1] stipulated that the strategy for monitoring should focus on: (1) locations where iodine concentrations and dose rates are expected to be high; (2) ground deposition in all directions in the vicinity of the NPP; (3) a 60° sector (fan shaped area) around the point at which the highest atmospheric releases of radioiodine concentrations are expected; and (4) densely populated areas downwind from the NPP.

3.3.5.2. Environmental monitoring as a basis for protective actions

Prior to the accident, 23 monitoring posts, under the responsibility of Fukushima Prefecture, were located within about 5 km of the Fukushima Daiichi NPP (Fig. 3.3–11). However, as a result of earthquake and tsunami, only one of these was functioning at the time of the accident [21]. The local government had 12 monitoring vehicles [1] and four germanium semiconductor detectors as well as a number of NaI scintillation detectors[78] [22]. However, two of the four germanium semiconductor detectors were not functioning due to the damage caused by the earthquake [27].

[77] Environmental monitoring is the measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media.

[78] Used for identifying released radionuclides (gamma emitters) and determining radionuclide concentrations.

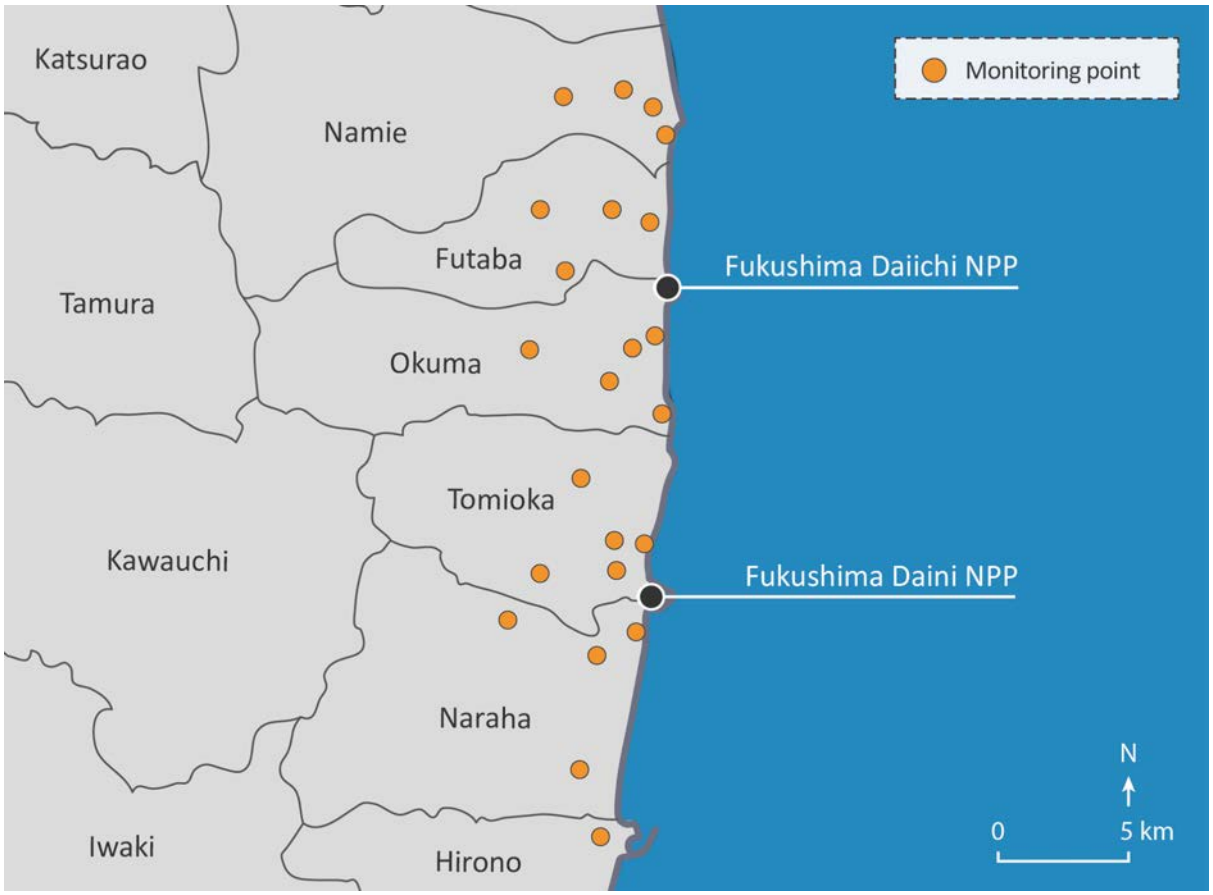


FIG. 3.3–11. Location of 23 monitoring posts located within about 5 km of the NPPs [142]

Initial environmental monitoring activities were associated with numerous difficulties, including: continuing tsunami warnings; dangerous conditions on the roads; vehicles falling into cracks; flat tyres; and shortages of fuel. In addition, the immediate priority was searching for missing people in the affected area rather than environmental monitoring. The relocation of the OFC, where monitoring was to be coordinated, on 15 March to Fukushima City, further complicated the situation [22, 27].

The 12 monitoring vehicles of the local government ran out of fuel and were abandoned [27], along with most of the monitoring equipment [27], and thereafter the national Government led the environmental monitoring efforts [27].

Vehicles and monitoring personnel were obtained from various response organizations (e.g. the National Police Agency and the Ministry of Defense), with 15 monitoring vehicles being used for monitoring from 15 March onwards [22, 27]. Locations for environmental monitoring were determined based on consideration of the results of previous measurements, the wind direction and topographical features [22], in accordance with the Fukushima Prefecture Disaster Management Plan [1].

Early in the morning of 12 March, monitoring began within a radius of 20 km of the Fukushima Daiichi NPP, which was suspended at 21:00 due to damaged roads, fuel shortages and an increase in dose rates. A reduced team of ten members continued monitoring activities on the next day [27]. Monitoring was terminated within the 20 km zone on 14 March, once evacuation within this area had been completed [27]. The first monitoring results measured on 12 March between 08:09 and 09:19 included handwritten results recorded on a photocopied map [143]. The first monitoring results were made public on 13 March.

On 15 March, there was a major release, with the airborne plume traversing over land. Rain on that evening resulted in significant deposition [17]. Dose rates between 255 and 330 μSv/h[79] were measured in the evening of 15 March in three locations beyond the 20 km evacuation zone, as shown in Fig. 3.3–12 [22, 25, 27].

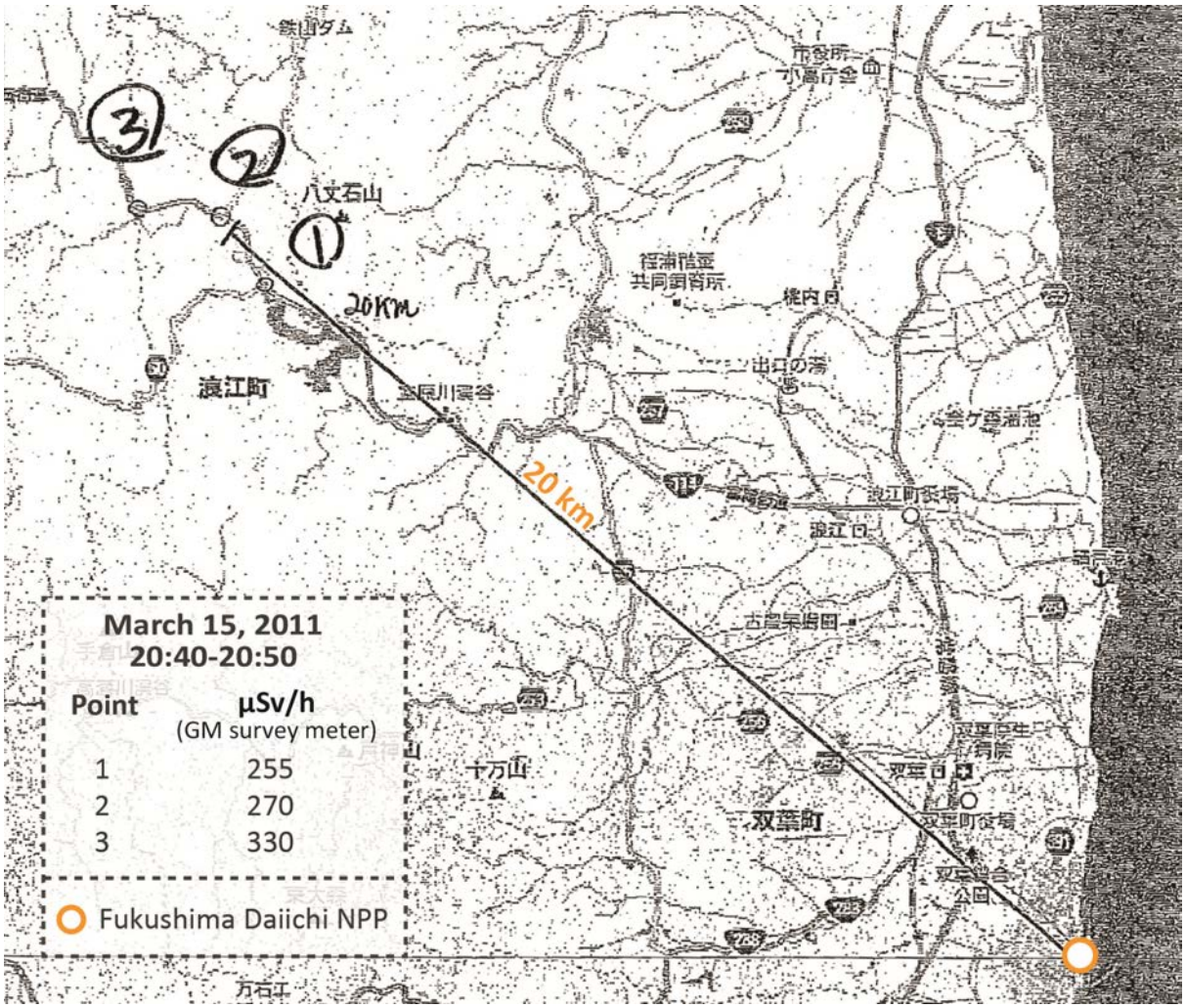


FIG. 3.3–12. Dose rates between 255 and 330 μSv/h measured on 15 March at three locations [22]

Figure 3.3–13 presents the dose rate (μSv/h) measurements from 16 March to 27 May at the locations indicated in Fig. 3.3–14. Figure 3.3–13 shows that on 17 March a value of 170 μSv/h was measured at Monitoring Point 32, which was at a location 30 km north-west of the Fukushima Daiichi NPP, in Namie Town. On 18 March, the NSC requested NISA to check if houses were located in the vicinity of that monitoring point [27]. On 24 March, integrated dosimeters were installed at 15 locations [22], which included Monitoring Point 32 [27]. On 29 March 2011, residents in Namie Town and Iitate Village were advised to shelter for as long as possible, even if they lived outside the 30 km radius

[79] This dose rate from deposition exceeded the dose rate OIL for relocation given in IAEA Safety Standards [14] (this comparison is performed due to the absence of national criteria). The IAEA was in contact with the official contact points in Japan providing explanatory information about the generic and operational criteria and the basis for their recalculation in the prevailing circumstances, as explained in IAEA Safety Standards and technical guidance.

zone. Residents of Namie Town and Iitate Village were relocated after 22 April, since they were located in the Deliberate Evacuation Area [27].

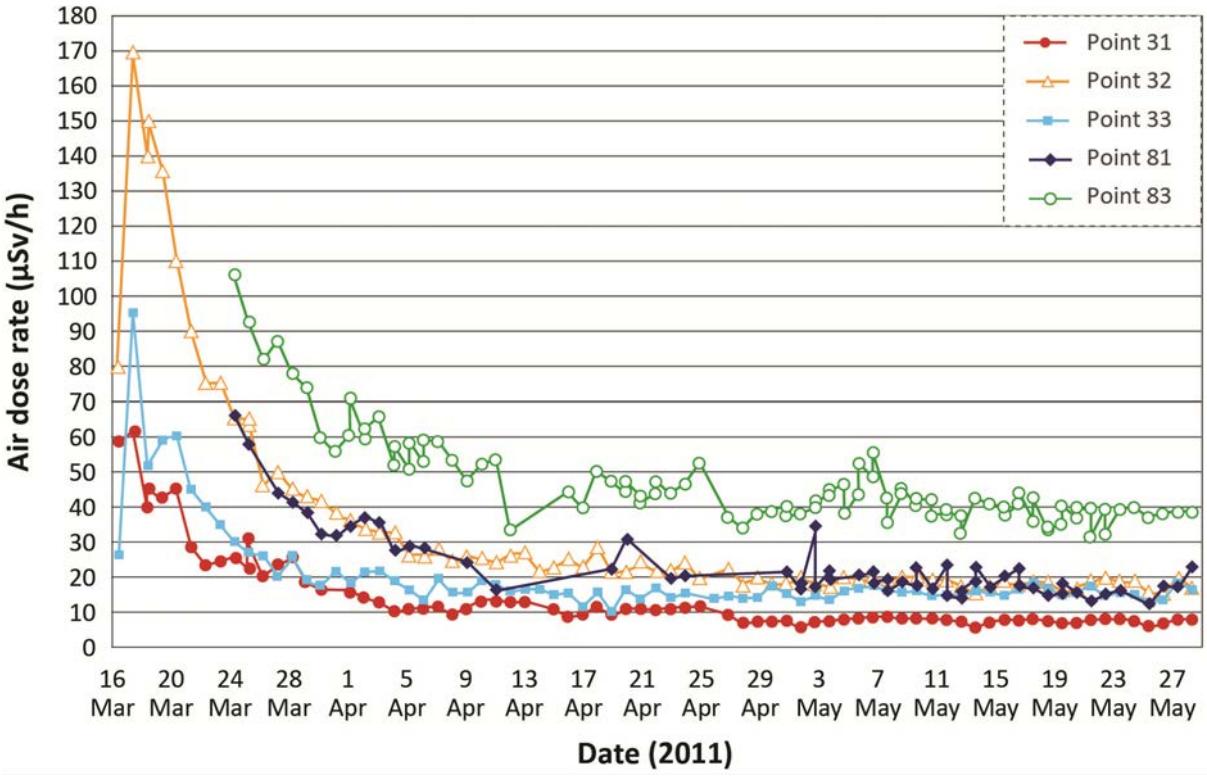


FIG. 3.3–13. Dose rate results (μSv/h) measured from 16 March 2011 onwards at the monitoring locations indicated in Fig. 3.3–14 [22].

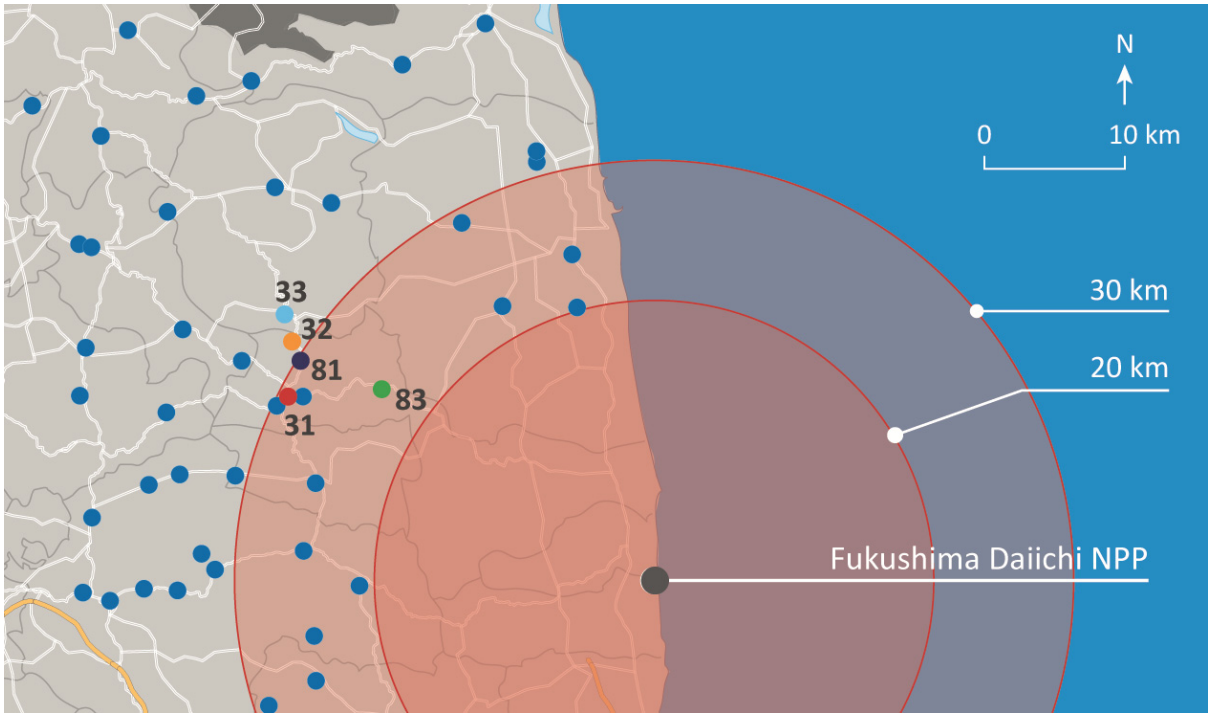


FIG. 3.3–14. Locations of dose rate measurements shown in Fig. 3.3–13 [22].

On 20 March 2011, MEXT received aerial monitoring data, via the Japanese Ministry of Foreign Affairs, from the United States Department of Energy (USDOE) [21]. Figure 3.3–15[80] shows the aerial monitoring results for measurements performed by the USDOE between 17 and 19 March. MEXT requested the Ministry of Foreign Affairs, on 21 March, to send the results also to the NSC. On the same day, the results were then sent to the NSC, the Cabinet Secretariat and MHLW [21].

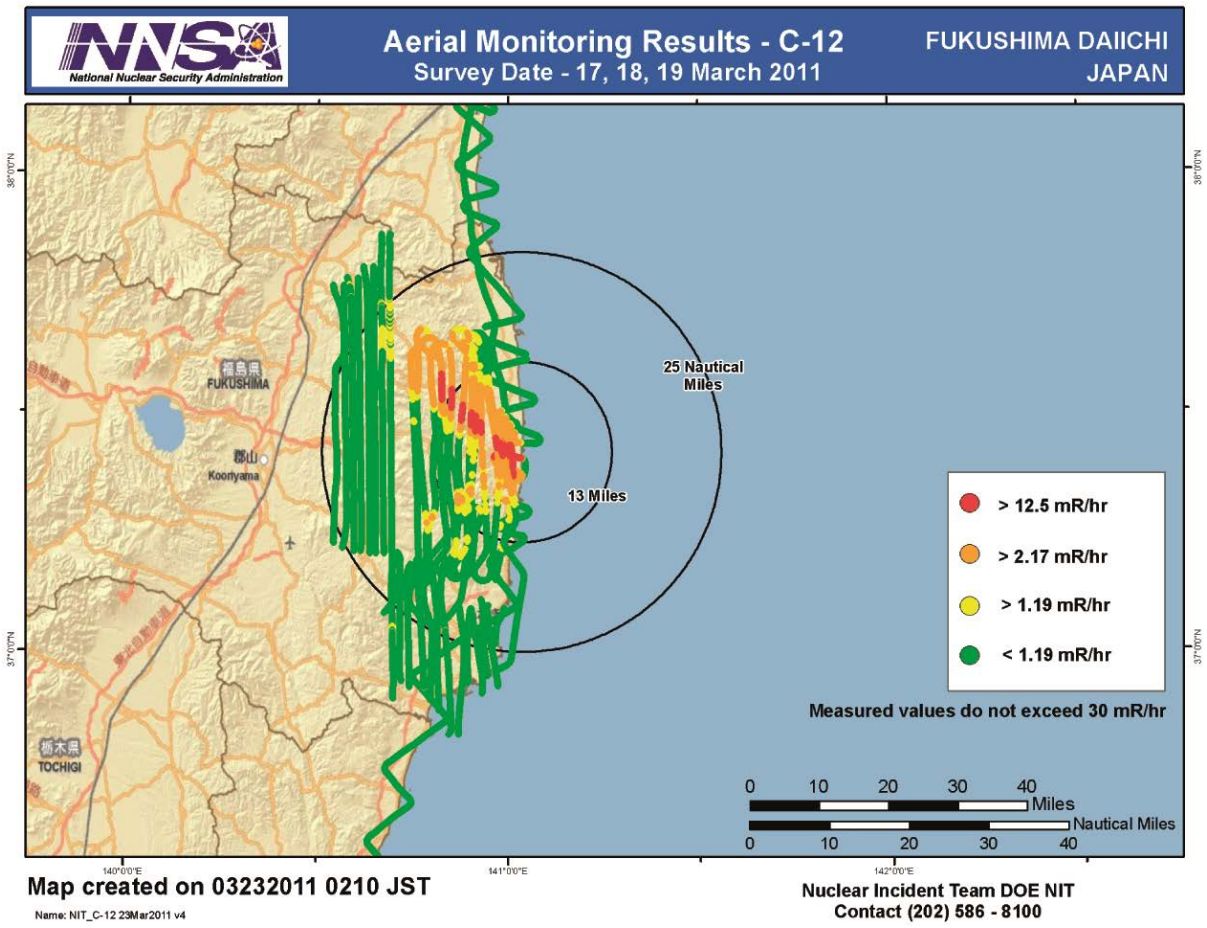


FIG. 3.3–15. Airborne measurements of the dose rate at 1 m above ground level (mR/h) taken between 17 and 19 March 2011 [144].

On 21 March, MEXT issued a monitoring plan for areas outside the 20 km zone from the Fukushima Daiichi NPP, called the Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone[81], which was revised three times before a plan to conduct detailed monitoring was issued on 13 June [145]. This plan did not describe the overall purpose of the monitoring and did not specify the criteria that would be used to determine the extent of areas for implementation of protective actions [146].

On 25 March, an Airborne Monitoring Action Plan was issued describing the strategy for airborne monitoring outside the 30 km zone from the Fukushima Daiichi NPP [147]. The plan was revised

[80] Note that the results in this figure are given in mR/hour, not in μSv/h.

[81] The Planned Evacuation Zone is identical to the Deliberate Evacuation Area discussed in Section 3.3.3.1.

three times during April–May 2011. Monitoring was to be conducted overland, out to a distance of approximately 50 km from the NPP.

On 22 April, the Enforced Plan on Environmental Monitoring was announced, which stated that the results of environmental monitoring were to be presented on maps showing dose rate, estimation of accumulated dose and soil contamination with the objective of verifying the boundaries of the areas to be relocated [148]. This plan was revised on 11 May [149].

On 6 May, based on joint airborne monitoring with the USDOE, MEXT created a map (Fig. 3.3–16) showing the dose rate at 1 m above the ground surface normalized to 29 April 2011 [22]. The data were obtained by 42 fixed wing and helicopter survey flights over a period of 23 days. Dose rates were averaged over areas of 300–1500 m in diameter. No aerial survey data were collected either directly over the NPP itself, or over the eastern part of the town of Inawashiro, because of the mountainous terrain, which was not easily accessible by low flying aircraft. The dose rate was confirmed to be below 1 μSv/h in the eastern part of Inawashiro by vehicle borne measurements [150]. The survey boundary was chosen based on preliminary measurements that showed the extent of the deposition [150, 151].

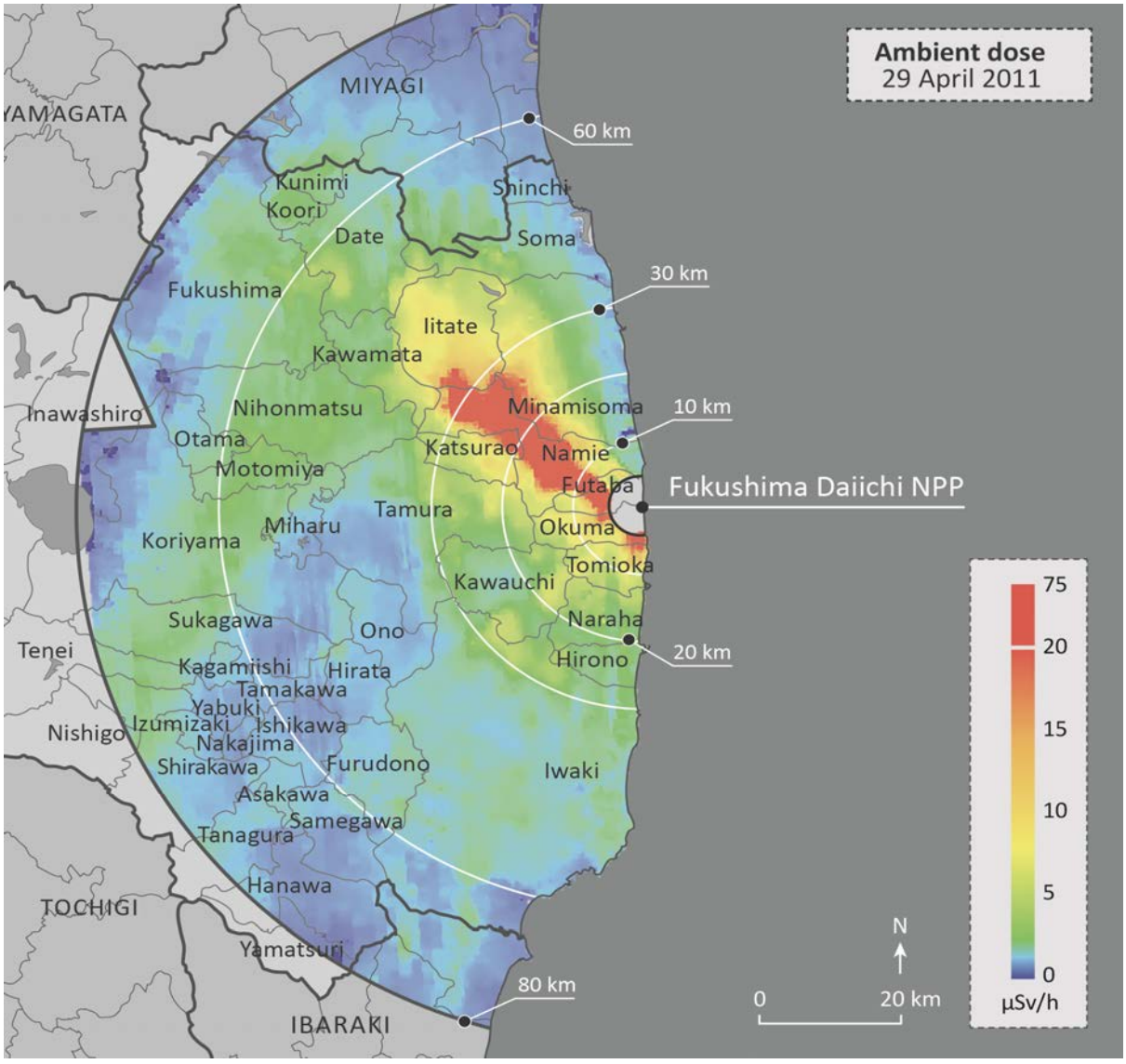


FIG. 3.3–16. Dose rate at 1 m above ground level (μSv/h) normalized to 29 April 2011 [22].

On 8 June, MEXT announced the Strenghtening of Monitoring of Environmental Radioactivity Levels by Prefecture [152], which specified that air dose rate monitoring should be performed by all 47 prefectures in Japan [152].

On 13 June, the Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone was announced, describing the detailed monitoring programmes in these areas [145]. As of 15 March, vehicle borne dose rate monitoring was performed[82] on national and prefectural roads within 100 km (and slightly beyond) of the Fukushima Daiichi NPP, and on city, town and village roads within 80 km of the NPP [30]. Dose rates were measured over the road and inside the vehicles [153]. During this campaign, up to 15 monitoring cars[83], each with three people, were used to record measurements every 10 s (approximately every 100 m). A total of about 17 000 km out of the targeted 20 000 km of roads were monitored. The following data were recorded for each measurement performed during the period of 6–13 June (see Fig. 3.3–17 [30]): location, time, date, dose rate (in μSv/h), meteorological conditions and the organization performing the measurement (e.g. JAEA, MEXT) [153].

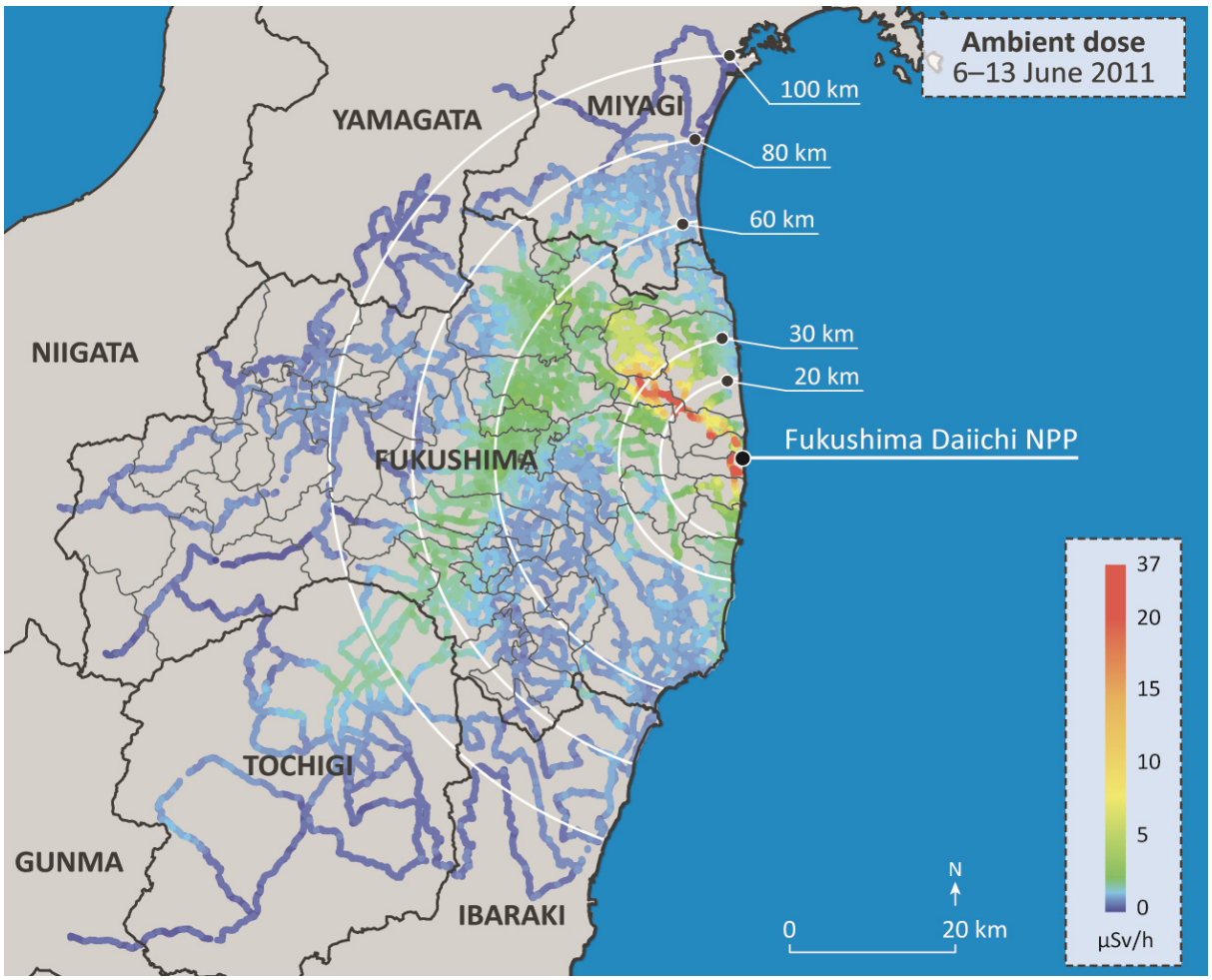


FIG. 3.3–17. Vehicle borne measurements of the dose rate at 1 m above ground level (μSv/h) taken between 6 and 13 June 2011 (released by MEXT on 2 August 2011) [30].

[82] Excluding the evacuated areas (within 20 km of the Fukushima Daiichi NPP).

[83] From MEXT, JAEA, Fukushima Prefecture, the National Police Agency, the Ministry of Defense and electrical power companies [22].

Figures 3.3–18 and 3.3–19 show the estimated integrated (cumulative) effective dose from external exposure while living normally[84] in the affected area for two months and for one year following the accident, respectively. These maps were created by MEXT and issued on 16 May [22]. Figure 3.3–18 presents the estimated dose received during the first two months from the start of the accident (until 11 May 2011). Figure 3.3–19 presents the estimated dose received during the first year (until 11 March 2012). The line in red shows the boundary of the area where the integrated dose over the first year was estimated to exceed 20 mSv, which was the dose criterion for establishing the Deliberate Evacuation Area. The population living in the Deliberate Evacuation Area was relocated, in some cases after 11 May 2011. By this time, projected doses, based on the assessment by MEXT, were greater than 20 mSv for those living in some locations, as shown in Fig. 3.3–18.

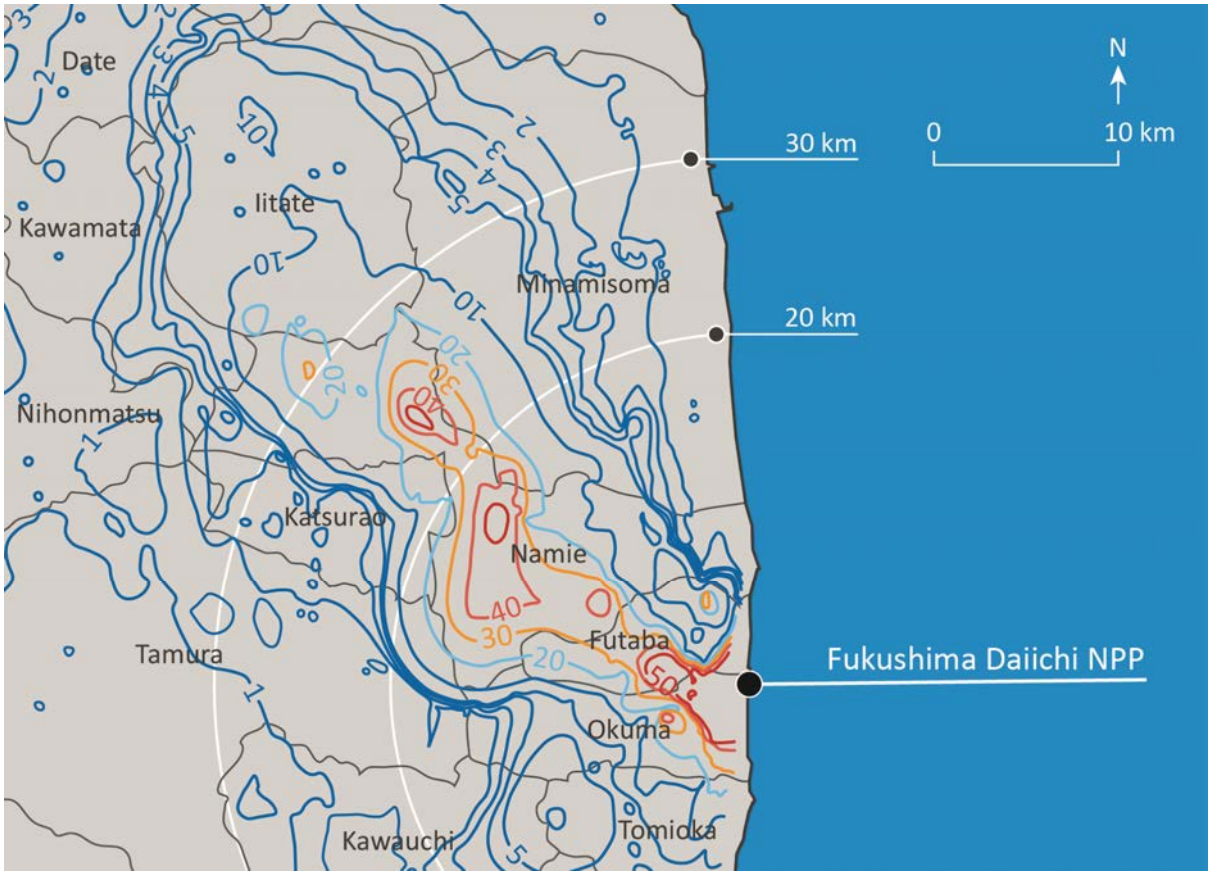


FIG. 3.3–18. First two months dose estimation (integrated dose, mSv, up until 11 May, 2011) [22].

[84] The dose rate value was multiplied by 0.6 in consideration of the reduction in the dose rate achieved by being in a wooden building for 16 hours a day [22]. This is essentially the same model used to calculate the relocation OILs in IAEA Safety Standards [14].

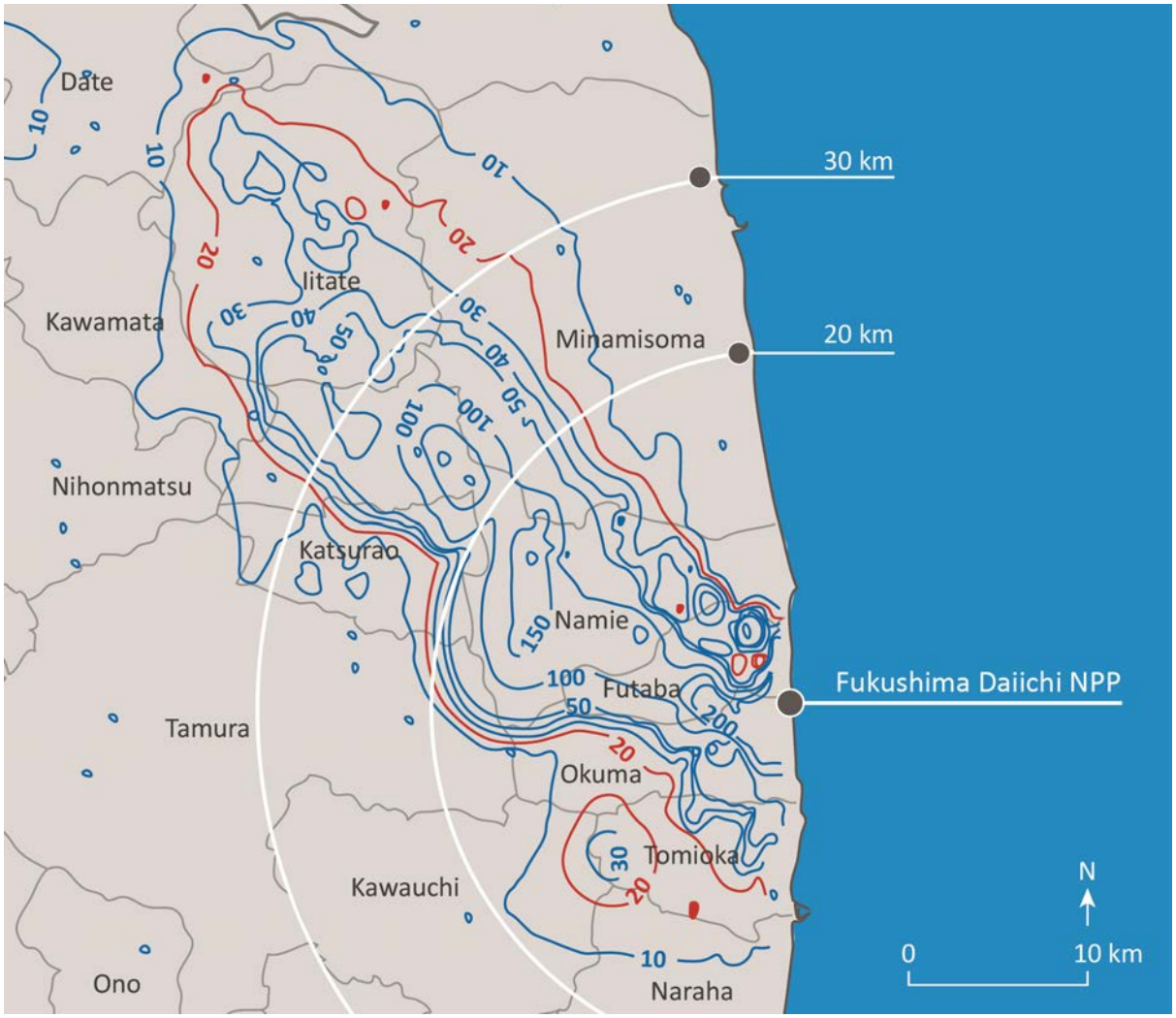


FIG. 3.3–19. First year dose estimate (integrated dose, mSv, up until 11 March 2012) [22].

3.3.5.3. Soil and seawater sampling and analyses

Development of the soil contamination map took almost three months and, as described below, was extremely resource intensive [22]. The soil contamination map was useful in the later phase of the emergency to inform decisions on lifting and adjusting protective actions, as it enabled the characterization of the deposition of radioactive material. Soil and seawater measurements were not used as a basis for decisions on relocation and designation or adjustment of the evacuation and relocation areas, as this was done based on dose rate measurements.

From mid-March 2011, MAFF took responsibility for transporting samples and performing the analysis at various national laboratories and institutes [27]. Initially, two institutes were able to analyse a total of about 40 samples a day [27]. Figure 3.3–20 shows a map of the surface activity concentration of ^{134}Cs made public on 30 August 2011. It shows the concentrations at about 2200 locations within roughly 100 km of the Fukushima Daiichi NPP [30].[85] More than 400 cooperators from 94 organizations, including universities, medical institutions and private companies, collaborated

[85] A ^{137}Cs map was also available from MEXT. The ratio between ^{137}Cs and ^{134}Cs is uniform across the survey region.

over 85 days to perform the radionuclide analysis of soil samples collected from the top 5 cm of soil [153, 154].

The dose rate was also measured at the sample locations [30]. Within 80 km of the Fukushima Daiichi NPP, samples were taken at one location within each 2 km × 2 km area. Beyond 80 km of the plant, samples were taken at one location within each 10 km × 10 km area [154, 155].

Samples were taken in accordance with the standardized method described by MEXT in a detailed manual issued on 26 May 2011 (a similar manual was issued in 1983) [156].

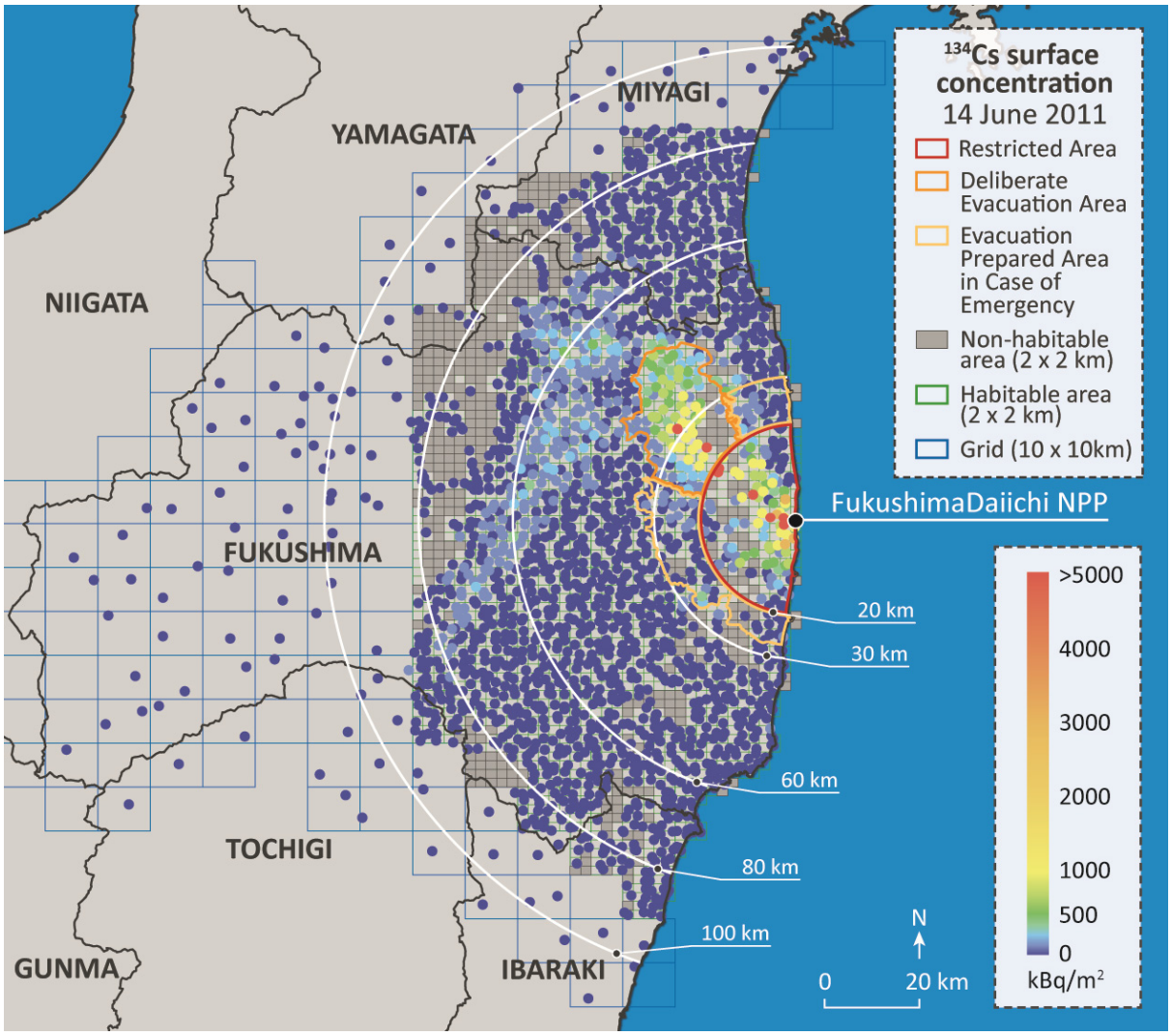


FIG. 3.3–20. Surface concentration of ^{134}Cs on soil (Bq/m^2) normalized to 14 June 2011. Samples were taken between 6 June and 8 July 2011 (released by MEXT on 30 August 2011) [30].

On 22 March, the Sea Area Monitoring Action Plan was announced [157]. According to this plan, activity concentrations in the sea water and airborne dust, and dose rates over the sea, were measured at locations approximately 30 km off the coast of the Fukushima Daiichi NPP. Samples of sea water were collected at eight locations parallel to the coastline at intervals of approximately 10 km [157].

On 5 April, it was announced that five sea monitoring buoys were to be placed at sampling locations [158]. On 25 April, it was announced that six additional water sampling points were to be established,

increasing the number of locations where sampling of sea water was performed from 28 to 34 points [159].

On 6 May, cooperation between the relevant ministries, agencies and institutions for sea monitoring in a wider area off the coasts of Miyagi, Fukushima and Ibaraki prefectures was announced [160]. The method of sea monitoring was to measure 0.5 L samples of sea water that were taken once every four days at 16 points (at 12 points prior to 21 April). Between 28 March and 7 May, samples were taken using a water sampler instrument at differing depths: top (nearly 1–2 m below the surface); middle (between the surface and seabed); and bottom (approximately 10 m above the seabed).[86] Samples of particulates in air above the sea were measured [22].

3.3.6. Public information

A timeline of key events relevant to providing information to the public is presented in Fig. 3.3–21.

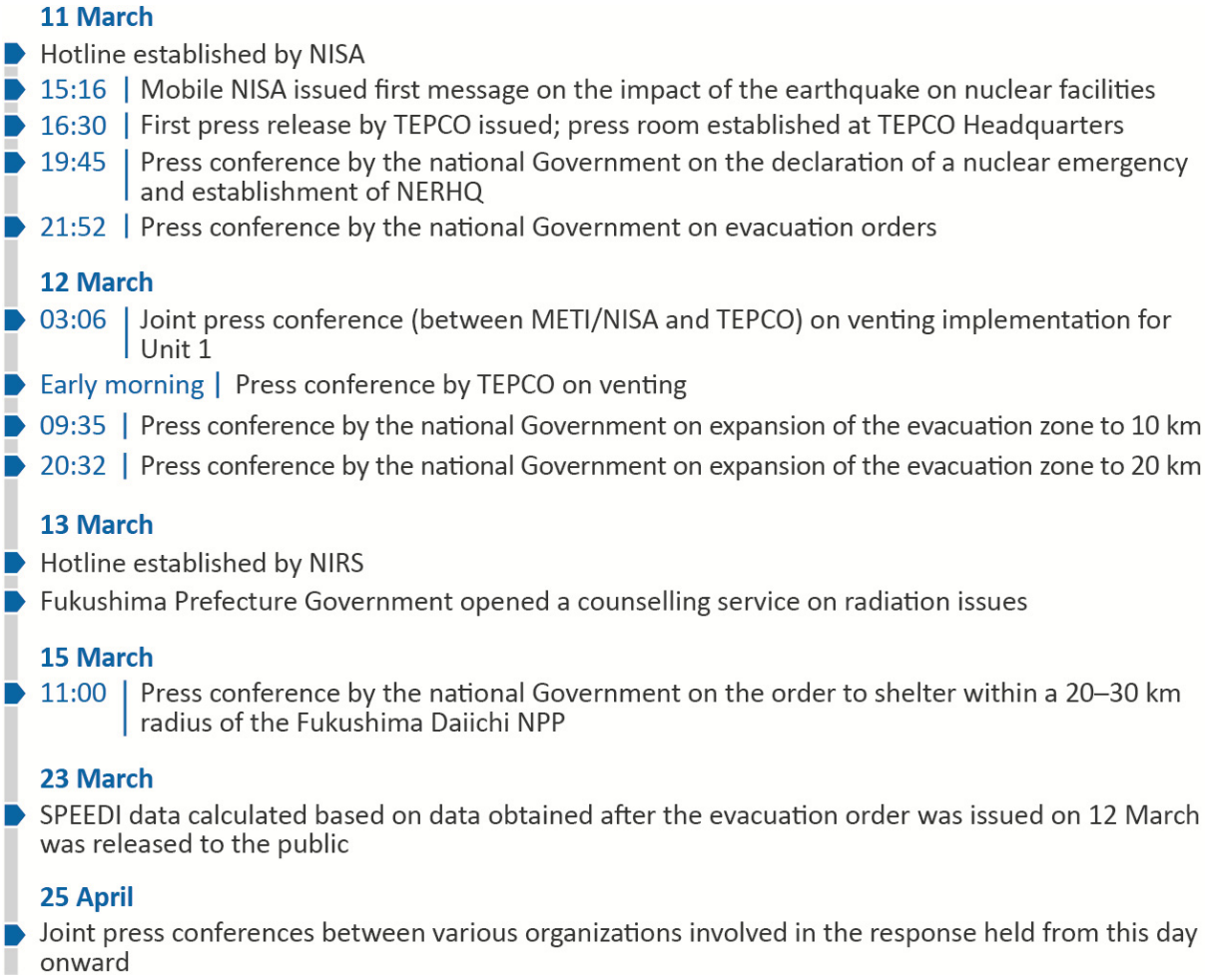


FIG. 3.3–21. Timeline of key events relevant to providing information to the public.

[86] From 23–27 March, seawater samples were taken at eight locations at the top every two days. Sampling from the middle and bottom levels began from 25 April and 28 March, respectively.

3.3.6.1. Relevant arrangements in Japan prior to the accident

Arrangements for keeping the public informed during a nuclear emergency were in place prior to the accident.

The Fukushima Prefecture Disaster Management Plan [1] included arrangements for the appointment of a press manager to be responsible for releasing information to the public and to manage announcements from the local emergency response centre. It was envisaged that the Director General of the Prefecture Headquarters for Disaster Control would provide public information on an emergency and related protective actions to the affected municipalities and organizations and would hold press conferences at the request of the news media [1].

At the local level, communication would be provided by a staff member from NISA, who was designated as the spokesperson. The designated individual had to travel from Tokyo to the OFC [8], which would take some time in an emergency. The arrangements also specified the need to establish a telephone hotline in order to respond to enquiries from the public. Consideration was given to the provision of information to vulnerable people in an emergency, such as the elderly, infants, pregnant women, the injured, physically or mentally handicapped people and foreign nationals. In addition, the plan specified the need to reduce the adverse effects of misinformation [1].

At the national level, arrangements were in place that recognized the need of relevant response organizations to coordinate the provision of information to the public, including the content, timing and method of any announcements [8]. In addition, the arrangements required that a spokesperson be designated in advance from both the regulatory body and the national Government, given that individual press conferences would be held by both the regulatory body and the Chief Cabinet Secretary[87] following the declaration of a nuclear emergency [8]. In addition, the Basic Disaster Management Plan [2] described the need for promotional measures (e.g. public information activities) during the recovery phase for small and medium enterprises, farmers and fishermen affected by a nuclear emergency. It also specified the need to prevent or mitigate negative effects of the emergency, such as those caused by misinformation.

The Basic Disaster Management Plan [2] of the national Government and the prefectural and city/town/village disaster management plans were publicly available. In addition, the prefecture and municipalities held explanatory meetings on nuclear emergency preparedness for the residents [161].

Although the arrangements identified the need to address public concerns and mitigate other non-radiological consequences[88] of the emergency, there was no specific technical guidance as to how this would be implemented. While arrangements recognized the need to ensure consistency in the release of information to the public, procedures for achieving this had not been formalized.

3.3.6.2. Keeping the public informed

Information was provided to the public throughout the emergency via several channels, including television, radio, internet and telephone hotlines.

The OFC was intended as the location for media announcements at the local level. Once the OFC began to operate, its location within the evacuation zone rendered it inaccessible to journalists.

[87] Or an alternate.

[88] These include economic, social and psychological effects, which are typically the most severe consequences of a nuclear or radiological emergency [11].

Following relocation of operations from the OFC, press conferences were held, beginning on 15 March, by spokespeople of the Local NERHQ at the Fukushima Prefecture Public Hall [21].

Some of the material released to the public was independently developed by the Local NERHQ [22]. The Local NERHQ took the initiative to publish newsletters and distribute them to each evacuation centre as of April 2011. Relevant information was also broadcast periodically via local radio stations, since television reception and internet connections were unavailable in some areas owing to the disruptions in power supplies. Five newsletters and 62 radio broadcasts had been issued by May 2011 [22].

The regulatory body, NISA, released its initial message on the impact of the earthquake on nuclear facilities via 'Mobile NISA' at 15:16 on 11 March 2011, 30 minutes after the earthquake. The spokesperson provided a press briefing on the status of the fuel of Unit 1 and subsequently resigned. NISA's spokesperson changed several times. At one point, four different people served as spokesperson within a two day period [27]. As NISA itself recognized, [162], the spokespeople were found to have insufficient training and experience in dealing with the media, and no arrangements were in place to facilitate the provision of technical advice to the individual acting as spokesperson. As a result, it happened that staff from the regulatory body presented conflicting opinions at a press conference [21].

On 12 March 2011, NISA held three press conferences on the expansion of the evacuation zone to 10 km. More than 150 press releases were issued and 182 press conferences were held by NISA between 11 March 2011 and 31 May 2011 [22]. On one occasion, fourteen press briefings were given in a single day by the NISA spokesperson. As the situation stabilized, the frequency of press conferences was reduced to twice or three times a day. The briefings focused on events relating to the accident, and very little information was provided on the preparation for evacuation [22]. Moreover, it became clear that there were not enough staff members available at NISA to ensure a 24 hour provision of information to the public and the media [162].

In the first few weeks after the accident, the national Government, NISA, local emergency response organizations, local governments and TEPCO held independent press conferences and in some cases, the information provided to the public was inconsistent [21]. The Chief Cabinet Secretary held regular press conferences twice a day, and also on an ad hoc basis, to provide information to the public on the accident and the views of the Government [22]. The results of environmental monitoring were presented at press conferences and press briefings by MEXT [22].

The NSC held daily press conferences from 25 March to 24 April 2011, and eight press conferences were held by the NSC from 25 April to 19 May 2011 [22]. The information presented by the NSC spokesperson focused on the rationale and justification for advice and recommendations made by the NSC [22].

TEPCO issued its first press release at 16:30 on 11 March 2011 and established a press room at its Headquarters in Tokyo. Technical personnel were required for explanations at these press conferences, making these staff members unavailable for emergency response activities. This problem was later solved by the recruitment of other experts, such as retirees, to provide technical explanations [17].

In early April, a proposal to hold joint press conferences between the Government and TEPCO was rejected out of concern within the Government that this cooperation between the regulator and the nuclear operator being regulated would be inappropriate [21]. However, as of 25 April 2011, joint

press conferences were held[89]. These press conferences were hosted by the Special Advisor to the Prime Minister, NISA, TEPCO, the NSC, MEXT and other organizations. Graphs, diagrams and pictures were used during the joint press conferences to help non-specialists understand the technical and specialized information on reactors and radiological conditions [22]. This approach contributed to the consistency of the information that was provided [27].

Arrangements established prior to the accident did not specify if SPEEDI dose projection results were to be made publicly available [2, 8]. On 23 March, SPEEDI projected dose estimates based on environmental data were made available to the public (Fig. 3.3–22) [25]. These estimates represented the projected integrated dose for the period 12–24 March. When this diagram was released to the public, it was not explained that these results had not yet been available on 12 March, when the decisions for evacuation had been taken, since the assessment was made based on environmental measurements taken after the evacuation [25]. The lack of this explanation before announcing the data resulted in misunderstanding and confusion among the public. For example, some people living within a 20 km radius of the NPP who had been instructed to evacuate on 12 March were moved to a shelter that was located in an area north-west of the NPP that was later found to be heavily contaminated. After release of the SPEEDI results, it was erroneously claimed that non-disclosure of these dose estimates resulted in exposures that could have been prevented [25].

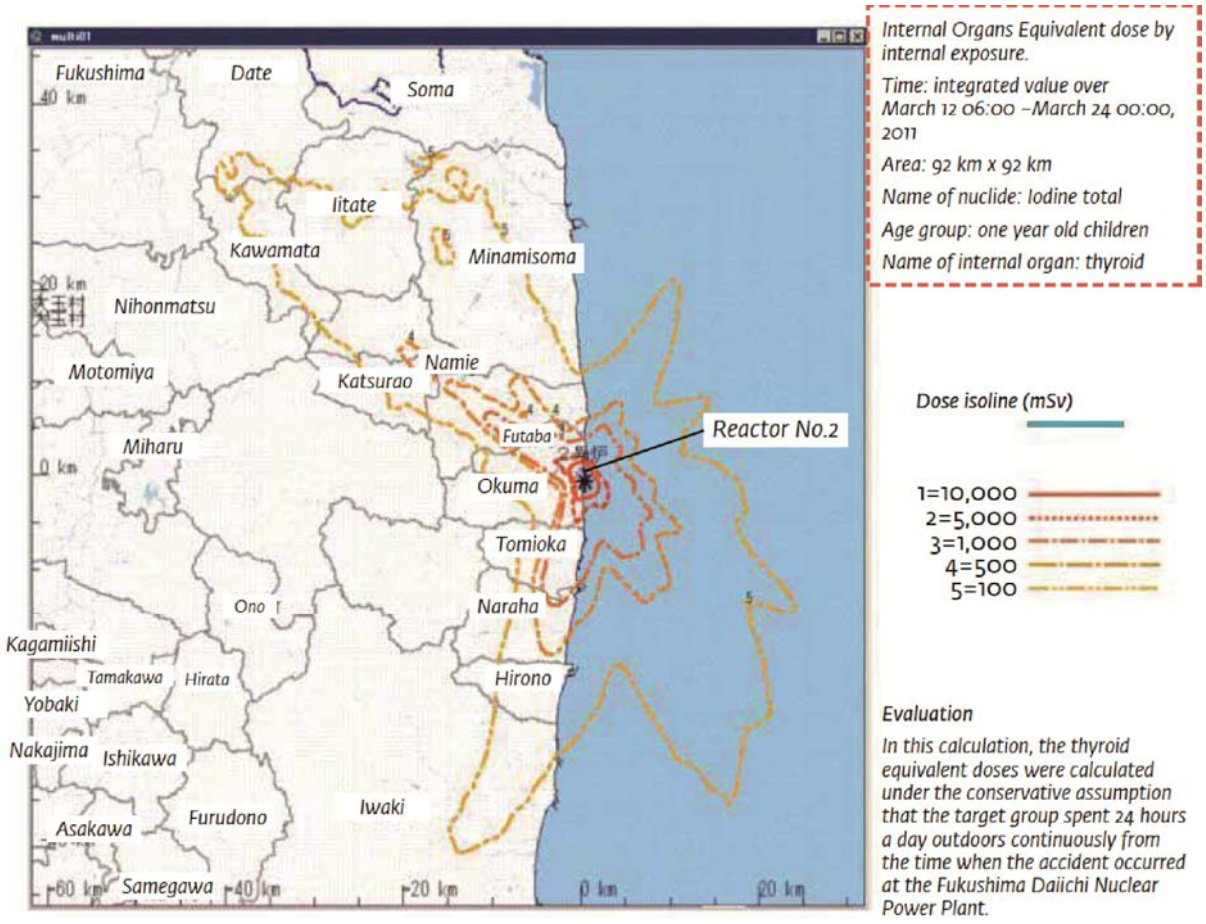


FIG. 3.3–22. SPEEDI dose estimates based on environmental data and released to the public on 23 March 2011 [25].

[89] The joint press conferences were held at the Joint Headquarters of Fukushima Nuclear Power Plant Emergency Response, which was renamed the Government-TEPCO Integrated Response Office on 9 May 2011.

Another set of SPEEDI data was released on 26 April 2011. It was the result of SPEEDI projections of dose rates for 12 March, 18:00–19:00, which had been calculated just before the evacuation orders for a radius of 20 km were issued at 18:25 (Fig 3.3–23). These projections were made using a unit release rate and, as noted on the results, they did "… not represent the actual distribution of radiation doses" [25]. Hence, they could not have been used as a basis for taking protective actions. However, this was not properly explained to the public, resulting in some misunderstanding.

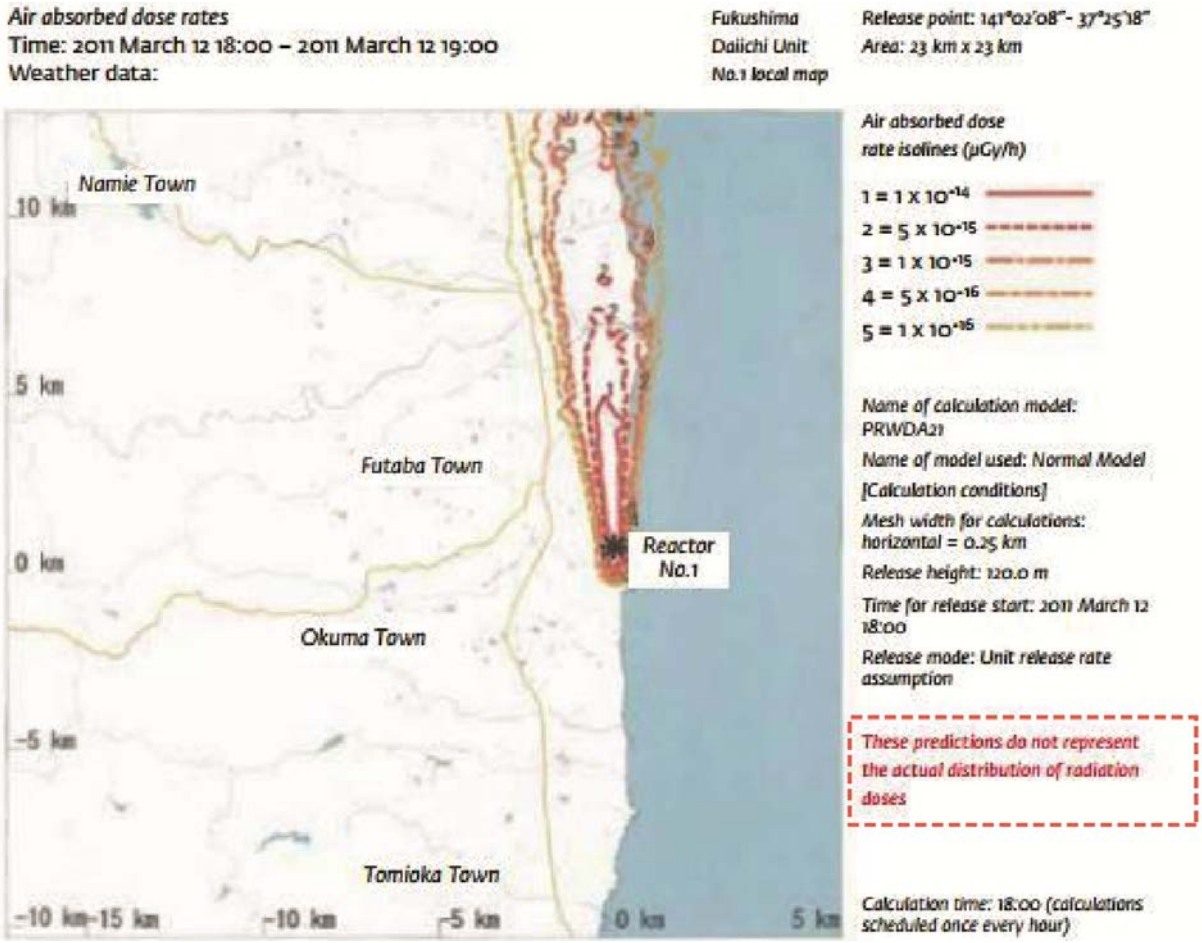


FIG. 3.3–23. SPEEDI dose rate projections based on unit release rate obtained just before evacuation orders were issued for a radius of 20 km at 18:25 on 12 March [25].

3.3.6.3. Addressing public concerns and communicating the health risks

While it was not possible to conduct activities related to answering enquiries from residents at the OFC as planned [1], owing to the power cuts causing failures in communication lines [45], enquiries from the public were addressed via several hotlines.

For example, on 11 March 2011, NISA established a hotline to respond to queries relating to the evolution of the emergency and radiation safety. It received approximately 15 000 calls between 17 March and 31 May 2011 [22]. The number of telephone lines was increased from five to 13 on 17 March, and additional assistance was provided by staff from the Japan Nuclear Energy Safety Organization (JNES). The largest number of enquiries was received on 30 March, with almost 500 calls [22]. On 17 March 2011, MEXT and the JAEA opened a hotline to provide health

counselling and facilitate the dissemination of correct information; it received a total of 17 500 calls by 18 May 2011 [22].

NIRS also opened a hotline on 13 March [163] to provide medical information on radiation exposure and health counselling, which received a total of 6500 calls by 11 April 2011 [163]. In addition, the Atomic Energy Society of Japan offered explanations and information to the public.

The Fukushima Prefectural Government was supported by the national Government in the opening of counselling services on radiation that were located at the Fukushima Prefectural Government office. More than 14 000 enquiries have been received since it opened on 18 March[90] [22, 165]. Questions ranged from concerns about the possible effects of radiation on pregnancy to the meaning of the numerical values reported by the media [166].

Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material [22]. It proved difficult to explain to the public radiation protection concepts and the basis for decisions on protective actions (e.g. references levels, exposure situations, stochastic effects) [21, 25].

Despite efforts to address public concerns, in some cases people took actions that were not helpful and were considered to do more harm than good in the belief that they were protecting themselves. Examples of such concerns, actions and responses included:

— Pregnant women worrying about their foetus based on the hazards to health from radiation [109, 167];
— Using inappropriate substitutes for ITB agents [109];
— Stigmatizing those from the affected area [167];
— Worrying about the possibility of radiation induced cancers [109];
— Rejecting products from the affected area [167];
— Cancelling necessary nuclear medical treatments due to fear of radiation [168].

An example of the tools used to address public concerns is shown in Fig. 3.3–24. This figure represents a good example of helpful material to enhance communication to the public by explaining the basics of radiation in everyday life. However, additional materials to complement this figure, when used in an emergency, are necessary. When applied to address public concerns in an emergency, it would need to be accompanied by appropriate explanations to remedy its shortcomings. For example, this figure explains/presents cases of external penetrating radiation only and does not address the intake, for instance, from radioactive iodine. It does not address the exposure scenarios at the time of the accident, such as people living on contaminated ground for extended periods of time or the equivalent dose to the foetal thyroid from ingestion or inhalation of radioactive iodine. It also fails to indicate the doses at which one could expect to see radiation induced effects. In addition, the figure does not address the numerous reported quantities, such as dose rate from deposition and concentrations in food, water and milk.

[90] The counselling services were still operating in December 2014 [164].

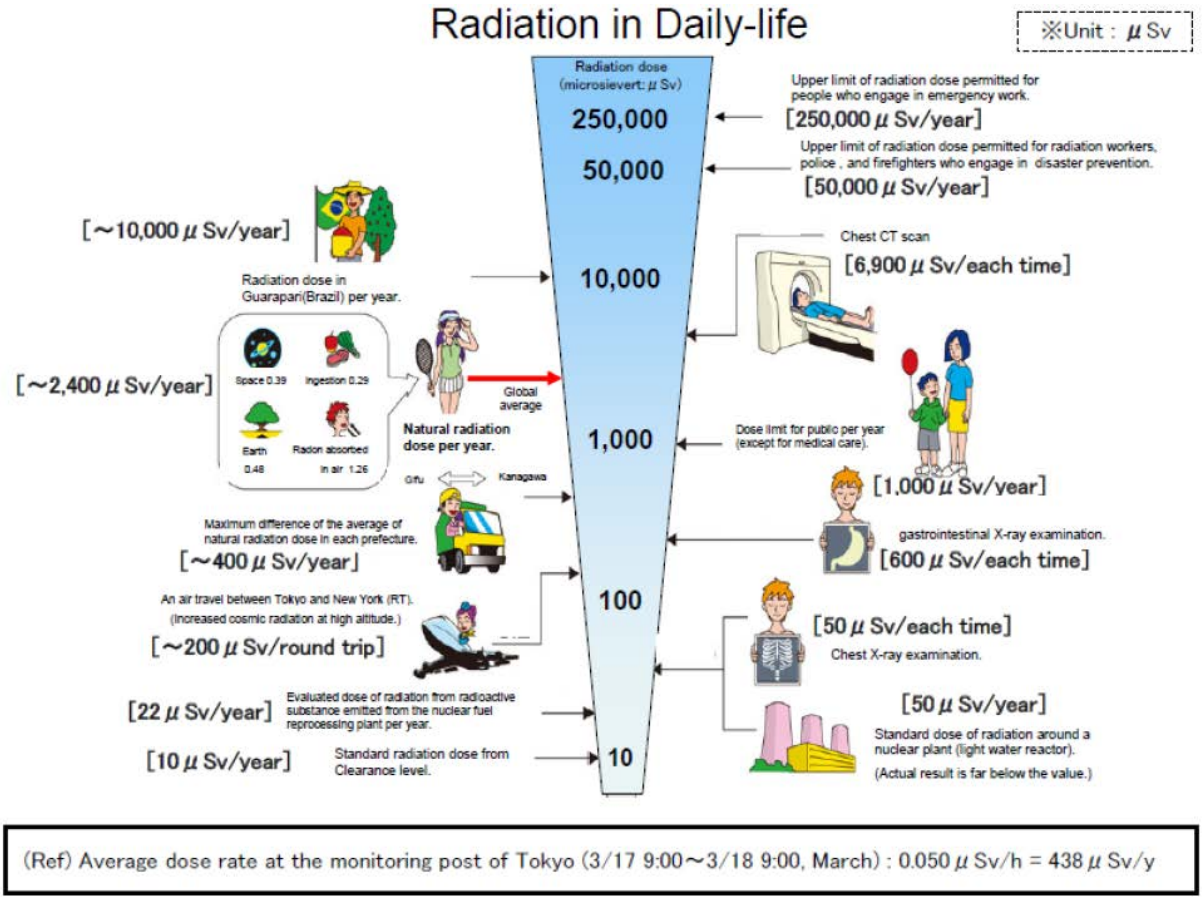


FIG. 3.3–24. Diagram used by Japanese authorities to explain radiation in daily life [169].

The International Commission on Radiological Protection (ICRP) has pointed out:

> "There are great difficulties to communicate radiological information to non-experts and the public at large using the ICRP system and its quantities. This is a consequence of the rather intricate concept behind the system of quantities which uses more than one quantity (organ (equivalent) doses and whole body (effective) dose) and combines physical exposure data with scientific data on radiation risk for organs and tissues. In other words, the system and the quantities have shown to be well suited for operational radiation protection but they are much less suited for communication with non-experts, particularly in emergency situations." [170]

In addition, the report by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) on the levels and effects of radiation exposure due to the Fukushima Daiichi accident [171] states:

> "The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported."

3.3.6.4. Providing information to foreign countries and foreign media

Information was provided to the diplomatic corps in Tokyo through regular briefings, held by the national Government on a daily basis from 13 March to 18 May 2011, and three times a week from 19 May onward [27]. During the briefings, an explanation was provided on the status of the accident and the protective actions and other response actions being taken by the staff responsible for their respective areas. The staff giving the briefings came mainly from the Foreign Ministry, but also from the NSC, MEXT, MHLW, MAFF, the Fishery Agency and NISA. In total, 46 such briefings were held by 11 May [22].

Beginning on 13 March 2011, joint press conferences on the status of the accident and actions taken by the Japanese Government were held, mostly on a daily basis, for the foreign news media by relevant national ministries and government agencies [27]. Videos of press conferences were posted on web sites of the Japanese Government Internet TV and the Foreign Press Center in Japan. When factual errors and unfounded rumours were identified in the coverage of the foreign media, the Japanese Government addressed them and encouraged the media in question to present the correct facts.

A notification channel via fax and email to the diplomatic corps was also established. The diplomatic missions of Japan provided information to their host States, which were posted on web sites in a total of 29 different languages [22]. Briefings were also given to businesses overseas and in Japan [22].

From 12 March 2011 onward, the national Government posted information in English, Chinese and Korean on the web sites of the relevant ministries and agencies [162]. In addition, Twitter and Facebook accounts were created under the name of 'Kantei'[91] to send summaries of the press conferences by the Prime Minister and Chief Cabinet Secretary to a wide range of audiences.

Challenges encountered in providing information to the international community related principally to the demands on human resources for translating materials and responding to information requests by telephone [162].

3.3.6.5. Using the International Nuclear and Radiological Event Scale

The International Nuclear and Radiological Event Scale (INES) is a tool for promptly and consistently communicating to the public the safety significance of events associated with sources of ionizing radiation with the aim of keeping the public as well as nuclear authorities accurately informed on the occurrence and consequences of reported events. The primary purpose of INES is to facilitate communication and understanding among the technical community, the media and the public on the safety significance of events. The INES scale applies to any event associated with the use, storage and transport of radioactive material and radiation sources, whether or not the event occurs at a facility.

INES uses a numerical rating to explain the significance of events associated with sources of ionizing radiation (see Fig. 3.3–25). Events are rated at seven levels: Levels 1–3 are 'incidents' and Levels 4–7 are 'accidents'. The scale is designed such that the severity of an event is approximately ten times greater for each increase in level of the scale. These levels consider three areas of impact: (1) people and the environment; (2) radiological barriers and control; and (3) defence in depth.

Events without safety significance are rated as Below Scale/Level 0. Events that have no safety relevance with respect to radiation or nuclear safety are not rated on the scale.

[91] The Prime Minister's Office in Japanese.

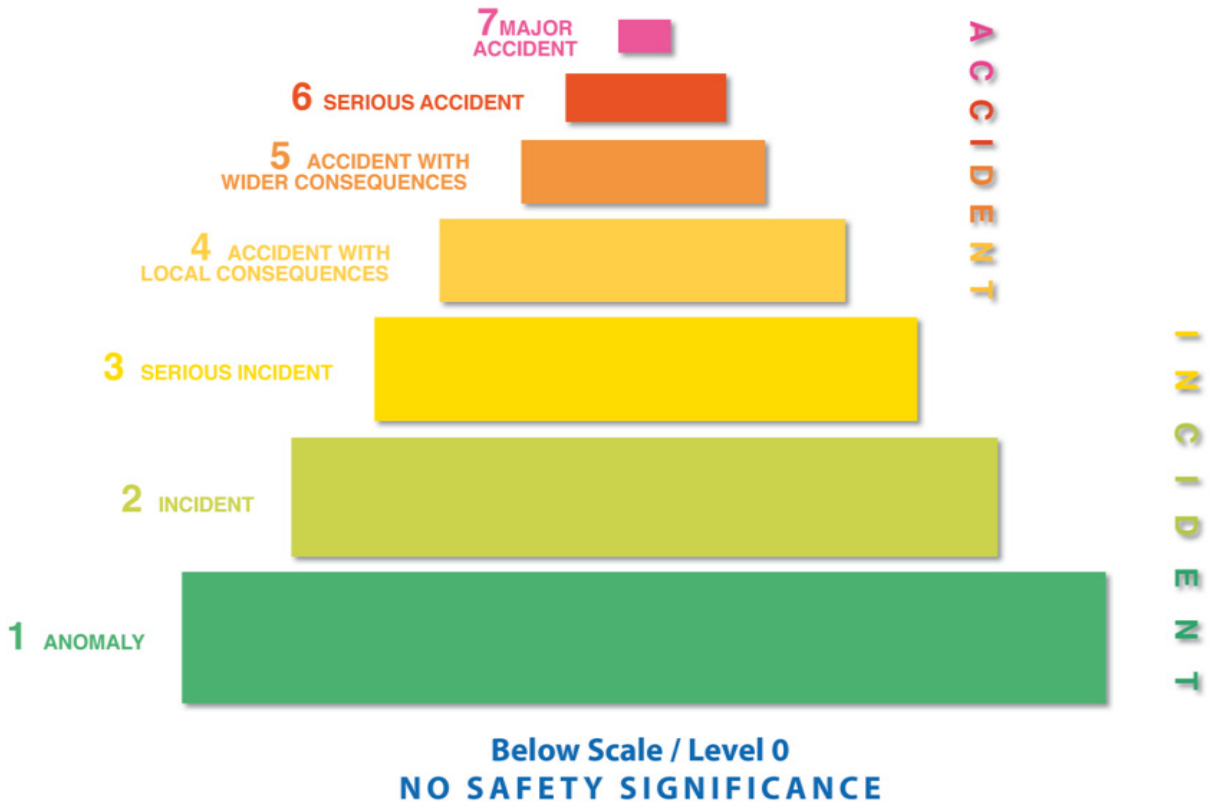


FIG. 3.3–25. The International Nuclear and Radiological Event Scale.

Various INES ratings were reported by Japan following the Fukushima Daiichi accident.

The first INES rating was posted on the Nuclear Events Web-based System (NEWS) at 00:41(UTC) on 12 March 2011. A provisional INES rating at Level 3 was assigned to the event at Unit 1 and 2, based on the elevated pressure in the confinement vessels of Units 1 and 2 and considering its impact on defense in depth. In this Event Rating Form (ERF), NISA also outlined the status of the Onagawa, Fukushima Daiichi and Fukushima Daini NPPs.

The second ERF was issued by NISA and published on NEWS at 15:05(UTC) on 12 March 2011. A provisional INES rating at Level 4 was assigned to the event at Unit 1, based on the dose rate at the site boundary, impact on the radiological barriers and controls at the facility.

The ERF with INES rating Level 4 for Unit 1 that had been issued on 12 March 2011 was up-rated to provisional Level 5 on 18 March 2011, based on the high dose rate at the site boundary and at the suppression chamber[92], i.e. considering the impact on the radiological barriers and controls at the facilities. It was also reported that at least one worker received a dose of about 106 mSv, which was in excess of the annual limit (100 mSv).

On the same day, separate ERFs were issued for the events at Units 2, 3 and 4. The event at Unit 2 was up-rated to provisional Level 5. The provisional Level 5 rating was also assigned to the event at Unit 3. The Unit 4 event was assigned provisional Level 3, based on the inoperability of the cooling

[92] The high values were thought to be the result of the release of more than a few percent of core inventory.

function and the water supply function at the spent fuel pool, taking into account their impact on the defence in depth.

On 12 April 2011, the fourth report was issued rating the accident at provisional Level 7. The rating was based on the estimation of the amount of radioactive material released.

The event at the Fukushima Daini NPP was rated on 18 March 2011. Provisional Level 3 was assigned to Units 1, 2 and 4, considering the impact on the defence in depth resulting from the loss of the residual heat removal system.

3.3.7. International trade

Protection and control of international trade in a nuclear emergency is both an urgent protective action and a long term measure. This measure is necessary to minimize the adverse non-radiological consequences of an emergency [13].

Many activities and measures were initiated that were aimed at: (1) reassuring the public, industries and States of the safety of Japanese products; (2) facilitating international trade of Japanese products and preventing delays in distribution; and (3) providing advice and guidance to businesses and industries, in particular in Fukushima Prefecture [59, 60, 172-176].

These activities also included explanations at different international conferences and ministerial meetings about the relaxation of restrictions on Japanese exported products and about the need for any measures restricting trade in Japanese goods to be based on scientific grounds and in line with World Trade Organization (WTO) agreements.

Most importing States introduced control measures on Japanese goods; many increased existing import controls or requested a certificate from the Government of Japan; and some banned the import of Japanese goods or those from certain regions of Japan (mostly agricultural products) for a period of time.

In June 2011, Japan established a certification system[93] for food products intended for export, which helped to reassure the public and other interested parties that controls were in place. This system was extended in September 2011 to cover shipping containers and some industrial products intended for export [177], including fee subsidization as a governmental measure to reduce the burden on Japanese companies. The list of government designated inspection organizations that issued certificates were made available on the Japan External Trade Organization (JETRO) web site [177] to facilitate access to information for the companies concerned.

In addition to the certification system, the regulatory developments of the destination countries (i.e. country specific restrictions and requirements) were followed, and easily accessible information was provided on web sites to those Japanese organizations and companies engaged in export activities of different products, such as food, crafts and textiles [178, 179].

A survey of radioactivity levels in textile products produced in various parts of Japan and the world was performed in order to ascertain the impact of radioactivity on Japanese textile products [180]. The survey was conducted from April to May 2011, and the results were published in June 2011. The results showed no significant differences in radioactivity levels among the various products analysed,

[93] The certification system was based on the Japan Chamber of Commerce and Industry Act issued in 1953 (Act No. 143, Aug.1, 1953).

regardless of their place of production, whether produced in different places within Japan or manufactured outside Japan [180].

On 23 June 2011, Australia reported that no radioactive contamination of automobiles imported from Japan could be detected [181]. Between 12 March and 15 July 2011, 522 transportation vehicles and 5846 cargo shipments were monitored at Russian border checkpoints [182]. Only six vehicles that exceeded the Russian Federation's operational criteria[94] were returned to Japan. The US Food and Drug Administration (FDA) did not detect any radioactivity or impose any ban on non-food products that were imported from Japan and were subjected to radiation control[95] [183].

3.3.8. Waste management in the emergency

Safe and effective management of radioactive waste requires preplanned arrangements, including criteria and plans for characterizing and categorizing waste; operational criteria to assess the effectiveness of decontamination efforts; a method of testing decontamination methods before their general use; a method of minimizing the amount of waste and avoiding the unnecessary mixing of different waste categories; a method of determining appropriate predisposal management; appropriate storage options and sites; and a plan for the long term management of waste [11].

3.3.8.1. Relevant arrangements in Japan prior to the accident

Arrangements for the management of radioactive waste established in Japan prior to the accident covered waste generated in facilities such as NPPs, but it did not include radioactive waste that had been generated in public areas [184]. Detailed strategies, guidelines and instructions for radioactive waste management were developed after the accident.

The Fukushima Prefecture Disaster Management Plan [1] specified activities to be carried out by the Fukushima Prefectural NERHQ. A team responsible for decontamination and radioactive waste disposal was established [1], but no technical guidance had been developed prior to the accident on how decontamination and waste management operations would be implemented.

3.3.8.2. Activities during the emergency phase

Off-site waste that was generated following the accident may be classified either as debris from the earthquake/tsunami (often referred to as disaster waste) or as a consequence of remediation activities. Around 2.3 million tonnes of contaminated debris from the earthquake and tsunami were collected during 2011, and the estimate[96] of the volume of soil generated from decontamination was between 16 and 22 million m^3 after volume reduction (incineration) [185]. The debris consisted of materials such as wood, concrete and metal, while remediation wastes included sludge from water and sewage treatment, incinerated ash, trees, plants and soil resulting from decontamination activities [30, 186].[97]

Various instructions and guidelines were developed to address issues related to waste.

---

[94] The dose rate measured up to 1.1 μSv/h above background. The Russian Federation's operational criterion was 0.3 μSv/h (above background).

[95] FDA regulated products such as medicines, porcelain plates and bowls, ceramic mortar and pestle, medical devices and cosmetic colour powder. For other shipments and products imported from Japan, the US Customs and Border Protection had the authority to carry out radiation control.

[96] At the time of writing this volume.

[97] For a detailed description of the management of contaminated material and radioactive waste, see Technical Volume 5, Section 5.4.

On 25 March, 12 April, 26 April and 6 May 2011, based on technical advice from the NSC [22], instructions were issued by MAFF on how to dispose of vegetables and raw milk in areas subject to food restriction(s). Instructions on what to do with foods that were not to be consumed were issued in the form of 'Question and Answers' on the MAFF web site on 26 April 2011 [187]. For example, it was recommended that harvested vegetables should not be ploughed under farmland or burned. Other vegetables could be harvested without ploughing, and, after the harvest, they should all be gathered and stored in one place. Farm works such as tillage could then be carried out. With regard to raw milk, taking into account the relatively low level of detected radionuclides it contained, farmers were advised to pour it into a specific point of their land or spread it on a specific and narrow area of their farm. In the case of large quantities (e.g. dairy companies), the milk was to be disposed of at waste disposal facilities [187].

Following the detection of radionuclides in waterworks and sewage sludge in prefectures located mainly in the east of Japan, an inquiry was initiated on 12 May 2011 on the approach to immediate handling of secondary by-products of sewage treatment in Fukushima Prefecture [30]. The results of the inquiry were issued on 16 June and specified the methods for the management of 'dewatered' sludge, such as the utilization of a particulate trap for concentrations exceeding 500 000 Bq/kg and a system for sealing the resulting ash in containers. The minimum distance of landfill storage locations from residential areas and the appropriate use of secondary by-products (e.g. concrete) that contained dehydrated sludge were also specified. In addition, the document described the condition of the disposal sites, including the criteria that indicated the appropriate long term management of the site and whether monitoring was warranted [188].

The storage, interim storage and transport of 'dewatered' sludge were outlined in the guidance [30, 186]. This included the thickness of shielding and recommendations on the frequency of monitoring of the shielding or containers (dose equivalent rate), exhaust gases from incineration (concentrations) and water (concentrations) at the facilities used for interim storage. The guidance also specified the need for maintaining records of the waste being kept at the interim storage.

For the decontamination works of the schools in Fukushima Prefecture, MEXT announced on 19 April its provisional concept on the utilization of school buildings and school yards, etc., of schools in Fukushima Prefecture [30, 72].

The Near-Term Policy to Ensure the Safety for Treating and Disposing Contaminated Waste around the Site of the Fukushima Daiichi NPP was issued by the NSC on 3 June 2011 [186]. This document provided dosimetric criteria for: recycled materials; protection of workers treating the materials; protection of members of the public in the vicinity of treatment facilities; and protection of members of the public in the vicinity of a disposal site. The NSC proposed that materials affected by the accident — i.e. debris, sludge from the water and sewage treatments, incinerated ash, trees, plants and soil resulting from decontamination activities — would be disposed of under proper management and that some materials may be considered for reuse. Products manufactured from these reused materials would be checked for contamination and managed appropriately before being released onto the market. Appropriate protective measures would ensure that radiation exposure of workers and the public was kept as low as reasonably achievable [186]. A final disposal strategy would be derived based on the quantities of waste, types of radioactive material, radioactivity concentration and evaluations of the long term safety of disposal facilities.

The radiation dose to workers engaged in processing contaminated materials was limited to 1 mSv/y. The same criterion of 1 mSv/y was specified for residents in the vicinity of contaminated waste treatment facilities, with a requirement that all necessary actions had to be undertaken to achieve this stipulated level. Furthermore, criteria of 10 μSv/y and 300 μSv/y were specified for residents in the vicinity of treatment facilities for the post-operational period, and for the basic and less likely exposure scenarios, respectively [30].

Guidelines on processing of disaster waste supposedly contaminated by radioactive materials were established on 19 June 2011, and the Guideline on Disaster Waste Processing in Fukushima Prefecture was issued on 23 June 2011. The basic approach, outlined in these documents, was for the volume of disaster waste to be minimized by recycling or by incineration, as appropriate [30].

The policy provided detailed instructions for recycling; in particular how disaster waste could be recycled if radionuclide concentrations were below those established using the clearance level of 10 μSv/y. In addition, provisions were made for the reuse of materials under controlled conditions at activity concentrations exceeding clearance levels. Guidance on the use of metals contaminated by radioactive materials and broken concrete waste was also provided [30].

The policy stipulated that flammable waste would be incinerated at facilities equipped with bag filter and exhaust fume absorption functions. Monitoring of the ground, water, exhaust gas and drains was to be performed on a continual basis. Detailed guidelines on the methods of incineration of combustible waste were provided, including the operational criteria for temporary storage (greater than 8000 Bq/kg) or disposal (8000 Bq/kg or less) of the ash. Operational criteria (dose rate in μSv/h), were specified for use in approximating the concentrations of the waste [30]. Incombustible disaster waste was subject to landfill processing.

The Basic Policy for Emergency Response on Decontamination Work [72] was established by the NERHQ on 26 August 2011 as an interim policy until the Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with Tohoku District: Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 [189] was fully in force. The Act was enacted on 26 August 2011, promulgated on 30 August 2011 — with portions of the Act entering into force the same day — and entered fully into force in January 2012 [189]. It outlined the management of the contaminated areas and included the assignment of responsibilities to the national and local governments, the operator and the public. It facilitated the transition from an emergency exposure situation to an existing exposure situation. It also formalized the long term management of environmental monitoring, decontamination measures and the designation, treatment, storage and disposal of soil and waste contaminated by radioactive material. For a detailed discussion on the above, see Technical Volume 5, Section 5.4.

3.3.9. Summary

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using the dose projection model SPEEDI. The arrangements did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions. However, in response to the accident, the initial decisions on protective actions were made on the basis of plant conditions. Estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power.

The arrangements prior to the accident included criteria for sheltering, evacuation and iodine thyroid blocking in terms of projected dose, but not in terms of measurable quantities. There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation.

Prior to the accident, 10 km emergency planning zones were in place around the Fukushima Daiichi and Fukushima Daini NPPs. However, the extent of these zones did not take into account the potential for a severe accident. In addition, provisions were not in place to extend relevant protective actions beyond the emergency planning zone.

Protective actions and other response actions for the public implemented during the accident included: evacuation; sheltering; iodine thyroid blocking (through the administration of stable iodine); restrictions on the consumption of food and drinking water; relocation; and the provision of information.

The evacuation of people from the vicinity of the Fukushima Daiichi NPP began in the evening of 11 March 2011, with the evacuation zone gradually extended from a radius of 2 km from the plant to 3 km, and then to 10 km. By the evening of 12 March, it had been extended to 20 km. Owing to a lack of detailed preplanned arrangements for evacuation to locations outside the 10 km emergency planning zone, and because of difficulties in coordination, many evacuees were relocated several times during the first 24 hours.

The area in which people were ordered to shelter extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by 15 March. In the area within a 20-30 km radius of the NPP, the public was ordered to shelter until 25 March, when the national Government recommended voluntary evacuation. Prolonged sheltering resulted in disruption in people's daily lives owing to the breakdown of the local infrastructure.

Administration of stable iodine for iodine thyroid blocking was not implemented uniformly, primarily due to the lack of detailed arrangements.

There were difficulties in evacuation due to the damage caused by the earthquake and tsunami and the resulting communication and transportation problems. In spite of damaged roads and traffic jams, most residents not requiring medical support left the evacuation areas within a few hours of the evacuation orders.

There were also significant difficulties encountered when evacuating patients from hospitals and nursing homes within the 20 km evacuation zone.

After the urgent protective actions had been taken on the basis of plant conditions, there was a need to obtain environmental monitoring data beyond the evacuated areas to verify the levels of radionuclides in the environment and to adjust the initial protective actions, if necessary. Environmental monitoring following the accident was performed in difficult and hazardous conditions and with limited equipment and staff.

On 22 April, the existing 20 km evacuation zone was established as a Restricted Area, with controlled re-entry. A Deliberate Evacuation Area was also established beyond the Restricted Area in locations where the specific dose criteria for relocation might be exceeded.

Once radionuclides were detected in the environment, arrangements were made on 17 March 2011 regarding restrictions on the consumption and distribution of food and consumption of drinking water and protective actions in the agricultural area. These arrangements included the development of levels of radioactive caesium and iodine in food and drinking water, called Provisional Regulation Values, above which foods and drinking water were restricted.

Later on, criteria were also established for fishery products, animal feed and agricultural soil for rice cultivation. The mechanism for placing restrictions on food and water evolved with the changing situation. A system was established to prevent foods with radionuclide levels exceeding the Provisional Regulation Values from entering the supply chain. Legal restrictions or voluntary measures were then communicated in order to: (a) prevent food with radionuclide levels in excess of the Provisional Regulation Values from entering the supply chain, and (b) provide advice on how to minimize (avert) the dose (e.g. residents were advised to refrain from having infants drink tap water).

A number of challenges were encountered in the process of controlling the distribution of food, milk and drink from affected areas, including: (i) defining the criteria (activity concentrations of radionuclides) that could be used as the basis for food control; (ii) determining which foods, in different geographical locations, were or could be affected above these criteria; (iii) dealing with insufficient infrastructure and resources for sampling and analyses; and (iv) addressing the concerns of some local governments about performing the sampling and analyses [25].

Several channels were used to keep the public informed and to respond to people's concerns during the emergency, including television, radio, the Internet and telephone hotlines. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material. There was a lack of formalized procedures to ensure consistency in the release of information to the public from different response organizations. In some cases, this led to inconsistent information being provided. There were also instances when spokespersons were found to have had insufficient training and experience in dealing with the media, and several changes in spokespersons occurred over a short time period.

While various protective actions were implemented to ensure the safety of the public, people's concerns with regard to their safety were not always addressed to their satisfaction. During the emergency, calculated doses or various measured quantities (e.g. dose rates or radionuclide concentrations) were used to explain the situation, without placing them into context and trying to explain the situation to the public.

The International Nuclear and Radiological Event Scale (INES) was used separately for rating different units at the same site. This led to public and media concerns each time the INES rating was revised to a higher level.

Most importing countries introduced radiation control measures on Japanese goods, and many intensified import controls or requested a certificate from the Japanese Government, and some banned the import of Japanese goods for a period of time. In this regard, the establishment of a testing and certification system in Japan for food and other products intended for export helped to reassure the public and interested parties, such as importing States.

The radioactive waste arising from the accident was managed in a manner that did not compromise the protection strategy. Detailed strategies, guidelines and instructions for radioactive waste management were developed during the response to the emergency.

Decisions of the national and local governments were not always properly coordinated, mainly owing to severe communication problems caused by the inoperability of the Off-site Centre. For example, Fukushima Prefecture decided on the evacuation of a 2 km zone around the Fukushima Daiichi NPP (based on information received directly from TEPCO personnel) at 20:50 on 11 March, without being aware that the national Government would take a decision to evacuate a 3 km zone only 33 minutes later, at 21:23.

Furthermore, there were insufficient instructions on how to prepare for the evacuation. Consequently, some residents returned home to collect belongings before full access controls were in place by the end of March 2011. In May 2011, short term temporary access was allowed to the Restricted Area in a controlled manner and with the necessary instructions and monitoring.

Dose rate measurements from 15 March onward indicated that relocation for some areas beyond the 20 km evacuation zone was warranted. The order for relocation of people from these areas (establishment of the Deliberate Evacuation Area) was given on 22 April, and relocation began around 15 May. In addition, areas warranting relocation were identified outside the Deliberate Evacuation Area until November 2011.

3.3.10. Observations and lessons

— **Arrangements need to be in place to allow decisions to be made on the implementation of predetermined urgent protective actions for the public based on predefined plant conditions.**

These arrangements are necessary because decision support systems, including those using computer models, may not be able to predict the size and timing of a radioactive release (the source term), the movement of plumes, deposition levels or resulting doses quickly or accurately enough in an emergency to be able to provide the sole basis for decisions on initial urgent protective actions.

At the preparedness stage, there is a need to develop an emergency classification system based on observable conditions and measurable criteria (emergency action levels). This system enables the declaration of an emergency shortly after the detection of conditions at a plant that indicate actual or projected damage to the fuel and initiation of predetermined urgent protective actions for the public (in the predefined zones) promptly following classification of the emergency by the operator. This emergency classification system needs to cover a full range of abnormal plant conditions.

— **Arrangements need to be in place to enable urgent protective actions to be extended or modified in response to developing plant conditions or monitoring results. Arrangements are also needed to enable early protective actions to be initiated on the basis of monitoring results.**

At the preparedness stage, there is a need to establish arrangements to, among others: (1) define emergency planning zones and areas; (2) establish dose and operational criteria (levels of measurable quantities) for taking urgent protective actions and other response actions, including dealing with special population groups within emergency zones (e.g. patients in hospitals); (3) enable urgent protective actions to be taken before or shortly after a release of radioactive material; (4) enable prompt establishment of access controls in areas where urgent protective actions are in place; (5) extend protective actions beyond the established emergency planning zones and areas if necessary; (6) establish dose and operational criteria for taking early protective actions and other response actions, e.g. relocation and food restrictions, that are justified and optimized, taking into account a range of factors such as radiological and non-radiological consequences, including economic, social and psychological consequences; and (7) establish arrangements for revision of operational criteria for taking early protective actions on the basis of the prevailing conditions.

Emergency planning zones and areas, within which arrangements for the implementation of urgent and other protective actions are made, need to be established with severe nuclear emergencies taken into account. Such zones are to be established at the preparedness stage as part of a comprehensive protection strategy. There is also a need to establish arrangements to extend actions beyond the established planning zones and areas, if needed under conditions prevailing in an emergency.

As part of preparedness for urgent protective actions, sheltering needs to be considered as a short term protective action, accompanied by iodine thyroid blocking.

Arrangements need to take into account the possibility of restricting consumption and distribution of possibly contaminated local produce, milk from grazing animals and drinking water before the monitoring and analysis of samples are carried out.

— **Arrangements need to be in place to ensure that protective actions and other response actions in a nuclear emergency do more good than harm. A comprehensive approach to decision making needs to be in place to ensure that this balance is achieved.**

These arrangements need to be developed with a clear understanding of the full range of possible health hazards presented in a nuclear emergency and of the potential radiological and non-radiological consequences of any protective actions.

Protective actions need to be taken in a timely and safe manner, taking into account possible unfavourable conditions (e.g. severe weather or damage to infrastructure).

Preparations in advance are necessary to ensure the safe evacuation of special facilities, such as hospitals and nursing homes. Continued care or supervision must be provided for those who need it.

The need for the provision of instructions to all categories of farmers and for assisting those individuals who have been relocated also needs to be addressed.

— **Arrangements need to be in place to assist decision makers, the public and others (e.g. medical staff) to gain an understanding of radiological health hazards in a nuclear emergency in order to make informed decisions on protective actions. Arrangements also need to be in place to address public concerns locally, nationally and internationally.**

Public concerns need to be effectively addressed in a nuclear emergency. This includes the means to relate measurable quantities (e.g. dose rates) and projected radiation doses to radiological health hazards in a manner that allows decision makers (and the public) to make informed decisions concerning protective actions. Addressing public concerns contributes to mitigating both the radiological and the non-radiological consequences of the emergency.

These arrangements need to ensure prompt explanation of any health risks and possible appropriate individual actions for reducing these risks. Arrangements need to be in place to provide the public with useful, consistent and understandable information throughout a nuclear emergency, including an answer to the public's principal concern about potential health consequences; and to provide the public with an explanation of the basis for protective action recommendations.

International concerns could be addressed, in part, by means of certification systems to demonstrate that tradable goods meet international standards and to reassure importing States and the public.

— **Medical staff (health care professionals) need to be trained in basic medical response to a nuclear emergency and in adequate management of (possibly) contaminated patients to avoid delays in the treatment of injured people.**

Facilities that could be used as potential reception centres for triage, screening, decontamination and primary care of patients (either emergency workers or the public) need to be identified at the preparedness stage to facilitate the mobilization of resources during an emergency. Those treating or transporting contaminated patients would need to take the same kinds of precautions that would normally be applied when dealing with potentially infectious patients.

— **Emergency arrangements need to include provisions at the preparedness stage for implementing restrictions on the use and distribution of non-food commodities which have been, or could be, contaminated as a result of the emergency.**

Generic and operational criteria are needed to assess, where necessary, the adequacy of goods for use and distribution, and to establish a system for ensuring that controls are placed on those goods intended for international trade. These arrangements need to minimize major disruptions in international trade, while ensuring protection of the public.

— **Radioactive waste arising from the emergency needs to be managed in a manner that does not compromise the protection strategy.**

Detailed technical guidance for the management of radioactive waste, including food waste and waste generated from decontamination and remediation activities, needs to be developed at the preparedness stage. The guidance needs to include consideration that possible locations for facilities to store the radioactive waste on an interim basis and for long term disposal may need to be identified in advance. These arrangements need to be determined and agreed with the involvement of all relevant stakeholders, such as the local communities, at the preparedness stage.

3.4. TRANSITION FROM THE EMERGENCY PHASE TO THE RECOVERY PHASE AND ANALYSES OF THE RESPONSE

3.4.1. Transition from the emergency phase to the recovery phase

Figure 3.4–1 represents a timeline of key events relevant to the transition from the emergency phase to the recovery phase.



FIG. 3.4–1. Timeline of key events relevant to the process of transitioning from the emergency phase.

3.4.1.1. Relevant arrangements in Japan prior to the accident

The specific policies, guidelines and criteria, as well as overall arrangements for the transition from the emergency phase[98] to the recovery phase, were developed after the accident [190]. Prior to the accident, the national framework in Japan had not taken into account situations requiring long term recovery operations over wide areas [57].

3.4.1.2. International standards and recommendations on transitioning prior to the accident

IAEA Safety Standards Series No. GS-R-2, Preparedness and Response for a Nuclear or Radiological Emergency [11], specifies requirements for the establishment of arrangements for the transition from emergency phase operations to routine long term recovery operations and for the resumption of normal social and economic activity, including generic optimized intervention levels for initiating and terminating temporary relocation. It emphasizes the need for planning for such a transition at the preparedness stage.

The approach with regard to radiation protection in ICRP recommendations, issued in Publication 103 in 2007, is based on the characteristics of radiation exposure for the following three situations: planned, emergency[99] and existing[100] exposure situations [115]. The management of long term exposures following a nuclear or radiological emergency is to be treated as an existing exposure situation. These recommendations also recognize that the process of transitioning to the existing exposure situation following an emergency requires planning in advance; this planning is to be done as part of the overall emergency preparedness process. In addition, it is recommended that the process of transitioning be carefully balanced to include the views of all relevant stakeholders, including the public, with the fundamental goal that this approach is justified, i.e. it does more good than harm [115].

The ICRP recommendations in Publication 103 introduced the concept of reference level that is to be applied to an emergency and an existing exposure situation as "…the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimisation of protection should be implemented" [115].

In addition, the recommendations specified the bands for reference levels in terms of residual dose to be applied for both exposure situation as follows: 20–100 mSv acute or annual effective dose for emergency exposure situations and 1–20 mSv acute or annual effective dose for existing exposure situations, stating that the "chosen value for a reference level will depend upon the prevailing circumstances of the exposure under consideration" [115].

In developing arrangements for the transition from the emergency phase to the recovery phase after the accident, the Japanese authorities decided to apply the latest recommendations of the ICRP [115, 191, 192].

---

[98] The period of time from the detection of conditions warranting an emergency response until the completion of all the actions taken in anticipation of or in response to the radiological conditions expected in the first few months of the emergency. This phase typically ends when the situation is under control, the off-site radiological conditions have been characterized sufficiently well to identify where food restrictions and temporary relocation are required, and all required food restrictions and temporary relocations have been implemented [12].

[99] An unexpected situation that occurs during the operation of a practice, requiring urgent action. Emergency exposure situations may arise from practices [115].

[100] A situation that already exists when a decision on control has to be taken, including natural background radiation and residues from past practices that were operated outside the ICRP's recommendations [115].

3.4.1.3. Plans for returning to normality

The process for transition from the emergency phase to the recovery phase included adjusting the protective actions and arrangements made early in the emergency response and taking account of the information available on the conditions in the affected areas (obtained primarily through comprehensive monitoring) [145, 193]. It also included consideration of the necessary longer term recovery operations.

Gathering relevant information through comprehensive environmental monitoring, which was aimed at supporting the implementation of early protective actions (relocation, food restrictions, etc.), also made it possible to plan and implement longer term remedial actions in an informed manner, including additional thorough monitoring and decontamination activities as well as the identification of any need for medical follow-up. The announcement that control of the situation had been regained at the Fukushima Daiichi NPP (attainment of 'cold shutdown state'[101]) in December 2011 and the enactment of Act No. 110 of 2011 [189] facilitated the process of transitioning from the emergency phase to long term recovery operations.

The overall responsibility of managing the process for returning to normality rested with NERHQ. The Nuclear Emergency Act [5] specified that termination of NERHQ would take place when the "..declaration of the cancellation of a nuclear emergency situation is issued…", with the NSC to provide advice on the termination of the emergency [5].[102]

On 17 April 2011, TEPCO issued a roadmap that outlined the steps towards recovery on the site (basic policy, targets and immediate actions in the areas of: cooling, mitigation of consequences, and monitoring and decontamination) [194].

The objectives and conditions to be met for the termination of the emergency phase were defined in the plan to return to normality announced by the Japanese Government on 17 May 2011 [190]. On 17 May 2011, METI issued the Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers [190]. This listed nine groups of actions divided into steps scheduled to be implemented over different time periods connected to TEPCO's roadmap. Step 1 had a target of mid-July, step 2 a target of around three to six months after achieving step 1, and step 3 for the mid-term period.

The nine groups of actions were:

(1) Actions for the recovery from the accident at TEPCO's Fukushima Daiichi NPP;
(2) Actions related to the area evacuated up to 20 km based on plant conditions (Evacuation Area);
(3) Actions related to the area whose population was to be relocated (Deliberate Evacuation Area);
(4) Actions related to the area whose population was advised to shelter (Evacuation Prepared Area in Case of Emergency);
(5) Actions to ensure the safety and reassurance of those affected;
(6) Actions to secure employment and provide support to farms and industries;
(7) Actions to support the local municipalities in the affected areas;
(8) Actions related to compensation of sufferers, affected businesses, etc.;
(9) Actions to assist those returning to areas that were evacuated.

[101] The term cold shutdown state was defined by the Government of Japan at the time specifically for the Fukushima Daiichi nuclear power plant. Its definition differs from the terminology used by the IAEA and others.

[102] As of June 2015, the formal cancellation of a nuclear emergency situation has not been issued.

This roadmap was intended to facilitate communication and preparations for the transition to long term recovery operations and the resumption of normal social and economic activity. It allocated responsibilities and specified other organizational aspects of the transition process and the objectives and conditions for termination of the emergency phase.

The roadmap was revised in July 2011 [195]. Status updates on the progress in implementing the roadmap were issued each month until December 2011 [196].

The attainment of Step 1 of Action 1 (radiation dose in steady decline) was confirmed in July 2011 by monitoring results indicating that the release of radioactive material had steadily declined since the start of the accident [194, 197].

Actions 2–4 outlined the steps to be taken in the areas where the population had been evacuated, relocated or advised to shelter.[103] These actions were to be carried out following completion of Step 2 of Action 1 (stability assessment of the reactors).

On 19 July 2011, the requirements for lifting protective actions were set forth in the NSC's Basic Policy of the Nuclear Safety Commission of Japan on Radiation Protection for Termination of Evacuation and Reconstruction (referred to hereafter as 'the Policy') [192] The Policy summarized the NSC's recommendations for the termination of protective actions and the restoration of normal life.

The Policy recommended that the areas categorized as being in an emergency exposure situation could be re-categorized as being in an existing exposure situation when the release of radioactive material from the Fukushima Daiichi NPP would be under control, and the exposures due to residual radioactive materials in the areas could be limited to 20 mSv/y[104] or less. The Policy stated that the public should participate in the planning and formulation of the protective actions, and that appropriate consideration should be given to all relevant aspects such as health, environment, society, economy, ethics, psychology and politics [30, 192].

The Policy also recommended that operational criteria should be used to determine where long term protective actions needed to be implemented. It stipulated that the reference level for the optimization of the protective actions be selected from the lower part of the 1–20 mSv/y band, in accordance with the ICRP's recommendation for the management of an existing exposure situation [192]. However, no recommendations were made related to the principle of justification.

On 13 June 2011, the Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone was announced, which explained that monitoring of air, soil, forests, human-made materials (e.g. homes, roads) and water would be performed within the Restricted Area and Deliberate Evacuation Area; with the results of monitoring used to develop model projects for decontamination [145]. In addition, a monitoring coordination meeting with representatives from the relevant ministries, Fukushima Prefecture and TEPCO was held in July to promote coordination. A Comprehensive Monitoring Plan that specified the roles of the organizations was issued in August 2011. This plan was revised in March 2012 to improve cooperation between the

[103] The steps included obtaining emergency housing, providing temporary access and making preparations for relocation of the population of these areas (Deliberate Evacuation Area).

[104] It should be noted that this benchmark (20 mSv/y) is the same as the one used to judge the need for evacuation of the public in the Deliberate Evacuation Area, as well as the one initially applied in determining the acceptability of reopening the schools (see also Section 3.3.4.2), which resulted in major public concerns and confusion over the level of protection being afforded [25].

organizations[105] and to increase the monitoring activities in order to enable a review of the areas where evacuation orders had been issued, and address increasing concern of the release of radioactive materials into the sea from the rivers over the medium to long term. An on-line portal was also launched to facilitate the joint provision of monitoring results by the various organizations [145].

The provisions for the protection of workers were gradually modified, depending on the work being undertaken [27, 69]. As more information about hazardous conditions in which specific work needed to be undertaken was gathered, and there was more time for detailed planning of the work in the affected areas, the requirements and arrangements for the protection of emergency workers and other workers started to become more stringent. As explained in Section 3.2.3.2, the increased dose criterion for emergency workers of 250 mSv was withdrawn gradually starting on 1 November 2011 for newly engaged emergency workers and on 16 December 2011 (attainment of cold shutdown state at the plant was announced) for most emergency workers. However, even when this was being announced, it was obvious that there was a continued need for about 50 TEPCO employees to be subject to less stringent dose criteria, owing to the specifics of the duties they carried out. It was about a year after the onset of the accident and several months after the attainment of a cold shutdown state was announced (30 April 2012) that the increased dose criterion of 250 mSv was fully withdrawn for emergency workers with specific duties to maintain the control over the reactors and spent fuel pools under hazardous emergency conditions [68, 198].

In parallel with these efforts to manage the doses of emergency workers on the site within the 100 mSv criterion (see Section 3.2.3.2), the preparation for the planned decontamination and restoration work necessitated the establishment of a new legal framework for ensuring adequate protection of workers engaged in these works. This was mainly because regulations in Japan, at the time of the accident, did not sufficiently cover activities during the existing exposure situation following an emergency. As of 26 August 2011, for all workers engaged in decontamination work, restoration and waste management, the requirements for occupational exposure in normal operation were applied for the existing exposure situation (i.e. planned exposure situation) [199, 200]. Later on, relevant ordinances were either developed, or revised, in 2012 and 2013 [57, 76, 77, 201, 202]. Although not explicitly referred to, the new requirements and respective guidelines for the protection of workers engaged in decontamination works or works under designated dose rates were considered by the MHLW as useful also for local residents and volunteers who were in the special decontamination areas [57, 76, 77]

Simultaneously with the ongoing efforts to characterize fully the exposure situation and to plan for decontamination activities, long term health surveillance was initiated at the end of June 2011 (the Fukushima Health Management Survey) [59]. The purpose of the survey was to perform thyroid examinations of those aged 18 or younger at the time of the accident who were located in Fukushima Prefecture at the time of the accident. In addition to this activity, a survey and other supporting activities were initiated to evaluate the doses received by the population of the prefecture [173].

On 4 August 2011, the NERHQ requested the advice of the NSC on the areas where protective actions were being implemented (evacuation, relocation and sheltering), in order to determine whether any changes were required. On the same day, the NSC provided a document entitled Standpoint of the Nuclear Safety Commission for the Termination of Urgent Protective Actions Implemented for the Accident at the Fukushima Daiichi Nuclear Power Plant [203], which included guidance on the termination of the protective actions specific to the areas that had been recommended to shelter, relocate and evacuate. The recommendations for the approach to the termination were: (1) the

[105] These organizations included, among others: MEXT; NSC; MHLW; MAFF; Fisheries Agency; Ministry of Land, Infrastructure, Transport and Tourism; Ministry of the Environment; Fukushima Prefectural Government; and TEPCO.

projected annual dose to the public is lower than the criterion of 20 mSv; (2) preparation for the implementation of long term protective actions had been made; and (3) a framework for the participation of the relevant local governments and residents in the process of deciding on the long term protective actions is developed.

On 9 August 2011, the Japanese Government prepared a review of the areas where protective actions were being implemented. The following three requirements for termination of the protective actions were outlined in the review: (1) the safety status of the NPP; (2) a decrease in the dose rate; and (3) restoration of the public service functions and infrastructure.

On the same day, a statement was issued by NISA and MEXT on the status of the NPP and environmental monitoring results that verified that requirements 1 and 2 of the Roadmap for Immediate Actions to Assist Residents Affected by the Nuclear Accident had been met [30].

On 19 August, all cities, towns and villages that had been advised to shelter (in the Evacuation Prepared Area) began preparing disaster recovery programmes, which were submitted to the Japanese Government. This was undertaken in order to fulfil requirement 3 of the Roadmap for Immediate Actions [190]. Over the next six weeks, consultations were held between the local governments and national Government on the areas where advice to shelter (in the Evacuation Prepared Area) had been given to the residents. On 30 September, the advice to shelter was withdrawn by the Japanese Government as a result of an assessment of the safety status of the Fukushima Daiichi NPP and measurements of the dose rate in the relevant areas. The announcement stated that monitoring would continue to be conducted and that local governments would implement their restoration plans. It was also noted that the date by which the public could return to the area would vary among local governments and would be undertaken with support provided by the national Government [193].

On 26 August, the goals and policies to be pursued over the next two years were issued by the NERHQ in the Basic Concept for Pushing Ahead with Decontamination Works and Basic Policy for Emergency Response on Decontamination Work [30, 72]. Act No. 110 of 2011 [189] outlined the management of the contaminated areas and included the assignment of responsibilities to the national and local governments, the operator and the public. It was enacted on 30 August 2011 and enforced in January 2012. The act facilitated the transition from an emergency exposure situation to an existing exposure situation; it formalized the long term management of environmental monitoring, decontamination measures, and the designation, treatment, storage and disposal of radioactive waste.

On 16 December 2011, a cold shutdown state was achieved at the NPP, which was used to indicate that the control of the situation had been regained [21]. This meant that Step 2 of Action 1 of the roadmap issued in May had been completed.

A review of the areas where protective actions were being implemented was required for completion of Step 2 of Action 1. The review of areas (Restricted Area and Deliberate Evacuation Area) was issued on 26 December 2011 by the Japanese Government in a document called Basic Concept and Issues to be Challenged for Rearranging the Restricted Areas and Areas to which Evacuation Orders have been Issued where Step 2 has been Completed [21]. The review of the areas was undertaken in consideration of the dose criterion of 20 mSv/y in terms of projected dose. Its criteria and area designations are presented in Table 3.4–1.

TABLE 3.4–1. CRITERIA, DESIGNATION AND COLOUR OF AREA SHOWN IN FIG. 3.4–2 [21]

Criteria	Designation	Colour shown in Fig. 3.4–2
Annual cumulative dose would be less than or equal to 20 mSv	Areas in which evacuation orders are ready to be lifted	Green (Area 1)
Annual cumulative dose may exceed 20 mSv but is less than 50 mSv	Areas in which residents are not permitted to live	Orange (Area 2)
Annual cumulative dose exceeds 50 mSv	Areas in which residents will not be able to return for a long time	Red (Area 3)

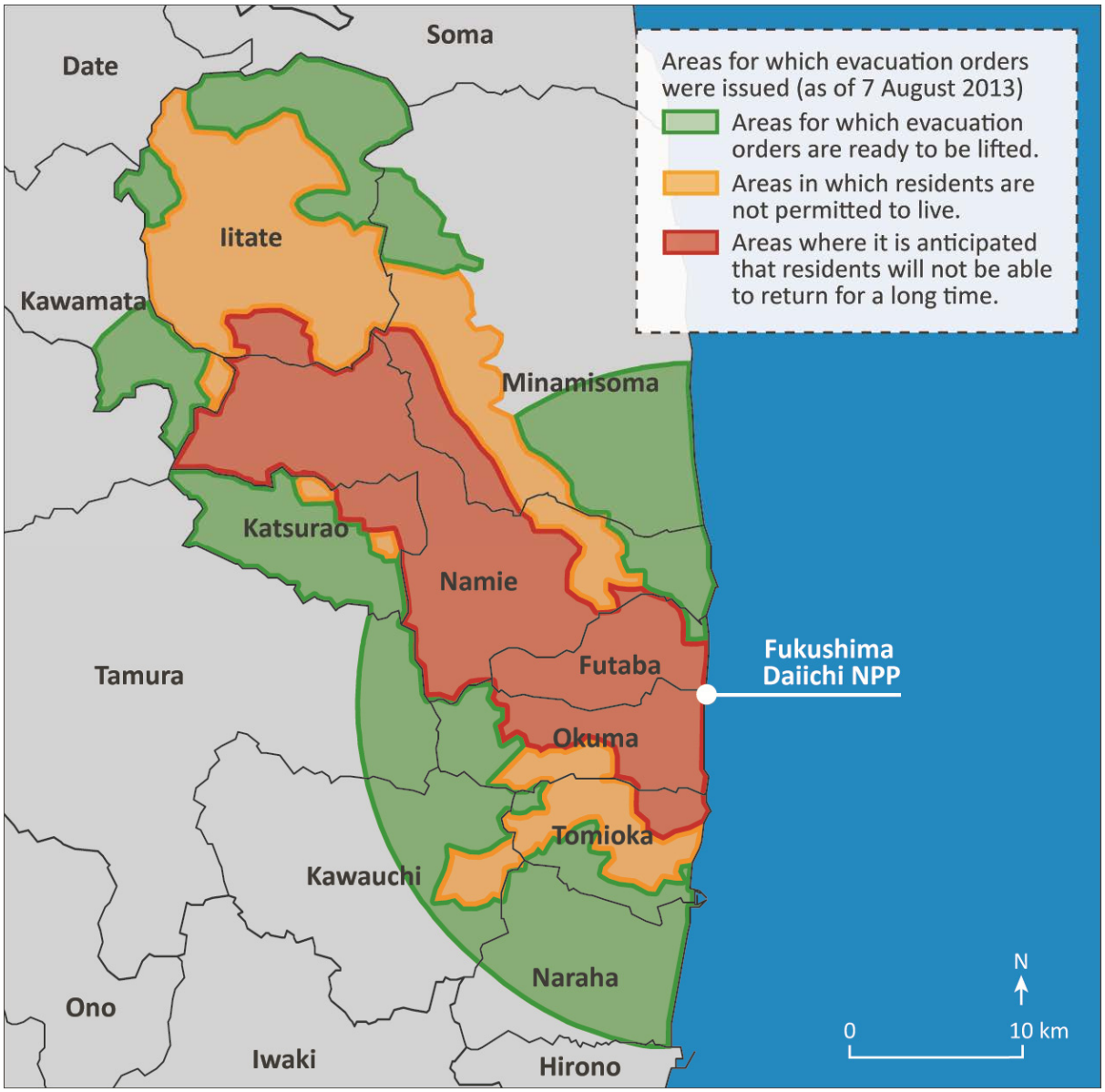


FIG. 3.4–2. Completion of the arrangement for areas where evacuation orders have been issued (7 August 2013) [204].

3.4.2. Analyses of the response

Analyses of the accident and the emergency response were undertaken by various bodies in order to identify lessons and to enhance, among other areas, emergency preparedness and response arrangements in Japan.

The timeline of events that are important for the analyses of the response are shown in Fig. 3.4–3.

24 May 2011
- Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company established

June 2011
- Report to the IAEA Ministerial Conference on Nuclear Safety submitted by NERHQ

July 2011
- NSC Working Group established to review the Regulatory Guide for Emergency Preparedness of Nuclear Facilities

September 2011
- Additional report by NERHQ submitted to the IAEA on the occasion of the Board of Governors meeting and General Conference 2011

26 December 2011
- Investigation Committee on the Accident at the Fukushima Nuclear Power Stations issued interim report

December 2011
- National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission established
- TEPCO Fukushima Nuclear Accident Analysis Report (interim version) issued

22 March 2012
- NSC Working Group submitted to NSC an interim report on revision of Regulatory Guide for Emergency Preparedness of Nuclear Facilities

June 2012
- Revision of Act on Special Measures Concerning Nuclear Emergency Preparedness

20 June 2012
- TEPCO Fukushima Nuclear Accident Analysis Report (final version) issued

5 July 2012
- National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission issued final report

23 July 2012
- Investigation Committee on the Accident at the Fukushima Nuclear Power Stations issued final report

19 September 2012
- Establishment of Nuclear Regulation Authority (NRA)

October 2012
- NRA released results to help determine the area of the Urgent Protective Action Planning Zone

FIG. 3.4–3. Timeline of key events important for analyses of the response

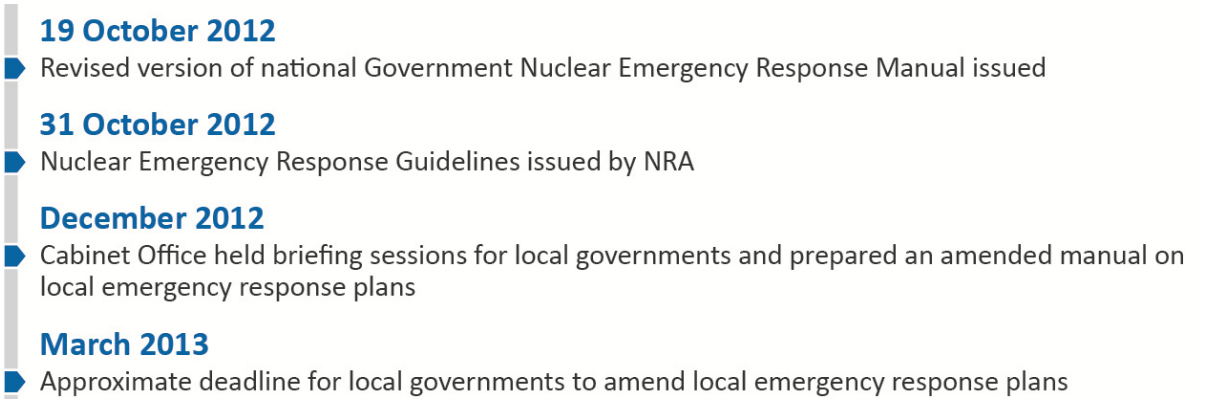


FIG. 3.4–3. Timeline of key events important for analyses of the response (cont.).

3.4.2.1. Analysis of the emergency performed in Japan

An analysis of the accident and of the emergency response was performed and presented in the form of reports[106], issued by the Government of Japan [22, 30], by two investigation committees created by the Government and the Parliament, respectively [21, 25, 27] and by the operating organization (TEPCO) [17] to identify actions to be taken that would prevent the occurrence of other emergencies and to improve the emergency arrangements in Japan. Following an agreement with the Government of Japan, the IAEA conducted a preliminary fact finding mission from 24 May to 2 June 2011 to identify initial lessons to be learned from the accident and share this information with the international community [51]. In addition, actions were taken by the NSC to review and update the organization's guidance, which was used as a basis for developing the relevant nuclear EPR documents of Japan. The regulatory body, NISA, also conducted a review to identify those measures that should be implemented immediately to update and improve the national EPR system.

The Government of Japan submitted the report to the IAEA Ministerial Conference on Nuclear Safety in June 2011 [22] presenting lessons in the following areas important for emergency preparedness and response: (1) combined natural disaster and nuclear emergency; (2) environmental monitoring; (3) allocation of roles between central and local organizations; (4) communication in an emergency; (5) response to assistance from other States and communication with the international community; (6) modelling of the release of radioactive materials; and (7) criteria for evacuation and radiation protection guidelines in nuclear emergencies. An additional report was submitted to the IAEA in September 2011 [30]. It provided information on further developments and progress in addressing the lessons that had been identified in the first report issued in June 2011.

The NERHQ and relevant government organizations were tasked with addressing these lessons.

On 2 December 2011, TEPCO released an Interim Report, which summarized the results of the investigations it had completed at the time and proposed various countermeasures, mainly in the equipment area, that were to address the causes of the accident and prevent a recurrence [31]. TEPCO's Final Report was issued in June 2012 [17] and highlighted issues that were identified during the response to the emergency, including: emergency response organization; communication of information; transportation of materials and equipment; and radiation protection.

[106] Reports from academia and from the private sector were also issued (e.g. from the Atomic Energy Society of Japan and the Rebuild Japan Initiative Foundation) [205, 206].

A detailed reconstruction of the accident scenario was performed to analyse the initiating event and determine the damage caused by the earthquake and tsunami. Consideration was given to the root causes of the emergency. Regulatory controls, general safety implications and necessary improvements concerning emergency arrangements were identified.

The report of the Fukushima Nuclear Accident Independent Investigation Commission established by the National Diet of Japan contained a recommendation for, among other things, reform of the national emergency preparedness and response system, including clarification of the roles and responsibilities of the Government, local government and operators in an emergency [25].

The Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, created by the government, found that there was a need for Japan to take into account lessons from the international community and to include international standards, such as those developed by the IAEA, in its national guidelines [21].

The NSC had been considering, since 2006, to apply the guidance provided in IAEA Safety Standards Series No. GS-G-2.1 [13, 25].

In 2010, the NSC initiated a review of its Regulatory Guide for Emergency Preparedness for Nuclear Facilities (Nuclear Emergency Preparedness Guide) [19]. As stated in The Basic Policies for the Near-Term Initiatives of the Nuclear Safety Commission of December 2010 [207] it was planned to consider adoption of international standards into the Emergency Preparedness Guide and was still under consideration when the accident occurred on 11 March 2011.

The NSC established a working group under the Special Committee on Disaster Countermeasures on Nuclear Facilities to review the Emergency Preparedness Guide in July 2011. While reviewing the guide, the following aspects were taken into consideration: (1) the circumstances of the accident; (2) the investigation and examination by the National Diet of Japan, Fukushima Nuclear Accident Independent Investigation Commission [25], as well as by the Government Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company [21, 27]; (3) ICRP recommendations and IAEA safety standards; (4) deliberations among the working group members; (5) nuclear emergency countermeasures taken in other countries; and (6) the actual state of affairs and the effectiveness of measures in Japan.

The Special Committee submitted its interim report on the revision of the Regulatory Guide for Emergency Preparedness of Nuclear Facilities to the NSC in March 2012 [208] This document was then used as a basis for the development of the new regulatory guidelines issued by the newly established Nuclear Regulatory Authority (NRA) [100]. The new regulatory guidelines were subsequently implemented by the local governments when the local arrangements were revised.

In June 2011, NISA specified the measures for all NPPs that were to be immediately implemented, which included securing the means of communication on-site to ensure a quick response in the event of a severe emergency. Operators were directed to implement these measures, and NISA then verified their implementation. Furthermore, in March 2012, in a report on the technical knowledge of the accident at the Fukushima Daiichi NPP [209], NISA consolidated these measures as items to be reflected in future safety regulations. There were 30 safety measures recommended by NISA that included securing and improving a command post at the time of an emergency, securing communication functions, securing reliability of instrumentation facilities, reinforcement of plant status monitoring functions, reinforcement of environmental monitoring functions in an emergency, building an emergency response system and implementation of training.

3.4.2.2. Strengthening the national EPR system

In order to strengthen the national EPR system based on the experience and lessons learned from the accident and the establishment of the NRA on 19 September 2012, the Atomic Energy Basic Act, the Nuclear Emergency Act [5], and other related laws and regulations were amended, and the Government developed a new framework for nuclear emergency preparedness and response. This included changes to the Government's Nuclear Emergency Response Manual [210] and preparation of the regulatory body's Nuclear Response Guidelines [211] in order to reflect the amendments [212].

As a result of the revision of the Atomic Energy Basic Act, a Nuclear Emergency Preparedness Commission was established within the Cabinet, with the Prime Minister serving as the Chairperson and the Chief Cabinet Secretary, the Minister of the Environment, and the NRA Chairman serving as Vice Chairpersons [212]. The purpose of the Commission is to implement and promote nuclear emergency response policies in a unified manner by the Government [212, 213].

The revision of the Nuclear Emergency Act enhanced measures to strengthen the functions of the NERHQ in an emergency [5]. The NERHQ would be established, with the Prime Minister serving as Chairperson and the NRA Chairman serving as one of the Vice Chairpersons [212].

Changes to the Nuclear Emergency Act also included clearer assignment of on-site and off-site roles [5, 212]. The NRA now oversees the technical and professional safety requirements of on-site nuclear facilities. Other relevant ministries and agencies will handle the procurement of equipment at nuclear facilities and other off-site activities under the supervision of the Chief of NERHQ [212]. The Secretary-General of the NRA Secretariat will serve as the Director General of the NERHQ.

The chapter on nuclear emergency response in the Basic Disaster Management Plan was also revised [216]. Jurisdictions were changed following the establishment of the NRA and the crisis management system at the Prime Minister's Office, and the allocation of roles in taking on-site and off-site actions were specified. As described in Section 3.1.1., the Basic Disaster Management Plan specified that a Nuclear Emergency Response Manual of the national Government was to be prepared; this was also revised to reflect the changes made in the Plan [210].

At the first meeting of the Nuclear Emergency Preparedness Commission, the Nuclear Emergency Response Manual was approved [210]. It addressed such issues as the deployment of staff and response procedures of the NRA and other ministries and agencies during an emergency.

In conjunction with the Nuclear Emergency Act [5], which was revised on 19 September 2012, the Cabinet Office revised the related ministerial ordinances that covered the off-site centres and the associated technical standards guidelines. Prefectures hosting off-site centres will be responsible for assessing their preparedness based on the revised ministerial ordinances and guidelines.

3.4.2.3. Strengthening national guidance on EPR

In accordance with the Nuclear Emergency Act [5], the NRA is required to establish the Nuclear Emergency Response Guidelines to ensure that operators, the national Government and local governments coordinate the implementation of nuclear emergency response measures [212]. The NRA initiated relevant discussions with interested parties immediately after its inauguration and established the guidelines on 31 October 2012. The guidelines were subsequently revised on 27 February, 5 June and 5 September 2013 [211].

The emergency preparedness arrangements specified in the Nuclear Emergency Response Guidelines [212] are based on the IAEA safety standards in the area of EPR [11, 13, 14]. Arrangements include the following:

— Predetermined criteria, to be established for decision making in an emergency; these include emergency action levels (EALs)[107] and operational intervention levels (OILs);
— New zones (see Fig. 3.4–4), to be established with PAZs and urgent protective action planning zones (UPZs), within which arrangements are to be made for urgent protective actions;
— Protective actions (e.g. sheltering, evacuation, administration of stable iodine tablets, etc.), to be taken within the zones based on the predetermined criteria;
— A new system, for providing information, emergency monitoring and medical management, as well as education and training (e.g. for emergency workers);
— Requirements for prompt emergency monitoring;
— Requirements for prompt public information;
— Requirements for long term monitoring of human health and the environment;
— Requirements for the implementation of decontamination.

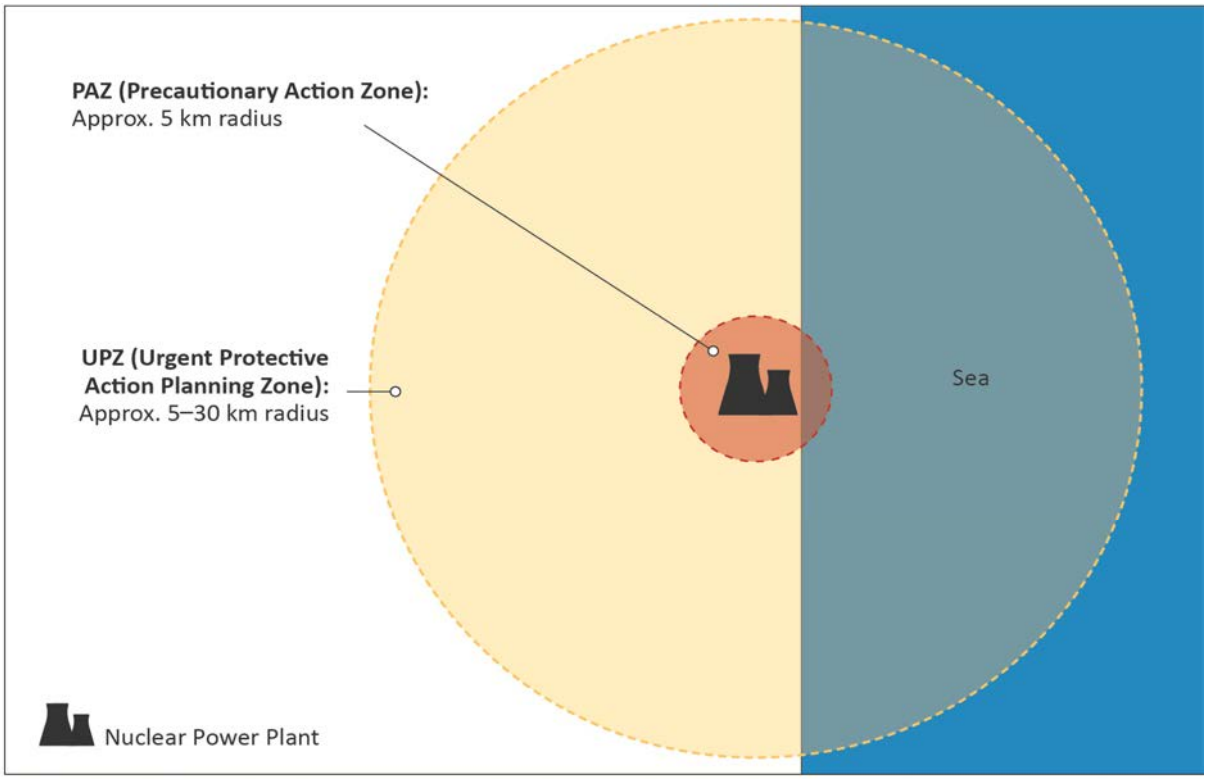


FIG. 3.4–4. Visual depiction of a PAZ and a UPZ [208].

Arrangements ensure that urgent protective actions are implemented within the predetermined zones upon the declaration of a General Emergency. Within the PAZ, evacuation of all local residents must

[107] The operator of a nuclear facility is required to immediately determine the applicable emergency class (based on the EALs), notify national and local governments and propose appropriate protective actions, if applicable. To enable appropriate protective actions to be implemented promptly, nuclear operators are required to consider establishing more detailed EALs that will reflect conditions at each power reactor and submit them to the NRA. The NRA will then examine the EALs and provide recommendations, if warranted [212].

generally be implemented immediately when the situation is classified as a General Emergency, and sheltering is recommended prior to evacuation. Within the UPZ, sheltering must be implemented as a general rule until phased evacuation or protective actions based on OILs are implemented. Beyond the UPZ, sheltering is generally implemented in the same way as within the UPZ. Accordingly, local residents must be warned that there is a possibility that temporary relocation might be necessary under the prevailing circumstances [212].

The NERHQ or local governments are required to issue orders and/or recommendations on the intake of stable iodine, in principle based on the decision by the NRA. Within the PAZ, the NERHQ or local governments are required to immediately issue orders and/or recommendations concerning evacuation and the administration of pre-distributed stable iodine tablets when the situation is classified as a General Emergency. Beyond the PAZ, the NRA determines the necessity of taking stable iodine, in addition to possible evacuation and sheltering, after which the NERHQ or local governments issue the necessary orders and/or recommendations [212].

The national and local governments are required to make arrangements for the provision of appropriate medical screening of evacuees and those temporarily relocated. Simple decontamination measures will be implemented, taking into account the effectiveness of such measures, if the specific OIL is exceeded [212].

For restrictions on the ingestion of food and drink, areas where dose rates exceeded a specific OIL are to be identified and the measurement of radionuclide concentrations in food and drink should be initiated. If these measurements confirm radionuclide concentrations in excess of the specific OIL, consumption of food or drink will be restricted. In implementing these restrictions, the NRA is required to disseminate all relevant information to local governments via the NERHQ; the local governments, in turn, are required to inform all local residents [212].

The guidelines emphasize the importance of stakeholder involvement in implementing intermediate and long term protective actions. The national and local governments are required to conduct continuous environmental monitoring to ascertain changes to a exposure situation to enable decisions, such as revisions to the evacuation zone size and determination of measures to manage and reduce exposures [212].

The national and local governments are required to take appropriate protective actions based on the results of estimating individual doses to the population living in long term contaminated areas. The national and local governments are also obligated to conduct long term health surveillance, including the mental health of residents, and to monitor for possible radiation induced health effects [212].

Government officials are obliged to implement decontamination to enable residents to return to their normal lives as quickly as possible. Government organizations will encourage public participation by providing all decontamination information, guidance, materials, equipment and training, and by deploying specialized advisors. The exposure of workers engaged in decontamination is to be managed in accordance with the relevant laws and regulations [199, 202, 212].

The authorities are required to carefully consider decisions on the transition from an emergency exposure situation to an existing exposure situation, such as lifting evacuation directives and other protective actions [212].

The most important changes in the national EPR system are summarized in Table 3.4–2. The table lists the guidance that was in place prior to the accident, which has been developed since the accident and the relevant IAEA safety standards [11, 13, 14]. Figure 3.4–5 shows an example of the implementation scheme of urgent and early protective actions in the guidance.

TABLE 3.4–2. NATIONAL GUIDANCE IN JAPAN BEFORE AND AFTER THE ACCIDENT AND THE ASSOCIATED IAEA SAFETY STANDARDS

National guidance in Japan		IAEA safety standards [11, 13, 14]
Before the accident [19]	After the accident [211]	
Emergency reporting system	Emergency classification system (General Emergency Alert) with predetermined associated protective actions and other response actions	Emergency classification system (General Emergency Alert) with predetermined associated protective actions and other response actions
EPZ of 10 km	PAZ of around 5 km and UPZ of around 30 km with arrangements to take urgent protective actions	PAZ and UPZ with arrangements to take urgent protective actions
No operational criteria in place	OIL1: dose rate criteria for evacuation within a day OIL2: dose rate criteria for relocation within a week OIL3: dose rate criteria for food restrictions OIL4: β counts/min for decontamination and medical screening OIL6: radionuclide concentrations for food and drink restrictions The OILs follow the system documented in the IAEA safety standards and technical guidance [14, 107]	OILs for evacuation, relocation, food restrictions, public monitoring, etc.

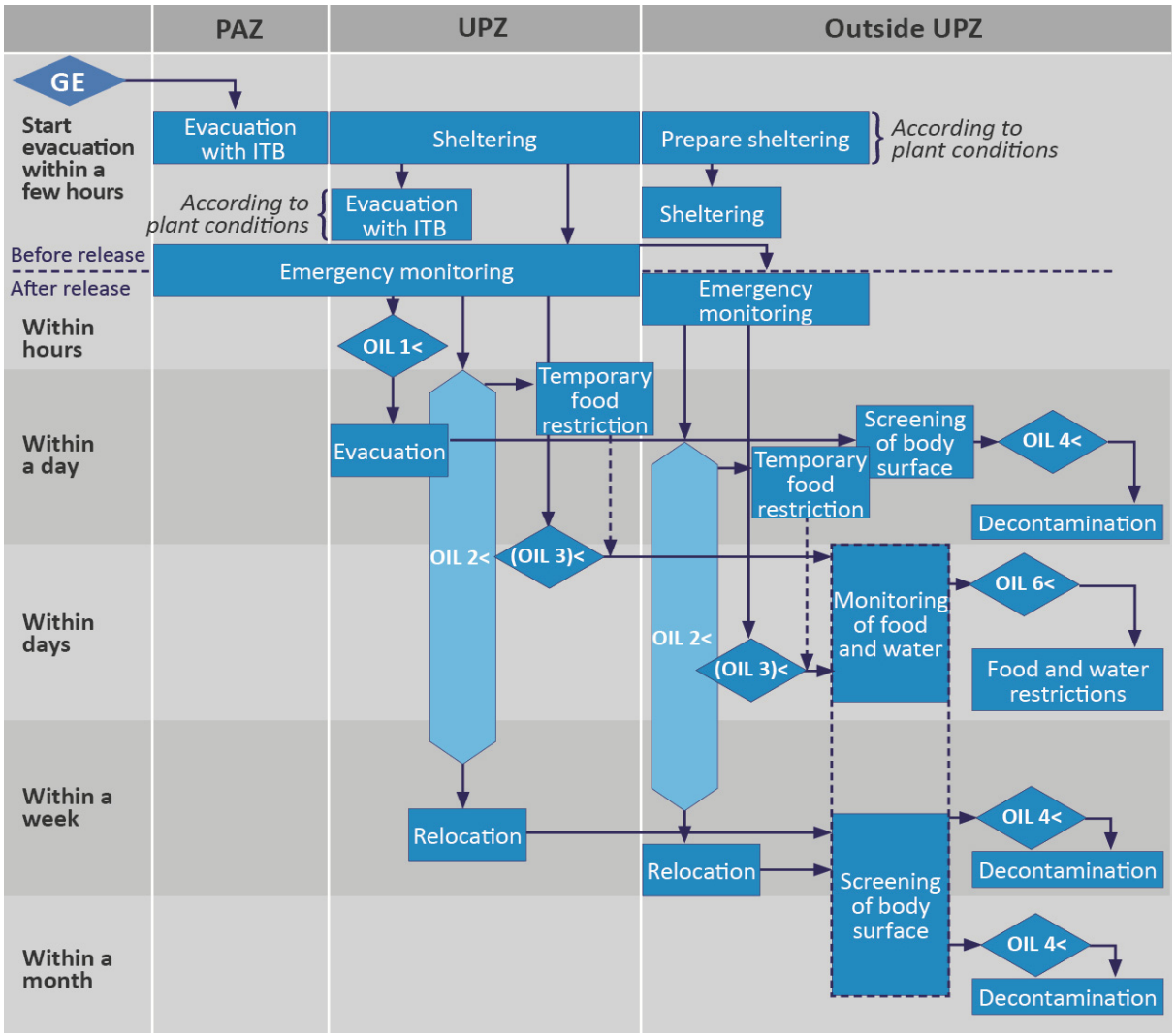


FIG. 3.4–5. Example of implementing protective actions [211].

3.4.2.4. Implementation of strengthened national guidance on EPR

Pursuant to the provisions of the revised Disaster Countermeasures Basic Act[108] [6] and the revised Nuclear Emergency Act [5], local governments were required to amend their local emergency response plans by 18 March 2013. These revisions were required to reflect the national guidance on EPR developed after the accident (i.e. the Nuclear Emergency Response Guidelines of the NRA) [211].

Owing to issues related to coordination and securing of evacuation sites, support was provided from the national Government and the regulatory body to the local government for the implementation of the national guidance on EPR developed after the accident.

In order to support local governments in revising arrangements, the Cabinet Office held briefing sessions and prepared amended guidance for local governments. As areas included in the UPZ may extend across multiple prefectures, the Cabinet Office held a conference to address this issue, and adjustments were then made to the protective actions to ensure coordination and consistency in their implementation [212].

To help determine the size of the UPZ, the NRA performed a simulation on the spread of radioactive materials resulting from an emergency corresponding to the Fukushima Daiichi accident, the results of which were released by the end of 2012 [212]. These results showed that the area requiring planning for protective actions had to be expanded beyond the 10 km zone established prior to the accident [214, 215]. It is anticipated that the NRA and the Cabinet Office will provide support to local governments to enhance the local emergency response systems [212].

Examples of activities to address lessons in the area of combined natural disaster and nuclear emergency included reinforcement of off-site centres and arrangements for the prompt deployment of materials and equipment [211]. Regarding environmental monitoring, it was stated that the national Government should prepare a system for emergency radiation monitoring centres located in relevant areas and make plans for deploying staff and equipment [211]. The chain of command structure across ministries and agencies was reviewed and revised [210] to address the need to clearly allocate roles between central and local organizations. Responsibilities were also designated and clearly assigned in the Basic Disaster Management Plan [216]. In the area of communication, arrangements to facilitate joint press conferences were established [210]. In response to the lessons learned in the area of assistance, contact points for each neighbouring country have been specified [210], and lists of equipment for responding to nuclear emergencies and methods for international information sharing, including through international notifications, are being developed.[109] In addition, to enhance the provision of information internationally, since December 2013, Japan has regularly provided information on the response to the accident to the international community in a comprehensive manner, which is reflected on the IAEA homepage [217].

In the area of modelling of the release of radioactive material, the utilization of analytical tools is expected to support effective environmental monitoring. After examining the major release of radioactive material after the Fukushima Daiichi accident, it was realized that it is not possible to obtain accurate information on emission sources in nuclear or radiological emergencies. In addition, in the report of The National Diet of Japan Fukushima Nuclear Accident Independent Investigation

[108] See Appendix I for more information.

[109] For example, the revised IAEA publication EPR-RANET 2013 reflected Japan's proposals, such as the addition of 'stabilization of situations at accident sites' into the functional areas of RANET, listing of equipment which can be utilized to stabilize situations on the site with detailed specifications, and the registration of equipment possessed by private entities, to enhance the IAEA's RANET capabilities [217].

Commission (NAIIC) [25], it was pointed out that "[t]he weather forecast information used for calculating predictions has limitations, particularly with regard to localized rainfall, snowfall, etc."

As a consequence, it is not considered possible to calculate predictions or estimations accurately using SPEEDI in nuclear or radiological emergencies [217].[110]

The national guidance on EPR developed after the accident was therefore changed mainly in order to reflect the IAEA safety standards and the latest technical guidance in the area of EPR [11, 13, 107].

3.4.3. Summary

Specific policies, guidelines, criteria and arrangements for the transition from the emergency phase to the recovery phase, were not developed until after the Fukushima Daiichi accident. In developing these arrangements, the Japanese authorities applied the latest recommendations of the International Commission on Radiological Protection (ICRP). The Japanese authorities decided to apply the latest ICRP recommendations to defined exposure situations (i.e. emergency exposure situations and existing exposure situations), although these recommendations had not been included in the national framework prior to the accident. This caused certain difficulties, for example, it proved difficult to define the termination of the emergency exposure situation and the subsequent transition to the existing exposure situation.

Developed arrangements included adjusting the protective actions and the arrangements made early in the emergency response and undertaking longer term recovery operations. These processes addressed the immediate needs arising during the transition process.

The Japanese authorities made substantial efforts in the development of specific policies, criteria and detailed guidelines and arrangements in this regard and in their subsequent implementation.

The transition process included the adjustment of implemented protective actions and arrangements to take account of the longer term exposure situation. The transitioning process required comprehensive monitoring to describe the exposure situation in detail.

The provisions for the protection of workers were gradually modified, depending on the work being undertaken.

The involvement of the public in policy making with regard to the transition from an emergency situation, and the relaxation or removal of previously imposed protective actions, gradually increased.

Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO) and two investigation committees created by the Government and the Parliament, respectively. This work was undertaken in order to identify lessons and to enhance EPR arrangements in Japan. The review and analysis included a reconstruction of the accident scenario, consideration of the root causes of the accident, regulatory controls and general implications for safety. A number of improvements in emergency preparedness and response arrangements were identified as a result.

On the basis of these analyses and lessons identified, corrective actions were taken to strengthen emergency preparedness and response arrangements [210, 212]. Reviews were conducted of the

[110] As described in the revised Nuclear Emergency Response Guidelines, EALs and radiation monitoring will be used for decisions about protective actions. It was decided that SPEEDI can be used as reference information for other purposes, except for the judgement of protective actions in emergencies.

relevant legislation and emergency plans and procedures by the various organizations. The necessary revisions to relevant national legislation and some relevant policies, plans and procedures have since been made in a timely manner. A Nuclear Emergency Preparedness Commission was established within the Cabinet to ensure that nuclear emergency response policies would be implemented and promoted by the Government [212]. The NRA developed Nuclear Emergency Response Guidelines [211], also taking into account the IAEA safety standards in the area of emergency preparedness and response.

Implementing corrective actions identified as a result of national analysis of the emergency and emergency response included prioritizing improvements to be made to the EPR system, assigning implementation of the improvements to a specific organization, establishing a coordinating body to oversee the improvements and providing support at the national level for improvements made at the local level.

3.4.4. Observations and lessons

— **Arrangements need to be developed at the preparedness stage for termination of protective actions and other response actions, and transition to the recovery phase.**
  At the preparedness stage there is a need to plan for the transition from the emergency phase to the long term recovery phase, and for resumption of normal social and economic activities. The arrangements need to: (1) establish formal processes to decide on the termination of protective actions and other response actions; (2) clearly allocate responsibilities; (3) establish criteria for the termination of protective actions and other response actions; and (4) provide a strategy and process for consulting the public.
  Transitioning may differ from one location to another in the affected areas. This may result in complex and simultaneous applications of different requirements specific to the exposure situation in each area. This needs to be clarified and clearly communicated to all organizations and the public at the preparedness stage to avoid raising concerns that some members of the public or some workers are less protected than others in the transition phase.
— **Timely analysis of an emergency and the response to it, drawing out lessons and identifying possible improvements, enhances emergency arrangements.**
  Such an analysis needs to include a review of all relevant arrangements, including national laws and regulations, allocation of authorities and responsibilities, emergency response plans and procedures, facilities, equipment, training and exercises. Analysis provides a basis for revision of the arrangements, as necessary. The adequacy of revised emergency arrangements needs to be demonstrated through exercises.

3.5. RESPONSE WITHIN THE INTERNATIONAL FRAMEWORK FOR EMERGENCY PREPAREDNESS AND RESPONSE

An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements.

3.5.1. International EPR framework for a nuclear or radiological emergency prior to the accident

The responsibility for emergency preparedness and response for nuclear or radiological emergencies

rests with the State, as does the protection of human life, health, property and the environment.[111] The State is responsible for ensuring that EPR arrangements are in place at the national, regional, local and operating organization/facility levels. Where appropriate, the State is also responsible for ensuring coordination of national EPR arrangements with the relevant international arrangements to which the State accessed or is otherwise a party (e.g. through bilateral and/or multinational agreements).

The impact of any nuclear or radiological emergency can rapidly become of regional and global interest and concern. Effective management of nuclear or radiological emergencies therefore requires efficient national and international arrangements for sharing reliable information related to the emergency to ensure protection of human life and health, property and the environment.

The international EPR framework at the time of the accident at the Fukushima Daiichi NPP consisted of: (a) international legal instruments; (b) IAEA safety standards; and (c) operational arrangements (see Fig. 3.5–1).



FIG. 3.5–1. International EPR framework at the time of the accident at the Fukushima Daiichi NPP.

The main international legal instruments on EPR are the Convention on Early Notification of a Nuclear Accident (Early Notification Convention) [219] and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention) [220]. These conventions are supplemented by bilateral or multilateral agreements between and amongst States and relevant international organizations. In addition, the Convention on Nuclear Safety [227] and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (Joint Convention) [228] address some aspects of EPR in relation to nuclear installations and to management of spent fuel and radioactive waste, respectively.

[111] According to IAEA safety standards [218], the government shall make provision for emergency preparedness to enable a timely and effective response in a nuclear or radiological emergency.

The key IAEA safety standards in the EPR area at the time of the accident consisted of the General Safety Requirements publication Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2 [11], published in 2002[112], supplemented by the Safety Guide on Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1 [13][113], published in 2007. In addition, in March 2011, a Safety Guide on the Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSG-2 [14], was published under the joint sponsorship of FAO, IAEA, ILO, PAHO and WHO. This Safety Guide provides guidance on the criteria for use in determining protective actions and other response actions to be taken in a nuclear or radiological emergency. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115 [49], which was published in 1996 and has since been superseded by IAEA Safety Standards Series No. GSR Part 3 (see Ref. [26]), also included parts that were related to EPR. These safety standards were supported by a series of technical guidance and tools in EPR covering specific aspects (examples include generic assessment procedures for determining protective actions during a reactor accident and generic procedures for medical response during a nuclear or radiological emergency [221, 222]).

The international operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), IAEA Response and Assistance Network (RANET), Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) and bilateral arrangements among relevant international organizations and/or States [223–225].

In addition, the international system for dealing with nuclear or radiological events relies on the central coordinating role and functions of the IAEA Secretariat and on IACRNE[114] as the prime interagency coordination mechanism in EPR.

3.5.1.1. The Early Notification Convention

Article 1, paragraph 1 of the Early Notification Convention states that:

> "This Convention shall apply in the event of any accident involving facilities or activities[115] of a State Party or of persons or legal entities under its jurisdiction or control…from which a release of radioactive material occurs or is likely to occur and which has resulted or may result in an international transboundary release that could be of radiological safety significance for another State" [219].

---

[112] This publication is jointly sponsored by the Food and Agriculture Organization of the United Nations (FAO), IAEA, International Labour Organization (ILO), OECD Nuclear Energy Agency (OECD/NEA), Pan American Health Organization (PAHO), United Nations Office for the Coordination of Humanitarian Affairs (OCHA) and World Health Organization (WHO).

[113] This publication is jointly sponsored by FAO, IAEA, ILO, PAHO, OCHA and WHO.

[114] Formerly, the Inter-Agency Committee for the Co-ordinated Planning and Implementation of Response to Accidental Releases of Radioactive Substances, which was established following a meeting of representatives of FAO, United Nations Environment Programme (UNEP), ILO, UNSCEAR, World Meteorological Organization (WMO), WHO and IAEA at the Special Session of the IAEA General Conference in September 1986 [226].

[115] Facilities and activities here refers to any nuclear reactor wherever located; any nuclear fuel cycle facility; any radioactive waste management facility; the transport and storage of nuclear fuels or radioactive wastes; the manufacture, use, storage, disposal and transport of radioisotopes for agricultural, industrial, medical and related scientific and research purposes; and the use of radioisotopes for power generation in space objects.

Article 2 of this Convention states that in the event of a nuclear accident or radiological emergency the State Party has to:

> "(a) forthwith notify, directly or through the International Atomic Energy Agency (hereinafter referred to as the "Agency"), those States which are or may be physically affected as specified in article 1 and the Agency of the nuclear accident, its nature, the time of its occurrence and its exact location where appropriate; and
> (b) promptly provide the States referred to in sub-paragraph (a), directly or through the Agency, and the Agency with such available information relevant to minimizing the radiological consequences in those States…" [219].

The notifying State Party is required to provide the following information and data, as then available:

"(a) the time, exact location where appropriate, and the nature of the nuclear accident;
(b) the facility or activity involved;
(c) the assumed or established cause and the foreseeable development of the nuclear accident relevant to the transboundary release of the radioactive materials;
(d) the general characteristics of the radioactive release, including, as far as is practicable and appropriate, the nature, probable physical and chemical form and the quantity, composition and effective height of the radioactive release;
(e) information on current and forecast meteorological and hydrological conditions, necessary for forecasting the transboundary release of the radioactive materials;
(f) the results of environmental monitoring relevant to the transboundary release of the radioactive materials;
(g) the off-site protective measures taken or planned;
(h) the predicted behaviour over time of the radioactive release." [219]

This information is required to be supplemented at appropriate intervals by further relevant information on the development of the emergency situation, including its foreseeable or actual termination (para. 2, Article 5 of Ref. [219]).

Further, with a view to minimizing the radiological consequences, States Parties may notify in the event of nuclear accidents other than those specified in Article 1 of the Early Notification Convention (Article 3) [219].

Although the IAEA is not a party to this convention, the following specific roles are accorded to the IAEA: (1) inform States Parties, Member States, other States which are or may be physically affected, and relevant international intergovernmental organizations, of a notification received from a State Party of the occurrence and location of a nuclear or radiological accident; and (2) promptly provide any State Party, Member State or relevant international intergovernmental organizations, upon request, with the information received relevant to minimizing the radiological consequences (Article 4 of Ref. [219]).

As part of emergency preparedness, each State Party should make known to the IAEA and to other States Parties, directly or through the IAEA, its competent authorities and point of contact responsible for issuing and receiving the notification and information. Such points of contact and a focal point within the IAEA should be available continuously. Each State Party should also promptly inform the IAEA of any changes that may occur. The IAEA is required to maintain an up to date list of States authorities and points of contact as well as points of contact of relevant international organizations and should provide it to States Parties and Member States and to relevant international organizations (paras 1–3, Article 7 of Ref. [219]).

3.5.1.2. The Assistance Convention

In accordance with the provisions of the Assistance Convention, the States Parties should cooperate between themselves and with the IAEA to facilitate prompt assistance in the event of a nuclear or radiological emergency to minimize its consequences and to protect life, property and the environment from the effects of radioactive releases. The Assistance Convention recognizes that States Parties may agree on bilateral or multilateral arrangements or, where appropriate, a combination of these, for preventing or minimizing injury and damage which may result in the event of a nuclear accident or radiological emergency (see para. 1 and 2, Article 1 of Ref. [220]).

If a State Party needs assistance in order to respond to a nuclear or radiological emergency, whether or not the emergency originates within its territory, jurisdiction or control, it may call for assistance from any other State Party, directly or through the IAEA, and from the IAEA, or, where appropriate, from other international intergovernmental organizations.

> "A State Party requesting assistance shall specify the scope and type of assistance required and, where practicable, provide the assisting party with such information as may be necessary for that party to determine the extent to which it is able to meet the request. In the event that it is not practicable for the requesting State Party to specify the scope and type of assistance required, the requesting State Party and the assisting party shall, in consultation, decide upon the scope and type of assistance required." (para. 2, Article 2 of Ref. [220]).

Each State Party to which a request for such assistance is directed shall promptly decide and notify the requesting State Party, directly or through the IAEA, whether it is in a position to render the assistance requested, and the scope and terms of the assistance that might be rendered.

The IAEA has the specific response role to respond to a State Party's or a Member State's request for assistance in accordance with the Statute and the terms of the Convention by: (a) making available appropriate resources allocated for this purpose; (b) promptly transmitting the request to other States and international intergovernmental organizations which according to the IAEA's information, may possess the necessary resources; (c) coordinating assistance at the international level which may thus become available, if so requested by the requesting State; (d) making available, to a State Party or a Member State requesting assistance, appropriate resources allocated for the purpose of conducting an initial assessment of the emergency; (e) offering its good offices to the States Parties and Member States; and (f) establishing and maintaining liaison with relevant international intergovernmental organizations for the purposes of obtaining and exchanging relevant information and data, and making a list of such organizations available to States Parties, Member States and the aforementioned organizations (para. 6 of Article 2 and Article 5 of Ref. [220]).

As part of emergency preparedness, States Parties shall, within the limits of their capabilities, identify and notify the IAEA of experts, equipment and materials which could be made available for the provision of assistance to other States Parties as well as the terms, especially financial, under which such assistance could be provided. The State Parties request the IAEA as a general matter, to: (a) collect and disseminate to State Parties and Member States information concerning: experts, equipment and materials which could be made available in the event of nuclear accidents or radiological emergencies; and methodologies, techniques and available results of research relating to response to nuclear accidents or radiological emergencies; and (b) assist a State Party or a Member State when requested in: (i) preparing both emergency plans in the case of nuclear accidents or radiological emergencies and the appropriate legislation; (ii) developing appropriate training programmes for personnel to deal with nuclear accidents or radiological emergencies; (iii) developing appropriate radiation monitoring programmes, procedures and standards; and (iv) conducting investigations into the feasibility of establishing appropriate radiation monitoring systems (Article 5 of Ref. [220]).

3.5.1.3. Other applicable legal instruments

The Convention on Nuclear Safety [227] and the Joint Convention [228] also address emergency preparedness aspects in relation to nuclear installations and to the management of spent fuel and radioactive waste, respectively.

The Convention on Nuclear Safety [227] has the objective of achieving and maintaining a high level of nuclear safety worldwide in relation to nuclear installations[116]. This includes establishing and maintaining effective defences in these installations against potential radiological hazards in order to protect individuals, society and the environment. This convention also includes the objective "to prevent accidents with radiological consequences and to mitigate such consequences should they occur" [227] In relation to the latter, Article 16 requires that each Contracting Party takes appropriate steps to ensure that on-site and off-site emergency plans are in place for nuclear installations and that these plans are routinely tested. In addition, each Contracting Party is required to ensure that its own population and the competent authorities of the States in the vicinity of the nuclear installation that are likely to be affected by an emergency at a nuclear installation are provided with information that is appropriate for emergency planning and response. For Contracting Parties that do not have nuclear installations on their territory but that are likely to be affected by an emergency at a nuclear installation in the vicinity, the Convention on Nuclear Safety requires adequate preparation and testing of emergency plans for their territories (paras 1–3, Article 16 of Ref. [227]).

Similarly, the Joint Convention [228] has the objective of ensuring a high level of safety worldwide in relation to spent fuel and radioactive waste management, including ensuring effective defences against potential hazards during all stages of spent fuel and radioactive waste management. The Joint Convention also seeks "to prevent accidents with radiological consequences and to mitigate their consequences should they occur during any stage of spent fuel or radioactive waste management" [228]. In light of this objective, Article 25 requires that each Contracting Party ensure that there are on-site and, if necessary, off-site emergency plans before and during operation of a spent fuel or radioactive waste management facility, and that these plans are tested at appropriate intervals. In addition, each Contracting Party that is likely to be affected by an emergency at a spent fuel or radioactive waste management facility in the vicinity of its territory is required to take appropriate steps to prepare and to test emergency plans for its territory (paras 1 and 2, Article 25 of Ref. [228]).

Both the Convention on Nuclear Safety and the Joint Convention establish mechanisms for reviewing measures taken by Contracting Parties to implement each of the obligations of the conventions. These mechanisms include preparation and submission of reports elaborating measures taken to meet the obligations under these conventions and their review and discussion at review meetings held at regular intervals[117]. Measures taken by each Contracting Party to fulfil obligations on emergency preparedness set forth in Article 16 of the Convention on Nuclear Safety and in Article 25 of the Joint Convention are thus subject to reporting, review and discussion (Article 25 of Ref. [228] and Article 16 of Ref. [227]).

---

[116] In this context, nuclear installation means for each Contracting Party to the Convention on Nuclear Safety any land based civil nuclear power plant under its jurisdiction, including such storage, handling and treatment facilities for radioactive materials as are on the same site and are directly related to the operation of the nuclear power plant. Such a plant ceases to be a nuclear installation when all nuclear fuel elements have been removed permanently from the reactor core and have been stored safely in accordance with approved procedures, and a decommissioning programme has been agreed to by the regulatory body.

[117] The interval between such review meetings should not exceed three years.

3.5.1.4. IAEA safety standards and technical guidance on EPR

IAEA Safety Standards Series No. GS-R-2 [11] establishes requirements for an adequate level of preparedness and response for a nuclear or radiological emergency with the aim of minimizing the consequences of an emergency should it occur. This publication addresses preparedness and response for all types of nuclear or radiological emergencies irrespective of their cause, including those of very low probability (e.g. events that are beyond the design basis of a facility) and those involving a combination of a nuclear or radiological emergency and a conventional emergency (e.g. earthquake).

Building on experience from responses to actual emergencies, IAEA Safety Standards Series No. GS-R-2 sets common goals to be achieved and the common concepts and approaches to be taken for adequate preparedness to effectively respond to a nuclear or radiological emergency. In addition, this publication sets comprehensive requirements for practical arrangements to be made to support the functions performed in an emergency response for achieving the goals set for the emergency response.

The general requirements that need to be fulfilled before planning include: (1) clear allocation of roles and responsibilities for emergency preparedness and response, including identification of a coordinating authority for that purpose and establishing a management system for ensuring timely, coordinated and effective response and decision making; and (2) assessing threats (hazards)[118] as a basis for a graded approach in establishing EPR arrangements [11]. Following these general requirements, functions to be performed in an emergency response are elaborated, and requirements for arrangements to support these functions are set. These functional requirements include:

— Managing and coordinating emergency response to a nuclear or radiological emergency at all levels (national, regional, local and operator levels and, where appropriate, at the international level) under an all-hazard approach and setting up a clear command and control system for that purpose.
— Identifying an emergency situation on the basis of observable conditions and measurable criteria (EALs) and declaring the emergency class; activating pre-planned on-site response actions and, where relevant, notifying an off-site notification point to activate pre-planned off-site response actions. This includes setting up notification point(s) for receiving such notifications as well as designating organization(s) for sending/receiving information to/from other States and the IAEA (in accordance with the Early Notification Convention).
— Taking actions to mitigate the development of hazardous conditions resulting in exposure or a release of radioactive material warranting response actions to be taken on-site and off-site. This includes the provision of off-site emergency services in support of the on-site emergency response.
— Taking urgent protective actions to avoid severe deterministic effects and to avert doses and to adjust these actions on the basis of information that becomes available. This includes: (1) setting national intervention levels/criteria in terms of doses and measurable quantities/observables for taking such actions, taking account of a range of national factors (such as financial and social aspects); (2) establishing off-site emergency zones[119]; (3) ensuring that off-site officials decide and promptly implement urgent protective actions off-site; and (4) ensuring that diverse means for communicating on-site and with off-site locations are available at all times.
— Providing information regarding emergency preparedness and response to the potentially affected population within emergency zones at the preparedness stage and warning and instructing them in an emergency on actions to take. This includes identification at the preparedness stage of special

[118] The term ‘threat’ is no longer used in IAEA safety standards in the area of EPR due to its specific meaning in the area of nuclear security; instead, the term ‘hazard’ is used.

[119] For facilities in threat (hazard) categories I and II only.

population groups within emergency zones (e.g. disabled persons, hospital patients or prisoners), for whom specific arrangements need to be made for the safe implementation of protective actions.

— Designating emergency workers and ensuring their protection. This includes establishing guidance for managing, controlling and recording their doses, identifying hazardous conditions in which they may need to perform their duties and providing specialized protective equipment, procedures and training.
— Assessing the magnitude and likely development of hazardous conditions (including ensuring monitoring and assessment capabilities), in order to identify new hazards promptly and to refine the strategy for response as necessary. This includes development of operational intervention levels (OILs) at the preparedness stage and their use and revision in light of conditions prevailing during the emergency.
— Communicating with the general public in a nuclear or radiological emergency, which would include responding to incorrect information and rumours and responding to enquiries from the public and news media.
— Taking agricultural countermeasures, countermeasures against ingestion and longer term protective actions in order to avert doses. This includes ensuring monitoring and assessment for the areas potentially or actually affected by the emergency, establishing national intervention levels and action levels in accordance with international standards, development and use of operational intervention levels, safe and effective management of radioactive waste, and assessment of exposure incurred by members of the public as a consequence of the accident.
— Mitigating the adverse psychological, social and economic consequences (i.e. non-radiological consequences) of the emergency and the response. This includes consideration of economic impacts and impacts on employment, as well as the need for social welfare in the longer term, when deciding on response actions to be taken within emergency zones. It also includes responding to public concerns in an emergency, promptly explaining the associated health risks and preventing inappropriate actions on the part of workers and the public.
— Transitioning from the emergency phase to routine long term recovery operations and resumption of normal social and economic activity. This includes clear allocation of responsibilities, sharing and transferring information, assessing consequences, establishing formal processes to decide on withdrawal of restrictions and other arrangements imposed during the emergency, setting principles and criteria to do so, and consulting the public.

These functional requirements are supplemented by the following requirements for elements of infrastructure that are essential for providing an adequate response capability:

— *Authority:* Assignment of authorities for emergency preparedness and response in national legislation and documentation of the assigned authorities, roles and responsibilities at all levels as part of emergency plans.
— *Organization:* Establishment of organizational relationships and interfaces among operating and response organizations, including documentation of the positions and specific functions assigned as part of emergency plans and identifying personnel to adequately fulfil these positions.
— *Coordination of emergency response:* Preparation of operational protocols to coordinate the emergency response at operator and local, regional, national levels and, where appropriate, at the international level and their documentation as part of emergency plans. This also includes coordination among different organizations to develop and use tools, procedures and criteria in emergency response in order to avoid inconsistencies and confusion on the part of the public and decision makers.
— *Plans and procedures:* The development and coordination of emergency plans and procedures at operator, local, regional and national levels on the basis of assessed hazards.
— *Logistical support and facilities:* Provision of tools, instruments, supplies, equipment, communication systems, specific functional facilities and documentation needed to ensure an effective emergency response. This also relates to the operability and usability of these items and

facilities under postulated radiological, working and environmental conditions that may be encountered in the emergency response.

— *Training, drills and exercises:* Selection of knowledge, skills and abilities necessary to perform specific functions in emergency response and selection of adequately qualified personnel for these positions. This includes the need to ensure continual training of personnel (to include the personnel responsible for making decisions on protective actions in the emergency zones) and to conduct drills and exercises on a regular basis.
— *Quality assurance programme:* Establishment of a programme to ensure that all the supplies, equipment, communication systems, facilities and documentation (plans, procedures, checklists, manuals, etc.) are, as appropriate, continuously up to date, available and functional for use in an emergency. This includes review and evaluation of responses in emergencies and in drills and exercises in order to identify and record areas requiring improvement and to ensure that these improvements are made.

In addition, IAEA Safety Standards Series No. GS-R-2 [11] contains three annexes that provide:

— Additional information on the protection of emergency workers performing specific tasks that may result in exceeding the dose limits for occupational exposure.
— Action levels of dose from acute exposure at which intervention is expected to be undertaken under any circumstances.
— Guidelines for intervention levels for taking specific protective actions (sheltering, evacuation, 'iodine prophylaxis'[120], temporary relocation and permanent resettlement) and action levels for imposing restrictions on foodstuffs.

IAEA General Safety Guide No. GS-G-2.1 [13] provides recommendations and guidance on the implementation of selected requirements established in IAEA Safety Standards Series No. GS-R-2 [11]. This guide describes appropriate responses (so called concepts of operations) to a range of nuclear or radiological emergencies and includes:

— A description of emergency zones and areas and their suggested radius;
— A description of abnormal facility conditions associated with a specific emergency class and immediate actions to be taken on-site and off-site upon declaration of the emergency class;
— A description and overview of urgent protective actions and other response actions;
— A description of adequate emergency related facilities and locations necessary to support emergency response.

The IAEA has also developed technical guidance and tools covering, in detail, particular aspects of EPR in order to support Member States and relevant international organizations in implementation of the IAEA safety standards in the area of EPR. At the time of the Fukushima Daiichi accident, extensive technical guidance and tools were already in place[121], of which the following are the most relevant:

— *IAEA-TECDOC-955 [221]:* Generic Assessment Procedures for Determining Protective Actions during a Reactor Accident (published in 1997) provides the technical procedures for determining protective actions for the public and for controlling dose to emergency workers in case of an accident at a nuclear reactor. These include: procedures for classifying an accident based on plant conditions and recommending protective actions, projecting consequences, coordinating

[120] The term 'iodine thyroid blocking' is used instead of iodine prophylaxis in the latest IAEA publications.

[121] Available on the IAEA web site at the following URL: http://www-ns.iaea.org/tech-areas/emergency/technicalproducts.asp?s=1.

environmental monitoring, interpreting environmental data, determining public protective actions and controlling emergency worker doses. The publication also describes an emergency assessment organizational structure recommended for the optimum implementation of the accident assessment procedures.

— *EPR-METHOD [112]:* Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency (published in 2003) provides tools and information needed to develop a response capability which complies with the safety requirements. The publication also provides information concerning methodologies, techniques and available results of research relating to a response to radiation emergencies. It includes a practical, step by step method for developing integrated operator, local and national capabilities for emergency response.
— *EPR-MEDICAL [222]:* Generic Procedures for Medical Response during a Radiation Emergency (published in 2005) provides the medical community with practical guidance for medical emergency preparedness and response. It describes the tasks and actions required of different members of the national, regional and local medical infrastructure that would be in accordance with the provisions of the IAEA safety standards. This publication provides the tools, generic procedures, and data needed for dose assessment and initial medical response to radiation emergencies. It explains the roles and responsibilities of the members of the emergency medical response organization within the general response organization.
— *IAEA-TECDOC-1092 [229]:* Generic Procedures for Monitoring in a Nuclear or Radiological Emergency (published in 1999) provides practical guidance for environmental, source, personal and equipment monitoring during a nuclear or radiological emergency. The publication provides procedures for radiation monitoring, environmental sampling and laboratory analyses in an emergency response. It includes information on measurement and sampling techniques, equipment and personnel specification and on recording results for further interpretation and analyses.

Although a range of IAEA safety standards, technical guidance and tools in EPR existed at the time of the Fukushima Daiichi accident, Japan did not fully utilize them in its national practice [21, 51]. Efforts that were initiated, particularly in 2006, to update and strengthen the national standards in Japan (such as the regulatory guide covering emergency preparedness in relation to nuclear facilities) and to make them conform to the relevant IAEA safety standards failed due to disagreements among different national authorities [21]. One of the reasons for not strengthening the national standards was the concern that significant changes in the existing EPR system would be a source of confusion among the public and that it would be extremely difficult to explain that there was a need for emergency preparedness that assumes the occurrence of a severe accident, when residents living in the vicinity of nuclear power plants had been persuaded that a major accident would not occur [21].

3.5.1.5. International operational arrangements in EPR

Emergency Notification and Assistance Technical Operations Manual

At the time of the accident at the Fukushima Daiichi NPP, the ENATOM Manual[122] [223] facilitated the implementation of those articles of the Early Notification Convention [219] and the Assistance Convention [220] that are operational in nature, such as the provisions for notification and information exchange and the communication protocols for Contact Points identified under the Early Notification Convention and the Assistance Convention.

[122] As of 1 June 2012, ENATOM was superseded by the Operations Manual for Incident and Emergency Communication (EPR-IEComm, 2012) [230].

As described in the manual, at the time of the accident at the Fukushima Daiichi NPP, the IAEA operated a secure and protected web site for the exchange of official information with contact points in Member States and at relevant international organizations called Emergency Notification and Assistance Conventions (ENAC) web site[123].

The IAEA has developed a set of exercises of various levels of complexity — called convention exercises (ConvEx) — to practise with Member States and relevant international organizations different arrangements within the international emergency preparedness and response framework. ConvEx exercises are divided into three levels of complexity: ConvEx-1, ConvEx-2 and ConvEx-3. The goal of the ConvEx-1 and ConvEx-2 exercises is to test whether National Warning Points and National Competent Authorities are available within the expected time frames, whether contact channels are accurate and whether National Competent Authorities can appropriately complete various reporting forms. The exercises are also intended to test the procedures for information exchange and for requesting/providing assistance using moderately complex scenarios. ConvEx-3 exercises are large scale international exercises focusing mostly on response in the early phase of a severe nuclear or radiological emergency, irrespective of its cause. The purpose of these exercises is to assess and evaluate national and international emergency response arrangements, including arrangements for information exchange, provision of assistance and coordination of public information [223].

IAEA Response and Assistance Network

The IAEA Response and Assistance Network (RANET) was established to facilitate the provision of international assistance upon request and in compliance with the Assistance Convention. This system forms an operational mechanism to provide assistance in different technical areas, with the help of national capabilities registered in the network. The capabilities for assistance cover specific areas, such as: radiation survey, environmental sampling and analysis, assessment and advice, decontamination, medical support, dose assessment, source search and recovery and advice on emergency response actions [224].

The role of the IAEA upon receipt of a request for assistance is to: (i) evaluate the situation and, if needed, deploy a fact finding assistance mission to the requesting State to further assess the situation; (ii) recommend activation of specific RANET capabilities, if appropriate; (iii) ensure development of an assistance action plan, in coordination with all parties; (iv) liaise with the requesting State to reach agreement on the assistance action plan; and (v) provide financial, organizational and logistic support, as appropriate [224].

Joint Radiation Emergency Management Plan of the International Organizations

The Joint Radiation Emergency Management Plan of the International Organizations [225] is a comprehensive interagency mechanism for nuclear and radiological emergency preparedness and response. It provides a practical mechanism for coordination and clarifies the roles and capabilities of the participating international organizations in preparing for and responding to nuclear and radiological emergencies [225].

[123] As of June 2011, this protected web site was replaced by the Unified System for Information Exchange in Incidents and Emergencies (USIE).

3.5.1.6. The EPR system of the IAEA

At the time of the accident, the IAEA's central role within the international EPR framework included: prompt notification of the emergency to States and relevant international organizations; exchange and/or provision of official (authenticated and verified)[124] information to States and international organizations; coordination of international assistance, upon request of the State concerned; provision and/or coordination of public information that is timely, accurate and appropriate; and coordination of the inter-agency response. The IAEA[125] discharged its role through its Incident and Emergency System (IES), consisting of a 24 hour contact point and an operational focal point, the Incident and Emergency Centre (IEC). The internal arrangements for the implementation of the IES were defined in the IAEA's Response Plan for Incidents and Emergencies [231].

The IES consists of a warning point, an on-call system, an on-duty system and the IES Steering Group, with the following functions:

— The warning point is a 24 hour communication centre through which incoming messages are received and acted on. Since the IEC is not normally continuously staffed, the Security Control Centre of the United Nations Security and Safety Service serves as a warning point.
— The on-call system ensures that the initial response to any incoming message is timely and adequate. The following on-call officers are available to facilitate and coordinate the initial response: an emergency response manager (ERM); a nuclear installation specialist; a radiation safety specialist; a nuclear security specialist; an external event specialist; and a logistics support officer. In addition, a public information officer is also available at all times. The on-duty system ensures that the IAEA response is effective and commensurate with the nature and magnitude of the event/situation. It consists of three modes of operation[126], a set of response functions and a roster of trained staff members.
— The IES Steering Group oversees the response of the IAEA and guides the response on matters of policy.

Each event is classified according to the extent of its actual or potential radiological consequences. The urgency and response actions vary depending on the actual or potential magnitude and seriousness of the event [231].

3.5.1.7. Inter-Agency Committee on Radiological and Nuclear Emergencies

Although the Early Notification Convention and the Assistance Convention assign specific response functions and responsibilities to the IAEA and the Parties, various international intergovernmental organizations have — by virtue of their statutory functions or related legal instruments — functions and responsibilities that encompass aspects of emergency preparedness and response.

The prime interagency coordination mechanism ensuring that coordinated and consistent arrangements and capabilities for preparedness and response to nuclear and radiological emergencies are developed and maintained is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), for which the IAEA provides the secretariat [225].

---

[124] In this context, authentication is the process of confirming that the message received originates from an official contact point. Verification is the process of confirming that a message received is clear, consistent and understood.

[125] This applies to the IAEA Secretariat.

[126] Normal/ready mode, basic response mode and full response mode.

It is recognized by the participating international organizations that good planning in advance of an emergency can substantially improve the response. With this in mind, IACRNE members develop, maintain and co-sponsor the Joint Radiation Emergency Management Plan of the International Organizations [225].

At the time of the accident, the IACRNE included 15 international intergovernmental organizations[127].

3.5.2. IAEA response

In its response[128] to the accident, the IAEA followed its mandate and operational arrangements [223, 224, 226, 231]; in accordance with the IAEA Statute, the Early Notification Convention and the Assistance Convention.

At the time of the accident, the official Japanese designated contact points and competent authorities, as required under the Early Notification Convention and the Assistance Convention, for communications with the IAEA's IEC during a nuclear or radiological emergency were the following organizations:

— Ministry of Foreign Affairs, International Nuclear Energy Cooperation Division, as the 24-hour National Warning Point (NWP)[129] and as both National Competent Authority (Abroad)[130] (NCA (A)) and National Competent Authority (Domestic)[131] (NCA (D)).
— Ministry of Economy, Trade and Industry (METI)/Nuclear and Industrial Safety Agency (NISA), as an NCA(D).
— Ministry of Education, Culture, Sports, Science and Technology (MEXT) as an NCA(D).
— Ministry of Land, Infrastructure and Transport (MLIT), Technology and Safety Division, as an NCA(D).

Additionally, as required by the IAEA Statute, the IAEA maintained information exchange with the Permanent Mission of Japan to the International Organizations in Vienna. In accordance with mandates under the IAEA Statute, the Early Notification Convention and the Assistance Convention,

---

[127] The European Commission (EC), European Police Office (EUROPOL), FAO, IAEA, International Civil Aviation Organization (ICAO), INTERPOL, International Maritime Organization (IMO), OECD/Nuclear Energy Agency (OECD/NEA), PAHO, United Nations Environment Programme (UNEP), United Nations Office for the Coordination of Humanitarian Affairs (OCHA), United Nations Office for Outer Space Affairs (UN OOSA), UNSCEAR, World Health Organization (WHO) and World Meteorological Organization (WMO). In addition, the Joint Plan was developed in cooperation with the UNSCEAR secretariat. The Preparatory Commission of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and the Euro-Atlantic Disaster Response Coordination Centre (EADRCC) became IACRNE members in 2012 and 2013, respectively.

[128] The activities of the IAEA Secretariat in response to the Fukushima Daiichi accident were reported to the Board of Governors on 3 June 2011 by the Director General (GOV/INF/2011/8) [232].

[129] In accordance with the ENATOM arrangements, a single institution in a State has been designated by its Government to receive at any time an initial notification/advisory/follow-up message and/or request for assistance or verification and immediately to act upon it. The NWP needs to be available 24/7 and must be staffed with persons who can understand and speak English [223].

[130] In accordance with the ENATOM arrangements, it is a single institution within a State that is expected to verify or arrange for the verification of any relevant information provided during a nuclear or radiological emergency originating in another State, as well as being in a position to receive notifications, advisory messages, follow-up information and requests for assistance [223].

[131] In accordance with the ENATOM arrangements, it is an institution within a State authorized by its Government to issue an initial notification/advisory/follow-up message, as appropriate, or reply to a request for verification/information regarding a nuclear or radiological emergency. A State can designated more than one NCA(D), but it is expected that each NCA(D) is in an appropriate position within the State's national emergency response system to send or provide relevant information during a domestic event [223].

and as documented in the ENATOM arrangements[132], these contact points and competent authorities were the only official sources of information regarding the accident. All communication between the IEC, as the IAEA focal point for response, and the designated organizations were through established ENATOM procedures to hasten the overall exchange and verification of information.

The IAEA, through its emergency arrangements, liaised directly with METI/NISA, which was the official contact point in Japan [232]. Japan provided information in accordance with Article 3 of the Early Notification Convention.

However, the Government of Japan, during the course of its response to the earthquake and tsunami and its response to the nuclear accident, assigned responsibilities for different aspects of these responses to other governmental organizations, including the MHLW and the Prime Minister's Office, where the NERHQ was located. These organizations were not official contact points for the IEC but served as key organizations for different aspects of the response in Japan [232]. During the early phase of the response, the Permanent Mission of Japan to the International Organizations in Vienna was used as the contact point to communicate with these organizations; however, as the emergency progressed, direct contact between these organizations and the IEC was established.

During the response to the accident, the IAEA's four key operational roles — notification and official information exchange through officially designated contact points; provision of timely, clear and easily understandable public information; provisions and facilitation of international assistance on request; and coordination of inter-agency response — were met by taking the following actions:

— Activation of the IEC response;
— Development of Status Summary Reports;
— Provision of briefings for Member States;
— Creation of the Fukushima Accident Coordination Team;
— Visit of the IAEA Director General to Japan;
— Meeting of the IAEA Board of Governors in March 2011;
— Maintaining coordination of the inter-agency response;
— Provision of information to the public;
— Provision of briefings for the press;
— Planning and implementation of IAEA technical missions to Japan;
— Planning and implementation of activities of IAEA laboratories;
— Organization and arrangements for the Ministerial Conference on Nuclear Safety in June 2011.

An overview of the IAEA's response through May 2011 is shown in Table 3.5–1. The initial actions taken in response to the accident on the first day are described in detail in Section 3.5.2.1.

[132] Under ENATOM arrangements, communication with the IAEA was expected to be in English.

TABLE 3.5–1 OVERVIEW OF EVENTS AND SUMMARY OF THE IAEA'S RESPONSE UNTIL THE END OF MAY 2011 [232]

Date	Time [UTC[133]]	Event/activity
IAEA's IEC operations		
03-11	05:46	An earthquake of magnitude 9.0 occurred off the east coast of Japan.
03-11	06:42	The on-call external events specialist contacted the on-call emergency response manager (ERM) to inform the IEC of the occurrence of the earthquake and the potential effect on the NPPs.
03-11	07:21	The Emergency Response Manager (ERM) made first contact with NISA.
03-11	07:48	The first of two offers of IAEA assistance sent to NISA and the Permanent Mission of Japan to the International Organizations in Vienna.
03-11	08:06	First information for Member States and international organizations — EMERCON[134] message No. 1 from NISA — published on the ENAC web site.
03-11	08:20	The IEC activated and declared Full Response Mode operations (staffed continuously).
03-11	08:25	The IEC distributed its first in-house email message.
03-11	08:30	First press statement published on the IAEA web site.
03-11	08:45	First of 170 EMERCON messages from NISA (ENAC web site) received — only the Onagawa plant mentioned.
03-11	09:39	First IEC request to the WMO Regional Specialized Meteorological Centres (RSMCs) (lead: Tokyo, Beijing and Obninsk) for standard meteorological products for a potential radioactive release from the Fukushima Daiichi NPP sent out.
03-11	09:45	Second EMERCON message from NISA received; Fukushima Daiichi and Onagawa plants mentioned.
03-11	10:20	NISA press release published on the ENAC web site.
03-11	11:00	The IEC decision to operate in eight hour shifts.
03-11	15:00	First answers to Member States and international organizations which had sent requests for information.
03-11	20:02	First of 203 IEC Status Summary Reports published on the ENAC web site and distributed to Member States.
03-11	22:00	Updated status of Fukushima Daiichi NPP published and distributed.
03-12	09:43	Updated information on explosion in Unit 1 sent to all contact points.
03-12	12:00	First satellite picture from IAEA safeguards satellite imagery unit received.
03-12	12:39	Second of the two offers of assistance sent to METI.
03-12	14:17	RANET members contacted on availability of registered services.
03-12	17:05	First atmospheric dispersion products published on the ENAC web site (subsequently at least daily).
03-12	19:40	Updated status report sent to all contact points (subsequently twice a day).
03-13	10:33	Reminder to all contact points that information is available on the ENAC web site.
03-13	20:00	Updated information on Onagawa plant sent to all contact points.
03-14	02:45	Confirmation of explosion at Unit 3 sent to all contact points.
03-14	07:00	The IEC changes to two 12 hour shifts.
03-15	05:10	Information on high radiation levels outside the Fukushima Daiichi NPP sent to all contact points.

[133] UTC – Universal Time Coordinated. UTC = JST –9 hours.

[134] EMERCON is, according to ENATOM arrangements [223], an emergency conventions code word to be used in communicating a nuclear or radiological emergency to the Agency [232].

TABLE 3.5–1 OVERVIEW OF EVENTS AND SUMMARY OF THE IAEA'S RESPONSE UNTIL THE END OF MAY 2011 [232] (cont.)

Date	Time [UTC[135]]	Event/activity
IAEA's IEC operations		
03-15	11:00	First of 14 video conferences of the IACRNE.
03-15	08:00	Expert from the Austrian National Weather Service (provided through WMO) joined the IEC.
03-15	08:00	FAO representative joined the IEC.
03-15	12:00	Request received from Japan for IAEA assistance (Note Verbale from the Permanent Mission of Japan to the International Organizations in Vienna).
03-16	11:00	The on-site and off-site radiological situation included in the Status Summary Report.
03-17	17:00	First special request for fine resolution atmospheric dispersion products sent to WMO RSMC Montreal. Status Summary Report expanded to cover situation at spent fuel pools.
03-18	09:00	Liaison with the IAEA Secretariat's field team 1 started.
03-20	05:00	Status Summary Report expanded to include radionuclide concentrations in food and water.
03-21	00:51	Status Summary Report expanded to include deposition data.
03-22	22:49	OECD/NEA compilation of governmental decisions published for the first time (and updated regularly thereafter).
03-23	09:15	Status Summary Report expanded to include isotopic concentrations in air, food and sea water.
03-24	13:36	Results of fine resolution atmospheric dispersion modelling around Fukushima Daiichi site published on the ENAC web site and summary included in Status Summary Report.
03-26	11:34	Questionnaire sent to Member States requesting information regarding governmental decisions and recommendations made in relation to the Fukushima Daiichi accident with regard to citizens in or going to Japan, food or goods exported from Japan and screening of passengers and goods; the information provided by Member States was compiled by the OECD/NEA.
03-30	08:00	WHO representative joined the IEC for two weeks.
04-05		The IEC reduced the number of staff on night shifts.
04-14	16:00	The IEC agreed with the WMO RSMCs to request the meteorological products three times a week.
04-22	21:32	The IEC reduced number of Status Summary Reports to one per day.
05-03	13:00	The IEC operations changed to Basic Response Mode (the IEC staffed during the day 12/7, the on-call officers ready to respond during the night 12/7).
05-09	18:20	The IEC reduced the number of Status Summary Reports to three times per week (Monday, Wednesday, Friday).
Assistance to Japan		
03-11	07:48	The first of the two offers of IAEA assistance sent to NISA and the Permanent Mission of Japan to the International Organizations in Vienna.
03-12	12:39	The second of the two offers of IAEA assistance sent to NISA and the Permanent Mission of Japan to the International Organizations in Vienna.
03-12	17:18	The IEC sent a communication to all Member States registered as a member of RANET asking registered Member States to advise the IEC of the current status of their capabilities regarding the provision of specialized assistance to Japan.
03-15	21:45	The Government of Japan requested IAEA assistance "through the dispatch to Japan of experts in the fields of environmental monitoring and effects of radiation on human health" [232].

[135] UTC – Universal Time Coordinated. UTC = JST –9 hours.

TABLE 3.5–1 OVERVIEW OF EVENTS AND SUMMARY OF THE IAEA'S RESPONSE UNTIL THE END OF MAY 2011 [232] (cont.)

Time [UTC[136]]		Event/activity
Assistance to Japan		
03-16	21:45	The IEC forwarded a request for assistance from the Government of Japan to contact points in the United States of America and France for remotely controlled aerial vehicles, robots and remotely controlled ground vehicles for carrying equipment in the high dose rate areas.
Missions to Japan		
03-17		IAEA Director General's visit to Japan.
03-18		First of four IAEA monitoring team missions.
04-03		Boiling water reactor expert team mission.
04-18		Last of four IAEA monitoring team missions.
03-26		Joint IAEA/FAO food safety assessment team mission.
03-31		Marine monitoring team mission.
05-24		IAEA international fact finding expert mission.
Other IAEA activities		
03-15		Fukushima Accident Coordination Team (FACT) established.
03-15		Fukushima Nuclear Safety Team (FNST) established.
03-15		Fukushima Radiological Consequences Team (FRCT) established.
Coordination with international organizations		
03-15	11:00	First IACRNE coordination meeting: EC, FAO, IAEA, OECD/NEA, UNEP/OCHA, UNSCEAR, WHO, WMO
03-17	12:00	Second IACRNE coordination meeting: EC, FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNEP/OCHA, UNSCEAR, World Tourism Organization (UNWTO), WHO, WMO.
03-21	12:00	Third IACRNE coordination meeting: EC, FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNEP/OCHA, UNSCEAR, WHO, WMO.
03-23	12:00	Fourth IACRNE coordination meeting: EC, FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNEP/OCHA, UNSCEAR, WHO, WMO.
03-25	12:00	Fifth IACRNE coordination meeting: FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNEP/OCHA, UNSCEAR, WHO, WMO.
03-29	12:00	Sixth IACRNE coordination meeting: EC, FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNSCEAR, WHO, WMO.
04-01	12:00	Seventh IACRNE coordination meeting: FAO, IAEA. ICAO, IMO, OECD/NEA, PAHO, UNSCEAR, WHO, WMO; Permanent Mission (PM) of Japan.
04-07	12:00	Eighth IACRNE coordination meeting: EC, FAO, IAEA, ICAO IMO, OECD/NEA, PAHO, UNSCEAR, WHO, WMO; PM of Japan.
04-11	12:00	Ninth IACRNE coordination meeting: EC, FAO, IAEA, ICAO, IMO, OECD/NEA, UNSCEAR, WHO; CTBTO, PM of Japan.
04-21	12:00	Tenth IACRNE coordination meeting: FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNSCEAR, WHO, WMO; CTBTO, PM of Japan.
05-05	12:00	Eleventh IACRNE coordination meeting: FAO, IAEA, ICAO, IMO, PAHO, UNSCEAR, WHO, WMO; CTBTO, PM of Japan.

[136] UTC – Universal Time Coordinated. UTC = JST –9 hours.

TABLE 3.5–1 OVERVIEW OF EVENTS AND SUMMARY OF THE IAEA'S RESPONSE UNTIL THE END OF MAY 2011 [232] (cont.)

Time [UTC[137]]		Event/activity
Coordination with international organizations		
26-05	12:00	Twelfth IACRNE coordination meeting: FAO, IAEA, ICAO, IMO, PAHO, UNSCEAR, WHO, WMO; CTBTO, PM of Japan.
16-06	12:00	Thirteenth IACRNE coordination meeting: EC, FAO Rome, IAEA, ICAO, IMO, PAHO, UNEP/OCHA, UNSCEAR, WHO, WMO, CTBTO, PM of Japan.
07-07	12:00	Fourteenth IACRNE coordination meeting: FAO/IAEA, FAO Rome, IAEA, ICAO, IMO, PAHO, UNSCEAR, WHO, WMO, CTBTO.

3.5.2.1. IAEA initial response

The response of the IAEA Secretariat to the accident is described in detail in Ref. [232].

At 06:42 UTC on 11 March 2011, fifty-six minutes after the magnitude 9.0 earthquake had occurred off the east coast of Japan, the IAEA's International Seismic Safety Centre (ISSC) notified the IAEA's on-call Emergency Response Manager of the earthquake and the potential for damage at four nuclear power plants on the north-east coast of Japan, and of the potential for a tsunami. This was a trigger for the IAEA's initial response.

Thirty-nine minutes later (at 07:21 UTC), the IAEA established communication with the official contact point in Japan designated under the Early Notification Convention and the Assistance Convention, METI/NISA, and verified information on the occurrence of the earthquake and the tsunami and commenced enquiries as to the safety of nuclear installations and radioactive sources in the affected areas of Japan. At 07:48 UTC, the IAEA sent an offer of assistance, formally offering its good offices, to METI/NISA and the Permanent Mission of Japan to the International Organizations in Vienna.

At 08:06 UTC, the IAEA published initial information for States and international organizations on the ENAC web site as EMERCON message No. 1. The message was posted as an Alert — this required acknowledgement by States and relevant international organizations confirming that they have read the message. Many did not acknowledge receipt of the message, which required the IAEA to follow-up non-responses (by telephone) ensuring that all Member States and relevant international organizations were aware of the situation.

Fourteen minutes later (at 08:20), the IAEA's IEC declared 'Full Response Mode' operations. An appropriate number of IAEA trained staff members were called into the response centre according to their allocated responsibilities defined in the IAEA emergency response plan (REPLIE) [231].[138]

[137] UTC – Universal Time Coordinated. UTC = JST –9 hours.

[138] The IEC continued to operate in Full Response Mode, working in shifts, until 3 May 2011. On 3 May 2011, the IEC made the transition from Full Response Mode to Basic Response Mode. In contrast to the initial phase of the event, when nuclear safety issues were addressed with priority, the emphasis shifted to aspects of radiation protection and radioactivity measurements, which were reflected in the material provided in the Status Summary Reports. Preparations remained in place to move rapidly back to Full Response Mode if necessary [200] [232]. Until 15 May 2011, 230 staff members from throughout the IAEA worked in the IEC in shifts. There were more than 20 staff members in each shift in the first few weeks following the accident.

At 08:30 UTC, an initial press statement of the Prime Minister was published on the IAEA web site. The information provided initially to the IAEA consisted primarily of press releases of the Prime Minister (in Japanese). The IAEA arranged for unofficial translations to speed up the operational understanding of the situation while waiting for the official translation from Japan (press releases also contained information that was not directly relevant to the accident and waiting for official translation in their entirety would have resulted in further delays of sharing relevant information).[139]

At 08:45 UTC, three hours after the earthquake and close to two hours after the tsunami hit the Fukushima Daiichi NPP the IAEA received the initial EMERCON message from NISA in which only the Onagawa NPP were mentioned. The second message, one hour later (at 09:45 UTC), mentioned also the Fukushima Daiichi NPP.

About the same time (at 08:56 UTC), the IAEA received the first request from its Member State's official contact point under the Early Notification Convention and Assistance Convention for information about the state of the safety of the power reactors in Japan. At 15:00 UTC, after gathering and compiling enough information, the IAEA's IEC initiated answers to its official contact points in Member States and international organizations requesting information. Requests for information received from organizations in Member States that were not official contact points and from members of the public (through the IAEA public web site) were followed up by the relevant IAEA technical divisions.

At 20:02 UTC, the IAEA published its initial Status Summary Report on the ENAC[140] web site and distributed it to all contact points by fax. Two hours later (at 22:00 UTC), the IAEA published and distributed an updated summary. That concluded official information sharing with Member States and international organizations on the first day of the accident.

3.5.2.2. Status Summary Reports

As mentioned above, at 20:02 UTC on 11 March, the IEC published on the ENAC web site the initial Status Summary Report, which, based on the official information received, described the understanding of the event and status of the facility at that time. Throughout the response, regular Status Summary Reports were developed and issued. The frequency of the Status Summary Reports was based on the rate at which new information was being received. For example, in the first weeks following the accident, the Status Summary Reports were issued at least twice a day; on 6 May 2011, the frequency of the distribution of Status Summary Reports was reduced to three times a week, and, on 1 July 2011, to once a week. From 21 December 2011 to 27 December 2012, the IEC provided Status Summary Reports to Member States on a monthly basis. However, special updates were issued whenever important information was received and verified.

In total, more than 200 Status Summary Reports, with almost 3500 pages of content, were prepared. These Status Summary Reports and subsequent technical analyses constituted the main basis of the Member State briefings and the media briefings provided by the IAEA, which subsequently formed the basis for some national briefings organized and provided by Member State organizations.

---

[139] Later it was revealed that the NERHQ was also providing information to the public that was relevant to the international community; however, since the NERHQ was not an official contact point, this information was not provided to the IAEA at the onset.

[140] On 29 June 2011, the ENAC web site, which contained all of the information being shared by Japan with the IAEA, was transitioned into the new USIE web site. All information available on the ENAC web site, which includes documents and EMERCON messages, was automatically transferred to the USIE system.

Individual documents and reports that were received from Japan, other Member States and international organizations were promptly published on ENAC (and later on USIE) and faxed/emailed to official contact points. In addition, web site links received from contact points in Japan, other States and international organizations were also published on ENAC (and later on USIE). On 13 September 2011, Japan submitted its last EMERCON message on USIE. The final document relating to the status of the Fukushima Daiichi NPP and environmental condition was published on USIE on 27 December 2012.[141] In total, 186 EMERCON messages were published, in addition to 1673 other documents. More than 950 messages were received from Japan, 31 from other States and 71 from the WMO.

3.5.2.3. Briefings of Member States

The IAEA prepared a total of 19 oral briefings and presentations on the Fukushima Daiichi accident for the Permanent Missions to the International Organizations in Vienna and official Member State representatives. The briefings were conducted every day from 14 to 23 March, and subsequently on 25, 28 and 30 March, 1, 4, 12 and 19 April, and 5 May 2011. These briefings were followed by the briefings to the press (see details in Section 3.5.2.8).

The briefings included the status of Units 1–6 of Fukushima Daiichi and Units 1–4 of Fukushima Daini; the status of the spent fuel cooling pools and the common spent fuel storage pool at Fukushima Daiichi; results of environmental monitoring, including information on trends, findings and conclusions and their significance; information on restrictions on the distribution and consumption of foodstuffs and drinking water; and related information on the marine environment.

In addition, background information was provided to help put technical data (such as doses, dose rates and action limits) into context for non-technical audiences. A presentation was also provided to explain the International Nuclear and Radiological Event Scale (INES).

The Government of Japan and the IAEA coorganized a side event during the Fifth Review Meeting of the Convention on Nuclear Safety from 4 to 14 April 2011 on The Fukushima Daiichi Accident and Initial Safety Measures Worldwide [232].

A total of 27 detailed written Update Briefs were prepared and posted on the IAEA's public web site between March and June 2011. Overall, 129 individual posts were prepared and uploaded to the IAEA's public web site in the Fukushima Nuclear Accident Update Log[142] to share information with States and the public during the first months after the accident. In addition, information was shared through social media channels, such as Facebook and Twitter.

After TEPCO's roadmap announcement on 17 May 2011, update briefs provided the status of Units 1–4 in terms of the fundamental functions of IAEA safety standards for achieving a safe state, namely: control of reactivity; residual heat removal; containment integrity; confinement of radioactive material; and limiting the effects of releases. This information was presented in the form of tables in terms of the roadmap's goals and proposed measures for transition from the emergency phase to a recovery phase [232].

During these briefings and within the material made available to the public, the IAEA provided statements to clarify and explain technical issues surrounding the event. These statements did not contain prognoses of the potential evolution of the event or an assessment of the potential consequences, since such prognoses or assessments were outside of the scope of the IAEA's response

[141] The IAEA continues to regularly receive information updates from Japan, which are shared with States and the public.

[142] The original entries remain available online: http://www.iaea.org/newscenter/news/tsunamiupdate01.html.

role at the time of the accident. The role[143] in responding to an emergency at an NPP was expanded through the adoption of the IAEA Action Plan on Nuclear Safety [234]. This requested the IAEA's Secretariat to provide Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information during a nuclear emergency on its potential consequences, including analysis of the available information, and prognoses of possible scenarios based on evidence, scientific knowledge and the capabilities of Member States.

3.5.2.4. Fukushima Accident Coordination Team

To ensure effective interdepartmental coordination, the IAEA Director General established the Fukushima Accident Coordination Team (FACT) on 15 March 2011[144]. FACT was headed by the Director General, with the assistance of the Deputy Director General, Head of the Department of Nuclear Safety and Security. The purpose of FACT was to ensure senior level coordination of response to the accident. FACT also ensured the provision of accurate and timely information, validated by the Japanese authorities, to Member States, the news media and the general public, via oral briefings and Update Briefs posted on the IAEA's web site. Two teams were formed to support FACT: the Fukushima Nuclear Safety Team (FNST) and the Fukushima Radiological Consequences Team (FRCT).

FNST and FRCT were composed of IAEA staff from the Departments of Nuclear Safety and Security, Nuclear Energy and Nuclear Sciences and Applications, with the assistance of external experts from Member States, including Argentina, Canada, France, Germany, Italy and the Republic of Korea. In close coordination with the IEC, these teams were tasked with: coordinating and assembling the results of technical work performed throughout the IAEA; providing accurate information to inform the Director General's decisions; providing information for detailed briefings to Member States, international organizations, the media and the public; and informing the dialogue with Japan and other State authorities.

The tasks of FNST included focusing on the condition of the Fukushima Daiichi NPP and its systems, as well as on the status of the fuel within the reactors and the spent fuel pools. Through analysis of the IEC Status Summary Reports and other information, FNST evaluated the status of plant safety functions and barriers, plant parameters and the progression of actions toward stable shutdown of the units. It provided information on radioactive releases to CTBTO and to WMO's RSMCs for use in atmospheric dispersion modelling. CTBTO communicated results of the atmospheric dispersion modelling to its Member States. FNST also evaluated the results of the boiling water reactor (BWR) experts' mission to Japan.

The tasks of FRCT included: analysis of radiological monitoring data provided by Japan; analysis of pathways relevant for public exposure; analysis of trends in environmental monitoring data; evaluation of issues relating to transportation and trade; and elaboration of possible further protective measures. FRCT consolidated the data provided by Japan with the results of the IAEA's radiation monitoring teams.

Other senior staff with relevant experience and experts from Member States worked in cooperation with FNST, FRCT and the IEC on subjects that included reactor engineering, fuel integrity, other safety assessment issues, radioactive waste management and radiation monitoring [232].

---

[143] In September 2013, the IAEA General Conference, in Resolution GC(57)/RES/9, further clarified that the IAEA Secretariat's response role in this context would cover all nuclear and radiological emergencies [233].

[144] FACT carried out the role and functions of the IES Steering Group within the IAEA's Secretariat response structure.

3.5.2.5. Director General's visit to Japan

The IAEA Director General visited Tokyo from 17 to 19 March for high level consultations: to express the solidarity of the international community and its full support to Japan in dealing with the consequences of the earthquake and the tsunami and to convey offers of assistance from more than a dozen countries; to ascertain whether there was any particular assistance the IAEA could provide or coordinate (such as expert missions); to obtain, first hand, information about the accident; and to stress the importance of the highest level of transparency and the timely provision by Japan to the IAEA of official information, and the confirmation (upon request) of its correct understanding by the IAEA.

The IAEA Director General met the Japanese Prime Minister, the Foreign Minister and the Minister of METI. He also had meetings with senior officials from TEPCO and from NISA, and pledged the IAEA's full support. The Prime Minister of Japan expressed his strong commitment to ensuring the highest level of transparency in sharing information and said that every effort would be made to improve the collection and provision to the international community of accurate and objective information [232].

During the Director General's visit, the IAEA's 'on the ground' support to Japan became operational. It consisted of the following three main actions [232]:

(1) A senior IAEA official was deployed in Japan to coordinate IAEA assistance activities and transmit offers of assistance from Member States to the Japanese authorities.
(2) IAEA liaison officers were deployed to Tokyo to facilitate and improve communication between the IAEA and NISA.
(3) The IAEA's radiation monitoring team began transmitting measurements to Vienna, from various locations, including locations close to the Fukushima site.

Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The visit to Japan from 17 to 19 March 2011 by the IAEA Director General, and the subsequent deployment of liaison officers in Tokyo, improved communication between the IAEA and the contact point [232].

3.5.2.6. Meeting of the Board of Governors

The IAEA Director General called a meeting of the Board of Governors on 21 March 2011. At this meeting, he reported to the Member States on the results of his visit to Japan. He emphasized that the IAEA was doing everything possible to provide accurate and factual information on the accident, and that the IAEA was "working at full stretch, together with other countries and international organizations, to help Japan bring the crisis to an end and ensure the effects are mitigated as much as possible." It was noted that the IAEA would continue to do everything in its power to help Japan to overcome the Fukushima crisis and deal effectively with the aftermath [232].

The Chairman of the Board of Governors noted in his summary of the Director General's report on his visit to Japan, inter alia, that, in addition to expressing solidarity with the people of Japan, several Board members had pledged their continued support to the Government and people of Japan. The Board also emphasized that the international community had a shared responsibility to ensure that the general public were provided with accurate and reliable information on such emergencies to alleviate their concerns and that they must be kept aware of how the respective national authorities were responding to those emergencies. The Board emphasized the importance of the universalization of the relevant international instruments in the field of nuclear safety, and reaffirmed the need for Member States' continuous commitment to the application of the highest standards of nuclear safety, to avoiding complacency, and to drawing and acting upon the lessons learned from the Fukushima

Daiichi accident. Following the meeting of the Board, the Chairman issued a press statement summarizing the Board's discussions [232].

3.5.2.7. Coordination of the interagency response

As has been mentioned, the primary interagency coordination mechanism with regard to nuclear and radiological emergencies is the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE). The IAEA (specifically, its IEC) provides the secretariat for the IACRNE, pursuant to the IAEA's own roles and responsibilities. The IACRNE, under IEC coordination, maintains the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) [225].

In accordance with its responsibilities under the JPLAN, the IAEA, on 11 March 2011, promptly notified all relevant international organizations and activated JPLAN. The IEC initiated coordination of the interagency response to the Fukushima Daiichi accident, with particular regard to reaching a common understanding of the accident situation, and to coordinating public information. According to the bilateral agreements between the secretariats of the IAEA, FAO, WHO and WMO, those international organizations sent liaison officers to the IEC to ensure effective response coordination.

On 15 March 2011, the first IACRNE coordination meeting was conducted through a video teleconference. The IEC held regular video teleconferences of the IACRNE[145] to brief participants on the situation, exchange information among international organizations, consider and coordinate response activities, reach a common understanding of the situation and inform the public through joint press releases and other forms of information distribution. Participants of the video conferences were the EC, FAO, IAEA, ICAO, IMO, OECD/NEA, PAHO, UNEP, OCHA, UNSCEAR, WHO and WMO. WTO and CTBTO participated as observers. In addition, the Permanent Mission of Japan to the International Organizations in Vienna attended the meetings at the invitation of the IACRNE Secretary.

At these meetings commonly agreed tasks were assigned to specific organizations. For some issues ad hoc task groups were established, for example on transport and on dose assessment. IACRNE facilitated the formation of a task group to address issues relating to transport and tourism comprising representatives of the Airport Council International (ACI), IAEA, the International Air Transport Association, ICAO, IMO, WTO, WHO, WMO and UN. From 17 March 2011, the task group held regular telephone conference calls, which continued throughout the event. ICAO chaired the group, and WHO provided web-based document sharing to facilitate collaboration.

One of the IACRNE agreed tasks was to conduct a survey[146] on the advice that countries provided to their citizens, and on their import/export and industrial activities with Japan. The IACRNE tasked the OECD/NEA with collecting and evaluating the information received. On 26 March 2011, a questionnaire was distributed to States requesting information regarding governmental decisions and recommendations related to the Fukushima Daiichi accident with regard to citizens in or going to Japan, food or goods exported from Japan and the screening of passengers and goods. In total, 34 countries participated in the survey. The information collected was then compiled by the OECD/NEA and published on the ENAC web site.[147] The findings of this survey are elaborated in Ref. [235].

The information gathered showed that countries responded in different ways in their efforts to ensure the protection of non-food goods exported from Japan with regard to controls introduced, products

[145] Fourteen video teleconferences in total.

[146] This survey was discussed and agreed upon in the meeting of IACRNE on 17 March 2011.

[147] The last update of the survey was published on ENAC on 21 April 2011.

covered, dates on which measures were initiated or relaxed and screening levels used [181, 235]. Some countries considered radiation controls on non-food goods unnecessary, while others initiated regular controls for possible contamination of non-food goods or intensified their regular controls in relation to specific Japanese products intended for import. At least one country performed a single radiation control of cars imported from Japan. The import of particular non-food items was banned by at least one country.

The information from the survey also showed that controls for possible contamination of non-food products intended for import were initiated by some countries as early as five days after the accident (16 March 2011). On the other hand, other countries did not impose controls of non-food products until 25 August 2011. Some countries introduced and relaxed their controls.

Non-food goods intended for import were subjected to varying types of controls by various countries. Overall, the following items were reported to be controlled differently by countries: machinery, electronic information and communications equipment, residential/commercial electrical and gas equipment, cars (both new and used), different car components, scrap, chemicals, construction materials, toys, shoes, clothes and other textile products, medicines, medical devices, cosmetics, and plates and dishes. Controls were mainly based on a screening level value of 0.2 μSv/h (as implemented by the EC), but values of 0.3 μSv/h (in the Russian Federation) and 1 μSv/h (in Singapore) were also used for screening purposes. Only if the screening level was exceeded were detailed assessments to be performed.[148]

About 40 Member States performed radiological screening of passengers, food and goods coming from Japan.

On 22 March 2011, the IEC received, through official channels, the first monitoring data from a Member State other than Japan. Subsequently, monitoring data was received from a total of 37 Member States[149]. In addition, the CTBTO provided data from its global network of radionuclide monitoring stations.

In cooperation with the International Air Transport Association and ICAO, an industry guideline for aircraft decontamination was reviewed by the IAEA for accuracy. In cooperation with ICAO, an exemption and associated guidelines were prepared for the transportation of people who may have been contaminated (internally or externally) with radioactive material. On 12 April 2011, the new guidelines were adopted and incorporated, as an addendum, in the ICAO Technical Instructions for the Safe Transport of Dangerous Goods by Air, thus bringing them into force internationally for air transport [236].

Maritime safety issues were reviewed together with the IMO, and guidance was jointly prepared. A delegation of major shipping lines met with the IAEA and IMO on 4 May 2011 to discuss the means of addressing the monitoring of containers at ports. Support has been provided to shipping companies through the IAEA's Denial of Shipment Network.

International organizations such as WHO, ICAO and IMO evaluated radiological impacts on human health and transportation infrastructure. They provided timely technical information to the global

[148] Variations in the criteria used for further assessments and the assessment itself were not evaluated due to the lack of available information.

[149] Algeria, Austria, Belgium, Bulgaria, Canada, China, Czech Republic, Denmark, Finland, France, Georgia, Germany, Greece, Iceland, India, Islamic Republic of Iran, Ireland, Italy, Republic of Korea, Latvia, Lithuania, Luxembourg, Malaysia, Mexico, Philippines, Poland, Portugal, Romania, Russian Federation, Singapore, Slovakia, Spain, Sri Lanka, Sweden, Switzerland, Ukraine and the United States of America.

community. For example, information showed that radiation levels at and around airports and seaports in Japan did not pose health or transportation risks. The three organizations also provided advice to travellers to Japan.

Under JPLAN, the IAEA has practical arrangements with WMO. Specifically, WMO's RSMCs, upon IAEA request, provide standard meteorological products[150] for actual or potential releases of radioactive material to the atmosphere.

At 09:39 UTC, on 11 March 2011, the IEC made its first request to the RSMCs to run models for a potential radioactive release from the Fukushima Daiichi NPP. Thereafter, the IEC worked with the RSMCs on a regular basis, requesting them to run models and provide standard meteorological products. The results of the modelling of the lead RSMCs in the regions (Tokyo, Beijing and Obninsk) were compiled and published on the ENAC web site on a regular basis. On 17 March 2011, the IEC estimated a source term and requested RSMC Montreal to provide results from a series of more detailed (finer resolution) atmospheric transport modelling runs for the local level and regional level around the Fukushima Daiichi site [232].

On a strategic level, and from the early days after the accident, the IAEA Director General was in close contact with the United Nations Secretary-General to ensure effective coordination among different international organizations. He also consulted with the Director General of WHO, the Executive Secretary of CTBTO, the Director General of FAO and the Secretary-General of WMO to maintain effective coordination of activities.

At its 22nd regular meeting on 8 and 9 December 2011 [237], IACRNE initiated an assessment of the interagency response to identify lessons to be learned for further enhancement of the response and coordination mechanism. At this meeting, international organizations discussed the following items extensively: (a) reports of international organizations on the response to the Fukushima Daiichi accident, as well as continual activities undertaken by each organization in strengthening its emergency arrangements; (b) the need to strengthen the procedures for cooperation and coordination in providing public information at the international level; (c) the need to strengthen the existing exercise regimes, including the ConvEx regime; (d) the need to maintain awareness of the inter-agency coordination mechanism on the part of senior management of IACRNE member organizations; (e) the need to establish an ad hoc working group on air and maritime transportation[151] considering the experience gained in the interagency response to the Fukushima Daiichi accident; and (f) the need to review and revise JPLAN (2010 Edition)[152].

3.5.2.8. Provision of information to the public and media by the IAEA

This section summarizes the public information activities by the IAEA, including the coordination that took place at the international inter-agency level (IACRNE).

In general terms, journalists and members of the public turned to the IAEA during the accident, expecting some answers that the IAEA could not always provide as doing so would have exceeded its mandate.

---

[150] Standard meteorological products include: the trajectory of particles, deposition and integrated concentration of radioactive material for up to 72 hours after the initial release.

[151] The ad hoc IACRNE Working Group on Air and Maritime Transportation was established in March 2013.

[152] JPLAN has since been revised, and the 2013 edition came into effect on 1 July 2013.

The IAEA's intense round-the-clock public information activities in response to the Fukushima Daiichi accident ensured that the information it could provide reached its audience, despite technical challenges and intense pressure. At the IAEA, the Division of Public Information maintained continuous emergency communications with the press and public from 11 March to 22 April 2011[153]. Public information officers supported the delivery of information to the media and the public, organizing press conferences, handling thousands of telephone calls, providing detailed technical responses to hundreds of email queries and drafting over 120 updates for the public web site. To handle the influx of these telephone calls and emails, extended shifts were established and temporary support staff deployed.

The IAEA called its first press conference on 14 March. Some journalists expressed frustration about this taking place several days after the tsunami, as they had hoped for an opportunity to pose questions to the IAEA sooner than that. Following the 14 March conference, the IAEA called frequent press conferences, with 16 held between that date and 2 June 2011. These press conferences were initially attended by over 150 journalists from major international news agencies and broadcasters. National media from 37 States attended the briefings, including staff of nine Japanese newspapers and television broadcasters. Information provided during the briefings was featured prominently in over 4000 articles published in Arabic, English, French, Italian, German, Japanese, Portuguese, Russian and Spanish. Following each of the briefings, audio and video packages were distributed to the media; they were downloaded over 2500 times by registered journalists. A news conference and five media briefings were held during the Director General's visit to Tokyo from 17 to 19 March 2011. In addition, major interviews were held by the Director General with the BBC, CNN, Le Monde, Nippon Hoso Kyokai (NHK) (Japan) and the New York Times and about a dozen further interviews were arranged for the international media with senior IAEA staff.

A purpose built emergency update web site (a 'dark web site'[154] called IAEA Alert Log) was activated by the IAEA shortly after the earthquake occurred. Over 260 updates, read by 3.6 million visitors, were delivered onto the IAEA Alert Log within six weeks. Posts initially were posted only to this site and not on the IAEA's front page, meaning that visitors to that page had to continue navigating to find information about the accident. Later, all of the communications issued via the traditional channels (press briefing, email) were also packaged for dissemination via the front page of the IAEA public web site, and Facebook, Twitter, Flickr, SlideShare, YouTube and Scribd. With the exception of the dark web site, these communication channels had been used routinely by the IAEA prior to the accident.

Because of the enormous volume of visits to iaea.org and to the IAEA Alert Log, both web sites crashed during the first post-accident weekend and intermittently for the first two weeks. The IAEA took immediate steps to fix the problem by adding internet bandwidth and intensifying its use of social media to disseminate information. Subsequently, the IAEA began using cloud computing to upload and disseminate information, reducing pressure on the IAEA's servers. The IAEA's Fukushima Nuclear Accident Update Log was a site used later in the emergency to host all information (press releases, status summaries, photos, videos, etc.). It included a resources box, which contained relevant resources such as external web sites and IAEA publications. In addition, a

---

[153] Emergency communications refer to those activities in public communications occurring during an emergency situation, including periodic press releases, press conferences, responses to enquiries from the media and public, and increased social media presence that are all related to a particular event. Routine communications are public communications activities that occur outside of an emergency. These include general stakeholder involvement activities such as public meetings and news stories.

[154] 'Dark web site' is an emergency blog web site [238]. The dark site was no longer used after it became clear that the web site was not accessible due to heavy demand. Instead, the regular IAEA public web site, with an emergency banner, was utilized. The updates that were posted on the dark site can now be found at: http://www.iaea.org/newscenter/news/tsunamiupdate01.html.

frequently asked questions (FAQs) section for this particular event was developed over several days during the emergency. This process required the cooperation and clearance of internal experts, as well as coordination with a number of international organizations within IACRNE (see below for further information on the work with IACRNE).

Every communication channel that the IAEA utilized during the emergency experienced a significant and sustained increase in traffic, downloads, active users and comments. The immediate surge dissipated within the first six weeks, yet the ongoing traffic and activity levels outpaced pre-accident average levels of usage until approximately November 2011. During this period, the IAEA's public web site received more visitors (3.6 million) than during the entire previous year, 2010 (2.1 million). The number of visitors to the public web site from Japan, the second largest national audience in this period, rose from a six week average of 7000 to over 540 000. Visitors to the IAEA's social media web sites rose, with the updates on the IAEA Facebook page viewed 7.7 million times as compared to 270 000 views from January to December 2010. The PowerPoint presentations from the IAEA's briefings given in the press conferences were posted on the IAEA's social media web sites; they were viewed over 500 000 times and downloaded 20 000 times.

Facebook and Twitter were key referral sources for the public web site, with the result that the web site's audience reach moved from its pre-accident position among the top 40 000 most-viewed web sites to among the top 10 000 [239]. Notably, Twitter usage nearly quadrupled. In fact, Twitter referrals contributed to a server overload of the public web site's capacity in the first two weeks of the emergency, necessitating Twitter links to be redirected to the IAEA's Facebook page. Rules of conduct for the public using the IAEA's Facebook forum were highlighted through a note to users during the first week of the emergency, and any editorial interventions by the IAEA Facebook team, such as comment deletions, were based solely on those rules. Only a handful of the thousands of commentators disregarded these rules, prompting comment deletions, and only one user was banned for obscene and inappropriate statements. As per the best practice advised in Ref. [240] users of social media that expressed criticism of the IAEA were not censored, in order to make it possible for users to freely exercise their right of expression in a transparently administered venue.

An analysis of the email traffic revealed that the main subjects of concern included (in order of the frequency of queries): status and condition of the reactors; radiation exposure; IAEA response; Japanese Government's response; the rating on the International Nuclear and Radiological Event Scale (INES); travel restrictions; environmental impact; evacuation; and food and/or water restrictions.

The use of the INES rating was a particular concern for the public due to various reasons: Japan used the INES rating as a public information tool early in the event, with different units rated separately. This led to significant public and media confusion and concerns each time the INES rating was revised to a higher level. In addition, some foreign authorities challenged Japan's rating; therefore, while the gravity of the accident was established, the use of INES did not help clarify the situation.

At the inter-agency level, joint public statements were prepared and joint press releases were issued.

As mentioned earlier, IACRNE facilitated the formation of an ad hoc task group to address issues related to transport and tourism (Transport Task Force). The group chaired by ICAO prepared joint public statements and, on several occasions, issued joint press releases. The first press release, issued on 18 March 2011, stated that there were no restrictions on travel to Japan, while the press release issued on 1 April 2011 responded to misleading press reports and provided the travelling public with authoritative information.

Within the IACRNE, the OECD/NEA was tasked with reviewing the FAQs mentioned above and answer pages on the web sites of all responding international organizations for possible

inconsistences. This review ensured consistent and accurate information and assisted in enhancing the credibility of the information being provided.

3.5.2.9. The IAEA's technical missions to Japan

The IAEA Secretariat's monitoring team missions

Between 18 March and 18 April 2011, the IAEA sent four radiological monitoring teams[155] to Japan to help validate the results of more extensive measurements by the Japanese authorities. The four teams took measurements in the Fukushima region at a number of locations inside and outside the 20 km evacuation zone. One team was also deployed in the general vicinity of Tokyo. The scope of the monitoring included dose rates and surface activity concentrations, as well as the collection of different samples and gamma spectra for selected locations from 20 km to around 80 km from the Fukushima Daiichi NPP, and in Tokyo and the surrounding area. Based upon their measurement activities, the mission demonstrated to the Japanese authorities the importance of creating a contamination map to consolidate all the measurements taken by Japan for future mitigation and decontamination activities.

A BWR expert team was sent to Japan on 3 April 2011 and concluded its mission on 12 April 2011. The mission included meetings with several government offices, with the majority of the time dedicated to detailed, technical discussions with TEPCO and METI/NISA. As the first international expert team to visit the Fukushima Daiichi site, the IAEA experts visited the Government–TEPCO Integrated Response Office in Tokyo, the Fukushima Daiichi Emergency Response Centre at the NPP (NPP-ERC) and site facilities, and the Fukushima Daini Technical Support Centre and site facilities. Detailed insights into the accident and the status of the plants were provided, and the team was given the full cooperation of the Japanese authorities and the plant operator, TEPCO. The mission proved valuable in helping to understand other information that had been provided to the IAEA. The data and findings obtained by the team were used in preparing for the IAEA International Fact-Finding Expert Mission to Japan (see p. 13 [232]).

Upon request from Japan, the IAEA sent an expert on marine monitoring programmes from the IAEA Environmental Laboratories to Japan, from 31 March to 7 April 2011, to participate for two days in the monitoring being performed from the research vessel 'Mirai', and to observe and give advice on the collection of seawater at locations about 30 km from the coast in the offshore monitoring campaign. The mission included participation in marine monitoring and laboratory visits as well as a briefing on the findings to all parties involved in the process and to the Ministry of Foreign Affairs, MEXT, the Ministry of the Environment (MOE) and the Office of the Chief Cabinet Secretary.

Joint IAEA/FAO Food Safety Assessment Team Mission

A Joint IAEA/FAO Food Safety Assessment Team (FSAT) visited Japan from 26 to 31 March 2011. The team provided advice and assistance to the Japanese authorities, including local government authorities, on technical issues related to food safety and agricultural countermeasures, including sampling and analytical strategies and interpretation of monitoring data to ensure that reliable, continual updates could be provided on the extent of food contamination in the affected areas. These data were used for the development of possible mitigation and remediation strategies to be shared with authorities at the local and national levels in Japan.

[155] None of these missions were triggered or carried out under the framework of the Assistance Convention.

IAEA International Fact Finding Expert Mission to Japan

Based upon an agreement between the Government of Japan and the IAEA, which set out the terms of reference, an IAEA International Fact Finding Expert Mission, comprising 18 experts from the IAEA and Member States, visited Japan from 24 May to 2 June 2011 [51]. The mission conducted fact finding activities for a preliminary assessment of the accident (in particular at the Fukushima Daiichi NPP). The mission also collected information on the Fukushima Daini and Tokai Daini NPP sites located in Fukushima Prefecture and in Ibaraki Prefecture, in order to make a preliminary assessment of the accident and the generic safety issues associated with the natural events, and identify issues that needed further exploration or assessment according to the IAEA safety standards.

The mission received information on the progress of the Japanese assessment of the accident and discussed specific technical issues to develop an informed assessment for sharing with the international nuclear community.

The scope of the mission focused on: external events of natural origin; plant safety assessment and defence in depth; plant response after an earthquake and tsunami; severe accident management; spent fuel management under severe facility degradation; emergency preparedness and response; and radiological consequences.

Participants in the meetings with members of the IAEA mission team included officials of the Government of Japan, governmental Advisory Committee members, representatives of licensees, and academic experts nominated by the Government of Japan, including participants from: the Prime Minister's Office, the Ministry of Foreign Affairs, NISA, MEXT, Nuclear Safety Commission (NSC), Japan Nuclear Energy Safety Organization (JNES), Japan Atomic Energy Agency (JAEA), TEPCO; and Japan Atomic Power Company Limited (JAPC).

The report of the mission was presented at the IAEA Ministerial Conference on Nuclear Safety in June 2011 [241].

3.5.2.10. Activities of the IAEA's Laboratories

The IAEA Laboratories in Seibersdorf and Monaco specialize in evaluating terrestrial and marine environmental samples, respectively. They provided an expert review of the environmental data received from the Japanese authorities. Contamination of the marine environment was monitored by TEPCO, near field, at the discharge areas of the reactors and by MEXT at offshore stations about 30 km east of the shore line. In addition, the IAEA Terrestrial Environment Laboratory in Seibersdorf received more than two hundred samples from Japan for independent analysis.

Contaminated water from the Fukushima Daiichi NPP was leaked into the sea. This gave rise to concerns about the marine life and seafood for the population. The IAEA Marine Environment Laboratory in Monaco reviewed all information concerning the marine environment. Information and advice with regard to the potential for contamination and the consumption of seafood was provided to WHO.

The laboratory also liaised with a number of centres to set up models to simulate the dispersion of radioactivity released into the Pacific Ocean. This included requesting the French group SIROCCO from the University of Toulouse to carry out a simulation of the contamination dispersed in the Pacific.

The IAEA Terrestrial Environment Laboratory provided information and methodological advice to laboratories from the ALMERA[156] network. From 29 March to 6 May 2011, the laboratory received seven sets of samples taken in Japan during IAEA missions. By 16 May 2011, more than one hundred of the samples had been analysed by high resolution gamma ray spectroscopy.

The IAEA's Radiation Monitoring and Protection Services laboratories provided radiation protection services and advice to IAEA staff travelling to Japan, as well as to staff of WHO and FAO. The services included: individual and workplace monitoring; basic protective clothing and personal protective equipment; and briefings on the radiological conditions at the plant sites and in Fukushima [232].

3.5.2.11. IAEA Ministerial Conference on Nuclear Safety

On 28 March 2011, the IAEA Director General called for a Ministerial Conference on Nuclear Safety, with broad support from Member States [242]. The conference was held in Vienna from 20 to 24 June 2011 with the overall objective of drawing lessons from the accident at the Fukushima Daiichi NPP in order to strengthen nuclear safety throughout the world. The specific objectives of the conference were to: provide a preliminary assessment of the Fukushima Daiichi NPP accident; assess national and international emergency preparedness and response levels in the light of the Fukushima Daiichi NPP accident, with a view to strengthening them; discuss safety implications and identify those areas of the global nuclear safety framework which may be reviewed with a view to strengthening them through launching a process to that effect; and to identify lessons learned and possible future action.

These main objectives were discussed both in a plenary session and in greater depth during the three working sessions. The conference provided an opportunity to undertake, at the ministerial and senior technical levels, a thorough preliminary assessment of the accident at the Fukushima Daiichi NPP and discuss actions for nuclear safety improvements, issues regarding emergency preparedness and response and the implication of the global nuclear safety framework. These three main topics were addressed in three working sessions.

An important achievement of the conference was the unanimous adoption of the Ministerial Declaration. It provided the political commitment and associated support and guidance, gave a mandate to the Director General for future work with concrete actions, and formally launched the process of strengthening post-Fukushima nuclear safety worldwide [243].

The Ministerial Declaration outlined a number of measures to improve nuclear safety and expressed the firm commitment of IAEA Member States to ensure that these measures would be actually implemented.

Ministers asked the Director General to prepare a report on the conference and a draft Action Plan building on the declaration and the conclusions and recommendations of the working sessions. They requested that the report and the draft Action Plan be presented to the IAEA Board of Governors and General Conference in their forthcoming meetings in September 2011. Ministers also called for the effective, prompt and adequately funded implementation of the Action Plan.

[156] ALMERA is the abbreviation for Analytical Laboratories for the Measurement of Environmental Radioactivity, which is a network representing, at present, 122 laboratories from 77 States.

The Director General requested the International Nuclear Safety Group (INSAG) to prepare a report of the Ministerial Conference, including associated recommendations for future action to be submitted to the Board of Governors at its meeting in September 2011 [244].

In preparation for the IAEA Ministerial Conference, the Japanese Government drew up an extensive report [22], providing a summary of the events, addressing safety and engineering issues related to the accident and discussing the major lessons learned to date. The main elements of the report were presented during the Ministerial Conference in the working sessions.

3.5.2.12. Fukushima Monitoring Database

On 7 September 2012, the IAEA (through the IEC) launched a database of radiation measurement results collected following the Fukushima Daiichi accident called the Fukushima Monitoring Database (FMD) (https://iec.iaea.org/fmd/). The FMD is available to all Member States and the public and provides the results of near and far field radiation measurements performed in 2011 (starting on 11 March and ending with the attainment of a cold shutdown state as announced by the Government of Japan on 16 December 2011).[157] The database also contains radiological monitoring results from other Member States that were provided to the IAEA. The FMD enables researchers to search and download results of measurements such as dose rate measurements and measurements of environmental samples, including leaves, water and soil.

3.5.3. Protective actions recommended to foreign nationals within Japan

The OECD/NEA, within the framework of IACRNE, collected information on governmental decisions and recommendations made in States other than Japan during the accident, as well as on the technical basis for these decisions and recommendations. One of the topics covered related to recommendations[158] made with regard to citizens of other States living in or visiting Japan.[159]

Each State participating in the surveys issued advice or a specific instruction for the protection of its nationals in Japan. Although some States recommended that their nationals in Japan follow the recommendations and instructions of the Japanese authorities, many States issued advice or recommendations that differed from each other and also from those provided by the Japanese authorities. Thus, some States recommended that their nationals in Japan leave either the area within a radius of 80–100 km of the Fukushima Daiichi NPP or, more generally, the affected areas, including Kanto region (Tokyo, Yokohama and north of Tokyo) and Chubu areas. One State also made a recommendation to its nationals staying within 250 km of the Fukushima Daiichi NPP, including the Tokyo region, to remain indoors, with closed windows and ventilation. Several States distributed stable iodine tablets to their nationals and immediate family members in Japan. However, only one State made a recommendation to its nationals staying within 250 km of the Fukushima Daiichi NPP, including the Tokyo region, to take stable iodine tablets as a precaution. At least one State advised its

---

[157] Monitoring information was collected as part of the IAEA's role in implementing the Early Notification Convention, under which Japan provided the IEC the requested information.

[158] Recognizing that inconsistencies in actions taken by different States may be difficult to explain and may possibly result in a loss of trust in officials on the part of the public, IAEA safety standards [13] recommend that arrangements be put in place to ensure that the recommended countermeasures or actions are consistent among States, or that any differences can readily be explained to the public, to allow the public (and decision makers) to make informed decisions. It also recommends that all States make arrangements to protect their interests in the event of an emergency, taking into account its citizens in the affected State(s), embassies in the affected State(s) and travellers to and from the affected State(s).

[159] The following countries responded to this question in the survey: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Islamic Republic of Iran, Ireland, Italy, Republic of Korea, Latvia, Lithuania, Luxembourg, New Zealand, Norway, Poland, Portugal, Romania, Serbia, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States of America.

nationals in Japan not to consume the food from the affected areas and to avoid buying food at local market places. At least seven States made sure that aircraft were available for their nationals wishing to leave Japan. In addition, many States issued recommendations for their nationals to avoid either travelling to Japan or, more specifically, travelling to the affected areas. Some States restricted their recommendations only to non-essential travel to Japan or to specific areas, including the Kanto region (Tokyo–Yokohama) [235].

Although each State was requested to provide the technical basis for its recommendations, this information was not given. Instead, responses referred to national policy and considerations that were driven by the feasibility of implementing the recommendations (and, possibly, by recommendations made by other States), rather than by radiation protection [235].

The Heads of the European Radiological Protection Competent Authorities (HERCA) reviewed the issues raised from the different approaches of the European States to protect their citizens living in or travelling to Japan, with the aim of proposing a more harmonized approach in responding to a distant emergency. The findings of this review are elaborated in Ref. [245].

3.5.4. Response of international organizations

A summary of responses[160] of relevant international organizations, based on the reports provided at the 22nd regular IACRNE meeting in December 2011 [237], follows.

3.5.4.1. Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization

The CTBTO detected the earthquake, the subsequent tsunami and the nuclear accident using all the networks of the International Monitoring System (IMS): seismic detections of the magnitude 9.0 earthquake and the subsequent ten thousand aftershocks; hydroacoustic detections showing the rupture forming under the sea; infrasound detections showing the explosions in the Fukushima Daiichi NPP; and subsequent radioactivity measurements in all the particulate and noble gas stations in the northern hemisphere and at several stations in the southern hemisphere. Atmospheric transport modelling (ATM) played an important role in predicting which stations were going to detect released radionuclides from the plant.

The CTBTO held six briefings for States Signatories, and the secure web site was used to provide data/products. Data from the CTBTO radionuclide stations (concentrations and isotopic ratios) supplied to the relevant organizations confirmed that the consequences of the event were significantly lower outside Japan and helped in the assessment of the health impact on both local and global scales.

Cooperation with the IAEA, WMO and WHO was initiated relatively early in the emergency, and the CTBTO began participation in the IACRNE videoconference meetings at the beginning of April. The CTBTO's prompt cooperation with relevant international organizations in severe nuclear or radiological emergencies is important, in particular during the initial phase of an emergency, for an early robust assessment of the situation.

3.5.4.2. European Commission

In response to the accident [246], the European Commission (EC), DG ENER, in Luxembourg immediately activated the European Community Urgent Radiological Information Exchange (ECURIE) emergency team, which operated on a 24/7 basis for three weeks.

[160] The summary of responses covers activities up to 1 April 2012.

Their main tasks included: ECURIE message handling, situation assessment, communication of new EC regulations, media monitoring, situation updates to Member States and other EC services, maintaining an overview of the protective actions/recommendations of ECURIE Member States, press release support to the EC spokespersons' service, support and advice to the EU Delegation in Tokyo, and general Q&A service for EC services and the European Parliament.

In Europe, very low levels of airborne radioactivity concentrations were measured. Only a few countries exchanged their measurement results through the European Radiological Data Exchange Platform (EURDEP), others opted for distribution via ECURIE channels in the form of spreadsheets, etc. The accident demonstrated the urgent need for a global environmental radiation data exchange system.

As a result of demand from European Union Member States, the EC issued non-binding guidance for criteria to be used for the measurement of ships and containers entering European harbours from the region. However, the accident demonstrated the need for harmonized measures for the radiation safety of goods and the protection of citizens.

When it appeared possible that certain foods originating from the region with radionuclide levels exceeding the relevant action levels applicable in Japan may enter the European market, the EC adopted regulations imposing special conditions governing the import of feed and food originating in or consigned from Japan.

In response to requests from Japan, the EC (DG ECHO) activated the EU Civil Protection Mechanism. Nineteen participating States offered financial assistance or in-kind support to Japan, such as protective equipment and radiation dose rate meters. Under these arrangements, a 15 person Civil Protection Assessment and Coordination Team was deployed to the site of the disaster to coordinate the distribution of assistance on the ground. The team, which included experts in logistics and radiation protection, worked with the Japanese authorities and set up the arrangements for the storage, transport and distribution of the assistance.

A key issue which arose concerning communication was how to facilitate rapid discussions among competent authorities of EU Member States in order to efficiently prepare and adopt a common European approach to challenges arising from the accident. In response, a High-Level EC Task Force was set up to follow-up the EU response to the nuclear accident.

Based upon a mandate from the European Council in March 2011, the EC, together with the European Nuclear Safety Regulators Group (ENSREG), launched EU wide comprehensive risk and safety assessments of nuclear power plants (stress tests), which included their capabilities for on-site emergency management. The mandate included a request to the EC to review the existing legal and regulatory framework for the safety of nuclear installations and to propose any improvements that may be necessary. Some of the lessons learned from the accident were expected to be taken into account during the revision of the EU Basic Safety Standards and Nuclear Safety Directives.

As part of the EU response, an inter-service group comprising EU External Action Service and EC services was formed to follow-up initiatives raised at the EU–Japan Summit of May 2011, to monitor the impact of the accident and the lessons learned, and to formulate proposals for cooperation with Japan. Proposals covered Member State activities, the supply of equipment and services, technical and scientific expertise, safety and regulatory issues, and participation in research and development programmes.

3.5.4.3. European Police Office

European Police Office (Europol), as an EU law enforcement agency which handles criminal intelligence and provides analyses in the area of serious international crime and terrorism, did not activate any general or specific response mechanism due to the accidental nature of the emergency. Also, the event fell outside the scope of Europol's competence. However, Europol officials monitored the development of the emergency through the IAEA's ENAC on a daily basis. The information received through ENAC allowed Europol to assess specific secondary but related events, such as the detection of contaminated goods at border crossings. It also made it possible for Europol to minimize the impact of speculative information by crosschecking media reports with official data.

3.5.4.4. Food and Agriculture Organization of the United Nations

FAO works in partnership with the IAEA through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture (based in Vienna) in preparing for and responding to nuclear or radiological emergencies affecting food and agriculture. This includes the application of FAO capabilities as a critical counterpart in defining and implementing agricultural countermeasures and remediation strategies in response to nuclear or radiological emergencies.

FAO activities related to the Japanese nuclear emergency helped to ensure the dissemination of information on food monitoring and food restrictions, the consideration of agricultural countermeasures and remediation strategies to mitigate immediate and longer term effects arising from radionuclide contamination, and the interpretation of standards related to radiation protection of the public.

Through the Joint FAO/IAEA Division, the FAO continually staffed the FAO Desk in the IAEA's Incident and Emergency Centre.[161] It also prepared information on food contamination, monitored data and restrictions on food distribution, established a multifunctional database for the management of data submitted by the Japanese authorities, prepared and disseminated questions and answers related to food safety and the application of international standards, including the Joint FAO/WHO Codex Alimentarius Guideline Levels for Radionuclides in Foods. FAO promoted knowledge and information sharing on radioactive contamination affecting food and agriculture, including the mechanisms and persistence of such contamination, radionuclide transfer rates and international standards.

In addition, FAO was involved directly in several international missions to Japan, including participation in and follow-up to the Joint FAO/IAEA Food Safety Assessment Mission to Japan (26–31 March 2011) and the IAEA Mission on the Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant (7–15 October 2011) [247].

An FAO Technical Meeting on Preparedness and Response to Nuclear and Radiological Emergencies Affecting Food and Agriculture, including the Application of Agricultural Countermeasures and Remediation Strategies, was held from 14 to 18 November 2011 at FAO Headquarters in Rome. The meeting provided a detailed road map on the development of appropriate contingency planning and capacity building in response to nuclear and radiological emergencies affecting food, agriculture, fisheries and forestry, with emphasis on the development of national and international laboratory networks and infrastructures, including coordination within existing networks, and designing and conducting emergency exercises with appropriate stakeholders, including the simulation of complex events.

[161] According to the arrangements between FAO and the IAEA.

3.5.4.5. International Civil Aviation Organization

ICAO's principal role within the context of the interagency response[162] was to ensure the dissemination of information to aircraft in flight about atmospheric releases of radioactive material. ICAO convened an ad hoc Transport Task Force on 15 March 2011 to better assist transportation modal agencies respond to the accident. The Transport Task Force, led by ICAO, prepared and coordinated a number of public statements regarding travel and transport to and from Japan. ICAO and its partners had benefited greatly from the collaborative effort of the ad hoc Transport Task Force. A collaborative response and 'one voice' public information message with concerned United Nations agencies proven successful in reassuring the travelling public.

Based on the lessons learned, ICAO was urgently pursuing the fine tuning of an in-house emergency response plan (and associated emergency response centre) to coordinate its response to events like the Fukushima Daiichi accident that would impact aviation.

In addition, ICAO proposed to the IACRNE several improvements to overcome the occasional disparity and/or lack of authoritative information concerning the screening of potentially contaminated passengers and cargo.

3.5.4.6. INTERPOL

The INTERPOL CBRNE (Chemical, Biological, Radiological, Nuclear and Explosives) Sub-Directorate's strategic priorities consist of three main pillars: (1) operational data services; (2) urgent investigative support; and (3) capacity building. Despite the accidental nature of the emergency, following the accident, INTERPOL sent a message to its National Central Bureau (NCB) in Tokyo offering INTERPOL General Secretariat assistance such as disaster victim identification (DVI). However, INTERPOL's assistance was not required, and no INTERPOL staff were deployed to Japan. INTERPOL monitored the situation in Japan as well as Fukushima for any potential implications for INTERPOL.

3.5.4.7. International Labour Organization

Immediately after the Fukushima Daiichi accident, ILO prepared and put on its web site a briefing note on Radiation Safety and Protection of Workers in Nuclear and Emergency Operations. It also updated its web page on radiation protection by uploading all the publications relevant to nuclear and radiological emergencies developed either by the ILO alone or in collaboration with other international organizations. Web sites of authentic accident related information from the IAEA, WHO, the Japan Nuclear and Industrial Safety Agency, the Japan Atomic Industrial Forum, TEPCO and information on levels of radioactivity from MEXT, were also added on the ILO web site.

ILO collaborated with the WHO, IAEA, WMO, IMO, UNWTO and ICAO in the preparation of the joint public statements (news releases) on travel and transport to and from Japan in the early days of the accident.

3.5.4.8. International Maritime Organization

IMO is the specialized agency responsible for the safety and security of international shipping and the protection of the marine environment. The organization also has several arrangements in place for all manner of crises impacting the maritime domain, including radiological/nuclear incidents, both at

[162] Set out in the Joint Emergency Management Plan of the International Organizations [225].

institutional (e.g. JPLAN) and divisional (e.g. divisional emergency response) levels. The Fukushima Daiichi accident led to the activation of JPLAN and the IMO Secretariat was able to participate effectively.

Guidance to ships during emergencies such as the Fukushima Daiichi accident is issued by Navigational Area (NAVAREA) Coordinators based on the system established through the IMO. The IMO Secretariat received the guidance issued by NAVAREA Coordinators and took it into account when formulating IMO's response to the various aspects of the incident as they emerged.

The IMO Secretariat also participated in the Transport Task Force and contributed to the joint press releases providing basic guidance to air and sea passengers and crews. The opinion of the IMO is that the joint press releases clearly demonstrated their value, although this joint approach came with its own challenges of accommodating the requirements of numerous organizations and obtaining timely approval of the final versions of the releases.

3.5.4.9. OECD Nuclear Energy Agency

Within the IACRNE framework, the OECD/NEA, not being a response organization, carried out a survey to compile governmental decisions and recommendations that were made by various countries regarding their protective and other response actions (decisions regarding advice to their own citizens, their imports and exports, their industries, etc.). The survey results were consolidated into a single document, indicating the corresponding country, decision taken or recommendation made, applicable date and applicable population with three updates (the last update was posted on 21 April 2011). It was posted on the ENAC web site for official use by competent authorities.

In addition, the Committee on Radiation Protection and Public Health (CRPPH), at its meeting in May 2011, agreed on a series of actions that should be taken both to assist Japan with recovery efforts and to assist other CRPPH members to adapt their own emergency response policies and plans, as needed, to address the lessons learned. The CRPPH created the Expert Group on the Radiological Protection Aspects of the Fukushima Accident (EGRPF), which was responsible for managing the work of the CRPPH and its subgroups as it related to the Fukushima Daiichi accident. These groups agreed, among other things, to address questions from Japan, assist with the organization of the Conference on Decommissioning and Environmental Recovery, offer experience with the implication of stakeholders in consequence management and assess the implementation of the advice provided in ICRP Publication 109 [191, 248] concerning the use of reference levels and the optimization of protection strategy and emergency management lessons.

3.5.4.10. Pan American Health Organization

The PAHO Emergency Operation Centre (EOC) was activated[163] on 11 March 2011 to level 2 and stayed at that level during the first 48 hours due to the threat of tsunamis to the coastal countries in the Americas. As a result, 12 countries activated their contingency plans and four of them evacuated communities and hospitals from areas deemed to be at risk. After this early period, the EOC continued to operate at level 1, monitoring the situation mostly via ENAC, the IAEA's emergency web site.

[163] Activation at Level 1 may be declared whenever an emergency situation can be managed primarily by the Member State and corresponding PAHO/WHO Representative Office, and requires only minimal support from PAHO Headquarters or other entities. Activation at Level 2 may be declared whenever an emergency situation occurs that requires strong regional support, especially when it involves more than one country; deployment of PAHO's Regional Health Emergency Response Team may be required. Activation at Level 3 may be declared whenever a major emergency occurs that requires the full involvement of PAHO.

PAHO's main activities included: participating in the IACRNE teleconferences as a member organization; responding to concerns and questions from the PAHO/WHO Country Representatives and from Member States; updating and maintaining the PAHO EOC web site, including links to relevant standards and technical documents as well as to frequently asked questions in both English and Spanish; presenting the situation to PAHO's Subcommittee on Program, Budget and Administration representatives; providing information to the press and addressing press conferences; responding to questions originating from the International Health Regulations (IHR) system; disseminating information to the IHR National Focal Point of update provided by the Ministry of Health, Labour and Welfare in Japan regarding the situation of radioactive materials in tap water and food; providing comments to WHO/HQ daily talking points; and requesting Member States to take the opportunity to revise their national capacities to respond to this type of emergency.

3.5.4.11. United Nations Environment Programme

In the immediate aftermath of the Fukushima Daiichi accident, a regular line of communication along with periodic conference calls was established and maintained among the following offices of UNEP: UNEP headquarters in Nairobi; UNEP Post Conflict and Disaster Management Branch (PCDMB) in Geneva; UNEP-OCHA Joint Environment Unit (JEU) in Geneva; the secretariat of UNSCEAR; and the UNEP offices in Tokyo and Osaka.

As a member of IACRNE, UNEP was involved in interagency coordination by following the arrangements elaborated in the JPLAN. Since the Fukushima Daiichi accident, UNEP has been interested in, and has been following up, two important aspects: the non-radiological impact of the earthquake and tsunami, including waste management in particular; and the non-radiological impact of the movement of populations resulting from the earthquake and tsunami as well as from the response to the earthquake and tsunami.

3.5.4.12. United Nations Office for the Coordination of Humanitarian Affairs

OCHA was immediately alerted to the earthquake through the Global Disaster Alert and Coordination System and a Virtual On-Site Coordination Centre was activated. A United Nations Disaster Assessment and Coordination (UNDAC) team was deployed on 13 March 2011 at the request of the Government of Japan to support information management and reporting for international audiences, as well as to coordinate the deployment of international Urban Search and Rescue (USAR) teams[164]. During the emergency phase of the disaster, OCHA issued a total of 16 Humanitarian Situation Reports as well as a number of related information products, such as maps. The UNDAC team handed over to a small residual OCHA team, which left Japan on 2 April 2011, after having undertaken three humanitarian assessment missions to the affected areas. OCHA was closely involved in the follow-up and lessons learned process in Japan. The Joint Environment Unit (JEU) further supported the Secretary-General's High Level Summit on Nuclear Safety and Security in September 2012, providing inputs for the United Nations' system wide study on the implications of the accident.

3.5.4.13. United Nations Scientific Committee on the Effects of Atomic Radiation

In the event of widespread contamination of water, surface, people or commodities or of significant concern to the United Nations General Assembly or the public, the UNSCEAR Secretariat, as appropriate: establishes liaison with the IAEA, WHO and/or UNEP to coordinate a review of the levels and effects of the exposures for the General Assembly, the scientific community and/or the

[164] The issue of radiation leakage and insecurity regarding appropriate operational and safety measures to be taken had a considerable impact on humanitarian relief operations. USAR teams were requested to include radiological and nuclear experts and to have equipment for radiation detection with them.

public; liaises with the Scientific Committee and its officers; and prepares general material for public release on the levels and risks of radiation exposure.

On the 11 March 2011, first news of the event was received informally by the secretariat over the news service regarding the earthquake and tsunami, prompting them to confirm that the IEC was activated, to review material on ENAC and to stay aware of developments. Within the next 24 hours, on request from the Executive Director of UNEP, the UNSCEAR Secretariat prepared briefing material on the status and possible scenarios which were shared with relevant UNEP staff. The briefing material was updated over the weekend of 12–13 March as the situation developed, and was continued by teleconference when the UNEP coordination mechanisms were activated.

The UNSCEAR Secretariat maintained close liaison with the WHO, IAEA and UNEP on developments over the coming weeks, through video conference, teleconference and direct meetings. The UNSCEAR Secretariat coordinated with other organizations to prepare appropriate public information material to be posted on the UNSCEAR web site. The Japanese delegation to UNSCEAR proposed that the Scientific Committee conduct a two year scientific assessment of the levels and effects of the radiation exposure from the accident (similar to the one conducted after the Chernobyl accident) [249]. This proposal was accepted by the Scientific Committee in May 2011, and endorsed formally by the United Nations General Assembly in December 2011 [250]. The study involved contributions from CTBTO, FAO, IAEA, WHO and WMO [171, 251]. In addition, when the WHO launched its initiative to conduct a preliminary assessment of doses and risks [252], the UNSCEAR Secretariat acted as an observer to the relevant meetings of experts.

3.5.4.14. World Health Organization

In the Fukushima Daiichi accident, the risk of direct human exposure to radiation received priority at the WHO Headquarters, its Western-Pacific Regional Office (WPRO), and the Urban Health Emergency Management Unit at the WHO centre in Kobe, Japan. The Ministry of Health, Labour and Welfare (MHLW) notified WPRO through the IHR National Focal Point (NFP) within a few hours after the event. WHO immediately communicated the event to all the Member States in the region through the NFPs.

During the early response to the Fukushima Daiichi accident, the information needs of the WHO Member States, media, and the general public were continuously monitored and addressed. Provision of timely, consistent and accurate information to the public was one of the key components of the WHO response to the accident. Numerous information products were developed and made available, including fact-sheets, Q&As and technical briefings.

The requests from WHO Member States for advice focused mainly on the travel advisory (safety of travel to Japan and nearby areas, border control measures, screening of passengers, aircrafts, cargo and ships) and technical advice on protective actions and other response actions (evacuation, sheltering, use of potassium iodide, relocation, interpretation of monitoring data and radiation protection limits/values, safety of food and drinking water, protection of pregnant women and breastfed infants and the mental health impact of the accident and public information).

In addition, technical briefing notes related to food safety aspects and regular updates on food monitoring results were provided to WHO Member States through the International Food Safety Authorities Network (INFOSAN).

The public health risk for populations in and outside of Japan was closely monitored. The WHO Department of Mental Health provided technical assistance and advice on matters relevant to psychological impact management and developed a number of key messages and Q&As.

Jointly with relevant agencies and institutions, WHO conducted a health risk assessment (HRA) of the accident. In this context, WHO established an international expert panel to make a preliminary estimation of population radiation doses inside and outside Japan and set up an expert group to assess the radiation related health implications of the accident to support the identification of needs and priorities for public health actions.

3.5.4.15. World Meteorological Organization

WMO activated its emergency response mechanism on 11 March 2011 at the first IAEA request to provide atmospheric transport, dispersion and deposition modelling (ATM) outputs and meteorological information to designated authorities on the likely evolution of the radioactive cloud that was accidentally released from the Fukushima Daiichi NPP. The WMO's three Regional Specialized Meteorological Centres (RSMCs) in Asia (Beijing, Tokyo and Obninsk) responded immediately and issued forecast ATM charts, based on the request of a default unit release, of the dispersion of the radioactive material from the power plant according to established procedures, until they were no longer required. These RSMCs responded to nearly 50 requests for standard ATM chart production. WMO's remaining five RSMCs in other parts of the world also prepared ATM charts for inter-comparison and validation purposes, and responded to requests from countries in their respective regions. The WMO Secretariat closely coordinated the overall real time response carried out by the RSMCs with the IAEA, ICAO and WHO.

Numerous specialized (non-standard) requests were also made by the IAEA to refine and apply a best estimate source sequence for ATM calculations. Simulations were performed on high resolution (5 km grid mesh) and medium resolution (50 km grid mesh) to estimate the atmospheric spreading in the immediate region, and for greater distances (trans-North Pacific), respectively.

WMO made immediate arrangements with the National Meteorological Service of Austria (ZAMG) to provide 24/7 expert meteorological and ATM support to the IAEA on-site at the IEC. Similar arrangements were made with MeteoSwiss (Switzerland) to provide an expert to the WHO in Geneva.

WMO RSMCs also responded to CTBTO ATM-backtracking requests starting on 18 March 2011, under operational arrangements established as of 1 September 2008. In total, there were 44 requests (for 422 samples).

A WMO task team on meteorological analyses for the Fukushima Daiichi NPP accident was formed in late 2011 to develop a series of meteorological analyses in numerical form, using as much observational data and related information as available, which would be suitable for estimating the atmospheric transport, dispersion and deposition of radioactivity released from the Fukushima Daiichi NPP in 2011. National Meteorological and Hydrological Services/RSMCs of Austria, Canada, Japan, the United Kingdom and the United States of America participated in this task team. Representatives from the European Commission Joint Research Centre (Ispra, Italy) were later invited to participate in the data analysis phase of the effort. The work of this task team has been completed, and the report has been published [253]. This work contributed to the post-accident study undertaken by UNSCEAR on the levels and effects of radiation released from the accident.

3.5.5. Provision of international assistance

Provision of international assistance can be based on the Assistance Convention, bilateral or multilateral agreements among States or ad hoc arrangements between the Accident State and assisting State(s) prepared and agreed upon during an emergency. In case of the accident in Japan the latter two possibilities were used.

An offer of assistance by the IAEA[165] was sent to NISA and the Permanent Mission of Japan to the International Organizations in Vienna at 07:48 UTC on 11 March 2011. A second offer of assistance was sent on 12 March at 12:39 UTC.

On 12 March 2011, the IEC sent a communication to all Member States registered under the Response and Assistance Network (RANET) asking about the current status of their capabilities regarding the provision of specialized assistance to Japan, should Japan request it.

Throughout the emergency, the IEC received offers of assistance to Japan from Member States (Argentina, Australia, Belgium, Canada, China, Czech Republic, Finland, France, Germany, Hungary, India, Indonesia, Islamic Republic of Iran, Israel, Kazakhstan, Republic of Korea, Mexico, Pakistan, Russian Federation, Spain, Sweden and the United States of America), the European Commission, international organizations and individuals. Copies of the official offers from Member States were published on the ENAC web site and provided to the Government of Japan [232].

As of 15 September 2011, 163 countries and 43 international organizations offered to provide equipment and materials necessary for stabilizing the units (e.g. pumps, fire engines) and for evacuating the local population [254]. While some countries and organizations provided equipment (e.g. survey meters and personal dosimeters) and expertise, others responded with humanitarian aid for residents affected by the earthquake and tsunami.

The United States of America was a major contributor to international assistance, both of a humanitarian nature and in relation to the nuclear accident, owing to the presence in Japan of about 25 000 US troops, bilateral agreements between the United States of America and Japan and a formal request for assistance from the Japanese Government on 11 March 2011. Initial activities included atmospheric plume modelling, conducted by the National Atmospheric Release Advisory Center (NARAC), and deployment of a DOE radiological response team to carry out aerial and ground based monitoring in Japan. On 17 March 2011, initial aerial radiological survey measurements were taken over the Fukushima Daiichi NPP, and the first compilation of results was publicly released on the DOE web site on 22 March 2011[166]. The ground measurements conducted included basic dose rate measurements, air and soil sample analyses and in situ gamma spectroscopy.[167] The data and map products were shared with the Government of Japan on an ongoing basis. The products went directly to the Ministry of Foreign Affairs; the Ministry of Agriculture, Forestry, and Fisheries; and the Ministry of Education, Culture, Sports, Science and Technology.[168] The DOE team remained in Japan through 28 May 2011 [255].

Much of the assistance from countries in the EU was, at the request of the Japanese Government, coordinated through the EC's Monitoring and Information Centre [256, 257].[169]

The Japanese Government received offers of assistance directly from countries via the Ministry of Foreign Affairs, with NISA coordinating the delivery of equipment and materials [27]. Initially, there was some confusion over the procedures for receiving assistance, as they had not been defined in the arrangements established prior to the accident. It proved difficult to identify actual needs or to obtain relevant information, including the specification, number and delivery times of equipment and

[165] Referred to formally as 'the offer of the IAEA's good offices'.

[166] Aerial surveys were conducted for the next two and a half months.

[167] Using high purity germanium (HPGe) detectors.

[168] This collaboration was described in a joint press release issued 6 May 2011.

[169] Renamed the EC's Emergency Response Coordination Centre (ERCC) on 15 May 2013 [258].

materials. Storage places were also not secured promptly, and there were insufficient numbers of officials available to handle the process. However, the situation improved in April 2011 [27].

The Japanese Government declined offers of equipment that required training before it could be used or equipment and supplies of which Japan had sufficient stock (e.g. stable iodine). In some cases, delays incurred because it took time to identify individuals who could operate specific equipment.

Many experts visited Japan from China, France, the Republic of Korea, the Russian Federation, the United Kingdom and the United States of America to discuss relevant issues and potential assistance with Japanese Government agencies and TEPCO [22]. Japan received advice on the stabilization of the reactors and spent fuel pools, prevention of dispersion of radioactive materials and measures to cope with the accumulation of radioactive water. US organizations and agencies with expertise and capabilities in radiation survey mobilized quickly and offered critical assistance. In addition to governmental assistance, the United States nuclear industry immediately offered private sector assistance by sending supplies, technology and an industry support team comprised of nuclear engineers and other experts to lend technical expertise. Radiation specialists from the Department of Energy took hundreds of radiation readings and collected soil samples in the region [255]. The Korea Atomic Energy Research Institute (KAERI) and the Korea Institute of Nuclear Safety (KINS) also provided technical support [254, 259]. In addition, assistance in equipment and transport was provided by the United States Army and the Royal Australian Air Force [254].

Furthermore, teams put together by the multinational nuclear industry organizations composed of representatives from vendors and electricity utilities also provided technical assistance. These included the World Association of Nuclear Operators (WANO), Institute of Nuclear Power Operations (INPO) and Electric Power Research Institute (EPRI). Private companies such as Exelon Corp., AREVA, Bechtel Corp., GE Hitachi Nuclear Energy, The Shaw Group, Westinghouse Electric provided support for assessment and issue resolution at the accident site [260].

The Assistance Convention was not invoked and RANET was not utilized. In spite of this, some lessons to be taken into account for the further enhancement of RANET were identified. This was extensively discussed at the meeting on the extension of RANET capabilities held from 31 January to 2 February 2012 in Vienna. In addition to RANET registered Member States, a number of States Parties to the Assistance Convention having nuclear power programmes, selected on the basis of regional distribution and the development of their programmes, were invited. On the basis of lessons learned from the accident, Japan made a proposal to extend RANET capabilities with the functional area of 'stabilization of situations at accident sites' and to enable the registration of equipment with detailed specifications, even from private entities [261].[170]

3.5.6. Summary

An extensive international emergency preparedness and response (EPR) framework existed at the time of the accident, consisting of international legal instruments, IAEA safety standards and operational arrangements. While international legal instruments are binding for the parties, IAEA safety standards can be adopted in national practice at the State's discretion.

At the time of the accident, the IAEA had four roles in the response to a nuclear or radiological emergency: (1) notification and exchange of official information through officially designated contact points; (2) provision of timely, clear and understandable information; (3) provision and facilitation of international assistance on request; and (4) coordination of the interagency response.

[170] The proposal was partially implemented in the revised RANET manual [262].

The IAEA's role at the time did not include providing a prognosis of the potential evolution of an accident or an assessment of the possible consequences. This role in responding to an emergency at an NPP was expanded through the adoption of the IAEA Action Plan on Nuclear Safety.

The international response to the accident involved many States and a number of international organizations.

The IAEA liaised with the official contact point in Japan, shared information on the emergency as it developed, and kept States, relevant international organizations and the public informed. Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The IAEA Director General's visit to Japan, and the subsequent deployment of liaison officers in Tokyo, improved communication between the IAEA and the contact point.

In addition, according to the Emergency Notification and Assistance Technical Operations Manual (ENATOM), States were expected to notify and share information with the Incident and Emergency Centre (IEC) using appropriate reporting forms, which were intended to assist the IEC contact point in the rapid sharing of relevant information. However, in its communications with the IEC at an early stage of the accident, Nuclear and Industrial Safety Agency (NISA) did not seem to have been as familiar with the ENATOM arrangements as would have been practical.

The Nuclear Emergency Response Headquarters (NERHQ) and the Ministry of Health, Labour and Welfare (MHLW) were among the key organizations/entities in the response for Japan. They were not official contact points for the IEC.

Some States issued advice or a specific instruction for the protection of their nationals in Japan. Some advised their nationals in Japan to follow the orders and recommendations issued by the Japanese authorities in response to the emergency, while some States issued advice that differed from that provided by the Japanese authorities and other States [235]. Differences in the recommendations among States were due to various factors, including a lack of information on the evolving situation. These differences were generally not well explained to the public and occasionally caused confusion and concern.

The IAEA sent expert missions to Japan and coordinated the provision of Member State offers of assistance to Japan. The Assistance Convention was not invoked and RANET was not utilized. States provided assistance to Japan directly. This support helped the Government of Japan to manage the nuclear emergency which, together with the effects of the earthquake and tsunami, challenged national response capabilities. One of the difficulties in accepting international assistance in the early stages of the national response was the absence of national arrangements for receiving such assistance [21, 232].

In accordance with its responsibilities, the IAEA Secretariat promptly activated JPLAN and initiated coordination of the interagency response. Members of IACRNE exchanged information, focusing in particular on reaching a common understanding of the aftermath of the accident, and coordinating efforts to keep the public informed. Regular video teleconferences were held until July 2011. Joint press releases were also issued.

As part of the bilateral agreements between the respective secretariats, FAO, WHO and the WMO sent liaison officers to the IAEA to ensure effective coordination of the international response.

The existence of the IACRNE, and its Joint Plan, demonstrated that there was already a well established interagency mechanism in place to provide coordination and facilitate clarity with regard to the roles and capabilities of the participating international organizations in preparing for and responding to nuclear or radiological emergencies. These interagency response coordination

mechanisms proved to be efficient; however, areas for further improvement in arrangements were also identified.

3.5.7. Observations and lessons

— **The implementation of international arrangements for notification and assistance needs to be strengthened.**
Awareness of international arrangements for notification and assistance in a nuclear or radiological emergency, as well as existing operational mechanisms, needs to be increased, including mechanisms and procedures for notification and information exchange, for requesting and providing international assistance, etc. There is a need for enhanced training and exercises on the operational aspects of the Early Notification Convention and the Assistance Convention.
Participation in existing mechanisms for the provision of international assistance under the Assistance Convention needs to be an integral part of national emergency preparedness efforts. Arrangements need to be in place at the preparedness stage for requesting and receiving assistance (on the basis of bilateral agreements or under the Assistance Convention) in a nuclear or radiological emergency.
Lists of officially designated contact points, as required under the Early Notification Convention and the Assistance Convention, need to be continuously updated and prepared for immediate requests for information from the IAEA.
Application of the IAEA safety standards on emergency preparedness and response at the national level would improve preparedness and response, facilitate communication in an emergency and contribute to the harmonization of national criteria for protective actions and other response actions.

— **There is a need to improve consultation and sharing of information among States on protective actions and other response actions.**
Consultation and sharing of information on protective actions and other response actions among States in an emergency helps to ensure that actions are taken consistently. In addition, a clear and understandable explanation of the technical basis for decisions on protective actions and other response action is crucial in order to increase public understanding and acceptance at both the national and international levels.

— **There is a need for the IAEA Secretariat to provide States, international organizations and the public with timely, clear, factually correct, objective and easily understandable information during the nuclear emergency on its potential radiological consequences and the prognosis of possible emergency progression.**

— **There is a need for continuous enhancements and exercising of the inter-agency coordination mechanism in the EPR area, and for further strengthening the role of the IACRNE.**

APPENDIX I.
KEY DOCUMENTS AND ELEMENTS THAT DEFINED THE NATIONAL EPR SYSTEM FOR RESPONSE TO A NUCLEAR EMERGENCY IN JAPAN PRIOR TO THE ACCIDENT

This appendix describes[171] the basic documents and elements of the emergency preparedness and response (EPR) system in Japan as they were prior to the accident at the Fukushima Daiichi NPP, including: (a) key documents that defined the national EPR system for response to a nuclear emergency in Japan; and (b) key entities.

Information provided in this appendix is focused on elements relevant to response to an emergency at an NPP. Particular emphasis is placed on EPR aspects related to the Fukushima Daiichi NPP and nearby areas off-site.

I.1. RELEVANT DOCUMENTS

The primary legal basis for the national emergency preparedness and response system in Japan was set out in the Disaster Countermeasures Basic Act [6] and the Act on Special Measures Concerning Nuclear Emergency Preparedness [5] (see Fig. I.1). These and other documents are further described in Table I.1.

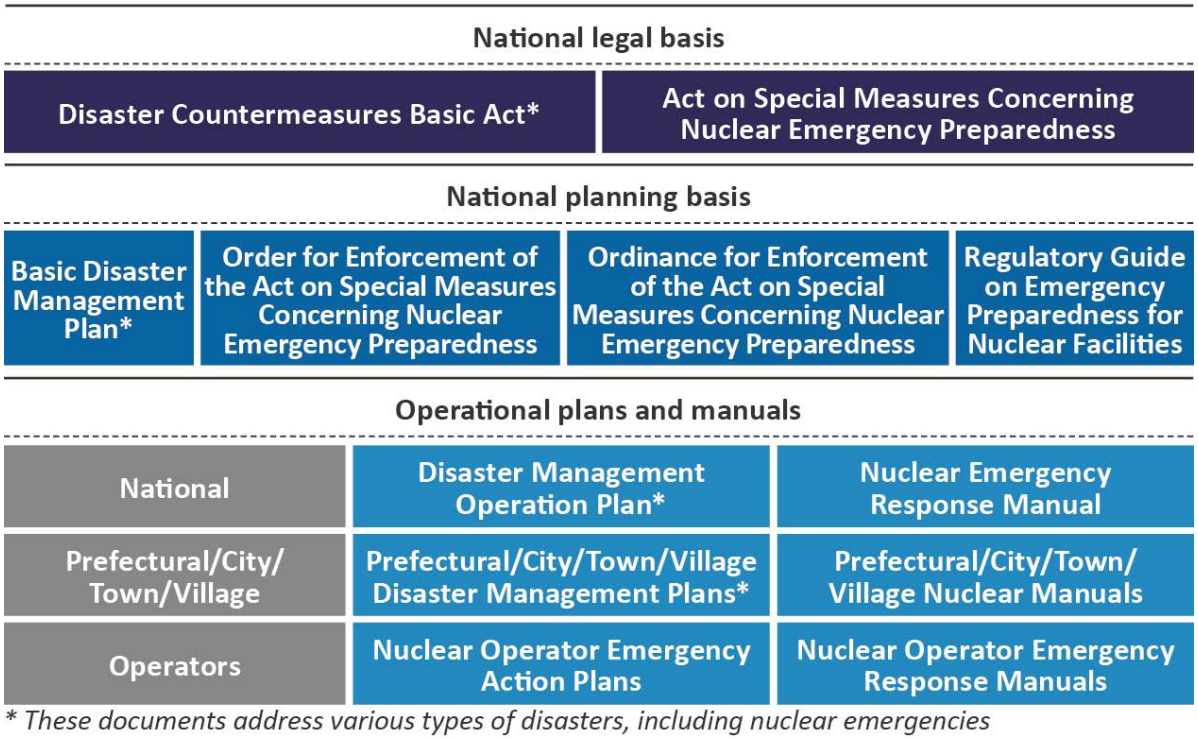


FIG. I.1. Key documents defining the national emergency preparedness and response system for a nuclear emergency in Japan at the time of the accident.

[171] This appendix uses consistent terms in presenting the titles of the various documents and, in most cases, does not use quotes from the various translations of documents, which in some cases used different terms for the same elements of the EPR system in Japan.

The first tier of documents shown in Fig. I.1 [9] and Table I.1 provided the primary legal basis for the national EPR system, which is set out in the Disaster Countermeasures Basic Act (Basic Act) [6] and the Act on Special Measures Concerning Nuclear Emergency Preparedness (Nuclear Emergency Act) [5]. The second tier shown in Fig. I.1 and Table I.1 lists the key planning basis documents. The Basic Disaster Management Plan (Basic Plan) [2] described the roles and responsibilities and other crucial elements of the EPR system. The Cabinet Order and Ministerial Ordinance on Special Measures Concerning Nuclear Emergency Preparedness [7, 10] provided the plant criteria for determining when off-site notifications for events at an NPP are warranted. The Regulatory Guide on Emergency Preparedness for Nuclear Facilities (Nuclear Emergency Preparedness Guide) provided general technical guidelines on matters such as the distances (radius) for emergency planning zones (EPZ), projected doses at which various protective actions were warranted, activity concentrations at which food and drink restrictions were to be implemented and the dose limits for emergency workers. The third tier lists the operational documents that were intended for use in responding to an emergency at the national, local and operator levels. The Nuclear Emergency Response Manual [8] described the procedures to be implemented by the relevant national Government ministries and agencies in the event of an emergency at an NPP to include notification and decision making.

TABLE I.1. DESCRIPTIONS OF THE KEY EPR DOCUMENTS THAT DEFINED THE NATIONAL EPR SYSTEM FOR RESPONSE TO A NUCLEAR EMERGENCY IN JAPAN PRIOR TO THE ACCIDENT

Document title (Short title in parentheses)	Description
Disaster Counter-measures Basic Act (Basic Act) [a] [6]	Represented the legal basis for the prevention of and response to disasters. It was general in scope and covered all types of disasters. It defined the roles and responsibilities of national Government ministries, local governments and designated public corporations (e.g. Nippon Hoso Kyokai (NHK), Japanese Red Cross Society, Nippon Telegraph and Telephone (NTT), etc.). It provided for the formulation of disaster prevention plans and basic policies related to preventive and emergency response measures. It defined a hierarchy of the emergency plans for all types of disasters in the following way: Basic Disaster Management Plan, Operational Disaster Management Plan, and Prefectural/City/Town/Village Disaster Management Plans.
Act on Special Measures Concerning Nuclear Emergency Preparedness (Nuclear Emergency Act) [a,b] [5]	Provided description of the responsibilities of the NPP operator, national and local governments in response to a nuclear emergency. For national and local governments it outlined their responsibilities upon notification to include those of the Prime Minister. It also outlined the response actions to be taken by national and local governments upon declaration of a nuclear emergency under Article 15 to include: (a) implementation of response actions; establishment of Nuclear Emergency Response Headquarters (NERHQ) and Local Nuclear Emergency Response Headquarters (Local NERHQ); and (b) establishment of a Joint Council for Nuclear Emergency Response (JCNER). For the operators, it outlined their responsibilities for response actions during an emergency to include: (a) notification under Articles 10 and 15[b] of this Act; (b) development of a Nuclear Operator Emergency Action Plan; (c) establishment of the on-site organization for emergency response; (d) appointment and responsibilities of a Nuclear Emergency Preparedness Manager; (e) designation of an Off-Site Centre (OFC[172]); and (f) other actions to be taken by the operator. It also described coordination and cooperation among relevant organizations, plans for emergency drills, restoration from an emergency, etc.

[172] The OFC was to be established within a 20 km radius of an NPP [8]. For the Fukushima Daiichi NPP and Fukushima Daini NPP, it was to be established within 5 km of the Fukushima Daiichi NPP. Every OFC had to have the necessary facilities and equipment to communicate with the Prime Minister's Office, the METI/NISA-ERC and relevant national and local governments. It was also to be equipped with the means to monitor environmental radiation levels and the status of nuclear installations, as well as with connection to SPEEDI.

TABLE I.1. DESCRIPTIONS OF THE KEY EPR DOCUMENTS THAT DEFINED THE NATIONAL EPR SYSTEM FOR RESPONSE TO A NUCLEAR EMERGENCY IN JAPAN PRIOR TO THE ACCIDENT (cont.)

Document title (Short title in parentheses)	Description
Basic Disaster Management Plan (Basic Plan)[a] [2]	Developed as required by the Basic Act. It covered all types of disasters. One chapter was on the response to nuclear emergencies, which described the responsibilities of the facility operator and national and local governments concerning the major aspects of a response to a nuclear emergency, including: (a) notification, (b) declaration of a nuclear emergency under Article 15, (c) determination of appropriate protective actions and their implementation, (d) the role of the Prime Minister and local officials in issuing recommendations for protective actions, (e) implementation of public protective actions, (f) protection of emergency workers, (g) public communication, including provision of information to the specific groups of population and foreign embassies in Tokyo, (h) coordination of response activities and (i) communications between response Headquarters and Centres. It formed the basis for nuclear emergency management arrangements according to the emergency phases as well as recovery and rehabilitation. It requested response manuals to be developed. The Basic Plan was prepared by the Central Disaster Prevention Council (reporting to the Prime Minister); the Prefectural Disaster Management Plans were prepared by the Disaster Prevention Council at Prefectural level and reported to the Prime Minister; the Local (Prefectural/City/Town/Village) Disaster Management Plans were prepared by the Disaster Prevention Council at local level and reported to the Governor of the Prefecture [26].
Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness and Ordinance for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness (Cabinet Order and Ministerial Ordinance)[b,c] [7, 10].	Provided details for implementation of the Nuclear Emergency Act, including criteria for identification of events warranting off-site notification by an NPP in accordance with Article 10 and Article 15 of the Nuclear Emergency Act [5].
Regulatory Guide on Emergency Preparedness for Nuclear Facilities (Nuclear Emergency Preparedness Guide)[a] [19]	Provided guidelines for specialized and technical matters related to protective actions that the national Government, local governments and operators should follow when formulating operational plans, implementing protective actions in case of emergency, etc. These topics included the nature of radioactive releases, effectiveness of various protective actions, information of residents, training of emergency workers, response facilities including the OFC, and documentation. It also provided detailed guidance on: (a) concept and sizes of the emergency planning zone (EPZ), (b) projected dose criteria for the implementation of sheltering, evacuation and iodine thyroid blocking (ITB), (c) dose limits for emergency workers, (d) radionuclide activity concentrations criteria for restrictions of food and drink, (e) emergency environmental radiation monitoring and (f) emergency exposure medical treatment. It also provided technical guidance on training and drills.
Disaster Management Operation Plan[a] [6]	Required by the Basic Act. It covered all types of disasters. Each relevant national governmental ministry, agency and designated public corporation had such a plan, which contained a chapter describing their response in a nuclear emergency.
Nuclear Emergency Response Manual [8] (NER Manual)[a]	Required by the Basic Plan [2]. It described the coordination of the national response actions for the relevant national ministries and agencies once a notification has been made by an NPP under Article 10 of the Nuclear Emergency Act [5]. It also described the actions taken if an event is considered a nuclear emergency under the Article 15 of the Nuclear Emergency Act. Specified arrangements for nuclear emergency drills.

TABLE I.1. DESCRIPTIONS OF THE KEY EPR DOCUMENTS THAT DEFINED THE NATIONAL EPR SYSTEM FOR RESPONSE TO A NUCLEAR EMERGENCY IN JAPAN PRIOR TO THE ACCIDENT (cont.)

Document title (Short title in parentheses)	Description
Prefectural/ City/Town/ Village Disaster Management Plans[a] [6]	Required by the Basic Act. The plans covered all types of disasters. One chapter dealt with the response to nuclear emergencies, which provided guidance for the local governments during the response to the emergency and included: (a) notifications; (b) description of protective actions to include the role of the Prime Minister and local officials; (c) implementation of public protective actions; (d) protection of emergency workers; (e) public communications; (f) environmental radiation monitoring; and (g) the system to coordinate response activities and communications among response organizations.
Prefectural/City/Town/ Village Nuclear Manuals [1][d]	Required by the Prefectural/City/Town/Village Disaster Management Plans. They contained details concerning the response actions of Prefectures and cities/towns/villages in case of a nuclear emergency (the tasks of each emergency staff member, criteria and procedures were specified).
Nuclear Operator Emergency Action Plan (EAP)[a] [16]	Required by the Nuclear Emergency Act [5]. The table of contents along with criteria for its approval were defined in the Ordinance for Enforcement of the Nuclear Emergency Act. Developed by the operator of the NPP and contained a description of the operator measures to prevent and respond to a nuclear emergency; and activities at the preparedness stage (e.g. preparations for liaison and coordination and details of implementation of drills and exercises). Needed to be reviewed every year and revised if revisions were found to be necessary. The plan needed to be submitted to Minister of the Ministry of Economy, Trade and Industry (METI/NISA) which could require modifications if deemed necessary. A senior Specialist for Nuclear Emergency Preparedness could provide guidance and advice concerning its preparation. The operator was also required to confer in advance with the local and neighbouring city/town/village governments and inform them of the content of the plan. The operator, when it had prepared or revised an EAP, promptly notified the competent minister and made an overview of the plan publicly available.
Nuclear Operator Emergency Response Manual [263]	Required by the Nuclear Operator Emergency Action Plan. It contained details of the response by the operator to a nuclear emergency in accordance with the Nuclear Operator Emergency Action Plan.

[a] Other titles of the documents used in various Japanese documents translated into English include:
- For Disaster Countermeasures Basic Act — Basic Act, Disaster Countermeasures Basic Law [21], the Basic Act on Disaster Control Measures [9, 22].
- For Act on Special Measures Concerning Nuclear Emergency Preparedness — Nuclear Emergency Act, Nuclear Emergency Preparedness Act.
- For Basic Disaster Management Plan — Basic Plan, Basic Disaster Management Plan [2] Basic Plan for Emergency Preparedness [21, 22, 25].
- For Regulatory Guide on Emergency Preparedness for Nuclear Facilities - Nuclear Emergency Preparedness Guide.
- For Nuclear Emergency Response Manual — NER Manual [21, 25].
- For Disaster Management Operation Plan — Operational disaster prevention plan of a designated administrative organ [6], Operational disaster prevention plans of designated public corporations [6], Operation Disaster Management Plan.
- For Prefectural/City/Town/Village Disaster Management Plans — Prefectural Disaster Prevention Plan; Prefectural/City/Town/Village area disaster prevention plan [6]; City, Prefectural/City/Town/Village disaster prevention plan for a designated area [6].
- For Nuclear Operator Emergency Action Plan (EAP) — Nuclear Licensee Emergency Action Plan, NPP Operator Nuclear Emergency Action Plan.

[b] The criteria for notification under Articles 10 and 15 for an event at an NPP are contained in the Nuclear Emergency Act, the Cabinet Order and Ministerial Ordinance.

[c.] The Nuclear Emergency Act requires a Cabinet Order to formulate the details, while a Cabinet Order requires a Ministerial Ordinance to formulate further details on the subject.

[d] This reference is provided as an example of a Prefectural Disaster Management Plan that would require the development of a Nuclear Manual.

I.2. MAIN ENTITITES IN THE EPR SYSTEM IN JAPAN

Table I.2 lists the main entities[173] within the EPR system in Japan that had to play key roles during the response to a nuclear emergency. It also summarizes their main roles as defined before the Fukushima Daiichi NPP accident and their planned locations, as appropriate. Figure I.2 shows the planned locations of the entities.

TABLE I.2. MAIN ENTITIES INVOLVED IN EPR SYSTEM

Entity	Summary of key EPR roles during a nuclear emergency and location of the entity
In Tokyo	
Prime Minister and Prime Minister's general support	Directs the response to any emergency as the Director General of the: Emergency Disaster Response Headquarters (for the response to non-nuclear emergencies). Nuclear Emergency Response Headquarters (NERHQ) (for the response to nuclear emergencies). In the case of an accident to the PM, a Minister of State designated by the Prime Minister in advance shall serve in this capacity. The Prime Minister is supported by an Emergency Operations Team composed of Director General level members from relevant government ministries and agencies that may meet in the event of any emergency to gather information and coordinate between related government ministries and agencies in support of the Prime Minister [25]. They are located in the Crisis Management Centre in the basement of the Prime Minister's Office in Tokyo.
Nuclear Emergency Response Headquarters (NERHQ)	Directs and provides comprehensive coordination of the national response to a nuclear emergency. Composed of those appointed by the Prime Minister from among the officials of the Cabinet Secretariat and designated administrative organs [5]. The Prime Minister serves as the Director General of the NERHQ. Located in the Prime Minister's Office.
Nuclear Emergency Response Headquarters (NERHQ) Secretariat	Plans and coordinates responses to the accident as directed by the NERHQ including collection of information on NPP status and monitoring results. Performs the key role in the national Government's response to include preparing and sending evacuation orders to the local government. Staffed by representatives from key organizations and headed by the Director General of NISA. Located in the METI/NISA-ERC in the METI building.
Nuclear Safety Commission (NSC)	Acts as an expert body on nuclear power and nuclear emergency preparedness activities and provides technical advice at the national and local level during an emergency (e.g. provides advice to the Director General of the NERHQ or the Prime Minister regarding Article 10 and 15 events) [5, 25]. Convenes an Emergency Technical Advisory Body within its secretariat upon receipt of a report on the notification of an occurrence of a specific event from METI, and provides advice to the Director General of the NERHQ or the Prime Minister to include on Articles 10 and 15 events and protective measures. Establishes an Emergency Technical Advisory Body at the OFC.
Ministry of Economy, Trade and Industry (METI)/Nuclear and Industrial Safety Agency (NISA)	Assesses the reports sent by an NPP under Article 10 or Article 15 of the Nuclear Emegency Act [5] and advises whether or not a declaration of a nuclear emergency is warranted, and relays relevant information to the PM's Cabinet Secretariat, NSC, MEXT, the Cabinet Office, concerned local governments, and the police headquarters of the concerned prefectures. If a declaration of nuclear emergency is warranted, prepares a draft public notice, which would be sent to the Cabinet Secretariat located in the Prime Minister's Office and Cabinet Office for consideration by the Prime Minister [2]. Provides the secretariat for the NERHQ with the Director General of METI/NISA as the Head of the secretariat. METI/NISA receives technical support from different bodies, such as the Japan Nuclear Energy Safety Organization (JNES).

[173] An individual or an organization.

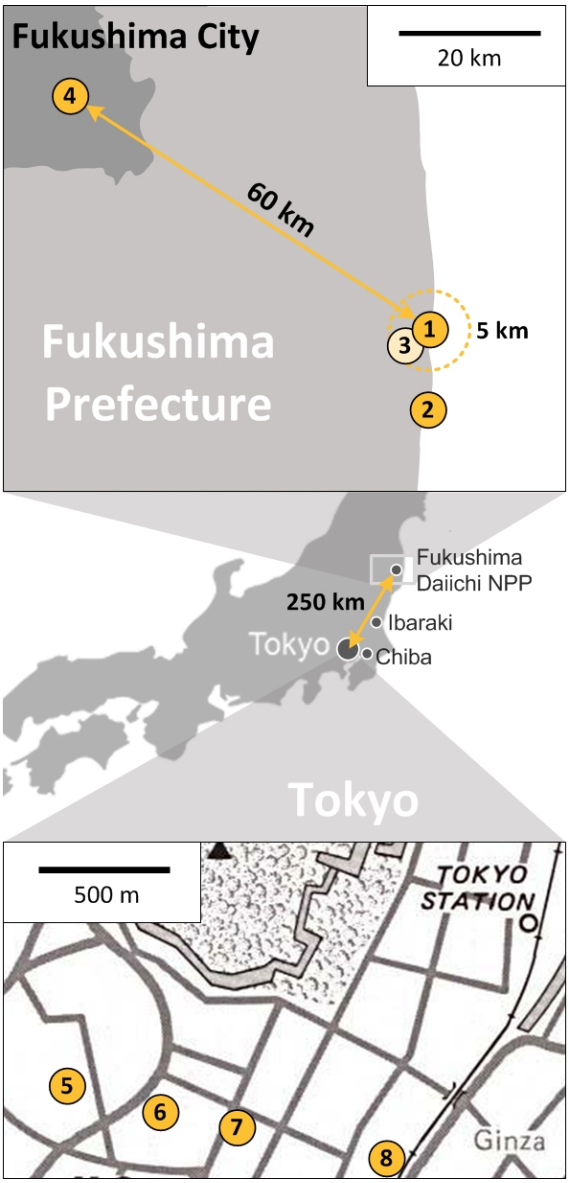
TABLE I.2. MAIN ENTITIES INVOLVED IN EPR SYSTEM (cont.)

Entity	Summary of key EPR roles during a nuclear emergency and location of the entity
In Tokyo	
Ministry of Education, Culture, Sports, Science and Technology (MEXT)	Provides support in environmental monitoring and prediction of off-site consequences (e.g. doses to the public) from the possible releases of radioactivity and environmental monitoring, using the System for Prediction of Environmental Emergency Dose Information (SPEEDI) [2]. Mobilizes emergency monitoring personnel and equipment to the site to provide support for the emergency monitoring activities.
Ministry of Health, Labour and Welfare (MHLW)	Conducts medical treatment for those suffering from emergency exposure, carries out dose evaluations of workers, ensures safety of food and water supplies, including setting intervention levels, setting of screening levels for public monitoring and setting of dose limits for personnel working for private companies [2]. Within OFC, reports implementation state of restriction of food and drink, reports state of shipment restriction of food and state of safety checks of agricultural, forestry, livestock and fishery products [2, 8].
Ministry of Agriculture, Forestry and Fisheries (MAFF)	Within OFC, reports implementation state of restriction of food and drink, reports state of shipment restriction of food and state of safety checks of agricultural, forestry, livestock and fishery products [2, 8]. Implements economic measures (e.g. monitor commodity prices of the bare necessities).
Ministry of the Environment (MOE)	Supports environmental monitoring [2, 8].
Japan Nuclear Energy Safety Organization (JNES)	Monitors conditions at the NPP and attempts to predict the timing, rate and composition of possible releases of radioactive material from the NPP (i.e. source term), based on plant conditions provided by the operator and using the Emergency Response Support System (ERSS).
Japan Meteorological Agency (JMA)	Provides the JCNER and other relevant bodies with meteorological information necessary for analysing radiological consequences and support of response actions.
Ministry of Defense (Self-Defense Force (SDF))	Provides general support of response operations to include transporting equipment, evacuation support, rescue and first aid and support of environmental monitoring [2].
TEPCO	Licensee of the Fukushima Daiichi NPP. TEPCO has a Licensee Headquarters Emergency Operations Centre, located at Headquarters, which was fitted with a dedicated communications link to the NPP-ERC. The Centre, led by TEPCO's President, conducts support activities for the NPP-ERC, such as by providing of staff or materials and equipment, and communicates information to the national Government and other organizations. Headquarters is located in Tokyo.
In Fukushima Prefecture	
Joint Council for Nuclear Emergency Response (JCNER)	Shares information and coordinates national and local activities to include implementing of protective actions. Consists of representatives from the national and local governments and operator [2, 5]. It was planned to be located at the OFC.
Local Nuclear Emergency Response Headquarters (Local NERHQ)	Once fully established, the Prime Minister may formally delegate, all or part of his/her authority to direct parts of the national response to the Local NERHQ, including the issuance of evacuation orders (see p.20 [8]). Local NERHQ was also responsible for organizing the JCNER. It was to be staffed with individuals from all relevant organizations, with the METI Senior Vice Minister as Director General. It was planned to be located at the OFC.

TABLE I.2. MAIN ENTITIES INVOLVED IN EPR SYSTEM (cont.)

Entity	Summary of key EPR roles during a nuclear emergency and location of the entity
In Fukushima Prefecture	
Local Prefectural Nuclear Emergency Response Headquarters (Local Prefectural NERHQ)	Had a liaison role by representing and providing information to the Prefectural Government. Various activities were to be carried out by this entity, including those related to: attendance at the local accident response liaison conference and the JCNER, assistance for dispatching personnel to functional teams and their activities, communication and coordination with the emergency response headquarters, the national Government, affected city/town/village and local emergency related organizations, among others [1]. It was planned to be located at the OFC.
Prefecture Headquarters for Disaster Control (for natural disaster or nuclear emergency)	Manages prefectural response to a natural disaster or nuclear emergency. The Prefectural Governor was planned to be its Director General. The Prefectural Disaster Management Plan included chapters on the response to natural disasters (e.g. earthquakes) or a nuclear emergency. The plan was formulated on the presumption that a natural disaster or nuclear emergency would not take place at the same time. Has nine squads within its structure: general affairs, information gathering, communications, public relations, external affairs, activity support, aid, supplies, and resident evacuation and safety (same nine functional squads described in the chapter on the response to a natural disaster or nuclear emergency) [25]. It was planned to be located at the Fukushima Prefectural Government Office. Municipalities Headquarters are located in the various cities, towns and villages in Fukushima Prefecture (not shown in Fig. I.2 for simplicity). Various activities were to be carried out by this entity, which included those related to: integration of emergency response measures, organizational structure and staffing of the Local Prefectural NERHQ, collection of disaster related information, determination and implementation of emergency response measures, among others [1].
Operator/Nuclear Emergency Preparedness Manager	Notifies off-site officials, protects those located on-site, takes actions to prevent the expansion of, and to mitigate, the accident. Provides data on the status of NPP to METI [5].
In other locations in Japan	
Japan Atomic Energy Agency (JAEA)	Nuclear research organization. It has a Nuclear Emergency Assistance and Training Centre (NEAT), which provides technical support to the OFC and provides JCNER with technical advice and information; it also performs dispatch of specialists, supply of emergency equipment and support for monitoring [2]. At the preparedness stage, NEAT conducts training on emergency response for various categories of emergency workers involved in off-site response [2, 27]. Located in Ibaraki Prefecture.
National Institute of Radiological Sciences (NIRS)	Provides technical support on activities such as emergency monitoring, medical support, etc. Designated as the tertiary level of radiation emergency hospital by the national Government to provide specialized medical treatment for those overexposed and/or contaminated, as well as physical and biological dose assessments. Also, designated as the national centre of radiation emergency medicine in Japan. Located in Chiba (approximately 40 km from Tokyo).

The locations of the core entities are shown in Fig. I.2.



1. FUKUSHIMA DAIICHI NUCLEAR POWER PLANT
- On-site – Emergency Response Centre at the NPP

2. FUKUSHIMA DAINI NUCLEAR POWER PLANT
- On-site – Emergency Response Centre at the NPP

3. OFF-SITE CENTRE
- Local NERHQ – Local Nuclear Emergency Response Headquarters
- JCNER – Joint Council for Nuclear Emergency Response
- Local Prefectural NERHQ – Local Prefectural Nuclear Emergency Response Headquarters

4. FUKUSHIMA PREFECTURAL GOVERNMENT OFFICE
- Fukushima Prefecture Headquarters for Disaster Control

KEY ENTITIES IN VARIOUS LOCATIONS IN JAPAN

Tokyo
- JNES – Japan Nuclear Energy Safety Organization
- MEXT – Ministry of Education, Culture, Sports, Science and Technology
- MHLW – Ministry of Health, Labour and Welfare
- MAFF – Ministry of Agriculture, Forestry and Fisheries
- MOE – Ministry of the Environment
- MOD (SDF) – Ministry of Defense (Self-Defense Forces)
- JMA – Japan Meteorological Agency

Ibaraki
- JAEA – Japan Atomic Energy Agency

Chiba
- NIRS – National Institute of Radiological Sciences

5. PRIME MINISTER'S OFFICE
- Prime Minister and general support staff
- NERHQ – Nuclear Emergency Response Headquarters

6. NUCLEAR SAFETY COMMISSION

7. EMERGENCY RESPONSE CENTRE OF MINISTRY OF ECONOMY, TRADE AND INDUSTRY/NUCLEAR AND INDUSTRIAL SAFETY AGENCY (METI/NISA)
- NERHQ Secretariat – Nuclear Emergency Response Headquarters Secretariat

8. TEPCO HEADQUARTERS
- TEPCO HQ-ERCs – Emergency Response Centres at TEPCO Headquarters

FIG. I.2. Locations of the core entities involved in the management of the response to a nuclear emergency.

APPENDIX II.
RADIATION AND DISASTER EMERGENCY MEDICAL SYSTEMS IN JAPAN PRIOR TO THE ACCIDENT

The radiation emergency medical system was comprised of three hospital levels (primary, secondary and tertiary), with the characteristics and functions of each level provided in Table II.1 [264, 265]. At the time of the Fukushima Daiichi accident, Japan had 54 operational nuclear reactors in 13 prefectures and other nuclear facilities, such as research facilities and reprocessing plants located in three prefectures. In prefectures with nuclear installations, 59 hospitals were designated as primary level hospitals, 34 as secondary level hospitals, and two as tertiary level hospitals in accordance with the radiation emergency medical system [266].

TABLE II.1. RADIATION EMERGENCY MEDICAL SYSTEM IN JAPAN PRIOR TO THE FUKUSHIMA DAIICHI ACCIDENT

	Designated level for the hospital		
	Primary	Secondary	Tertiary
Basic roles	Provide first aid and emergency treatment regardless of presence of contamination Treatment of contaminated wounds (including decontamination) Simple decontamination procedures of the head and body surface by removing clothes and/or wiping off Refer exposed patients to an appropriate hospital	Perform appropriate initial treatment for those exposed (local and whole body exposure) Perform medical treatment of concurrent health problems Perform decontamination to those contaminated, including using special wet-decontamination facilities, if available Manage internal contamination Perform triage and send to tertiary radiation emergency hospitals as appropriate	Provide highly advanced and specialized treatment, decontamination and dose assessment, as required Treatment of severe external exposure Management of patients with internal contamination which requires long term and specialized treatment Treatment of concurrent severe health problems Advanced intensive care requiring multidisciplinary medical approaches
Locations	Near the nuclear facilities	In areas where patients can be transported from the nuclear facilities and the primary hospitals by appropriate methods within relatively short time	One facility in the eastern and western parts of Japan

The local plan provided for ambulance transportation of exposed and/or contaminated patients from a nuclear facility to a primary or secondary hospital. The long distance transportation of patients from secondary to tertiary hospitals was to be provided by local government helicopters or fixed wing aircraft of the Japan Self-Defense Force (SDF) [267, 268].

In parallel, there was an established national disaster response medical system, comprising more than 600 hospitals throughout Japan. These hospitals were designated as disaster medical centres and were equipped with medical stockpiles for disasters and staffed with trained Disaster Medical Assistance Teams (DMATs) [269]. The hospitals in Fukushima Prefecture were designated as follows: four were primary radiation emergency hospitals, two were designated as both a primary radiation emergency hospital and a disaster medical centre, one as both a secondary radiation emergency hospital and a disaster medical centre, and a further five were designated only as disaster medical centres (Fig. II.1) [80].

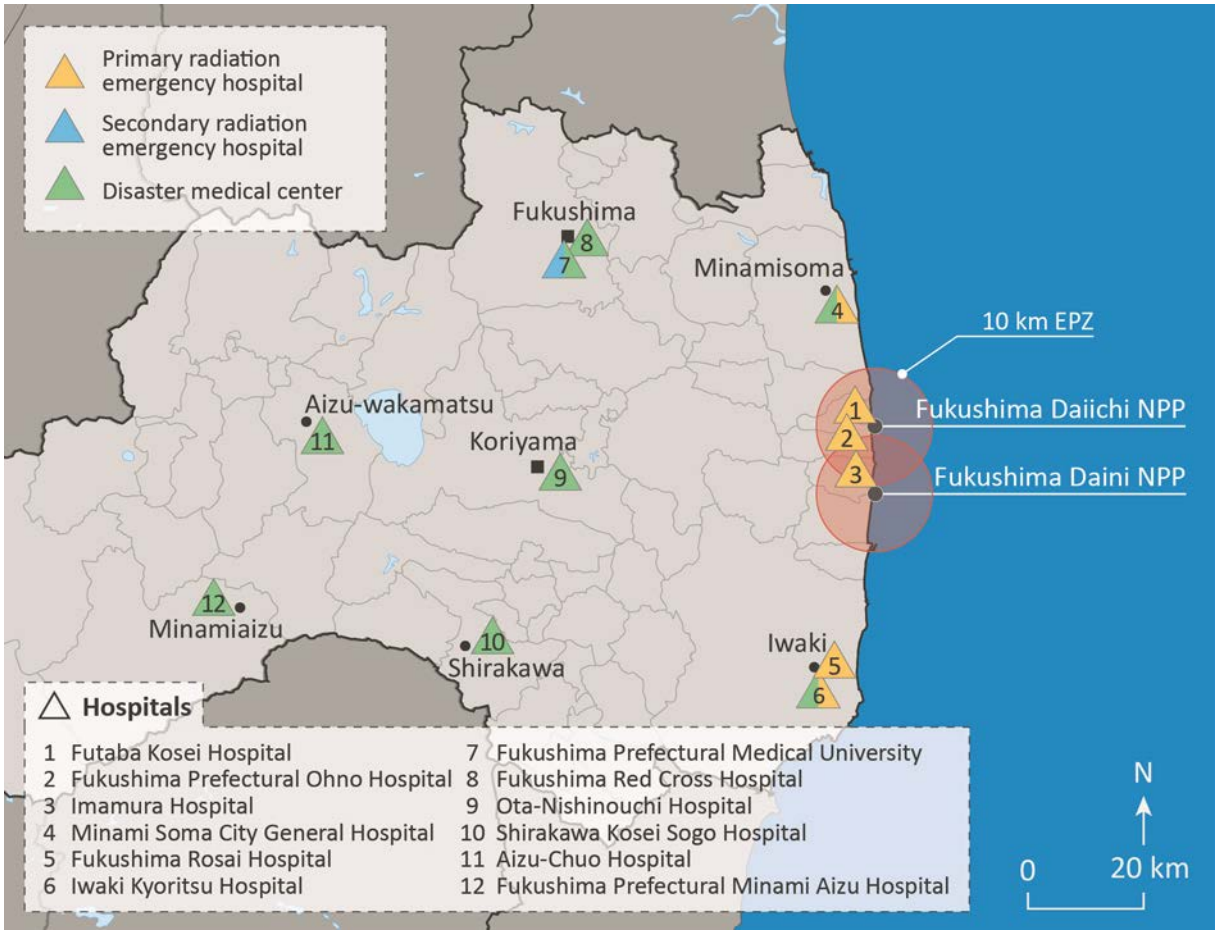


FIG. II.1. The radiation emergency medical system and disaster medical system in Fukushima Prefecture prior to the accident [270].

Overall, not all designated radiation emergency hospitals were also designated as disaster medical centres [271], meaning that they are unlikely to have been appropriately prepared for the medical management of the combined consequences of the Fukushima Daiichi accident and the Great East Japan Earthquake.

APPENDIX III.
PLANS FOR EMERGENCY DRILLS AND EXERCISES PRIOR TO THE ACCIDENT

The Nuclear Emergency Response Manual specified that nuclear emergency drills would be planned by the national Government each year and that the manual would be reviewed afterwards, as required [2, 5, 8]. NISA was designated as the main coordinator of the nuclear emergency drills. In particular, the METI Emergency Plan stipulated that the drills would include the participation of local communities, in cooperation with designated administrative agencies as well as the Government, local governments, nuclear operators and other parties involved. The drills would include the use of the OFC [272].

In addition, the Nuclear Emergency Preparedness Guide [19] provided technical guidance on training and drills, including the need for evaluating/reviewing the results of the drills in cooperation with a third party[174]. It described, inter alia, the need to periodically train emergency preparedness personnel, particularly on notification, emergency monitoring and emergency exposure medical treatment. It also recommended that the following drills and exercises to be conducted:

— An emergency notification drill;
— An emergency monitoring drill;
— An exercise combining notification and monitoring drills as well as communication to residents, etc., in the vicinity;
— A comprehensive exercise for each region including a governmental support system;
— A comprehensive joint exercise including the launch of a Nuclear Emergency Response Headquarters (NERHQ) by the national Government [19].

In October 2008, an Integrated Nuclear Emergency Response Drill was conducted at the Fukushima Daiichi NPP, involving national and local (prefectural and city/town/village) authorities, the operator (TEPCO) and about 600 local residents [275].

Public relations and information activities concerning accidents at nuclear power plants were practised mainly in association with the drills [9].

[174] Third parties are, for example, the NSC and the Sub-Committee on Nuclear Emergency and Preparedness under the Sub-Committee on Nuclear and Industrial Safety of the Advisory Committee for Natural Resources and Energy (an advisory committee to the METI Minister) [273, 274].

REFERENCES

[1] FUKUSHIMA PREFECTURE, Fukushima Prefecture Disaster Management Plan (2009) (in Japanese).

[2] GOVERNMENT OF JAPAN, Central Disaster Management Council, The Basic Disaster Management Plan, Government of Japan, Tokyo (2008).

[3] NUCLEAR SAFETY COMMISSION, 1999 White Paper on Nuclear Safety: Summary (2000), http://www.nsr.go.jp/archive/nsc/NSCenglish/outreach/whitepapers/1999WhitePaper.pdf

[4] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Nuclear Emergency Response Activity (2014), http://www.nsr.go.jp/archive/nisa/english/regulation/nuclearsafety/crosscuttingarea/emergencyprepared/nuculearemergency.html

[5] Act on Special Measures Concerning Nuclear Emergency Preparedness, as last amended by Act No. 156, 17 December 1999 (Japan), http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf

[6] Disaster Countermeasures Basic Act, Act No. 223 of 15 November 1961, as last amended in 1997 (Japan), http://www.adrc.asia/documents/law/DisasterCountermeasuresBasicAct.pdf

[7] Ordinance for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 2 of April 5, 2000 (Japan)(in Japanese), http://law.e-gov.go.jp/haishi/H12F03103016002.html

[8] GOVERNMENT OF JAPAN, Nuclear Emergency Response Manual, Government of Japan (2010) (in Japanese).

[9] GOVERNMENT OF JAPAN, National Report to the 5th Review Meeting on the Convention on Nuclear Safety (2010), http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/conventions/2011.pdf

[10] Order for Enforcement of the Act on Special Measures Concerning Nuclear Emergency Preparedness No. 195 of April 5, 2000 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/H12/H12SE195.html

[11] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE CO-ORDINATION OF HUMANITARIAN AFFAIRS AND WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition), IAEA, Vienna (2007).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSG-2, IAEA, Vienna (2011).

[15] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Comment no. 4: July review, official communication (2014).

[16] TOKYO ELECTRIC POWER COMPANY, Nuclear Operator Emergency Action Plan for the Fukushima Dai-ichi Nuclear Power Station, TEPCO, Tokyo (2010).

[17] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report, TEPCO, Tokyo (2012).

[18] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Nuclear Emergency Response and Preparedness Department (2015), http://www.nsr.go.jp/archive/jnes/english/gyomu/bousai.html

[19] NUCLEAR SAFETY COMMISSION, Regulatory Guide: Emergency Preparedness for Nuclear Facilities, NSC, Tokyo (1980).
[20] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression, Progress Report No. 2 (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1240140_5892.html
[21] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Final Report (2012), http://www.cas.go.jp/jp/seisaku/icanps/eng/final-report.html
[22] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety: The Accident at TEPCO's Fukushima Nuclear Power Stations, Government of Japan (2011), http://www.iaea.org/newscenter/focus/fukushima/japan-report
[23] TOKYO ELECTRIC POWER COMPANY, Specific Event Report, Fax No. 0042 (11 March 2011).
[24] TOKYO ELECTRIC POWER COMPANY, Report from Nuclear Power Plant Management of TEPCO to Minister of Economy, Trade and Industry, Fax No. 1560 (11 March 2011).
[25] NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of The Fukushima Nuclear Accident Independent Investigation Commission, National Diet of Japan, Tokyo (2012).
[26] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
[27] INVESTIGATION COMMITTEE ON THE ACCIDENT AT THE FUKUSHIMA NUCLEAR POWER STATIONS OF TOKYO ELECTRIC POWER COMPANY, Interim Report (2011), http://www.cas.go.jp/jp/seisaku/icanps/eng/interim-report.html
[28] YOSHIDA, M., Testimony of Mr. Yoshida — General Manager of the Fukushima Daiichi Nuclear Power Station (2011) (in Japanese), http://www.cas.go.jp/jp/genpatsujiko/hearing_koukai_3/hearing_list_3.html
[29] Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, Act No. 166, 1957, as last amended by Act No. 84 of 2007 (Japan), http://www.nsr.go.jp/archive/nisa/english/resources/legislativeframework/files/ReactorRegulation.pdf
[30] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: Accident at TEPCO's Fukushima Nuclear Power Stations, Second Rep., Government of Japan (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html
[31] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accident Analysis Report (Interim Report) (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/111202e14.pdf
[32] GOVERNMENT OF JAPAN, Official web site of the Prime Minister of Japan and His Cabinet (2015), http://japan.kantei.go.jp/index.html
[33] NUCLEAR REGULATION AUTHORITY, About NISA (2015), http://www.nsr.go.jp/archive/nisa/english/aboutnisa/contact.html
[34] TOKYO ELECTRIC POWER COMPANY, TEPCO at a Glance (2015), http://www.tepco.co.jp/en/corpinfo/overview/p-glance-e.html
[35] NUCLEAR REGULATION AUTHORITY, About the Nuclear Safety Commission (2015), http://www.nsr.go.jp/archive/nsc/NSCenglish/aboutus/overview/overview.htm
[36] NUCLEAR REGULATION AUTHORITY, About JNES (2015), http://www.nsr.go.jp/archive/jnes/english/shoukai/index.html
[37] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Offical home page of the Ministry of Education, Culture, Sports, Science and Technology (2015), http://www.mext.go.jp/english/

[38] MINISTRY OF HEALTH, LABOUR AND WELFARE, Home page of the Ministry of Health, Labour and Welfare (2015), http://www.mhlw.go.jp/english/
[39] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Ministry of Agriculture, Forestry and Fisheries (2015), http://www.maff.go.jp/e/
[40] MINISTRY OF THE ENVIRONMENT, Home page of the Ministry of Environment, Government of Japan (2015), http://www.env.go.jp/en/
[41] MINISTRY OF DEFENSE, Home page of the Ministry of Defense of Japan (2015), http://www.mod.go.jp/e/index.html
[42] JAPAN METEOROLOGICAL AGENCY, Home page of the Japan Meteorological Agency (2015), http://www.jma.go.jp/jma/indexe.html
[43] JAPAN ATOMIC ENERGY AGENCY, Home page of the Japan Atomic Energy Agency (2015), http://www.jaea.go.jp/english/index.html
[44] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Home page of the National Institute of Radiological Sciences (2015), http://www.nirs.go.jp/ENG/index.shtml
[45] JAPAN NUCLEAR ENERGY SAFETY ORGANIZATION, Initial Operations in the Local Nuclear Emergency Response Headquarters (2013), https://www.nsr.go.jp/archive/jnes/content/000124530.pdf
[46] FUKUSHIMA PREFECTURE, Review of Fukushima Prefecture's Urgent Response to Great East Japan Earthquake (2012) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/41222.pdf
[47] Ordinance on Prevention of Ionizing Radiation Hazards, Ordinance of the Ministry of Labour No. 41 of September 30, 1972, as last amended by Ordinance No. 172 of July 16, 2001 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/S47/S47F04101000041.html
[48] RADIATION COUNCIL, Incorporation of Recommendations of ICRP (Publication 60) into the National Legal Framework (1998) (in Japanese), http://www.nsr.go.jp/archive/mext/b_menu/shingi/housha/sonota/81009.htm
[49] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANISATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996). (This publication is superseded by GSR Part 3 (2014)).
[50] NATIONAL PERSONNEL AUTHORITY, National Personnel Authority Rules 10–5, Prevention of Radiation Injuries in Staff, Tokyo (1963).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Fact Finding Expert Mission Report of the Fukushima Daiichi NPP Accident Following the Great East Japan Earthquake and Tsunami, Tokyo, Fukushima, IAEA, Vienna (2011).
[52] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: Accident at TEPCO's Fukushima Nuclear Power Stations, Second Rep., Government of Japan (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html
[53] MINISTRY OF HEALTH, LABOUR AND WELFARE, Response and Action Taken by the Ministry of Health, Labour and Welfare of Japan on Radiation Protection at Works Relating to TEPCO's Fukushima Daiichi Nuclear Power Plant Accident 2nd edn (FY2014), MHLW, Tokyo (2015).
[54] YASUI, S., Lessons learned: Radiological protection for emergency workers at the TEPCO Fukushima Daiichi APP (Part 2), J. Occup. Environ. Hyg. 10 12 (2013) D163–D171.
[55] YASUI, S., Lessons learned: Radiological protection for emergency workers at the TEPCO Fukushima Daiichi APP (Part 1), J. Occup. Environ. Hyg. 10 11 (2013) 151–158.
[56] NATIONAL POLICE AGENCY, WG3 question 10, 5th submission, official communication (2014).

[57] MINISTRY OF HEALTH, LABOUR AND WELFARE, Response and Action Taken by the MHLW of Japan on Radiation Protection for Workers Involved in the TEPCO Fukushima Daiichi NPP Accident, MHLW, Tokyo (2013).
[58] MINISTRY OF HEALTH, LABOUR AND WELFARE, Cautions Issued for Wearing "Respiratory Protective Equipment" Used By Workers Engaged in Restoration Operations at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111014.html
[59] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress Status of the "Roadmap for Immediate Actions for the Assistance of Residents Affected By the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_assistance_03.pdf
[60] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110617roadmap_assistance_report.pdf
[61] TOKYO ELECTRIC POWER COMPANY, Status of Improvement on Working Environment of Workers in Fukushima Daiichi Nuclear Power Station, Attachment 2: About Cool Vest, Press Release (2011), http://www.tepco.co.jp/en/press/corp-com/release/11061013-e.html
[62] TOKYO ELECTRIC POWER COMPANY, Progress Status of Cooling (Reactors) (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110517e5.pdf
[63] YASUI, S., Lessons learned: Medical and health care management for emergency workers at the TEPCO Fukushima Daiichi APP accident, J. Occup. Environ. Hyg. 11 5 (2014) D49–58.
[64] NATIONAL POLICE AGENCY, WG3 question 11, 5th submission, official communication (2014).
[65] WATANABE, Y., "Relief activities conducted by the Japanese Red Cross Society after the Fukushima Daiichi Nuclear Power Plant Accident and the challenges for the future", IAEA Report on Severe Accident Management in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2015).
[66] GONZÁLEZ, A.J., AKASHI, M., BOICE, J.D., JR., CHINO, M., HOMMA, T., ISHIGURE, N., KAI, M., KUSUMI, S., LEE, J.-K., MENZEL, H.-G., NIWA, O., SAKAI, K., WEISS, W., YAMASHITA, S., YONEKURA, Y., Radiological protection issues arising during and after the Fukushima nuclear reactor accident, J. Radiol. Prot. 33 3 (2013) 497–571.
[67] MINISTRY OF HEALTH, LABOUR AND WELFARE, Enforcement of the Ministerial Ordinance on Exemption of the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011 (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/ri_0315_07.html
[68] YASUI, S., 250 mSv: Temporary increase in the emergency exposure dose limit in response to the TEPCO Fukushima Daiichi NPP accident and its decision making process, J. Occup. Environ. Hyg. (2014).
[69] MINISTRY OF HEALTH, LABOUR AND WELFARE, Consultation with and Recommendation from the Labor Policy Council on "the Outline of the Draft Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011" (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111121.html
[70] TOKYO ELECTRIC POWER COMPANY, WG 3 question 9, 5th submission, official communication (2014).
[71] MINISTRY OF HEALTH, LABOUR AND WELFARE, Re: Guidance about the Radiation Exposure Dose during Later Radiation Works Other than Emergency Works for the Workers Who Had Been Engaged in Emergency Works (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/ri_0428_01.html
[72] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Basic Policy for Emergency Response on Decontamination Work (2011), http://www.kantei.go.jp/jp/singi/genshiryoku/dai19/19_03_gensai.pdf
[73] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Guidelines for Municipal Decontamination Work (2011), http://www.city.kitaibaraki.lg.jp/docs/2015021800063/files/shityouson_zyosen_gaidoline.pdf

[74] MINISTRY OF HEALTH, LABOUR AND WELFARE, Occupational Safety and Health Department Notification (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/ri_0909_01.html
[75] Ordinance on Prevention of Ionizing Radiation Hazards at Work to Decontaminate Soil and Wastes Contaminated by Radioactive Materials Resulting from the Great East Japan Earthquake and Related Works No. 152 of December 22, 2011 (Japan), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_111222_a04.pdf
[76] MINISTRY OF HEALTH, LABOUR AND WELFARE, A Ministerial Ordinance for Preventing Radiation Hazards of Workers Engaged in the Decontamination Works was Published, and its Guidelines were Formulated (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_111222.html
[77] YASUI, S., Establishment of new regulations for radiological protection for decontamination work involving radioactive fallout emitted by the Fukushima Daiichi APP accident, J. Occup. Environ. Hyg. 10 9 (2013) D119–D124.
[78] GOVERNMENT OF JAPAN, WG3 question 5, 6th submission, official communication (2014).
[79] TOMINAGA, T., HACHIYA, M., AKASHI, M., Lessons learned from response to the accident at the TEPCO Fukushima Daiichi nuclear power plant: From the viewpoint of radiation emergency medicine and combined disaster, Radiat. Emerg. Med. 1 1–2 (2012).
[80] TANIGAWA, K., HASEGAWA, A., Medical perspective, Radiat. Disaster Med., Springer, Heidelberg (2014).
[81] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Seismic Damage Information (the 121st Release) (2011), http://www.nsr.go.jp/archive/nisa/english/files/en20110430-3-1.pdf
[82] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Comment no. 10: July review, official communication (2014).
[83] TOMINAGA, T., HACHIYA, M., TATSUZAKI, H., AKASHI, M., The accident at the Fukushima Daiichi nuclear power plant in 2011, Health Phys. 106 6 (2014) 630–637.
[84] LOCAL NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Revised Management Plan for Injured Individuals in Accidents (2011) (in Japanese).
[85] MORIMURA, N., et al., Emergency/disaster medical support in the restoration project for the Fukushima nuclear power plant accident, Emerg. Med. J. 30 12 (2013) 997–1002.
[86] MORI, K., et al., How occupational health can contribute in a disaster and what we should prepare for the future: Lessons learned through support activities of a medical school at the Fukushima Daiichi nuclear power plant in summer 2011, J. Occup. Health 55 1 (2013) 6–10.
[87] MINISTRY OF HEALTH, LABOUR AND WELFARE, A Round-the-clock Health Care System was Established at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/pr_110527.html
[88] TOKYO ELECTRIC POWER COMPANY, Medical Care System at the TEPCO Fukushima Daiichi Nuclear Power Plant will be Improved (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/pr_110630.html
[89] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidance was Provided on Enhanced Measures to Prevent Heat Stroke at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/pr_110610.html
[90] TOKYO ELECTRIC POWER COMPANY, Current Status of Irradiation Dose of the Facility Workers at Fukushima Daiichi Nuclear Power Station (2012) (in Japanese).
[91] MINISTRY OF THE ENVIRONMENT, Josen Joho Plaza: Information on Volunteers' Remediation Activities (2014) (in Japanese), http://josen-plaza.env.go.jp/volunteer/
[92] MINISTRY OF THE ENVIRONMENT, Josen Joho Plaza: Important Notice for Volunteers to Join Remediation Activities (2014) (in Japanese), http://josen-plaza.env.go.jp/volunteer/prior_information.html
[93] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_120615_a03.pdf

[94] MINISTRY OF THE ENVIRONMENT, Josen Joho Plaza: For Volunteers to Join Remediation Activities (March 2012) (2012) (in Japanese), http://josen-plaza.env.go.jp/volunteer/pdf/borantea_0323.pdf
[95] NUCLEAR REGULATORY COMMISSION, Severe Accident Risks: An Assessment for Five US Nuclear Power Plants, Rep. NUREG-1150, Office of Nuclear Regulatory Research, Washington, DC (1990).
[96] NUCLEAR REGULATORY COMMISSION, State-of-the-Art Reactor Consequence Analyses (SOARCA) Report, Rep. NUREG-1935, Office of Nuclear Regulatory Research, Washington, DC (2012).
[97] NUCLEAR REGULATION AUTHORITY, WG3 question 1, 1st submission, official communication (2013).
[98] NUCLEAR REGULATION AUTHORITY, WG3 question 5, 1st submission, official communication (2013).
[99] NUCLEAR REGULATION AUTHORITY, WG3 question 4, 1st submission, official communication (2013).
[100] NUCLEAR REGULATION AUTHORITY, WG3 question 7, 1st submission, official communication (2013).
[101] TANIGAWA, K., HOSOI, Y., HIROHASHI, N., IWASAKI, Y., KAMIYA, K., Loss of life after evacuation: Lessons learned from the Fukushima accident, Lancet 379 9819 (2012) 889–891.
[102] GOVERNMENT OF JAPAN, WG3 question 2, 6th submission, official communication (2014).
[103] TANIGAWA, K., OHJINO, M., Testimony of Doctors — Initial Medical Responses in the Fukushima Daiichi Nuclear Power Plant Accident, Herusu Shuppan, Tokyo (2013) (in Japanese).
[104] KONDO, H., et al., Establishing disaster medical assistance teams in Japan, Prehosp. Disaster Med. 24 6 (2009) 556–564.
[105] KONDO, H., et al., Activities of the Disaster Medical Assistance Team (DMAT) in response to the TEPCO Fukushima nuclear power plant accident, J. Natl. Inst. Public Health 60 6 (2011) 502–509.
[106] ARKHANGEL'SKAYA, G.V., LIKHTAREV, A., IL'IN, L.A., KONSTANINOV, Y.O., Radioactive Iodine in the Problem of Radiation Safety, Atomizdat, Moscow (1972) (in Russian).
[107] INTERNATIONAL ATOMIC ENERGY AGENCY, Actions to Protect the Public in an Emergency due to Severe Conditions at a Light Water Reactor, EPR–NPP (2013), IAEA, Vienna (2013).
[108] MINISTRY OF HEALTH, LABOUR AND WELFARE, WG3 question 21, 5th submission, official communication (2014).
[109] VANO, E., OHNO, K., COUSINS, C., NIWA, O., BOICE, J., Radiation Risks and Radiation Protection Training for Healthcare Professionals: ICRP and the Fukushima Experience, J. Radiol. Prot. 31 3 (2011) 285–287.
[110] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, Evaluation of Skin and Ingestion Exposure Pathways, Washington, DC (1989).
[111] INTERNATIONAL ADVISORY COMMITTEE, The International Chernobyl Project: Technical Report, IAEA, Vienna (1991).
[112] INTERNATIONAL ATOMIC ENERGY AGENCY, Method for Developing Arrangements for Response to a Nuclear or Radiological Emergency, EPR–METHOD (2003), IAEA, Vienna (2003).
[113] GOVERNMENT OF JAPAN, WG3 question 6, 2nd submission, official communication (2013).
[114] NUCLEAR SAFETY COMMISSION, Provisions for a Deliberate Evacuation Area and an Evacuation-prepared Area (2011), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110410advise_1.pdf
[115] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Pergamon Press, Oxford and New York (2007).
[116] GOVERNMENT OF JAPAN, WG3 question 1, 6th submission, official communication (2014).
[117] NUCLEAR SAFETY COMMISSION OF JAPAN, Accident Management: Measures against Severe Accidents at Light Water Nuclear Power Reactor Facilities (1992) (in Japanese), http://www.mext.go.jp/b_menu/hakusho/nc/t19920528001/t19920528001.html
[118] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Food Contaminated by Radioactivity (2011), http://www.mhlw.go.jp/english/topics/foodsafety/dl/food-110317.pdf

[119] NUCLEAR REGULATION AUTHORITY, Readings of Environmental Monitoring Samples (Weed) as of 7 June 2011 (2011) (in Japanese), http://radioactivity.nsr.go.jp/en/contents/4000/3563/24/1307583_0622.pdf.
[120] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of Provisional Regulation Values for Radioactive Iodine in Fishery Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110405.pdf
[121] MINISTRY OF HEALTH, LABOUR AND WELFARE, Issuance of Instruction to Restrict Distribution of Foods Concerned, in Relation to the Accident at Fukushima Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110321.pdf
[122] MINISTRY OF HEALTH, LABOUR AND WELFARE, Restriction of Distribution and/or Consumption of Foods Concerned in Fukushima and Ibaraki Prefectures (2011), http://www.mhlw.go.jp/stf/houdou/2r98520000015wun-att/2r98520000015xym.pdf
[123] MINISTRY OF HEALTH, LABOUR AND WELFARE, Monitoring of Radioactive Contaminants for Agricultural and Livestock Products (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110323.pdf
[124] MINISTRY OF HEALTH, LABOUR AND WELFARE, Levels of Radioactive Contaminants in Foods Tested in Respective Prefectures (2014), http://www.mhlw.go.jp/english/topics/2011eq/index_food_radioactive.html
[125] MINISTRY OF HEALTH, LABOUR AND WELFARE, Measures Taken to Deal with the Presence of Radioactive Contaminants in Seawater in the Coast Near the Fukushima Daiichi Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110322.pdf
[126] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Revision of the "Concepts of Inspection Planning and the Establishment and Cancellation of Items and Areas to which Restriction of Distribution and/or Consumption of Foods Concerned Applies" (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-110804.pdf
[127] MINISTRY OF HEALTH, LABOUR AND WELFARE, New Standard Limits for Radionuclides in Foods (2012), http://www.mhlw.go.jp/english/topics/2011eq/dl/new_standard.pdf
[128] MINISTRY OF HEALTH, LABOUR AND WELFARE, Detection of Radioactive Materials in Tap Water in Fukushima Prefecture (March 22) (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/march_22_01.pdf
[129] MINISTRY OF HEALTH, LABOUR AND WELFARE, Information on Radioactive Materials Detected in Tap Water in Fukushima Prefecture (Including Iitate-mura Village) (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/march_21_02.pdf
[130] MINISTRY OF HEALTH, LABOUR AND WELFARE, Detection of Radioactive Materials in Tap Water in Fukushima Prefecture (Iitate-mura Village) (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/march_21_01.pdf
[131] MINISTRY OF HEALTH, LABOUR AND WELFARE, Detection of Radioactive Materials in Tap Water in Fukushima Prefecture and Tokyo (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/march_23_01.pdf
[132] MINISTRY OF HEALTH, LABOUR AND WELFARE, Detection of Radioactive Materials in Tap Water (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/march_23_02.pdf
[133] MINISTRY OF HEALTH, LABOUR AND WELFARE, Handling of the Index Levels on Radioactive Materials in Tap Water, etc. (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/april_8_01.pdf
[134] HAMADA, N., OGINO, H., FUJIMICHI, Y., Safety regulations of food and water implemented in the first year following the Fukushima nuclear accident, J. Radiat. Res. 53 5 (2012) 641–671.
[135] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, FY2011 Annual Report on Food, Agriculture and Rural Areas in Japan (2012), http://www.maff.go.jp/j/wpaper/w_maff/h23/pdf/e_all.pdf
[136] MINISTRY OF HEALTH, LABOUR AND WELFARE, Restriction of Distribution of Foods based on the Act on Special Measures Concerning Nuclear Emergency Preparedness (2011), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-111129.pdf

[137] HASKIN, F.E., CAMP, A.L., HODGE, S.A., POWERS, D.A., US Nuclear Regulatory Commission, Perspectives on Reactor Safety, Rep. NUREG/CR-6042, SAND93-0971, Revision 2, Washington, DC (2002).
[138] HOMMA, T., TAKAHARA, S., KIMURA, M., KINASE, S., Radiation Protection Issues on Preparedness and Response for a Severe Nuclear Accident: Experiences of the Fukushima Accident, International Commission on Radiological Protection (2014).
[139] LINDELL, M.K., An overview of protective action decision-making for a nuclear power plant emergency, J. Hazard. Mater. 75 2-3 (2000) 113–129.
[140] URBANIK T., II, Evacuation time estimates for nuclear power plants, J. Hazard. Mater. 75 2–3 (2000) 165–180.
[141] NUCLEAR SAFETY COMMISSION OF JAPAN, Guidelines for Environmental Radiation Monitoring (2008), http://www.nsr.go.jp/archive/nsc/NSCenglish/guides/thematic/T-EN-II_02.pdf
[142] FUKUSHIMA PREFECTURE, TOKYO ELECTRIC POWER COMPANY, Report of the Results of Environmental Monitoring around the Nuclear Power Plant 2011 (2013) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/42294.pdf
[143] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Regarding the Results of Emergency Monitoring (March 11–15 Samples) in the Vicinity of Fukushima Dai-ichi and Dai-ni Nuclear Power Stations (2011), https://www.nsr.go.jp/archive/nisa/english/press/2011/06/en20110615-4.pdf
[144] UNITED STATES DEPARTMENT OF ENERGY, Radiological Assessment (17–19 March 2011) (2011), http://energy.gov/sites/prod/files/amsdatamarch25udpated1-110325170504-phpapp02.pptx
[145] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Plan to Conduct Detailed Monitoring in Restricted Area and Planned Evacuation Zone (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0613.pdf
[146] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Enhanced Local Monitoring Program in the Area Farther than 20 km around Fukushima Dai-ichi NPP (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/03/23/1304084_1.pdf
[147] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Airborne Monitoring Action Plan (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0325.pdf
[148] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Enforced Plan on Environmental Monitoring (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0422.pdf
[149] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Strengthening of Monitoring in Response to the "Enforced Plan on Environmental Monitoring" (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0511.pdf
[150] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, UNITED STATES DEPARTMENT OF ENERGY, Results of Airborne Monitoring by the Ministry of Education, Culture, Sports, Science and Technology and the US Department of Energy (2011), http://radioactivity.nsr.go.jp/en/contents/4000/3180/24/1304797_0506.pdf
[151] UNITED STATES DEPARTMENT OF ENERGY, Radiological Assessment (17 March–29 April 2011) (2011), http://pbadupws.nrc.gov/docs/ML1209/ML120970264.pdf
[152] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Strengthening of Monitoring of Environmental Radioactivity Levels by Prefecture (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0608.pdf
[153] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Amendment of Preparation of Distribution Map of Radiation Doses, etc. (Air Dose Rate Map) by MEXT: Released on August 2 (2011), http://radioactivity.nsr.go.jp/en/contents/5000/4163/24/1750_081218.pdf
[154] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Preparation of Distribution Map of Radiation Doses: Map of Radioactive Cesium Concentration in Soil (2011), http://radioactivity.nsr.go.jp/en/contents/5000/4165/24/1750_083014.pdf

[155] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Commencement of Air Dose Rate Monitoring and Soil Survey for Creating Maps of Distributions of Radiation Doses, etc. (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/08/1305904_0603.pdf
[156] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Methods for Environmental Monitoring (2011) (in Japanese).
[157] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Sea Area Monitoring Action Plan (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/03/23/1304084_2_1.pdf
[158] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Enhancement of Sea Area Monitoring (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0405_2.pdf
[159] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY Strengthening of Sea Area Monitoring in Response to the "Enforced Plan on Environmental Monitoring" (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0425.pdf
[160] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Sea Area Monitoring in Wider Areas (2011), http://www.mext.go.jp/component/english/__icsFiles/afieldfile/2011/06/29/1304084_0506.pdf
[161] GOVERNMENT OF JAPAN, WG3 question 16, 5th submission, official communication (2014).
[162] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Issues in Public Communications Activities and Future Efforts Related to the Accident at the TEPCO's Fukushima Dai-ichi Nuclear Power Station, NISA, Tokyo (2012).
[163] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Telephone Consultations on Radiation Exposure: Report on Tabulated Results from the Year Following the TEPCO Fukushima Daiichi Nuclear Disaster (2014), http://www.nirs.go.jp/publication/irregular/pdf/nirs_m_265en.pdf
[164] FUKUSHIMA PREFECTURE, Consulting Service for Various Issues Related to East Japan Great Earthquake (2014), http://www.pref.fukushima.lg.jp/sec/01010d/shinsai-sodanmadoguchi.html#02
[165] JAPAN ATOMIC ENERGY AGENCY, Actions in Response to TEPCO Fukushima Daiichi Accident (2014) (in Japanese), http://www.jaea.go.jp/04/shien/fukushima_j.html
[166] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, FAQ about Radiation Exposure (revised) (2013) (in Japanese), http://www.nirs.go.jp/information/qa/qa.php
[167] GONZÁLEZ, A. J., The recommendations of the ICRP vis-a-vis the Fukushima Dai-ichi NPP accident aftermath, J. Radiol. Prot. 32 1 (2012) N1-7.
[168] KINUYA, S., A nuclear power plant accident in Fukushima: What should we do?, Ann. Nucl. Med. Annals Nucl. Med. 26 2 (2012) 113–114.
[169] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Radiation in Daily-life (2011), http://www.meti.go.jp/english/electricity_supply/pdf/20110319_radiation.pdf
[170] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP ref 4832-8604-9553 (2012), http://www.icrp.org/docs/ICRP%20TG84%20Summary%20Report.pdf
[171] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCER 2013 Report, Volume I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).
[172] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/111216_assistance_02.pdf
[173] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110920_assistance_02.pdf

[174] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/111017_assistance_02.pdf
[175] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110817_assistance_02.pdf
[176] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Progress of the "Roadmap for Immediate Actions for the Assistance of Residents Affected by the Nuclear Incident" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/111117_assistance_02.pdf
[177] JAPAN EXTERNAL TRADE ORGANISATION, Great East Japan Earthquake Influence on International Business (2014) (in Japanese), www.jetro.go.jp/world/shinsai/20110318_11.html
[178] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, METI Measures and Requests in Response to the Great East Japan Earthquake: Business Support (2014), http://www.meti.go.jp/english/earthquake/business/
[179] JAPAN EXTERNAL TRADE ORGANISATION, Impact of East Japan Great Earthquake on the International Business Activities (2014) (in Japanese), http://www.jetro.go.jp/world/shinsai/
[180] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Results of Sampling Survey on Radioactivity Levels in Textile Products — Domestic and International Comparisons (2011) (in Japanese), http://warp.da.ndl.go.jp/info:ndljp/pid/8946648/www.meti.go.jp/press/2011/06/20110606002/20110606002.pdf
[181] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Radiation Inspections Performed by Foreign Countries/Regions (for Industrial Products) (2013), http://www.meti.go.jp/english/earthquake/business/pdf/20131030_inspection.pdf
[182] ROMANOWICH, I. K., BALONOV, M. I., BARKOWSKY, A. N., NIKITIN, A. I., Accident at the Fukushima-1 NPP: Organization of Preventive Measures to Protect the Health of the Russian Federation Population, Academician RAMN G.G. Onishenko, St. Petersburg (2012) (in Russian).
[183] UNITED STATES FOOD AND DRUG ADMINISTRATION, FDA Response to the Fukushima Dai-ichi Nuclear Power Facility Incident (2014), http://www.fda.gov/NewsEvents/PublicHealthFocus/ucm247403.htm
[184] GOVERNMENT OF JAPAN, National Report of Japan to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (2011), http://www.nsr.go.jp/english/cooperation/conventions/data/jc_4th.pdf
[185] MINISTRY OF THE ENVIRONMENT, Progress on Off-site Cleanup and Interim Storage in Japan (2015), http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf?150601
[186] NUCLEAR SAFETY COMMISSION, Near-term Policy to Ensure the Safety in Treating and Disposing Contaminated Waste around the Site of Fukushima Dai-ichi Nuclear Power Plants, NSC, Tokyo (2011).
[187] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Actions such as Shipment Restraint Due to the Accident (as of April 26) (2011), http://www.maff.go.jp/e/quake/press_110426-3.html
[188] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, The Approach to Immediate Handling of Secondary Byproducts of Water and Sewage Treatment in which Radioactive Materials Were Detected (2011), http://www.nsr.go.jp/archive/nisa/english/press/2011/09/en20110909-2-2.pdf
[189] Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011, Act No. 110 as of 2011 (Japan), http://josen.env.go.jp/en/framework/pdf/special_act.pdf?20130118
[190] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110517roadmap_assistance.pdf

[191] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations, Publication 109, Pergamon Press, Oxford and New York (2009).
[192] NUCLEAR SAFETY COMMISSION OF JAPAN, Basic Policy of the Nuclear Safety Commission of Japan on Radiation Protection for Termination of Evacuation and Reconstruction (2011), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110719suggest_4.pdf
[193] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Lifting the Evacuation-Prepared Area in Case of Emergency Designation (2011), http://www.reconstruction.go.jp/topics/41gennshiryoku.pdf
[194] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (2011), http://www.meti.go.jp/english/speeches/pdf/20110417_a.pdf
[195] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Roadmap for Immediate Action for the Assistance of Residents Affected by the Nuclear Incident (as of July 19) (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_assistance_02.pdf
[196] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Assistance of Residents Affected by the Nuclear Incidents (2014), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/
[197] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Points of Progress Status of "Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station, TEPCO" (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/110719_nps_02.pdf
[198] MINISTRY OF HEALTH, LABOUR AND WELFARE, Publication and Enforcement of "The Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku — Pacific Ocean Earthquake in 2011" (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111216.html
[199] MINISTRY OF HEALTH, LABOUR AND WELFARE, A Ministerial Ordinance for Preventing Radiation Hazards of Workers Engaged in the Disposal of Accident-derived Waste, etc. Was Published, and Its Guidelines Were Formulated (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/wd/pr_130412.html
[200] YASUI, S., New regulations for radiation protection for work involving radioactive fallout emitted by the TEPCO Fukushima Daiichi APP accident: Disposal of contaminated soil and wastes, J. Occup. Environ. Hyg. 11 10 (2014) D147–D156.
[201] MINISTRY OF HEALTH, LABOUR AND WELFARE, Measures to Prevent Radiation Hazards will be Required for Rehabilitation and Reconstruction Works other than Decontamination Works (2012), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_120615.html
[202] YASUI, S., New regulations for radiation protection for work involving radioactive fallout emitted by the TEPCO Fukushima Daiichi APP Accident: Application expansion to recovery and reconstruction work, J. Occup. Environ. Hyg. 11 8 (2014) D105–114.
[203] NUCLEAR SAFETY COMMISSION, Standpoint of the Nuclear Safety Commission for the Termination of Urgent Protective Actions implemented for the Accident at Fukushima Dai-ichi Nuclear Power Plant, NSC, Tokyo (2011).
[204] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Areas to Which Evacuation Orders have been Issued (2013), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20130807_01.pdf
[205] ATOMIC ENERGY SOCIETY JAPAN, The Fukushima Daiichi Nuclear Accident: Final Report of the AESJ Investigation Committee (Announcement) (2014), http://www.aesj.or.jp/en/announcement/finalreport20141119.pdf
[206] REBUILD JAPAN INITIATIVE FOUNDATION, The Independent Investigation Commission on the Fukushima Nuclear Accident (2014), http://rebuildjpn.org/en/project/fukushima/
[207] NUCLEAR SAFETY COMMISSION, The Basic Policies for the Near-term Initiatives of the Nuclear Safety Commission (2010), http://www.nsr.go.jp/archive/nsc/NSCenglish/pdf/101202.pdf

[208] NUCLEAR SAFETY COMMISSION, Interim Report for Reviewing "Regulatory Guide: Emergency Preparedness for Nuclear Facilities" (2012) (in Japanese), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20120322review_3.pdf
[209] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Technical Knowledge of the Accident at Fukushima Dai-ichi Nuclear Power Station of Tokyo Electric Power Co., Inc. (2012), http://www.nsr.go.jp/archive/nisa/english/press/2012/06/en20120615-1-1.pdf
[210] NUCLEAR EMERGENCY PREPAREDNESS COMMISSION, Nuclear Emergency Response Manual (2012) (in Japanese), http://www.kantei.go.jp/jp/singi/genshiryoku_bousai/pdf/taisaku_manual.pdf
[211] NUCLEAR REGULATION AUTHORITY, Nuclear Emergency Response Guidelines (2012) (in Japanese), http://www.nsr.go.jp/data/000024451.pdf
[212] NUCLEAR REGULATION AUTHORITY, National Report to the 6th Review Meeting of the Convention on Nuclear Safety (2013), http://www.nsr.go.jp/data/000067034.pdf
[213] NUCLEAR REGULATION AUTHORITY, FY2013: Annual Report (2014), https://www.nsr.go.jp/data/000067054.pdf
[214] NUCLEAR REGULATION AUTHORITY, The Trial Calculation Result of Simulation on the Spread of Radioactive Materials (2012) (in Japanese), https://www.nsr.go.jp/data/000024430.pdf
[215] NUCLEAR REGULATION AUTHORITY, The Trial Calculation Result of Simulation on the Spread of Radioactive Materials (Comprehensive Review Version) (2012) (in Japanese), https://www.nsr.go.jp/data/000024448.pdf
[216] GOVERNMENT OF JAPAN, Council, C. D. M., The Basic Disaster Mangement Plan (revised), Tokyo (2014) (in Japanese).
[217] GOVERNMENT OF JAPAN, WG3 question 6, 6th submission, official communication (2014).
[218] INTERNATIONAL ATOMIC ENERGY AGENCY, Governmental, Legal and Regulatory Framework for Safety, IAEA Safety Standard Series No. GSR Part 1, IAEA, Vienna (2010).
[219] Convention on Early Notification of a Nuclear Accident, INFCIRC/335, IAEA, Vienna (1986).
[220] Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, INFCIRC/336, IAEA, Vienna (1986).
[221] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Assessment Procedures for Determining Protective Actions during a Reactor Accident, IAEA-TECDOC-955, IAEA, Vienna (1997).
[222] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, Generic Procedures for Medical Response During a Nuclear or Radiological Emergency, EPR–MEDICAL (2005), IAEA, Vienna (2005).
[223] INTERNATIONAL ATOMIC ENERGY AGENCY, Emergency Notification and Assistance Technical Operations Manual, EPR–ENATOM (2007), IAEA, Vienna (2007).
[224] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Response and Assistance Network (2010), http://www-ns.iaea.org/downloads/iec/info-brochures/13-27031-ranet.pdf
[225] INTERNATIONAL ATOMIC ENERGY AGENCY, Joint Radiation Emergency Management Plan of the International Organizations, EPR–JPLAN (2010), IAEA, Vienna (2010).
[226] COMPREHENSIVE NUCLEAR-TEST-BAN TREATY ORGANIZATION, EURO-ATLANTIC DISASTER RESPONSE COORDINATION CENTRE, EUROPEAN COMMISSION, EUROPEAN POLICE OFFICE, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL CIVIL AVIATION ORGANIZATION, INTERPOL, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, UNITED NATIONS OFFICE FOR THE CO-ORDINATION OF HUMANITARIAN AFFAIRS, UNITED NATIONS OFFICE FOR OUTER SPACE AFFAIRS, WORLD HEALTH ORGANIZATION, WORK METEOROLOGICAL ORGANIZATION, Joint Radiation Emergency Management Plan of the International Organizations, EPR–JPLAN (2013), IAEA, Vienna (2013).
[227] Convention on Nuclear Safety, INFCIRC/449, IAEA, Vienna (1994).

[228] Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, INFCIRC/546, IAEA, Vienna (1997).
[229] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Procedures for Monitoring in a Nuclear or Radiological Emergency, TECDOC-1092, IAEA, Vienna (1999).
[230] INTERNATIONAL ATOMIC ENERGY AGENCY, Operations Manual for Incident and Emergency Communication, EPR–IEComm (2012), IAEA, Vienna (2012).
[231] INTERNATIONAL ATOMIC ENERGY AGENCY, Response Plan for Incidents and Emergencies, Vienna, unpublished data.
[232] IAEA Activities in Response to the Fukushima Accident, GOV/INF/2011/8, IAEA, Vienna (2011).
[233] Measures to Strengthen International Cooperation in Nuclear, Radiation, Transport and Waste Safety, Resolution GC(57)/RES/9, IAEA, Vienna (2013).
[234] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Action Plan on Nuclear Safety (2011), http://www.iaea.org/sites/default/files/actionplanns.pdf
[235] OECD NUCLEAR ENERGY AGENCY, Patterns in Governmental Decisions and Recommendations (GDR) Information Exchange During the Fukushima NPP Accident, NEA/CRPPH(2012)3, OECD, Paris (2012).
[236] INTERNATIONAL CIVIL AVIATION ORGANIZATION, Technical Instructions for the Safe Transportof Dangerous Goods by Air, Doc 9284-AN/905, 2011-2012 Edition, Addendum No. 2 (2012), http://www.icao.int/publications/Documents/9284_2011_2012_add_02_en.pdf
[237] Report to the 22nd Meeting of the Regular Meeting of the Inter-agency Committee on Radiological and Nuclear Emergencies, Paris (2011).
[238] COOMBS, W. T., Ongoing crisis communication: Planning, managing, and responding, 2nd edn, Sage Publications, Thousand Oaks, CA (2007).
[239] ALEXA.COM, Analytics Website (2011), http://www.alexa.com/siteinfo/iaea.org
[240] UNITED STATES DEPARTMENT OF HEALTH AND HUMAN SERVICES, CENTERS FOR DISEASE CONTROL AND PREVENTION, Crisis and Emergency Risk Communication by Leaders for Leaders (2011), http://emergency.cdc.gov/erc/leaders.pdf
[241] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Ministerial Conference on Nuclear Safety Conference Documentation (2011), http://www-pub.iaea.org/MTCD/Meetings/cn200_documentation.asp
[242] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Ministerial Conference on Nuclear Safety: 20–24 June 2011 (2011), http://www.iaea.org/conferences/ministerial-safety/
[243] Declaration by the IAEA Ministerial Conference on Nuclear Safety in Vienna on 20 June 2011, INFCIRC/821, IAEA, Vienna (2011).
[244] INTERNATIONAL NUCLEAR SAFETY ADVISORY GROUP, Response to Request for INSAG Recommendations to Guide Future Actions Related to the Fukushima Accident, INSAG Letter (2011), http://www-ns.iaea.org/committees/files/insag/743/INSAGLetterReport20117-26-11.pdf
[245] HEADS OF THE EUROPEAN RADIOLOGICAL PROTECTION COMPETENT AUTHORITIES, Emergency Preparedness: Practical Proposals for Further Harmonisation of the Reactions in European Countries to Any Distant Nuclear or Radiological Emergency (2013), http://www.herca.org/documents/HERCA-WGE%20distant%20accidents%20recommendations%20report.pdf
[246] EUROPEAN COMMISSION, Radiation Protection (2015), http://ec.europa.eu/energy/en/topics/nuclear-energy/radiation-protection
[247] INTERNATIONAL ATOMIC ENERGY AGENCY, Summary Report of the Preliminary Findings of the IAEA Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Daiichi NPP (2011), https://www.iaea.org/sites/default/files/preliminaryfindings2011.pdf
[248] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas After a Nuclear Accident or a Radiation Emergency, Publication 111, Pergamon Press, Oxford and New York (2009).

[249] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2000 Report, Vol. II, Scientific Annex J: Exposures and Effects of the Chernobyl Accident, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2001).
[250] UNITED NATIONS, Report of United Nations Scientific Committee on the Effects of Atomic Radiation, A/66/46, UN, New York (2011).
[251] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Vol. II, Scientific Annex B: Effects of Radiation Exposure of Children, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).
[252] WORLD HEALTH ORGANIZATION, Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation, WHO, Geneva (2013).
[253] WORLD METEOROLOGICAL ORGANIZATION, Evaluation of Meteorological Analyses for the Radionuclide Dispersion and Deposition from the Fukushima Daaichi Nuclear Power Plant Accident, WMO, Geneva (2013).
[254] GOVERNMENT OF JAPAN, WG3 question 3, 3rd submission, official communication (2014).
[255] UNITED STATES DEPARTMENT OF ENERGY, National Nuclear Security Administration, Office of Emergency Operations, Internal After Action Report for the 2011 Fukushima Daiichi Nuclear Power Plant Accident in Japan, unpublished data.
[256] EUROPEAN COMMISSION, Humaniatrian Aid and Civil Protection: Japan, Factsheet (2012), http://ec.europa.eu/echo/files/aid/countries/factsheets/japan_en.pdf
[257] EUROPEAN COMMISSION, The European Union's Response to the Earthquake and nuclear plant situation in Japan (2011), http://europa.eu/rapid/press-release_MEMO-11-177_en.htm?locale=en
[258] EUROPEAN COMMISSION, Emergency Response Coordination Centre: ECHO Factsheet (2014).
[259] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, UNITED STATES DEPARTMENT OF ENERGY, Foreign Countries' Response To East Japan Great Earthquake in the Science and Technology Field (2011), http://www.mext.go.jp/b_menu/shingi/gijyutu/gijyutu9-3/shiryo/attach/1307054.htm
[260] NUCLEAR ENERGY INSTITUTE, US Experts Help and Learn at Fukushima (2012), http://safetyfirst.nei.org/industry-actions/u-s-experts-help-and-learn-at-fukushima/#
[261] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Preparedness and Response for a Nuclear or Radiological Emergency in the Light of the Accident at the Fukushima Daiichi Nuclear Power Plant, IAEA, Vienna (2013).
[262] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Response and Assistance Network, EPR-RANET (2013), IAEA, Vienna (2013).
[263] TOKYO ELECTRIC POWER COMPANY, Nuclear Operator Emergency Response Manual (2011) (in Japanese).
[264] NUCLEAR SAFETY COMMISSION, Medical Guidelines for Radiation Emergencies, First Edition 2001, NSCRG: T-EP-II.05 (2008), http://www.nsr.go.jp/archive/nsc/NSCenglish/guides/thematic/T-EP-II_05.pdf
[265] NUCLEAR SAFETY COMMISSION, Requirements and Status of the Radiation Emergency Medical System (2001) (In Japanese).
[266] THE NUCLEAR SAFETY RESEARCH ASSOCIATION, Radiation Emergency Medicine Training Homepage — Regional Information (2014) (in Japanese), https://www.remnet.jp/pref/index.html
[267] HIROSHIMA UNIVERSITY RADIATION MEDICINE PROMOTING CENTRE, 2009 Study on the Local Tertiary Radiation Emergency Medical System (2010) (in Japanese), http://wjrempan.rerf.jp/report/report-H21.pdf
[268] MINISTRY OF INTERNAL AFFAIRS AND COMMUNICATIONS, Overview of the Status of Improvement of Nuclear Disaster Prevention in Accord with the Recommendations based on the Administrative Evaluation and Inspection Results (2010) (in Japanese), http://www.soumu.go.jp/main_content/000079271.pdf
[269] MINISTRY OF HEALTH, LABOUR AND WELFARE, Emergency Medical Information System (2014), http://www.wds.emis.go.jp/

[270] TANIGAWA, K., et al., Lessons learned from the Fukushima Daiichi nuclear power plant accident: The initial 5 days medical activities after the accident, Nihon Kyukyu Igakukai Zasshi 22 9 (2011) 782–791.
[271] TANIGAWA, K., Initial medical management for radiological accidents and disasters, J. Japanese Assoc. Acute Med. 20 2 (2009) 45–59 (in Japanese).
[272] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, METI Emergency Action Plan, Tokyo (2010) (in Japanese), http://www.meti.go.jp/policy/general_policy/20100412bousaigyoumukeikaku.pdf
[273] NUCLEAR SAFETY COMMISSION, 58th Nuclear Safety Commission: Records (2008) (in Japanese), http://www.nsr.go.jp/archive/nsc/anzen/soki/soki2008/genan_so58.pdf
[274] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Minutes of 16th Meeting of Nuclear Emergency Preparedness Sub-Committee at the Nuclear Industrial Safety Subcommittee of the Advisory Committee for Natural Resources and Energy (2009) (in Japanese), http://www.meti.go.jp/committee/summary/0004125/gijiroku16.pdf
[275] CABINET SECRETARIAT OF JAPAN, MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, MINISTRY OF ECONOMY TRADE AND INDUSTRY, Implementation Guidelines for the Nuclear Disaster Drill in FY2008 (2010), http://www.meti.go.jp/committee/materials2/downloadfiles/g81006b02j.pdf

CONTENTS OF CD-ROM

The following annexes to Technical Volume 3 are included on the attached CD-ROM:

Annex I: Provisional English translation by the IAEA of notification faxes sent by the Fukushima Daiichi NPP Site Superintendent to off-site officials on 11 March 2011

Annex II: ICRP message issued 21 March 2011

ABBREVIATIONS

ACI	Airport Council International
ALMERA	Analytical Laboratories for Measurement of Environmental Radioactivity
ATM	atmospheric transport modelling
BWR	boiling water reactor
ConvEx	Convention Exercises
CRPPH	Committee on Radiation Protection and Public Health
CTBTO	Comprehensive Nuclear Test-Ban Treaty Organization
DMAT	Disaster Medical Assistance Team
DOE	United States Department of Energy
DVI	disaster victim identification
EADRCC	Euro-Atlantic Disaster Response Coordination Centre
EO	evacuation order
EAL	emergency action level
EAP	Emergency Action Plan
EC	European Commission
ECCS	emergency core cooling system
ECURIE	European Community Urgent Radiological Information Exchange
EDG	emergency diesel generator
EGRPF	Expert Group on the Radiological Protection Aspects of the Fukushima Accident
ENAC	Emergency Notification and Assistance Conventions
ENATOM	Emergency Notification and Assistance Technical Operations Manual
ENSREG	European Nuclear Safety Regulators Group
EOC	emergency operation centre
EPD	electronic personal dosimeter
EPR	emergency preparedness and response
EPRI	Electric Power Research Institute
EPR-IEComm	Operations Manual for Incident and Emergency Communication
EPZ	emergency planning zone
ERC	Emergency Response Centre
ERF	event rating form
ERM	Emergency Response Manager
ERO	Emergency Response Organization
ERSS	emergency response support system
EURDEP	European Radiological Data Exchange Platform
EUROPOL	European Police Office
FACT	Fukushima Accident Coordination Team
FAO	Food and Agriculture Organization of the United Nations
FDA	US Food and Drug Administration
FMD	Fukushima Monitoring Database
FMU	Fukushima Medical University Hospital
FNST	Fukushima Nuclear Safety Team
FRCT	Fukushima Radiological Consequences Team
FSAT	Food Safety Assessment Team
GM	Geiger-Mueller
HERCA	Heads of the European Radiological Protection Competent Authorities
HPGe	High Purity Germanium
HRA	Health Risk Assessment
IACRNE	Inter-Agency Committee on Radiological and Nuclear Emergencies
ICAO	International Civil Aviation Organization
ICRP	International Commission on Radiological Protection
IEC	Incident and Emergency Centre
IES	Incident and Emergency System

IHR	International Health Regulations
ILO	International Labour Organization
IMO	International Maritime Organization
IMS	International Monitoring System
INES	International Nuclear and Radiological Event Scale
INFOSAN	International Food Safety Authorities Network
INPO	Institute of Nuclear Power Operations
INSAG	International Nuclear Safety Group
Interpol CBRNE	Interpol Chemical, Biological, Radiological, Nuclear and Explosives
ISSC	International Seismic Safety Centre
ITB	iodine thyroid blocking
JAEA	Japan Atomic Energy Agency
JAPC	Japan Atomic Power Company
JCNER	Joint Council for Nuclear Emergency Response
JCO	Japan Nuclear Fuel Conversion Co.
JEU	UNEP-OCHA Joint Environment Unit
JMA	Japan Meteorological Agency
JNES	Japan Nuclear Energy Safety Organization
JPLAN	Joint Radiation Emergency Plan of the International Organizations
JRCS	Japanese Red Cross Society
JST	Japan Standard Time
KAERI	Korea Atomic Energy Research Institute
KINS	Korea Institute of Nuclear Safety
MAFF	Ministry of Agriculture, Forestry and Fisheries
METI	Ministry of Economy, Trade and Industry
METI/NISA	Ministry of Economy, Trade and Industry/Nuclear and Industrial Safety Agency
METI/NISA-ERC	METI/NISA Emergency Response Centre
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MHLW	Ministry of Health, Labour and Welfare
MLIT	Ministry of Land, Infrastructure and Transport
MOD (SDF)	Ministry of Defense (Self-Defense Force)
MOE	Minister of the Environment
mSv	millisievert
NAIIC	National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission
NARAC	National Atmospheric Release Advisory Centre
NAVAREA	navigational area
NCA (A)	National Competent Authority (Abroad)
NCA (D)	National Competent Authority (Domestic)
NCB	National Central Bureau
NEAT	Nuclear Emergency Assistance and Training Centre
NERHQ	Nuclear Emergency Response Headquarters
NEWS	Nuclear Events Web-Based System
NFP	national focal point
NHK	Nippon Hoso Kyokai
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NPP-ERC	Fukushima Daiichi Emergency Response Centre at the NPP
NRA	Nuclear Regulation Authority
NSC	Nuclear Safety Commission
NTT	Nippon Telegraph and Telephone
NWP	National Warning Point
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OECD/NEA	OECD Nuclear Energy Agency

OFC	Off-site Centre
OIL	operational intervention level
OP	Onahama Port
PAHO	Pan American Health Organization
PAZ	precautionary action zone
PCDMB	UNEP Post Conflict and Disaster Management Branch
RANET	Response and Assistance Network
REMAT	Radiation Emergency Medical Assistance Team
RSMC	Regional Specialized Meteorological Centres
SDF	Self-Defense Force
SPEEDI	System for Prediction of Environmental Emergency Dose Information
TAF	top of active fuel
TEPCO	Tokyo Electric Power Company
TEPCO HQ-ERC	Emergency Response Centre at TEPCO Headquarters
UNOOSA	United Nations Office for Outer Space Affairs
UNDAC	United Nations Disaster Assessment and Coordination
UNEP	United Nations Environment Programme
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UNWTO	United Nations World Tourism Organization
UPZ	urgent protective action planning zone
USAR	urban search and rescue
USIE	United System for Information Exchange in Incidents and Emergencies
UTC	Universal Time Coordinated
WANO	World Association of Nuclear Operators
WBC	whole-body counters
WHO	World Health Organization
WMO	World Meteorological Organization
WPRO	Western-Pacific Regional Office
WTO	World Trade Organization
ZAMG	National Meteorological Service of Austria

CONTRIBUTORS TO DRAFTING AND REVIEW

WORKING GROUP 3 (WG3): EMERGENCY PREPAREDNESS AND RESPONSE

Co-Chairs

Drábová, D.
State Office for Nuclear Safety
Czech Republic

Buglova, E.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Shiraga, K.
Department of Nuclear Safety and Security
IAEA

Members

Aaltonen, H.
Radiation and Nuclear Safety Authority
Finland

Ahier, B.
Radiation Protection Bureau
Canada

Bardelay, J.
Institute for Radiological Protection and Nuclear Safety
France

Blackburn, C.
FAO

Byron, D. †
FAO

Chen, P. (until June 2014)
World Meteorological Organization

Chugunov, V.
State Atomic Energy Corporation 'Rosatom'
Russian Federation

Cortes Carmona, A.
Nuclear Safety and Safeguards National Commission
Mexico

Dela Rosa, A.
Philippine Nuclear Research Institute
Philippines

Harou, A. (June 2014 onwards)
World Meteorological Organization

Hernández, D.
Nuclear Regulatory Authority
Argentina

Homma, T.
Japan Atomic Energy Agency
Japan

Hubbard, L.
Swedish Radiation Safety Authority
Sweden

Kelly, N.
Senior Consultant
United Kingdom

Kenigsberg, J. †
National Commission of Radiation Protection
Belarus

Maree, M.
Eskom
South Africa

McClelland, V.
Department of Energy
USA

Molina, G.
Instituto Nacional de Investigaciones Nucleares
Mexico

Pascal, G.
European Commission Joint Research Centre

Sigouin, L.
Canadian Nuclear Safety Commission
Canada

† Deceased.

Soufi, I.
National Energy Center of Sciences and Nuclear Techniques
Morocco

Sumargo, D.E.
Nuclear Energy Regulatory Agency
Indonesia

Takahara, S.
Japan Atomic Energy Agency
Japan

de la Vega, R.
Nuclear Safety Council
Spain

Invited experts and contact points

Taminami, T.
Tokyo Electric Power Company
Japan

Tanigawa, K.
Hiroshima University
Japan

Tominaga, T.
National Institute of Radiological Sciences
Japan

Wiley, A.
REAC/TS–WHO Collaborating Center
USA

Yamashita, S.
Nagasaki University
Japan

IAEA Secretariat staff supporting WG3

Callen, J.
Chaput, J.
Kaiser, P.
Martincic, R.
McKenna, T.
Mutluer, A.
Nestoroska Madjunarova, S.
Vilar Welter, P.
Yoshimoto, Y

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group (INSAG)

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Mohammad Jais, A.
International Nuclear Safety Group

Niu, S.
International Labour Organization

Sharma, S.K.[†]
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

14–17 April 2014
6th meeting of WGs 1, 2 and 3, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)

The Fukushima Daiichi Accident

Technical Volume 4/5
Radiological Consequences

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 4
RADIOLOGICAL CONSEQUENCES

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 4
RADIOLOGICAL CONSEQUENCES

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.
STI/PUB/1710
ISBN 978–92–0–107015–9 (set)
Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This publication has been prepared from contributions submitted by many international experts to the five Working Groups for the preparation of the technical volumes. The content does not necessarily reflect the views of IAEA Member States, or the organizations nominating experts.

Great care has been taken to maintain the accuracy of information contained in this publication. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with this publication.

This publication is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from this publication may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this publication indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continued existence of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from this report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

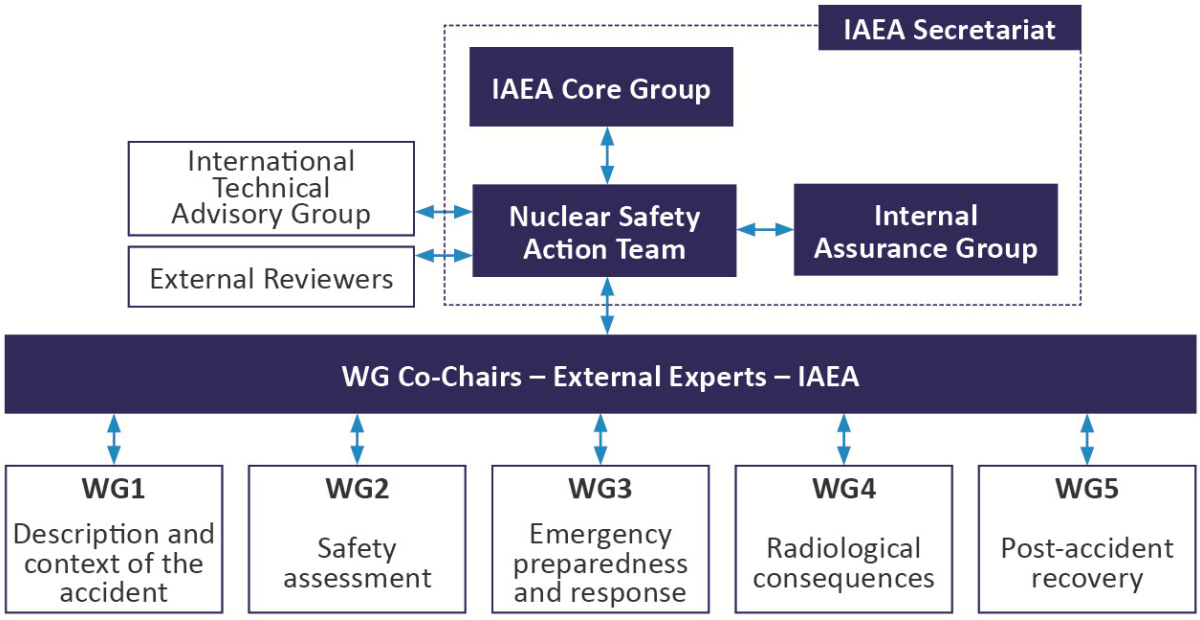


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

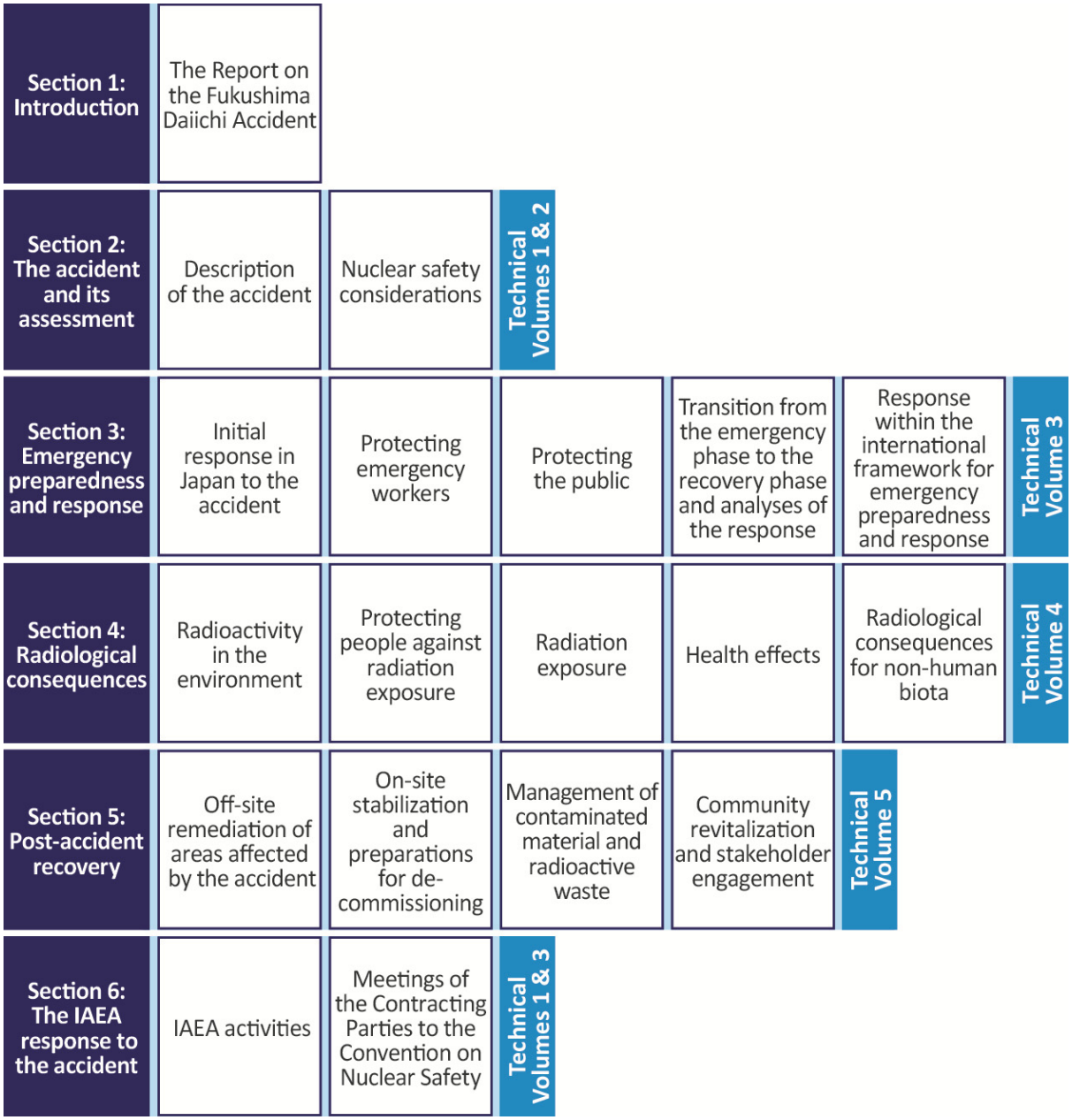


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

RADIOLOGICAL CONSEQUENCES 1

4. INTRODUCTION 1

4.1. RADIOACTIVITY IN THE ENVIRONMENT 2
4.1.1. The natural environment around the Fukushima Daiichi NPP 3
4.1.2. Releases of radionuclides to the atmosphere and radioactivity in the terrestrial environment 5
4.1.3. Deposition and releases to the marine environment and radioactivity in the aquatic environment 32
4.1.4. Levels of radionuclides in terrestrial and aquatic foods 51
4.1.5. Levels of radioactivity worldwide 65
4.1.6. Summary 68
4.1.7. Observations and lessons 70
4.2. RADIATION EXPOSURE 70
4.2.1. Occupational exposures 71
4.2.2. Public exposures 91
4.2.3. Summary 123
4.2.4. Observations and lessons 125
4.3. RADIATION PROTECTION 126
4.3.1. International organizations, recommendations and standards 127
4.3.2. Radiation protection regulations in Japan at the time of the accident 135
4.3.3. Aspects of radiation protection relevant to the response 137
4.3.4. Reactions to the situation for radiation protection in Japan and globally 143
4.3.5. Social issues associated with protective actions 143
4.3.6. Summary 145
4.3.7. Observations and lessons 146
4.4. HEALTH CONSEQUENCES 147
4.4.1. Previous international assessments 148
4.4.2. Post-accident health surveys in Japan 151
4.4.3. Evidence of observable health effects 154
4.4.4. Studies of effects on the thyroid 156
4.4.5. Inference of future risk 159
4.4.6. Non-radiation effects: Mental health 163
4.4.7. Summary 166
4.4.8. Observations and lessons 167
4.5. CONSEQUENCES FOR NON-HUMAN BIOTA 168
4.5.1. Background to the assessment 169
4.5.2. Dose assessment approaches, end points and benchmarks 170
4.5.3. The dose assessment of non-human biota in the vicinity of the Fukushima Daiichi NPP 172
4.5.4. The radiological consequences for non-human biota 182
4.5.5. Review of relevant studies on modelling of doses and field observations of effects in proximity to the Fukushima Daiichi NPP 185
4.5.6. Summary 187
4.5.7. Observations and lessons 188

APPENDIX I: MAPS OF LEVELS OF RADIOACTIVITY AND RADIONUCLIDES IN THE ENVIRONMENT 189

APPENDIX II: STATISTICAL ANALYSIS OF INDIVIDUAL DOSE DATA 197

REFERENCES 221
CONTENTS OF CD-ROM 243
ABBREVIATIONS 244
CONTRIBUTORS TO DRAFTING AND REVIEW 246
INTERNATIONAL TECHNICAL ADVISORY GROUP 249
MEETINGS 250

RADIOLOGICAL CONSEQUENCES

4. INTRODUCTION

This technical volume describes the consequences associated with radioactivity and radiation from the accident at the Fukushima Daiichi nuclear power plant (NPP) for people and the environment. A number of international organizations have already issued reports on the potential health and environmental consequences of the accident, notably the World Health Organization (WHO) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). The intention of the assessments presented in this volume is to build on their work, using more recent data where available. Quantitative information arising from both personal and environmental monitoring has been provided by the Government of Japan.

Section 4.1 provides the best estimates of the magnitude and form of radioactive releases during the accident to the atmosphere and directly into the surrounding sea. It also explains the movement of the discharged radionuclides through air and water and the eventual deposition of the atmospheric activity on land in Japan and other countries worldwide, as well as on the open oceans. The goal is to provide a consolidated repository of information on releases to, and levels of radionuclides in, the environment. Some of this information is used in the analyses in subsequent sections of this volume.

Section 4.2 gives an overview of exposures to the main groups of emergency workers at the Fukushima Daiichi NPP, to groups of off-site workers and to members of the public. Where sufficient data are available, average effective dose and thyroid equivalent doses derived from personal measurements are compared with the results of previous assessments for specific locations, population groups and time periods.

Section 4.3 summarizes relevant aspects of the system of radiation protection in place at the time of the accident. It includes an overview of the legislation and guidance used to implement the radiation protection framework in Japan. This section also provides a description of the main aspects of radiation protection related to the accident at the Fukushima Daiichi NPP.

Section 4.4 presents a review of post-accident studies of the health of members of the public and workers, including the possible radiation induced health effects and psychological consequences to individuals resulting from the accident.

Section 4.5 covers the impact of the radioactive releases from the Fukushima Daiichi NPP on the environment (more specifically on non-human biota). The International Commission on Radiological Protection (ICRP) methodology has been applied to estimate dose and effects to a range of reference animals and plants from the marine, terrestrial and freshwater environments.

There are 2 appendices and 12 annexes that provide supplementary information. Appendix I contains maps of levels of radioactivity and radionuclides in the environment. Appendix II provides details of a statistical analysis of individual dose data. The annexes are included on the CD-ROM attached to this volume and provide the following information:

— Annex I: Characteristics and measurement of radioactivity and radiation levels.
— Annex II: Local and regional meteorological conditions in east Japan during 11–23 March 2011.
— Annex III: Levels of radioactivity in the terrestrial environment.
— Annex IV: Radioactivity in the marine environment arising from releases following the Fukushima Daiichi accident.
— Annex V: UNSCEAR assessment of the dose to the public.

— Annex VI: Information on measurement studies investigated in the production of this Technical Volume 4.
— Annex VII: Analysis of thyroid measurements of children conducted in Fukushima Prefecture, 26–30 March 2011.
— Annex VIII: Conventions, recommendations, safety standards, laws and regulations.
— Annex IX: Introduction to radiation effects on the thyroid.
— Annex X: Radiation and health effects and inferring radiation risks from the Fukushima Daiichi accident.
— Annex XI: Risk assessments for workers and the population following the Chernobyl accident.
— Annex XII: Calculations used in the assessment of doses to non-human biota.

4.1. RADIOACTIVITY IN THE ENVIRONMENT

The accidental releases from the Fukushima Daiichi NPP resulted in an increase in levels of artificial radioactivity in parts of the Japanese terrestrial environment and the marine environment to the east of Japan. Radioactive material released to the atmosphere was transported according to the meteorological conditions prevailing at the time and was deposited on land masses and the ocean. The majority of the atmospheric releases occurred during the period from 12 to 23 March 2011 [1]. Variations in the emission rates, in the physical and chemical properties of individual elements released from each of the three damaged reactors, and in the changing meteorological conditions during this period resulted in complex and heterogeneous dispersion of the radioactive material. The spatial variation of deposition densities on land was further complicated by the influence of precipitation, topography and land cover.

Direct releases of radionuclides to the ocean also occurred via a variety of mechanisms including runoff of contaminated water from the flooded plant, deliberate release of low level waste and drainage of contaminated groundwater. This material, as well as that deposited from atmospheric releases, was dispersed in the ocean under the influence of wind, tides and currents. Some of the radioactive material became attached to suspended sediments and was subsequently deposited onto riverbed sediments and plants.

Once dispersed and deposited, radioactive material migrated through the environment and led to elevated activity concentrations in soil and marine sediments and in plants and animals, including foods. It also resulted in additional radiation exposures of residents of the affected areas (see Section 4.2).

The first part of this section deals with the characteristics of the environment around the Fukushima Daiichi NPP. This is followed by a description of the nature of the releases to the atmosphere, including estimates of the amounts of each radionuclide released. The factors influencing the dispersal and deposition of radioactive material released during the Fukushima Daiichi accident in the atmosphere and in the terrestrial environments are also outlined. The section then describes the results of the extensive environmental surveillance and assessment programmes undertaken in Japan following the accident. The second part of the section considers releases of radionuclides to the aquatic environment, the factors influencing the dispersion of radionuclides in this environment and the results of the environmental monitoring that has been conducted. The third part considers the levels of radionuclides in relevant foods. The final part describes the global transport and detection of very low levels of radiocaesium, radioiodine and other fission products in air samples and other environmental media. This compilation of all aspects of radioactivity in the environment resulting from the accident at the Fukushima Daiichi NPP provides a comprehensive resource for future analysis.

4.1.1. The natural environment around the Fukushima Daiichi NPP

The Fukushima Daiichi NPP (37°25′N, 141°02′E) is located on the north-eastern Pacific Ocean coast of Honshu (Japan's largest island), about 200 km north-east of Tokyo. In this area, the continental shelf is narrow, extending 40 km offshore, and broadens further north up to 70 km in the area of Sendai Bay. Offshore of the Fukushima Daiichi NPP, the ocean depth increases steadily, reaching some 200 m at 50 km from the coast. Beyond the shelf break, the slope plummets as deep as 9000 m into the Japan Trench. An abyssal plain lies further east, at depths of about 5000 m. As explained in more detail in Section 4.1.3.2, the Fukushima Daiichi NPP is located at the confluence of two wind-driven western boundary currents of the North Pacific: the Kuroshio Current, which transports warm, saline waters northwards along the south coast of Japan and then eastward; and the Oyashio Current, which transports cold, less saline, water southward. Another characteristic of the region is the Tsugaru Warm Current, flowing from the Sea of Japan through the Tsugaru Strait north of Honshu and then southward along the slope of the east coast.

The northernmost part of Japan (Hokkaido and neighbouring islands) is situated in the boreal zone. In addition, the eastern coast of Honshu has fauna similar to that of Hokkaido, because the area is influenced by the cold Oyashio Current. The ecosystem is characterized by rich primary production. The major primary producers are not only phytoplankton but also macro algae, especially brown algae. Such algae harbour rich fish and invertebrate fauna in the area [2].

Fukushima Prefecture is located in the southernmost part of the Tohoku region, which is situated on Honshu Island and borders on the Kanto region in the south. The centre of the Kanto region is the Kanto Plain, which is the largest plain in Japan and which adjoins the sea to the east and the south.

The Tohoku region, which occupies about 30% of Honshu Island, contains a mountainous expanse running from north to south. Some of the mountains are relatively high at more than 1500 m; they effectively divide the region into two distinct areas with different watersheds and climates, on the Sea of Japan side and the Pacific Ocean side. The Abukuma Mountains are located in Fukushima Prefecture on the east side of the Ou Mountain range, an area of approximately 170 km from south to north and 40 km from east to west. The Abukuma Mountains are gentle hills with an average altitude of about 600 m, with their highest point rising to 1192 m. They are characterized by small valleys with steep streams scattered among agricultural fields and forests. The Abukuma Mountains are surrounded by a 10 km wide narrow plain bounded to the east by the Pacific coast (Hamadori area), the Abukuma River plain to the west (Nakadori area) and the north, and the Kuji River valley to the south. The Ou Mountains also divide Fukushima Prefecture into two areas, the Nakadori area and the Aizu area. In the Abukuma River plain, many tributary rivers meet with the Abukuma River, which runs into the Pacific Ocean. The Uda, Mano, Niida and other rivers also run into the Pacific Ocean. A large part of the Aizu area is mountainous, with the exception of the Aizu Basin. The Tadami River and many tributaries meet the Agano River, which runs to the Sea of Japan. Lake Inawashiro (with an area of 104.8 km^2) and many small lakes are located in the mountain area on the east side of the basin.

The climate of the Tohoku region can be divided into different zones. The western area is characterized by warm days in the summer that are due to the föhn wind[1], while in winter, there are relatively short periods of sunshine and the area tends to have heavy snowfall. In the eastern area, the climate has both inland and Pacific coastal characteristics. Although temperatures occasionally rise owing to the föhn wind, summers tend to be cloudy with low temperatures, while the winter weather is usually mild, with occasional snowfall due to cold air masses moving in from the north.

[1] A generic term for warm, strong and often very dry downslope winds that descend in the lee of a mountain barrier.

About 80% of the area of Fukushima Prefecture is mountainous, with about 70% covered by forests; as of 2002, artificial forests accounted for 35% of the forested area. A large part of the non-mountainous area of the Tohoku region contains a mixture of paddy fields, farmlands, secondary deciduous forest and evergreen coniferous trees (primarily cedar), with a high biodiversity. The flora and fauna in the Tohoku region are as diverse as those of Japan as a whole. Since Fukushima Prefecture is located at the boundary between areas of deciduous broadleaf forests and evergreen broadleaf forests, an especially high diversity of plants can be found. Typical plants in the deciduous broadleaf forest are Fagaceae, and those in evergreen broadleaf forest include a species of Castanopsis, Japanese evergreen oak (*Quercus acuta*) and *Quercus salicina*. Regarding the fauna, surveys have shown that the following mammals, birds and reptiles inhabit the Tohoku region [3]:

— Mammals: Japanese monkey (*Macaca fuscata*), Asiatic black bear (*Selenarctos thibetanus*), Japanese raccoon, Japanese deer, Japanese serow (*Capricornis crispus*);
— Birds: Yellow Bittern (*Ixobrychus sinensis*), *Butastur indicus, Accipiter gentilis, Alcedo atthis*, belted kingfisher, Japanese green woodpecker, barn swallow, water wagtail, *Cinclus pallasii*;
— Reptiles: Forest green tree-frog, Tohoku salamander, blacked salamander, Japanese clawed salamander, black-spotted pond frog (*Rana nigromaculata*) [4].

The map in Fig. 4.1–1 shows the geographical features of Fukushima Prefecture.



FIG. 4.1–1. Geographical features of Fukushima Prefecture.

4.1.2. Releases of radionuclides to the atmosphere and radioactivity in the terrestrial environment

Technical Volume 1 includes a detailed description of the accident and the sequence of events that took place after the earthquake and tsunami on 11 March 2011. A detailed description of the deterioration of the conditions of the reactor cores and of the different barriers designed to prevent the release of fission products is provided in Technical Volume 1, Section 1.4. The aims of this section are to provide summaries of:

— The source term[2], including estimates of the total activities of the most important radionuclides released to the atmosphere and into the ocean as a result of the Fukushima Daiichi accident, as well as temporal variations in these releases.
— The dispersion and, for relevant radionuclides, subsequent deposition of radionuclides onto the terrestrial environment, taking into account both changing meteorological conditions and emission rates and other influences, including topography and land cover.
— The temporal and spatial variations in levels of radionuclides in the environment in order to provide the context for the discussions of exposures of members of the public and of workers in Section 4.2 and of non-human biota in Section 4.5.

4.1.2.1. Atmospheric releases

A detailed description of the various events which took place in Units 1, 2 and 3 of the Fukushima Daiichi NPP over the period from 11 March until the end of March 2011 and which led to releases of radioactivity to the environment is provided in Technical Volume 1. Key events included a hydrogen explosion in the reactor building of Unit 1 on 12 March, a hydrogen explosion in the reactor building of Unit 3 on 14 March and the failure of the Unit 2 primary containment vessel, leading to significant releases to the atmosphere on 15 March. Further releases occurred as a consequence of the venting of the different units [5].

As described in Technical Volume 1, Section 1.4, the accident source term has been estimated by many research groups, generally by using one of two complementary and well established approaches. Firstly, releases were estimated based on simulations of the accident progression and phenomena that contribute to the atmospheric release of radionuclides using severe accident simulation computer codes, such as MELCOR [6], ASTEC [7] or MAAP [8]. Secondly, reverse or inverse modelling of the transport and dispersion in the environment was used, which involves the use of measurements of radionuclides in the environment to estimate the source term. Both approaches were hampered by the complexity of the situation during the accident at the Fukushima Daiichi NPP and by the scarcity of key data (for the first approach, particularly information on key plant parameters over the period in question was lacking, and, for the second approach, measurements in the environment, especially in the early phase). In addition, the time periods over which source term estimates were integrated differed. The dispersion of released material over the sea was also a factor. As a result, significant uncertainties remain in estimates of the total releases of each radionuclide and, to an even greater extent, of release rates.

Despite these uncertainties, the different estimates of the releases of ^{131}I and ^{137}Cs are reasonably consistent. Technical Volume 1, Section 1.4 presents the total releases of key radionuclides estimated

[2] The source term is of fundamental importance for assessing the consequences of releases of radionuclides following a nuclear accident. The source term describes the composition of the releases (the total amount of each radionuclide released) and the release rates (the temporal variation of the release of each radionuclide). It also includes information on the chemical form of each radionuclide released (for example, gaseous or particulate phase), particle size, release height, temperature and enthalpy (the total energy of a thermodynamic system indicating the energy of the released material which affects the effective height of the release).

by many different organizations around the world and explains the uncertainties involved. The atmospheric releases of ^{131}I and ^{137}Cs have been estimated to lie in the ranges 90–700 PBq and 7–50 PBq, respectively. If the very first estimates, made in March–April 2011 and based on the very limited information available at that time are excluded, then the range becomes narrower: 100–400 PBq for ^{131}I and 7–20 PBq for ^{137}Cs. The preliminary estimates of the source term for ^{133}Xe were more uncertain, being between 500 and 15 000 PBq. However, in more recent calculations [9], this uncertainty has also decreased (6000–12 000 PBq). The estimated atmospheric releases of ^{131}I, ^{137}Cs and ^{133}Xe are summarized in Table 4.1–1.

TABLE 4.1–1. ESTIMATED ATMOSPHERIC RELEASES OF KEY RADIONUCLIDES (PBq)

Nuclide	All estimates	Early estimates excluded[a]
I-131	90–700	100–400
Cs-137	7–50	7–20
Xe-133	500–15 000	6000–12 000

[a] Estimated releases excluding those made in March–April 2011.

Section 1.4 of Technical Volume 1 also describes a statistical analysis of the numerical estimates of the total releases of these key radionuclides. Bayesian techniques were used to obtain mean values of the total release and the confidence limits.

Section 1.4 in Technical Volume 1 also considers the estimates of releases of other radionuclides and compares them with those from the accident at Chernobyl. A summary of the published range of estimated releases of each of the key radionuclide is provided in Tables 4.1–1 and 4.1–2. The ranges of estimates are greater for radionuclides other than iodine and caesium, reflecting the lack of direct measurements of these isotopes around the site in the period immediately after the accident. However, it is clear that the releases of all radionuclides are significantly less than those from the accident at Chernobyl.

It is clear that a wide range of radionuclides are known to have been released to the atmosphere during the accident at the Fukushima Daiichi NPP [10–15]. Most have been detected by radiological measurements of environmental media.

The fission noble gases ^{85}Kr and ^{133}Xe were released during the early phase of the accident. Nearly the entire inventories of these gases were released as a result of ventings, explosions and other events in Units 1, 2 and 3.

The maximum temperature in the reactors at the time of the releases has been estimated as 2100–2300°C [16]. It can therefore be assumed that all releases of volatile elements with boiling points significantly less than this temperature [17] were in the form of vapour, which, with the exception of iodine, soon condensed onto particulate matter under ambient conditions.

Very low levels of semi- and low volatile elements were released. In particular, low-volatile gamma emitting fission products, including isotopes of ruthenium, ^{140}Ba/^{140}La and cerium, have not been detected at significant levels in the area around the Fukushima Daiichi NPP. During the accident, the release was mainly due to core overheating and fuel melting, without the presence of air; less volatile elements were therefore not released. Similarly, only very low levels of isotopes of strontium and the actinides, including plutonium, were released owing to the nature of the accident. This contrasts with the releases from the Chernobyl NPP, where there was an explosion at an operating reactor releasing fragments containing these less volatile elements. As described in Technical Volume 1, neutrons were

detected near the main gate of the Fukushima Daiichi NPP (which is around 1 km away from Units 1–3), between 05:30 and 10:50 on 13 March. It is estimated that the neutrons came from the spontaneous nuclear fission of radionuclides that could have been released as a result of damage to the reactor core. Such a phenomenon was predictable and the presence of these radionuclides at relatively low levels, which are not of radiological concern, has been reported [18]. Zheng et al. [18] note that discharges of isotopes of plutonium based on their measurements of levels in soil are similar to other estimates of the discharges as given in Table 4.1–2.

TABLE 4.1–2. AN ILLUSTRATIVE RANGE OF ESTIMATES OF ATMOSPHERIC RELEASES OF A WIDER RANGE OF RADIONUCLIDES (PBq) AND COMPARISON WITH THOSE FROM THE CHERNOBYL ACCIDENT

Radionuclide	Fukushima Daiichi[a]	Chernobyl[b]
Fission noble gases		
Kr-85	6.4–32.6	33
Xe-133	6 000–12 000	6 500
Volatile fission products		
Te-129m	3.3–12.2	240
Te-132	0.76–162	~1.15×10^3
I-131	100–400	~1.76×10^3
I-133	0.68–300	2500
Cs-134	8.3–50	~47
Cs-136	—	36
Cs-137	7–20	~85
Semi- and low volatile fission products		
Sr-89	4.3×10^{-2}–13	~115
Sr-90	3.3×10^{-3}–0.14	~10
Ru-103	7.5×10^{-6}–7.1×10^{-5}	>168
Ru-106	2.1×10^{-6}	>73
Ba-140	1.1–20	240
Refractory elements		
Zr-95	0.017	84
Mo-99	8.80×10^{-8}	>72
Ce-141	0.018	84
Ce-144	0.011	~50
Np-239	0.076	400
Pu-238	2.4×10^{-6}–1.9×10^{-5}	0.015
Pu-239	4.1×10^{-7}–3.2×10^{-6}	0.013
Pu-240	5.1×10^{-7}–3.2×10^{-6}	0.018
Pu-241	3.3×10^{-7}–1.2×10^{-3}	~2.6
Cm-242	9.8×10^{-6}–10^{-4}	~0.4

[a] Range of estimates from JNES, 2012 [19], NISA, 2011 [20, 21], IRSN-2, 2012 [22–24], IBRAE, 2012 [25–27], with the exception of Xe-133, I-131 and Cs-137, where the estimated range is based on the greater number of estimates described in Technical Volume 1, Section 1.4 (excluding early estimates, made in March–April 2011).
[b] From Ref. [28].

Relatively small amounts of ^{129}I were released. This long lived radionuclide is not radiologically significant under such conditions, but has been used to reconstruct maps of the distribution of the much shorter lived ^{131}I in the environment.

Four years after the accident, atmospheric releases from the Fukushima Daiichi NPP continue, but at very low levels which are not of radiological concern. Since the summer of 2011, the levels measured on the Fukushima Daiichi NPP have been low (concentrations of ^{134}Cs and ^{137}Cs in air of the order of 1 Bq/m^3 or less for both ^{134}Cs and ^{137}Cs); since April 2012, they have been below detection limits [29].

4.1.2.2. Dispersion of radionuclides in the atmosphere and deposition onto the terrestrial environment

Radionuclides released to the atmosphere following the accident at the Fukushima Daiichi NPP were subjected to a variety of physical and chemical processes that determined their eventual fate. Both the meteorological conditions and the release rates of different radionuclides varied considerably during the period of atmospheric releases from the Fukushima Daiichi NPP [1].

The releases that contributed most to the observed deposition pattern in Japan occurred in the following three time periods [1, 5], which are also illustrated in part in Fig. 4.1–2:

(1) Early on 12 March 2011, the wind direction carried released material towards the Pacific Ocean. From the afternoon of 12 March until midnight, the releases following the venting and hydrogen explosion in Unit 1 were transported over north-east Fukushima Prefecture and the coastal area of Miyagi Prefecture, resulting in dry deposition.
(2) From the evening of 14 March to the morning of 16 March, releases (mainly from Unit 2) were transported by changing weather conditions over wider areas of Honshu. Initial southerly transport resulted in dry deposition along the south-eastern coastal area of Fukushima Prefecture and north-eastern parts of Ibaraki Prefecture. This material was subsequently dispersed more widely, leading to lower levels of dry deposition in the more distant areas towards the south-west. Light precipitation began during the afternoon of 15 March and resulted in wet deposition in northern areas of the Gunma, Tochigi and Fukushima prefectures. A major release on the morning of 15 March from Unit 2 moved initially toward the south-west and then, following a change in wind direction, the north-west, resulting in wet deposition over north-east Fukushima, south-east Yamagata and south-west Miyagi prefectures.
(3) From 20 to 22 March, release rates were lower. Dispersion was dominated by air movement towards the north-west in the afternoon of 20 March and southward transport from the late night of 21 March to the early morning of 22 March. Subsequently, further releases encountered wet deposition in a number of areas, such as parts of the prefectures of Iwate, Miyagi, Ibaraki, Chiba and other prefectures in the Kanto plain on 23 March.

This pattern of dispersion and deposition was largely supported by the results of early atmospheric dispersion modelling by researchers in Japan (e.g. [1, 30–34] although uncertainties remain [5, 35]).

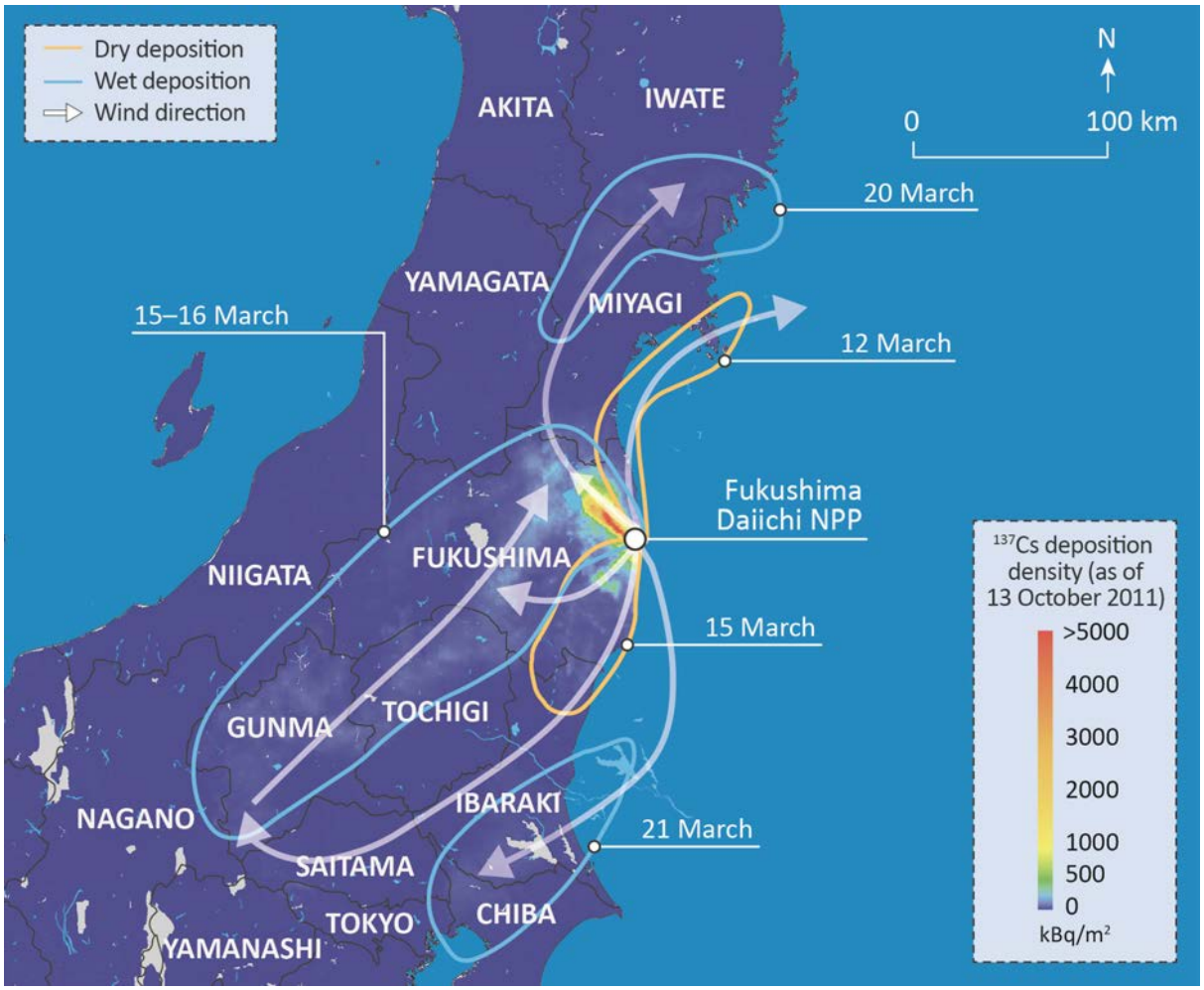


FIG. 4.1–2. Timing and locations of the main deposition events [36, 37].

A summary of the key events and factors influencing dispersion and deposition of radionuclides is summarized in Table 4.1–3.

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
	—	9–12 March (early morning)	—	—	Light rain	—
	—	12 March (early morning–afternoon)	—	Plume transported over the Pacific Ocean	—	—
1	Initial and substantive releases from venting and H_2 explosions in Units 1 and 3 with resultant dry deposition.	12 March (afternoon–midnight)	Venting of Unit 1 started approx. 14:00. H_2 explosion Unit 1 at 15:36.	High concentration plume first transported NNW over NE Fukushima Prefecture and then NNE over coastal area of Miyagi Prefecture.	—	Elevated ambient dose equivalents recorded at some local monitoring posts to the north of the site, at Minamisoma at 20:00 and at Onagawa at 00:00 on 13 March.
		13 March–14 March (night)	Venting of Unit 3 primary containment vessel started at approx. 08:45 (13 March). H_2 explosion Unit 3 at 11:01 (14 March).	Plume transported generally E/NE over the Pacific Ocean.	—	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
2	Large releases mainly from Unit 2 due to melting of core and breach of reactor containment. Major contributor to deposition of radioactive material on (eastern) Japanese landmass. Changing weather conditions.	14 March (late night)–15 March (morning)	H_2 explosion in Unit 4 at approx. 06:00 (15 March) due to backflow of gases vented from Unit 3. Following failure of Unit 2 reactor pressure containment function on evening of 14 March, release of a large amount of radioactive material from approximately 07:38 (15 March). Peak ambient dose equivalent rates measured at approximately 09:00 at the site boundary.	Plume transported SSW along the SE coastal area of Fukushima Prefecture and NE Ibaraki Prefecture. Subsequently, a more dispersed plume was transported over the Kanto region, resulting in lower levels of dry deposition in Tokyo, and Saitama and Miyagi prefectures.	—	Increase in dose rates measured at Iwaki (Fukushima), Kitaibaraki and Tokai (Ibaraki) on morning of 15 March.
		15 March (afternoon–night)	—	High concentration plume transported NW. Plume transported generally S resulting in dry deposition over SE Fukushima and E Ibaraki prefectures.	Light precipitation due to a low pressure system passing eastwards over Honshu resulted in high levels of wet deposition which was higher than dry deposition over NE Fukushima, SE Yamagata and SW of Miyagi prefectures.	Increase in dose rates measured at some local monitoring posts and portable monitors at Fukushima and Iitate in the west and north-west direction from Fukushima Daiichi NPP. Two increases in dose rates measured at Kitaibaraki (Ibaraki) during 16 March.
		16 March (morning)–19 March	—	Plume transported generally E to SE (fluctuating) mainly over the Pacific Ocean.	—	—
		20 March (early morning)	—	Plume transported east over the Pacific Ocean.	—	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
3	Releases dispersed over Japanese landmass encountering rainfall on occasions. Release rates lower from 23 March.	20 March (morning–afternoon)	—	Plume transported south over the Kanto region.	—	—
		20 March (afternoon)	—	Plume transported NW over W Miyagi, E Yamagata and S Iwate prefectures.	Precipitation in the evening causes wet deposition over the same areas.	—
		20 March (late night)–21 March	—	Plume transported S into Ibaraki Prefecture via the ocean and then dispersed over the Kanto region (Tokyo, and Ibaraki, Chiba and Kanagawa prefectures).	Precipitation during the morning of 21 March causes wet deposition over the same areas.	Increase in dose rates measured at Tokai, Setagaya (Tokyo), Chiba, Wako, Tsukuba (mainly in the Kanto plain) from the morning of 21 March.
		22 March	—	Plume transported in fluctuating E/SE directions over the Pacific Ocean. Plume due to releases from 21 March remain (stagnant) over the Kanto region.	Precipitation in the evening results in wet deposition over E Fukushima Prefecture and over the Kanto region.	
		23 March–24 March (morning)	—	Lower concentration plume transported generally S and SE, resulting in dry deposition along coastal parts of Ibaraki and Chiba prefectures and subsequently into the SE part of the Kanto region.	Precipitation from evening until late night results in wet deposition over the same areas.	—
		24 March (morning)–25 March (morning)	—	Plume transported over the Pacific Ocean.	—	—
		25 March (morning)–26 March (morning)	—	Plume transported NW over Fukushima Prefecture and southern parts of Yamagata and Miyagi prefectures.	Precipitation results in wet deposition over the same areas.	—

TABLE 4.1–3. SUMMARY OF KEY EVENTS AT THE FUKUSHIMA DAIICHI NPP: RELEASE RATES, METEOROLOGICAL CONDITIONS, DRY AND WET DEPOSITION AND RELEVANT MONITORING RESULTS (cont.)

No.[a]	Overview	Time period	Significant releases	Plume advection and dispersion	Precipitation and wet deposition	Monitoring results
		26 March (morning)	—	Plume transported SE over the Pacific Ocean.	—	—
		26 March (morning)–29 March	—	Plume transported eastwards over the Pacific Ocean.	—	—
		30 March (morning–afternoon)	—	Plume transported SW into the Kanto region resulting in dry deposition.	Precipitation in the afternoon results in wet deposition over Tochigi and Ibaraki prefectures.	—
		30 March (afternoon–night)	—	Plume transported NW.	—	—
		31 March	—	Plume transported mainly over the Pacific Ocean.	—	—

[a] These numbers relate to the summary of the main sequence of events presented above.

The combined influence of these factors has been analysed by several research groups [1], the World Meteorological Organization (WMO) [38], UNSCEAR [5], and the model review report by the Science Council of Japan [35]. A task group of WMO undertook an analysis of the meteorological conditions influencing the dispersion and deposition of the releases, the key features of which are presented in Annex II. This group also compared the results with different atmospheric transport dispersion and deposition models and with environmental monitoring data.

An illustration of the results of a global dispersion model is presented in Fig. 4.1–3 [39]. The figure shows activity concentrations in air; the original colours of the reference are retained so that small changes in the degree of colour correspond to a one order of magnitude change in the activity concentration. This shows that the activity concentrations in air decrease significantly with distance from the Fukushima Daiichi NPP.

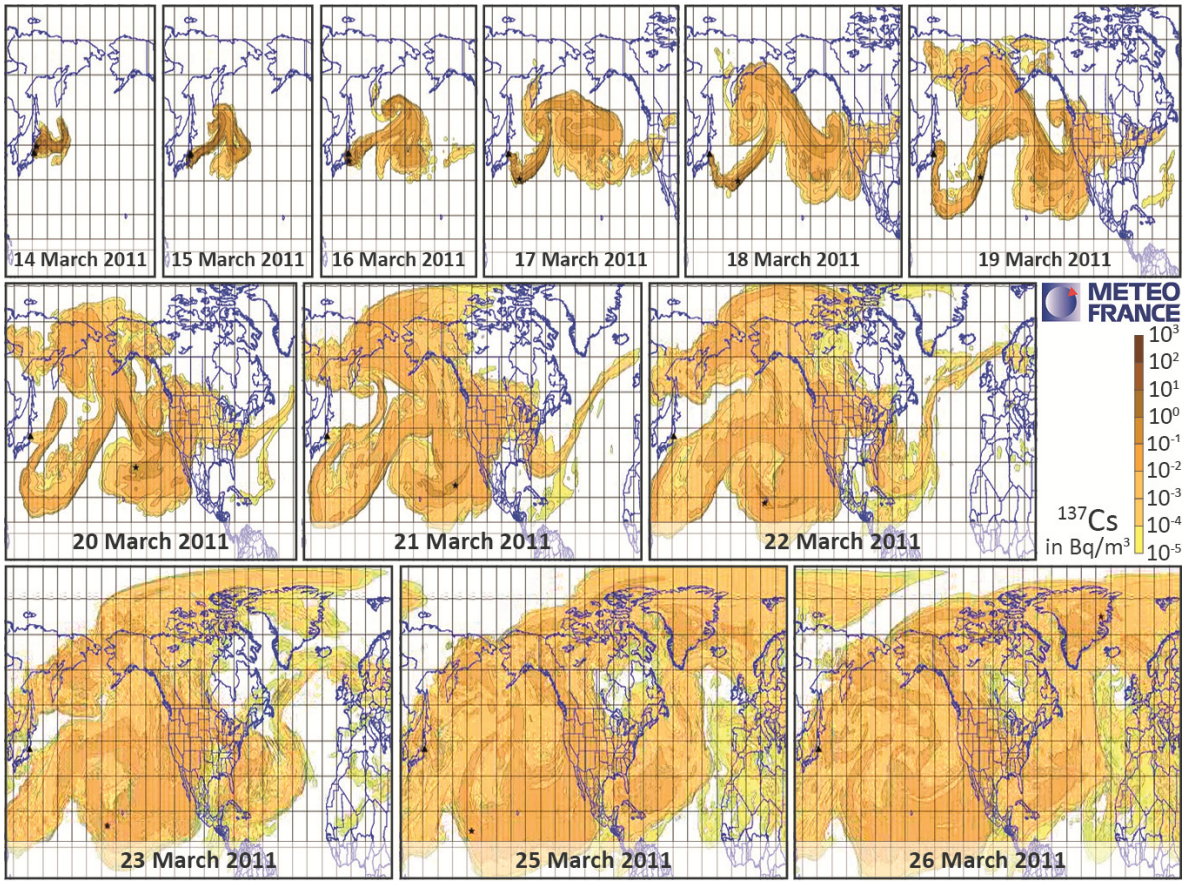


FIG. 4.1–3. Results from one of the global models of the atmospheric dispersion of ^{137}Cs, presented in its original colour scale (see Ref.[39] for details) (Illustration courtesy of Meteo-France).

In general, the pattern of dispersion and deposition can also be confirmed by the results of environmental monitoring at locations at, or close to, the Fukushima Daiichi NPP and throughout the affected area.

Measurements of ambient dose equivalent rates

The pattern of releases can be correlated with ambient dose rate measurements exemplified by those measured at the front gate of the Fukushima Daiichi NPP (Fig. 4.1–4). For example, the contribution of the early release of fission noble gases to the elevated ambient dose equivalent rates that were measured at the Fukushima Daiichi NPP is evident from Fig. 4.1–4.

Unit	Symbol in Fig.	Time of occurrence	Event
1	1a	12.03.2011 14:00	Venting No.1
	1b	12.03.2011 15:36	Explosion
2	2a	14.03.2011 21:00	Venting No.1 or PCV leakage
	2b/4a	15.03.2011 06:15	Loud sound in torus room
	2c	15.03.2011 11:25	Pressure drop in dry well
3	3a	13.03.2011 09:20	Venting No.1
	3b	13.03.2011 12:30	Venting No.2
	3c	13.03.2011 20:30	Venting No.3
	3d	14.03.2011 05:20	Venting No.4
	3e	14.03.2011 11:01	Explosion
	3f	14.03.2011 16:00	Venting No. 5
	3g	15.03.2011 16:05	Venting No.6
	3h	16.03.2011 02:00	Venting No.7

The variation of dose rates associated with later events are presented in Technical Volume 1, Section 1.4 (Fig. 1.4–3)

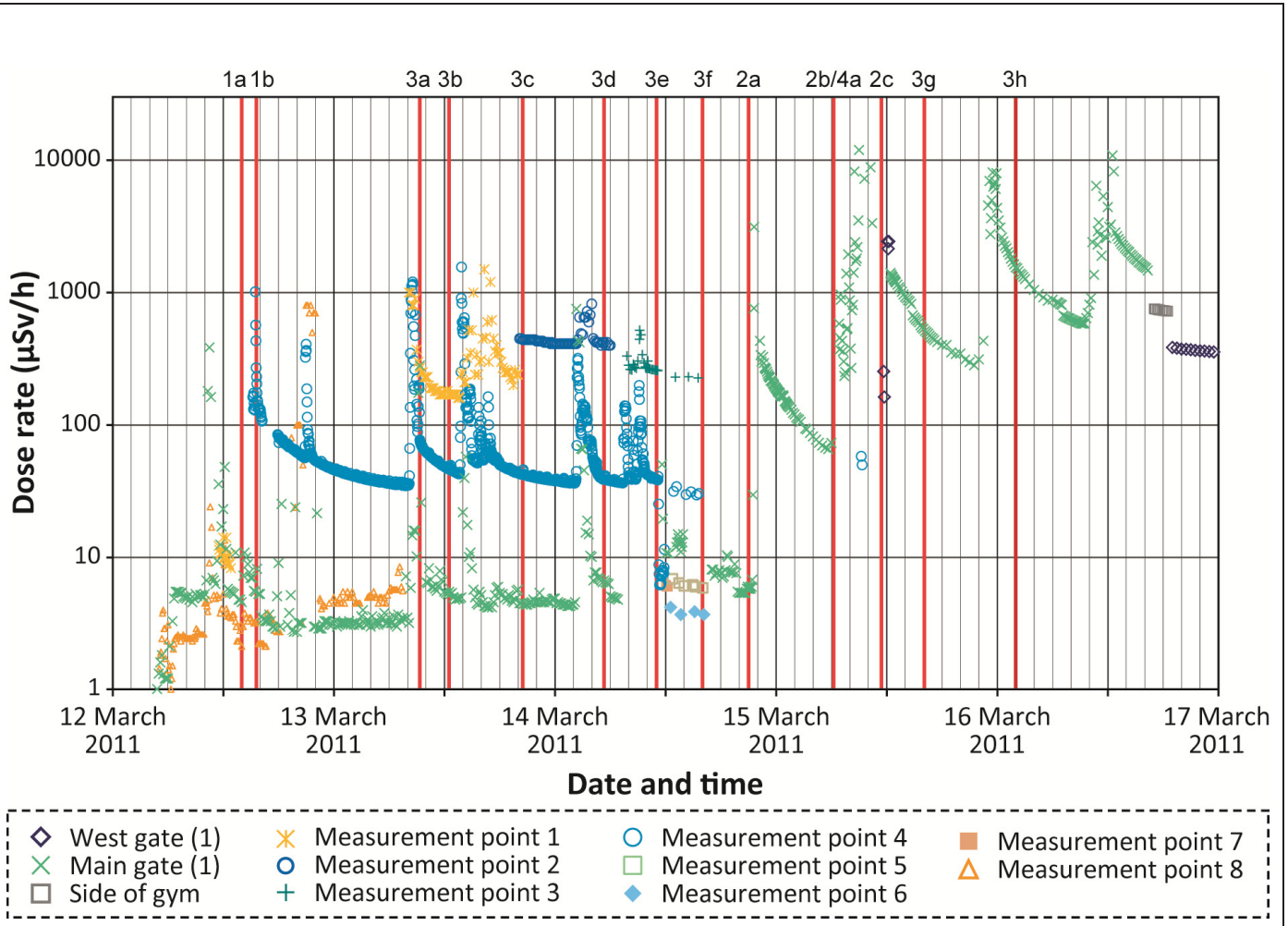


FIG. 4.1–4. Graph of dose rates measured at the Fukushima Daiichi NPP between 11 and 17 March 2011 (the vertical red lines indicate the major events registered during the accident) [40].

The movement of the plume can be demonstrated from the fluctuation in ambient dose equivalent rates measured at the fixed monitoring points and by portable monitors deployed by Fukushima Prefecture and observations at the Japan Atomic Energy Agency (JAEA) site at Tokaimura Village. The monitoring points are shown on the map in Fig. 4.1–5 [41].

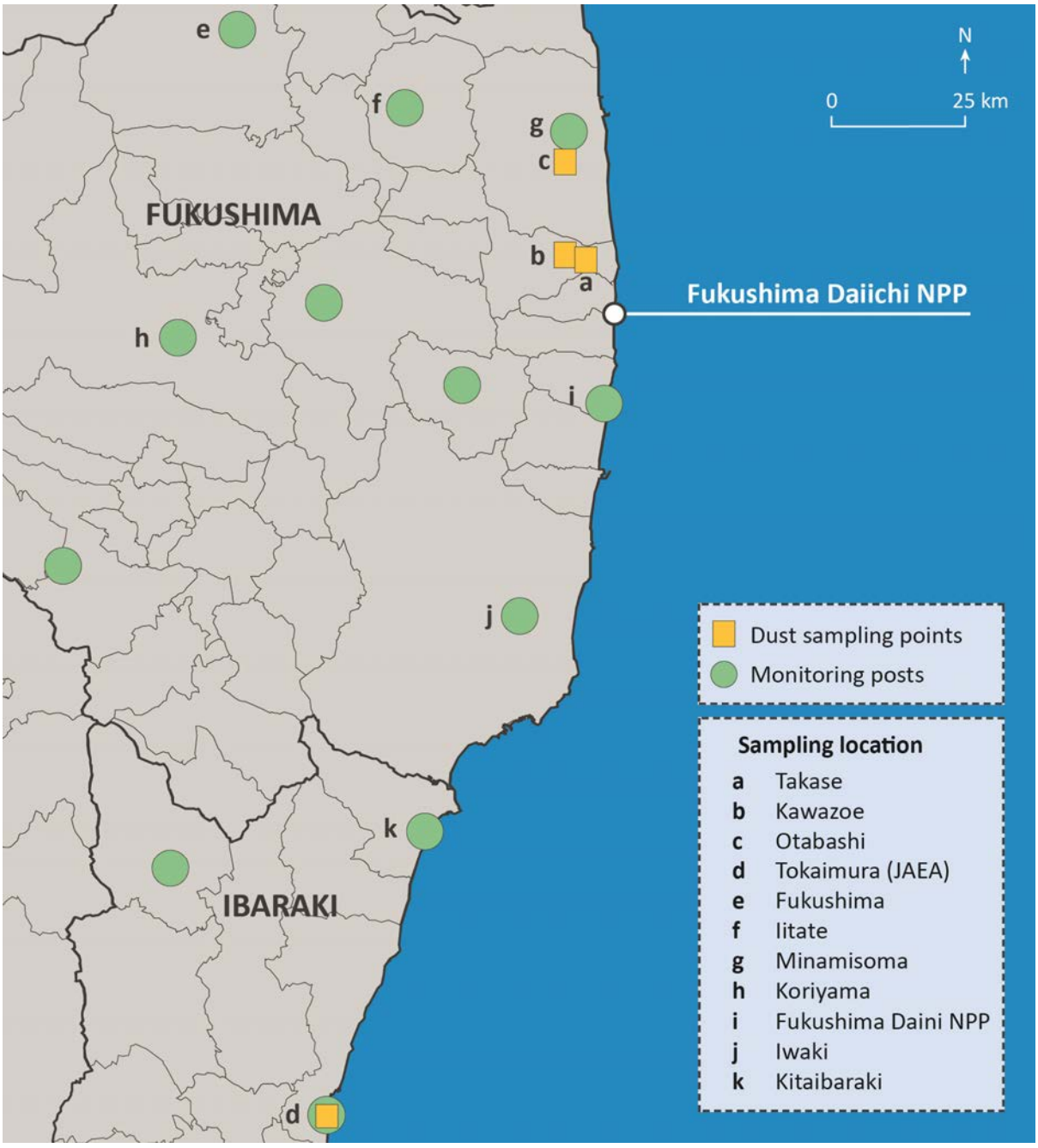


FIG. 4.1–5. Map of environmental monitoring points in Fukushima Prefecture [41].

The environmental monitoring data in the early stage of the accident were incomplete; consequently, it is not possible to analyse all aspects of the movement of the plume. However, the observations mentioned above support the results of the atmospheric dispersion simulation shown in Fig. 4.1–3. The various deposition events related to the main release periods which resulted in deposition onto the terrestrial environment (12, 14–16 and 20–22 March) can thus be observed in measurements of

ambient dose equivalent rates from fixed locations in Fukushima Prefecture and surrounding areas [42]. These measurements also provided information that was important for decisions concerning public safety at the time of the accident. Figure 4.1–6 shows aerially measured ambient dose equivalent rates as a function of time resulting from deposits following releases that spread to the north-west of the Fukushima Daiichi NPP. The largest long lived deposits of ^{137}Cs were found in this area of Japan, where the total deposition of ^{137}Cs has been estimated to have been around 2–3 PBq [43].

Dry deposition occurred in the afternoon of 12 March and during the night of 14–15 March, relatively close to the Fukushima Daiichi NPP. Subsequent wet deposition occurred at a greater distance from the Fukushima Daiichi NPP due to the wide precipitation area over East Japan. The highest dose rates shown in Fig. 4.1–6 illustrate the importance of wet deposition, which created higher levels of deposition over a wider area than did dry deposition. Precipitation is a key factor in determining the contamination of water, land and agricultural products.

Measurements of airborne radionuclides

Time series results of measurements of airborne radionuclides at four monitoring locations — the Fukushima Daiichi NPP, Tokaimura, Takasaki City, Tsukuba City (locations shown in Fig. 4.1–5) — are shown in Figs 4.1–7 (a)–(d). All off-site monitoring of activity concentrations of airborne radionuclides was performed at locations generally to the south-west of the plant. Three off-site locations were selected for Figs 4.1–7 (b)–(d). Activity concentrations of ^{134}Cs and ^{137}Cs were measured at all locations. Total ^{131}I was measured at all locations except for Takasaki City, where only particulate ^{131}I was sampled. Xenon-133 was also measured at Takasaki City, where a station of the International Monitoring System of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) is located. Data for approximately the first 50 days after the accident are shown [45–49].

Figure 4.1–7 (a) [45] shows the results of measurements performed at the Fukushima Daiichi NPP. It needs to be pointed out that significant releases had been occurring for approximately a week before on-site monitoring of activity concentrations of airborne radionuclides began. It should also be noted that on-site monitoring will detect most releases, even those eventually transported over the ocean, whereas the detection of releases at off-site locations will depend on the prevailing wind direction. Maximum activity concentrations of ^{131}I in air of almost 10 000 Bq/m^3 were measured in the period of 19–23 March 2011 and remained above 100 Bq/m^3 until mid-April. Activity concentrations of gaseous phase ^{131}I were consistently higher than particulate phase ^{131}I. Activity concentrations of ^{134}Cs and ^{137}Cs in air at the Fukushima Daiichi NPP were between 10 and 100 Bq/m^3 during March and early April for each radionuclide; elevated levels of well over 100 Bq/m^3 were measured later in April. These levels are particularly relevant when considering the exposure of workers on the site during the accident.

Figures 4.1–7 (b)–(d) [46–49] show the results of measurements performed at off-site monitoring locations. A number of peaks can be observed in these figures, detected with a fair degree of consistency at approximately the same dates at each location. The first was observed around 14–16 March. Measured levels of airborne ^{131}I were generally high relative to those of radiocaesium. The Japan Chemical Analysis Center [50] reported, on the basis of measurements using an in situ (outdoor) high purity germanium (HPGe) gamma spectrometer in Chiba, that the sharp rise observed during this period resulted from airborne ^{133}Xe, ^{131}I and ^{132}I. Two subsequent, more sustained, peaks were observed around 20–21 March and 29–30 March. Levels of ^{131}I, ^{134}Cs and ^{137}Cs were roughly equal in these later peaks. The timing of these peaks corresponds qualitatively to the main release periods that resulted in deposition onto the terrestrial environment; some influence of these releases can be observed in the results from all three locations. These results therefore support the pattern of releases and dispersion described earlier.

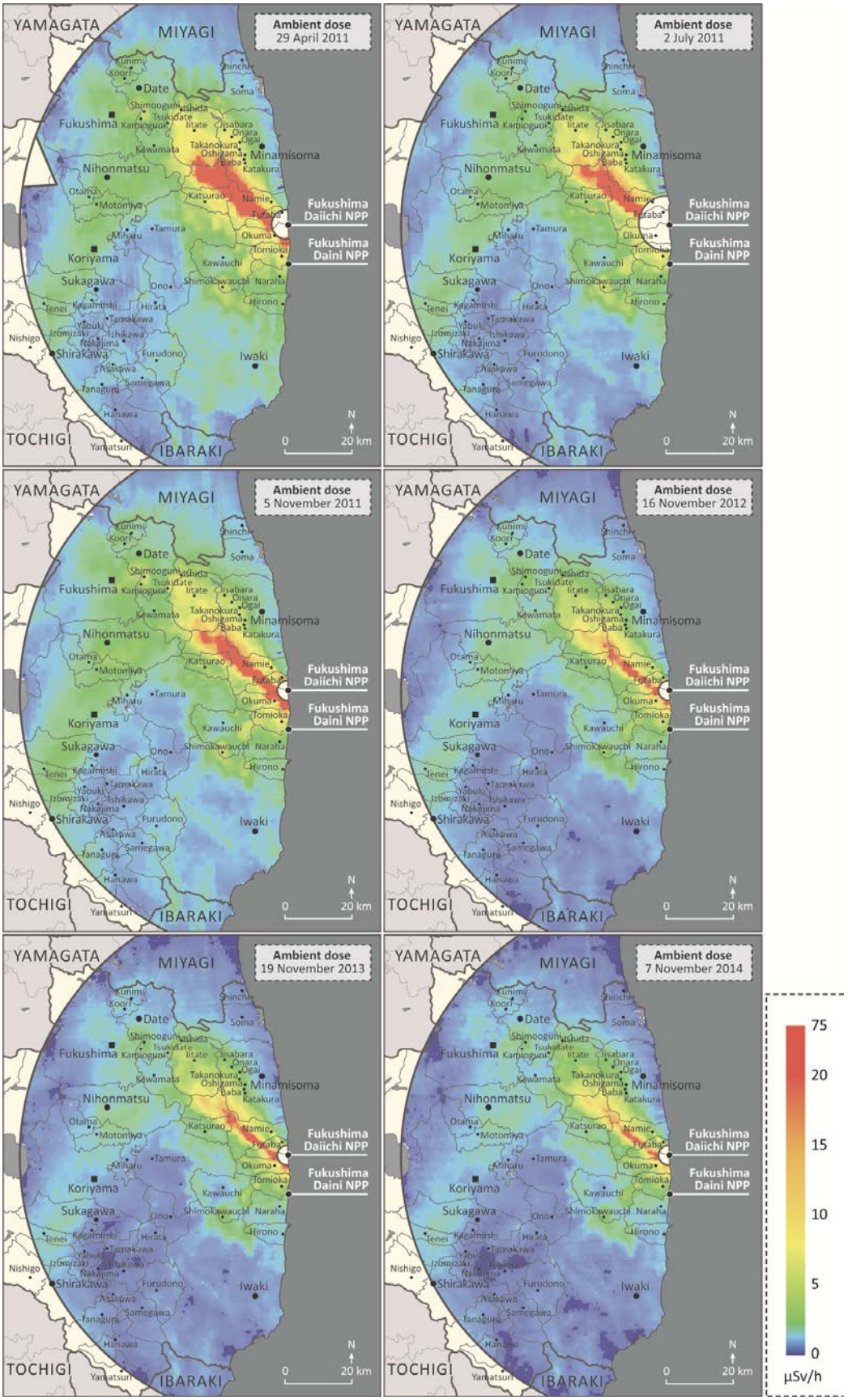


FIG. 4.1–6. Measured aerial ambient dose equivalent rate (in μSv/h) resulting from deposits from the releases that spread in areas to the north-west of the NPP [44].

Smaller peaks were observed in late April and in May, confirming that lower level releases from the Fukushima Daiichi NPP continued after the main release period of 12–23 March.

A maximum activity concentration of ^{131}I in air of 1600 Bq/m^3 was measured in Tokai City, the closest monitoring point to the Fukushima Daiichi NPP, on the morning of 15 March. Maximum activity concentrations of ^{134}Cs and ^{137}Cs of 180 and 190 Bq/m^3, respectively, were measured during the same sampling period. These values are of the same order of magnitude as those measured by Tokyo Electric Power Company (TEPCO) at the Fukushima Daiichi NPP (Fig. 4.1–7(a)) [45]. The maximum concentration of ^{133}Xe measured at Takasaki City was 400 Bq/m^3 on 16 and 17 March 2011.

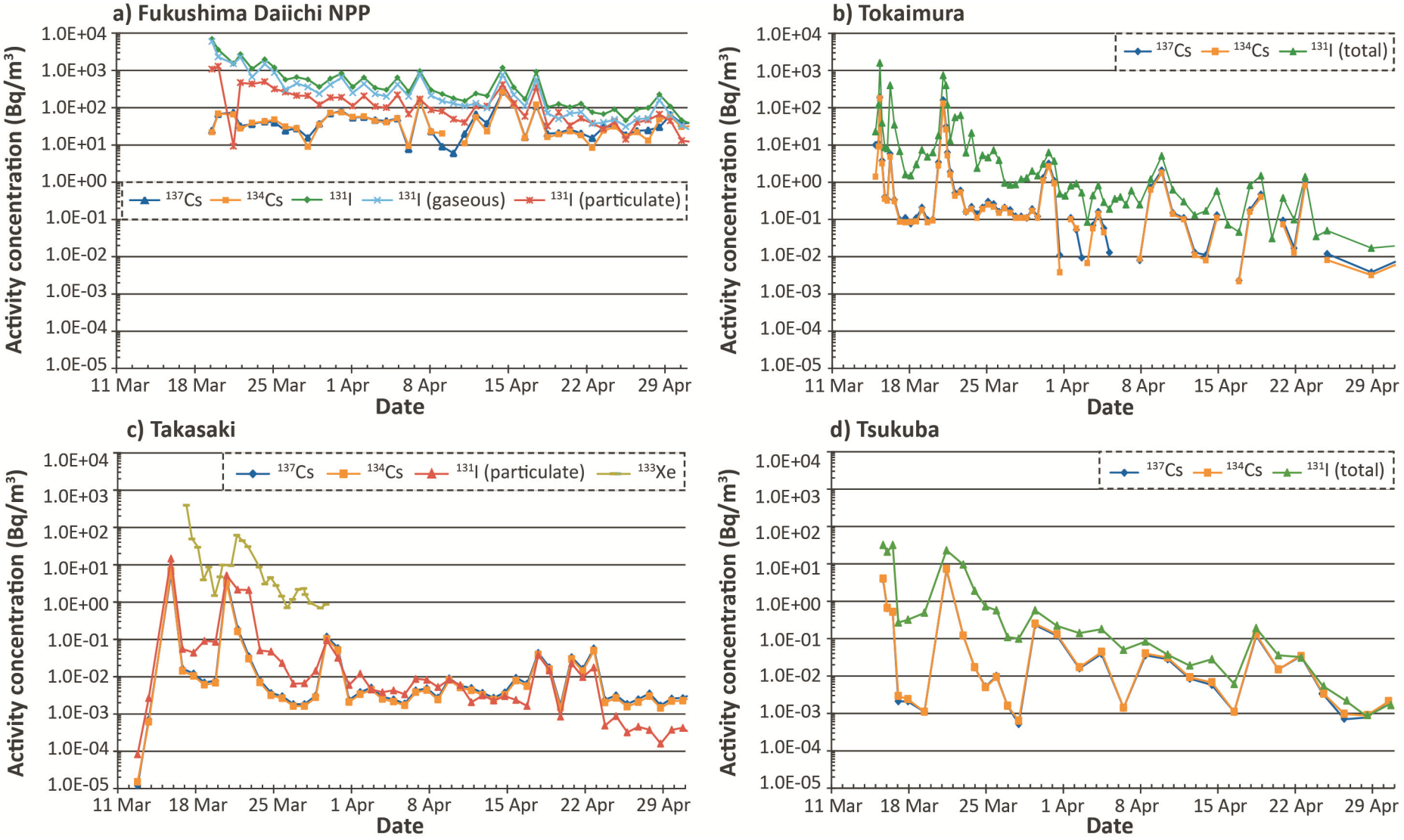


FIG. 4.1–7. Results of measurements of airborne radionuclides at four monitoring locations: at the Fukushima Daiichi NPP, Tokaimura, Takasaki, Tsukuba [45–49].

As can be seen from Fig. 4.1–8, the observed ratio of ^{134}Cs to ^{137}Cs was approximately 1 at all locations.

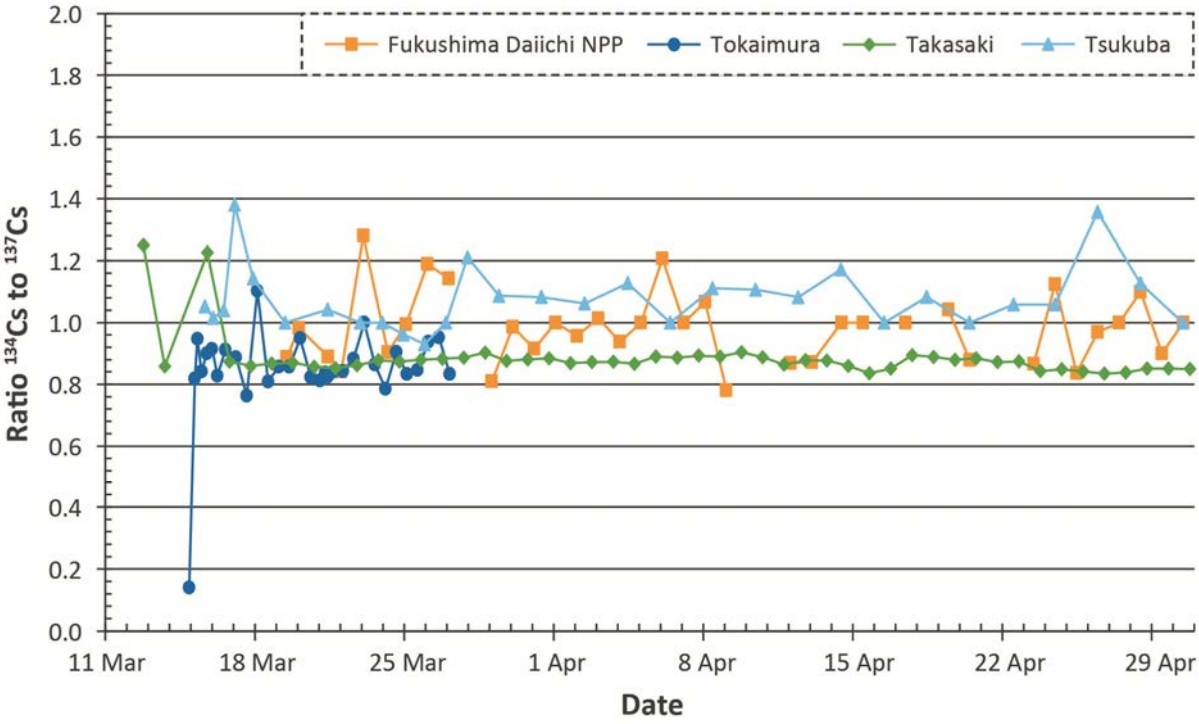


FIG. 4.1–8. Ratios of activity concentrations of airborne ^{134}Cs to ^{137}Cs [45–47].

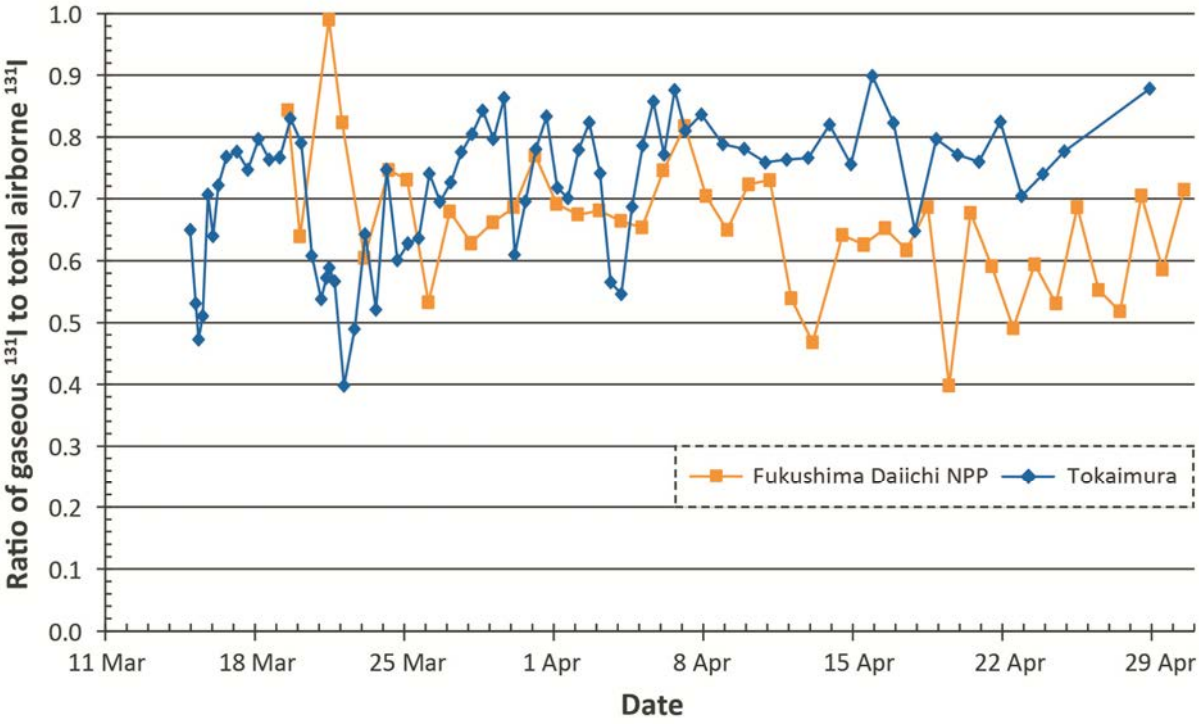


FIG. 4.1–9. Ratios of activity concentrations of gaseous ^{131}I to total airborne ^{131}I measured at the Fukushima Daiichi NPP site and at Tokai [45, 46].

The ratio of gaseous ^{131}I to total airborne ^{131}I is shown for two locations in Fig. 4.1–9. This ratio varied significantly with time and location, due in part to such factors as the different dry and wet deposition of the different forms of iodine, but it averaged around 0.8. Particulate iodine included all chemical species, particularly iodide (I^-) and iodate (IO^{3-}) [51]. The chemical form of iodine in rainwater was mainly in the anion exchangeable form. However, this also varied with time and location, with indications having been found that a portion of ^{131}I was bound to organic matter [52].

Daily deposition rates of ^{137}Cs and ^{131}I were measured in all prefectures in Japan from 18 March 2011, following the Fukushima Daiichi accident. The results for Fukushima Prefecture are shown in Fig. 4.1–10 for ^{137}Cs and ^{131}I. The results for surrounding prefectures are presented in Annex III. This monitoring was hampered in the early period by the damage caused by the earthquake and tsunami, particularly in Fukushima Prefecture. Elevated deposition rates in the period 20–23 March were measured in all prefectures, presumably as a result of the third period of significant releases, which resulted in terrestrial deposition of radionuclides from the Fukushima Daiichi NPP between 20 and 22 March.

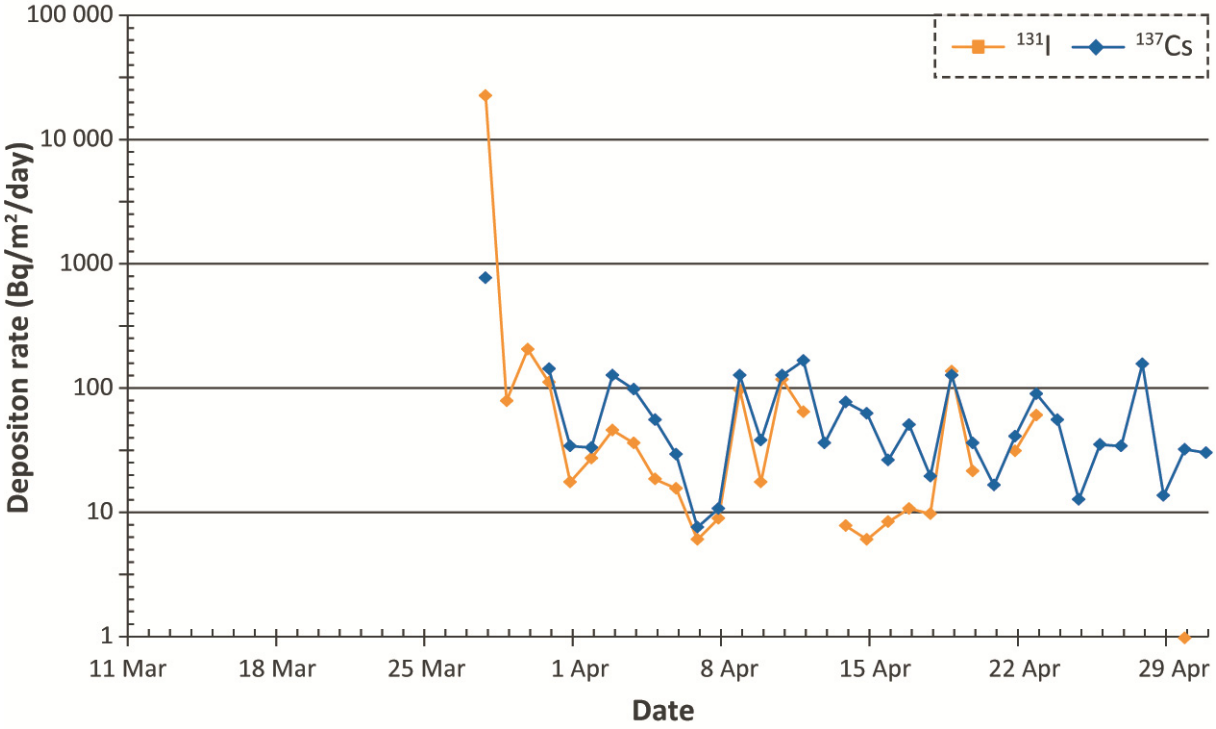


FIG. 4.1–10. Measurements of daily deposition of ^{131}I and ^{137}Cs in Fukushima Prefecture in 2011.

Monthly deposition rates have been measured at the prefectural level in Tokyo since 1954 and in neighbouring Tsukuba City since 1980 [53]. Figure 4.1–11 shows a series of monthly deposition rates of ^{137}Cs and ^{90}Sr, covering the period from 1955. The figure illustrates the effects of above ground nuclear weapons testing and the increased levels of deposition following the accident at the Chernobyl NPP. Also shown are the highest levels of deposition measured following the releases from the Fukushima Daiichi NPP in 2011. Levels of ^{137}Cs were around 2.3×10^4 Bq/m^2 per month in March 2011, compared with a peak from weapons fallout of 5.5×10^2 Bq/m^2 per month in June 1963. In contrast, the highest deposition rate of ^{90}Sr measured in March 2011 was 4.4 Bq/m^2 per month, which is significantly less than the highest deposition from weapons fallout of 170 Bq/m^2 per month in June 1963. This provides confirmation that low levels of ^{90}Sr were released from the Fukushima Daiichi NPP, as explained earlier.

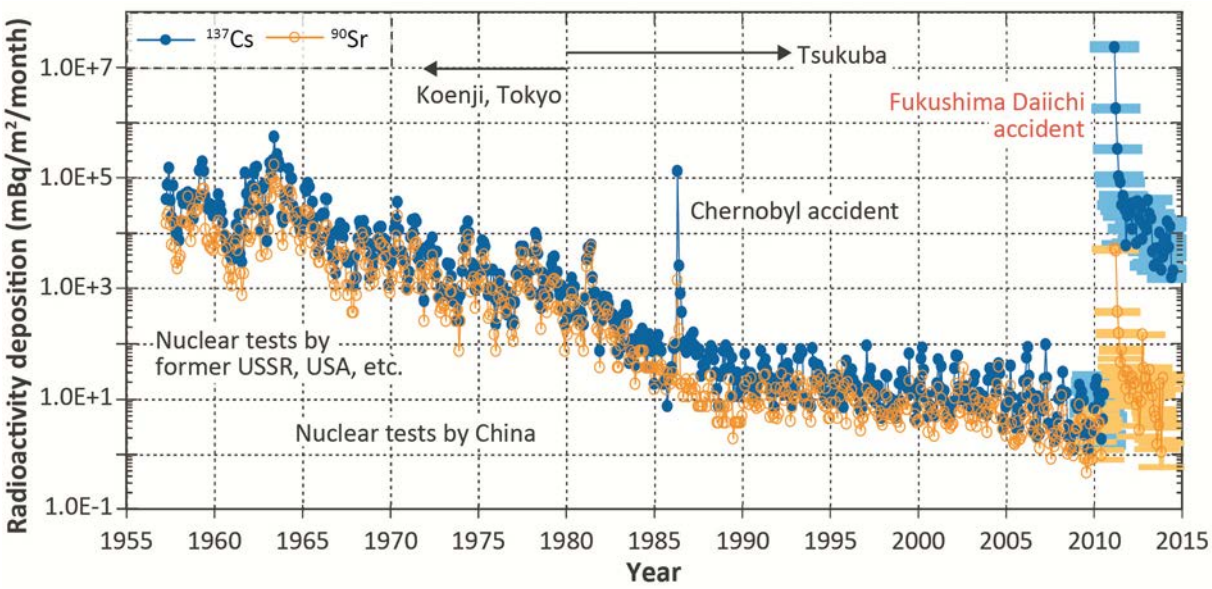


FIG. 4.1–11. Monthly deposition rates of ^{137}Cs and ^{90}Sr measured in Japan since 1955 (in Suginami ward, Tokyo, before 1980, and in Tsukuba City after 1980) [54].

It can also be observed that monthly deposition rates of ^{137}Cs measured in Tsukuba City are still elevated and comparable to those from fallout from atomic weapons tests measured in the mid-1960s [53]. Hirose [55] has analysed the temporal variation in deposition rates measured in several locations in Fukushima Prefecture and the Kanto plain for more than one year from the beginning of the releases and has concluded that there is evidence of resuspension supporting continued deposition of ^{137}Cs. The measured levels are not considered to be radiologically significant.

Information is available on the size distribution of the caesium particulates in the atmosphere. Kaneyasu et al. [56] measured size distributions of ^{134}Cs and ^{137}Cs in aerosols collected in Tsukuba City up to 47 days after the accident (see Fig. 4.1–5 — map of sampling locations). The median aerodynamic diameters of ^{134}Cs and ^{137}Cs in the first sampling period (28 April–12 May 2011) were found to be 0.54 μm and 0.53 μm, respectively, and their value in the second sampling period (12–26 May) was 0.63 μm in both cases. The authors concluded that caesium was associated with sulphate. Given this particle size, gravitational settling was not a significant dry deposition mechanism.

4.1.2.3. Distribution of radionuclides in the terrestrial environment

The radionuclides of most significance for assessing radiation exposures of people are ^{134}Cs, ^{137}Cs, ^{131}I and, to a lesser extent, ^{129m}Te. Caesium-134 and ^{137}Cs will persist in the environment for longer periods, determined by their physical half-lives (of around 2 and 30 years, respectively) and the behaviour of caesium in the environment. With a half-life of approximately eight days, ^{131}I was present in this environment for a few months following the accident, until the summer of 2011. Tellurium-129m persisted until about the end of 2011. Short lived radionuclides, particularly ^{136}Cs, ^{132}Te, ^{132}I and ^{133}I, lasted only days to weeks in the environment but may have contributed to early inhalation and external exposures as described in Section 4.2 below. Isotopes of strontium and plutonium were released in low quantities and were detectable in soil and other environmental samples and, with the exception of ^{89}Sr, will persist for many years.

A number of maps of the deposition densities of radionuclides released after the accident at the Fukushima Daiichi NPP has been produced. The most accurate are those based on soil sampling followed by laboratory analysis. Measurements in surface soil of ^{134}Cs, ^{137}Cs, ^{131}I, ^{129m}Te, ^{110m}Ag, ^{89}Sr,

^{90}Sr, ^{238}Pu and $^{239,240}Pu$ have been performed according to consistent sampling and analytical procedures (see Appendix I for details) and used to develop maps of the distribution of each radionuclide in Fukushima Prefecture and surrounding areas (see Appendix I). The area within a radius of 80 km of the Fukushima Daiichi NPP was divided into 2 km × 2 km grid squares. Five samples were taken from each grid square during a period between June and July 2011 and measured individually. The average result for each radionuclide was reported with a reference date of 14 June 2011. This information, together with in situ measurements of ambient dose equivalent rates, was used in the UNSCEAR assessment of radiation doses to the public living in different locations [5].

Maps of the deposition densities of ^{134}Cs, ^{137}Cs and ^{131}I have also been derived from aerial survey data. Repeated aerial surveys have resulted in the availability of 'snapshot' views of the deposition densities of ^{134}Cs and ^{137}Cs at intervals of a few months, thus enabling changes over time to be inferred (^{131}I had decayed to levels below the detection limit before the second and subsequent surveys). More information is presented in Appendix I.

A map of the deposition density of ^{137}Cs derived from laboratory analyses of soil samples is shown in Fig. 4.1–12. The map shows that the highest levels were measured in the evacuated areas: the Restricted Area within a radius of 20 km of the Fukushima Daiichi NPP and the Deliberate Evacuation Area[3] to the north-west of the plant. A maximum value of 15.5 MBq/m^2 was measured in a grid square from the municipality of Okuma located just north of the Fukushima Daiichi NPP. An average ambient dose equivalent rate of 54.8 μSv/h was measured in this grid at the same time as soil sampling was performed. Deposition densities of ^{137}Cs greater than 3 MBq/m^2 were measured in several other locations close to the plant — in Namie Town, Futaba Town and Tomioka Town, as well as in further locations in Okuma Town.

A similar map was developed for ^{134}Cs (see Appendix I). A $^{134}Cs/^{137}Cs$ isotopic ratio of 0.92 ± 0.07 was calculated from all measurements. After correcting the reported values for physical decay to the start of the main release phase on 12 March 2011, the ratio was found to be 1.00 ± 0.07. Therefore, it can be concluded that the two main isotopes of caesium were deposited in equal quantities. This decay corrected isotopic ratio is consistent with that derived from the results of monitoring of airborne radionuclides (see above).

[3] See Technical Volume 3 for more details on the various evacuation areas.

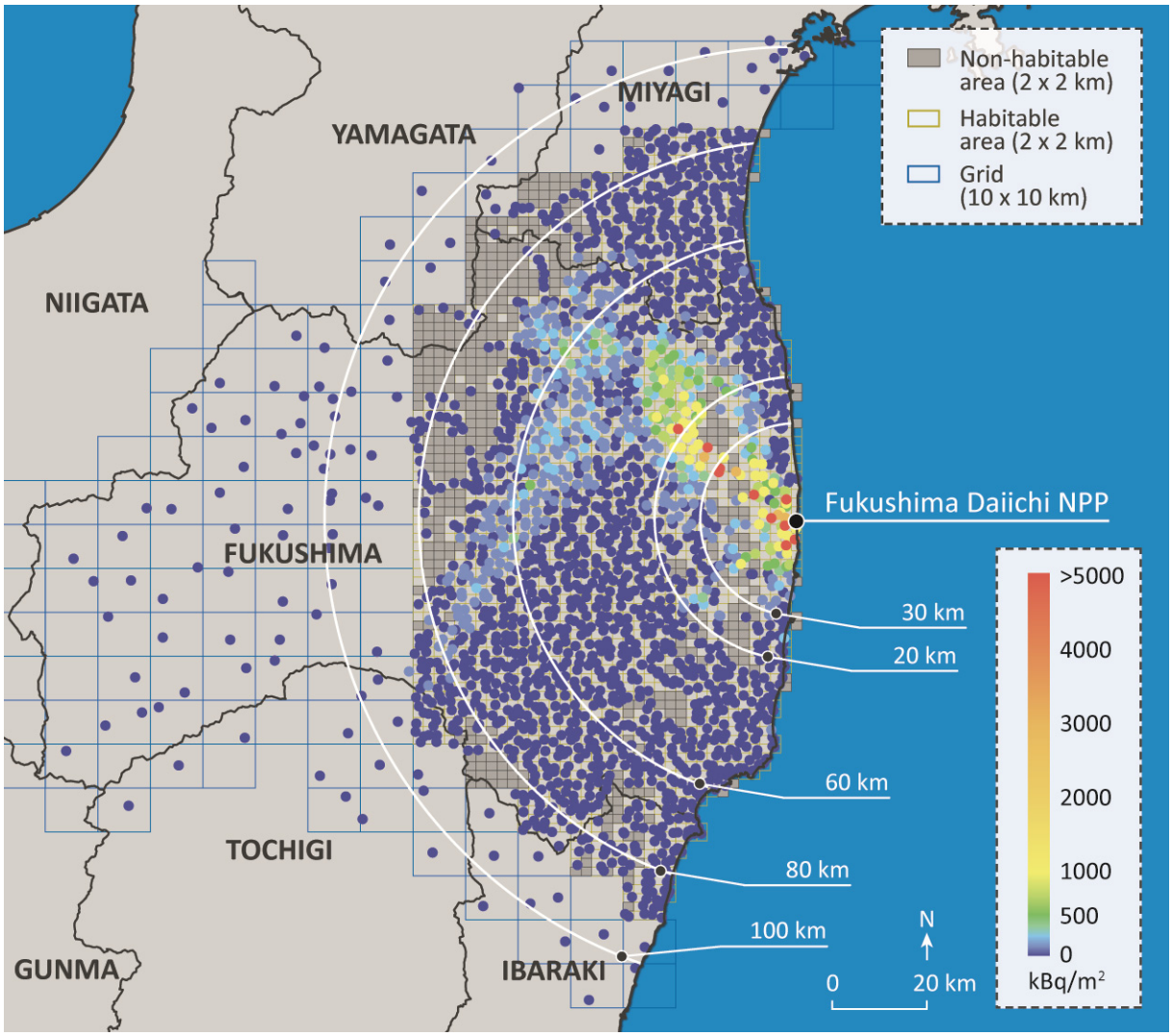


FIG. 4.1–12. Deposition density of ^{137}Cs from soil sampling and laboratory based analysis (decay corrected to 14 June 2011).

Maps of ^{134}Cs and ^{137}Cs derived from aerial survey results [7, 57–68] are shown for regular time intervals in Figs 4.1–13 and 4.1–14, respectively. It can be observed that the results are qualitatively consistent with those derived from laboratory analyses of soil samples. Some decrease in the levels of ^{134}Cs relative to those of ^{137}Cs can be observed for later surveys owing to radioactive decay of the shorter lived radionuclide.

The consistency of the soil sample measurements with the results of the first aerial[4] survey has been analysed quantitatively [69]. A high degree of correlation was found, thus providing confidence in the reliability of these key measurements of the pattern of radionuclides in the terrestrial environment.

[4] Referred to as 'airborne surveys' in MEXT literature.

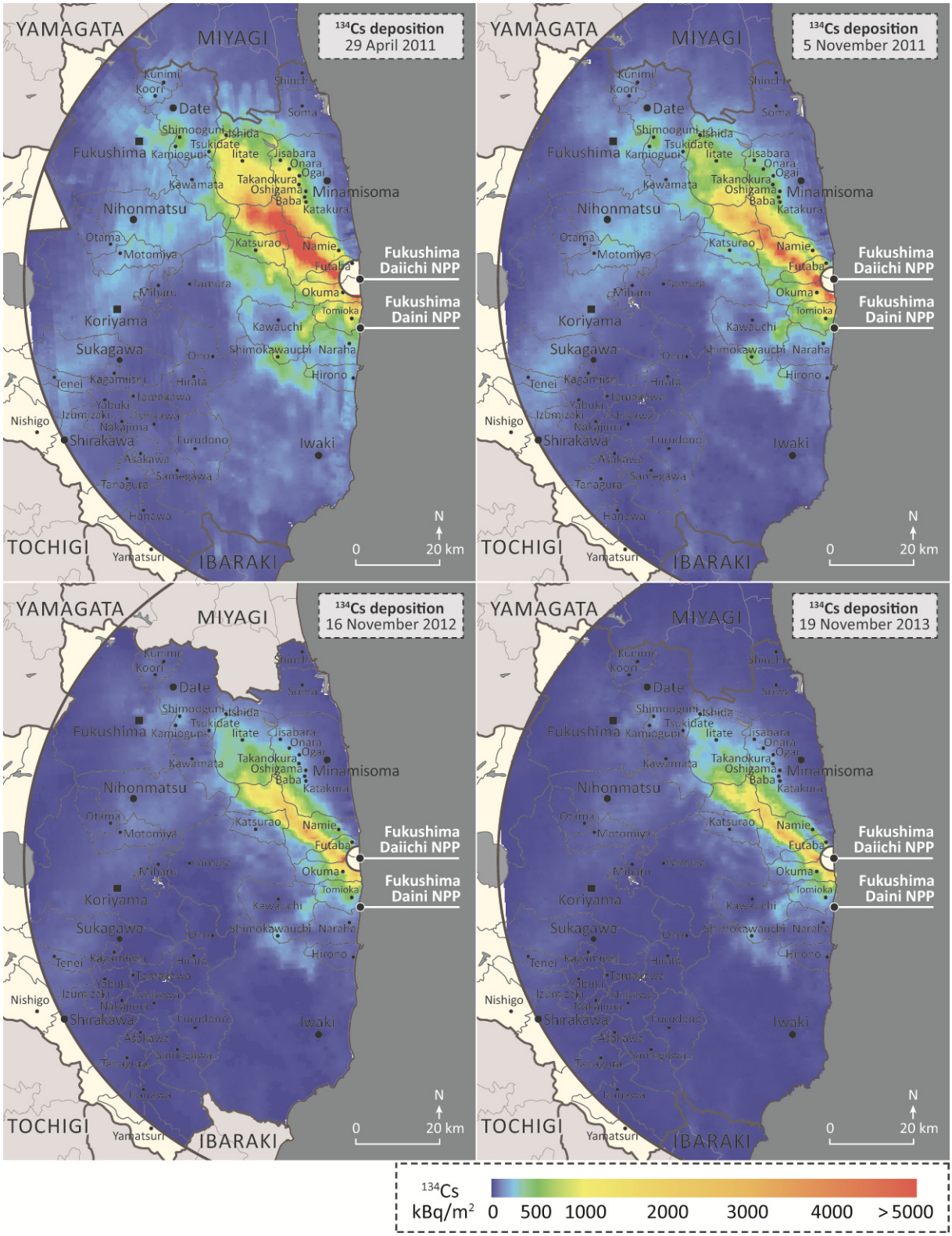


FIG. 4.1–13. Deposition density of ^{134}Cs as measured by aerial surveys.

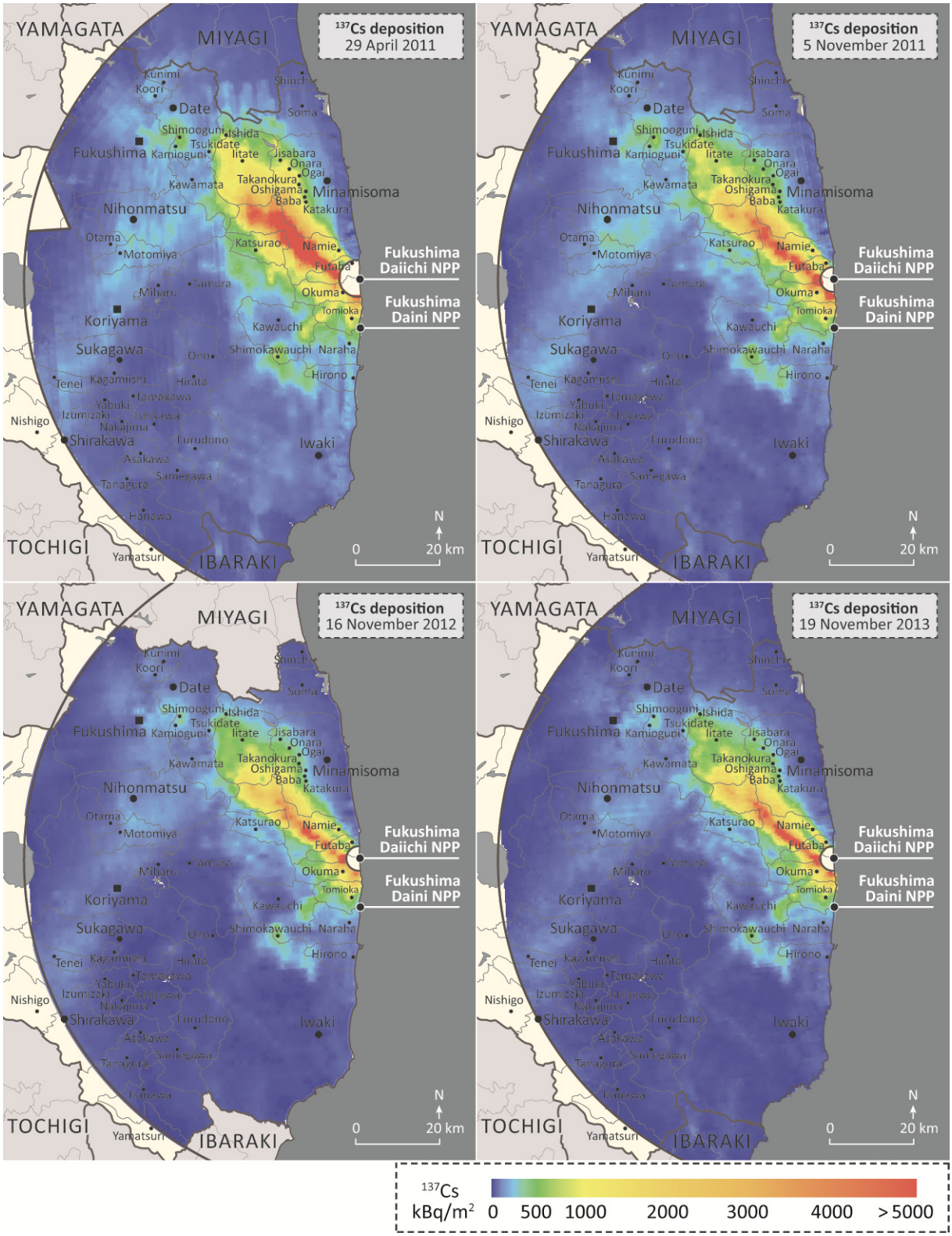
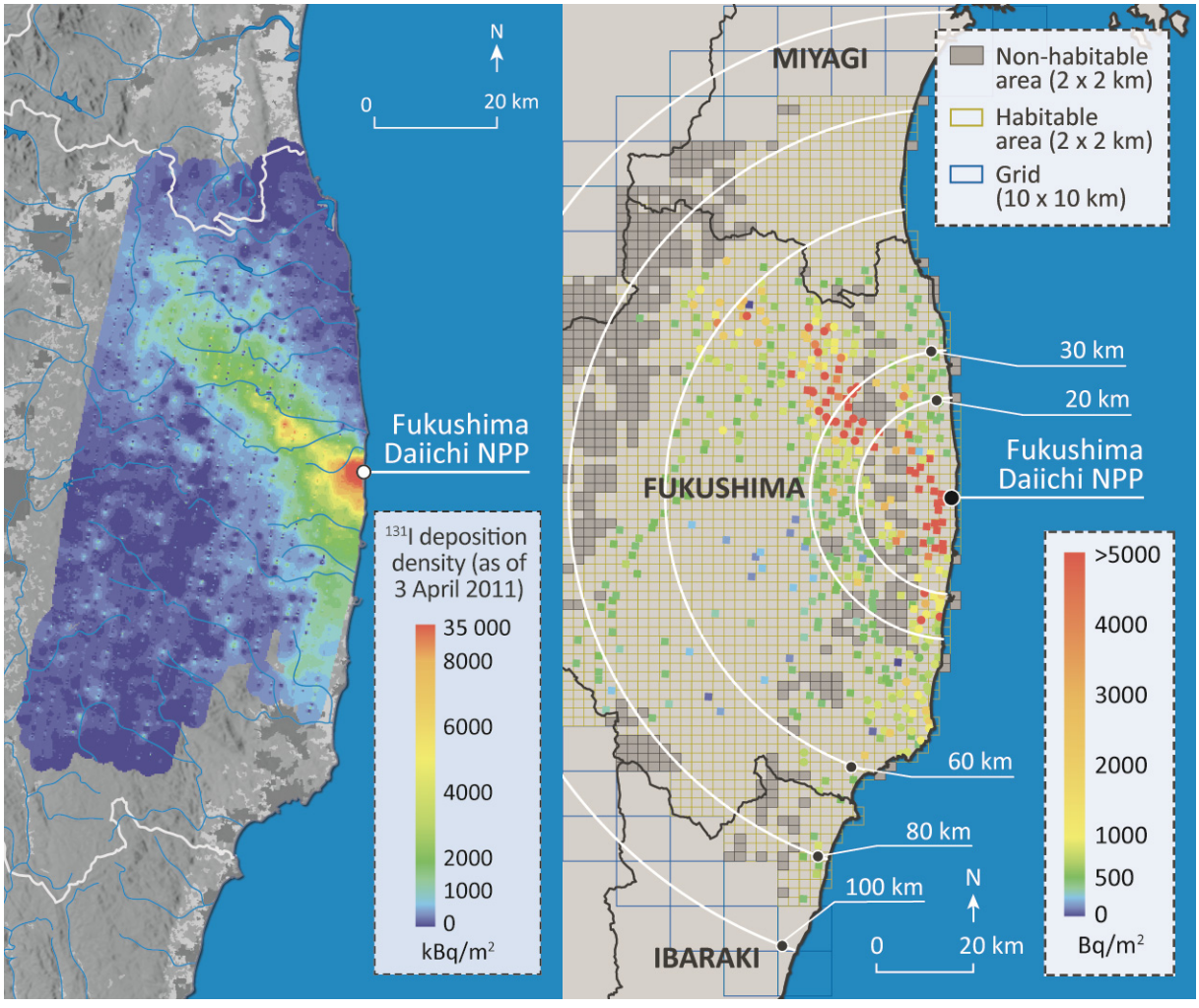


FIG. 4.1–14. Deposition density of ^{137}Cs as measured by aerial surveys.

Maps of the deposition density of ^{131}I derived from laboratory analyses of soil samples and from aerial survey results are shown in Fig. 4.1–15. The former dataset includes estimates of ^{131}I which were derived from accelerator mass spectrometry measurements of ^{129}I in the same soil samples using a calculated ^{129}I to ^{131}I conversion factor; the initial ratio between levels of the two isotopes ^{129}I/^{131}I was

~16 for rain water [70] and ~22.3 for soil samples, comparable with the estimated ratio from the operation history of the reactor (18–21) [71]. This additional analysis was required, as activity concentrations of ^{131}I in soil samples, collected some three to four months after the beginning of accidental releases from the Fukushima Daiichi NPP, had mostly decayed to levels that were undetectable by gamma spectrometry. The levels of ^{131}I were derived from aerial survey results by fitting iodine photo peaks to measured gamma spectra. This is a more accurate method than that used for the maps of ^{134}Cs and ^{137}Cs resulting from aerial surveys, which were derived by applying constant conversion coefficients.

A maximum value of 0.055 MBq/m^2 was recorded from a grid square in the municipality of Tomioka. This corresponds to some 187 MBq/m^2 when decay corrected to 12 March 2011. Deposition densities of ^{131}I of more than 5000 Bq/m^2 (17 MBq/m^2 when decay corrected to 12 March) were measured in several other locations close to the plant — in Okuma Town, Futaba Town, Tomioka Town, Namie Town, Iwaki City, Minamisoma City, Naraha Town and Iitate Village, as well as in further locations in Tomioka Town.



(a) (b)

FIG. 4.1–15. Deposition density of ^{131}I. (a) Map derived from aerial survey (normalized to 3 April 2011); (b) map derived from soil sampling and laboratory based analysis, including values derived from measurements of ^{129}I (normalized to 14 June 2011)

The different physicochemical forms of iodine and caesium resulted in different behaviour of these two elements in the atmosphere following release. As a result, a different deposition pattern from that of radiocaesium is expected and can be observed in the ^{131}I maps. Although the same pattern of high levels in the evacuated areas is evident, higher levels of ^{131}I relative to those of radiocaesium have been measured in areas to the south of the plant. It is not clear whether the different deposition pattern for ^{131}I and ^{137}Cs in the southern area compared with the north-western area is due to different deposition processes for these two elements or the result of different release times based on variations of reactor core temperatures.

Maps of the deposition densities of ^{129m}Te, ^{110m}Ag, ^{89}Sr and ^{90}Sr, and ^{238}Pu and ^{239,240}Pu are shown in Appendix I. In general, the deposition pattern of ^{129m}Te was similar to that of ^{137}Cs. This was to be expected given the similar chemical form and behaviour of caesium and tellurium in the atmosphere. However, a larger concentration of ^{129m}Te relative to that of ^{137}Cs was measured south of the plant. The different isotopic ratio may be the result of differences in the deposition process or differences in the time trend of the releases of ^{129m}Te and ^{137}Cs.

The deposition pattern of ^{110m}Ag is different from that of caesium, reflecting potential differences in release, transport and deposition behaviour. The concentrations were relatively low (a maximum value of 89 kBq/m^2 was measured from a grid square in Futaba Town).

A map of deposition densities of ^{89}Sr and ^{90}Sr is shown in Appendix I. Values of ^{89}Sr and ^{90}Sr of greater than 15.5 and 3.7 kBq/m^2, respectively, were measured in grid squares in Futaba Town and Namie Town. As previously noted, the measured levels of these strontium isotopes were three to four orders of magnitude lower than those of radiocaesium, reflecting the relatively low amounts released owing to the low volatility of this element.

Plutonium isotopes (^{238}Pu and ^{239,240}Pu) were measured in a number of samples from Fukushima Prefecture as shown in Appendix I. Isotopic ratios (^{240}Pu/^{239}Pu atom ratio ~0.32 and ^{238}Pu/$^{239+240}$Pu activity ratio of 1.1–2.9) were found to be distinct from those of global fallout and subsequently shown to have been characteristic of the fuel from Fukushima Daiichi Unit 3 [18, 72]. The activity concentrations measured are very low — close to, or often below, the limit of detection — and are not of any radiological significance. It is difficult to discern a clear pattern in the distribution of the measured levels of plutonium isotopes. The density of detected values is higher in the evacuated areas. However, where detected, the measured levels are similar throughout the survey up to an 80 km radius of the Fukushima Daiichi NPP. It is somewhat surprising that plutonium was detected so far from the release point and at levels comparable with those measured close to the site but this may be due to the importance of wet deposition at greater distances. There is no convincing evidence of hot particles (fuel fragments), which were ubiquitous following the Chernobyl accident [72, 73]. This is expected given the different nature of the events leading up to releases from the Fukushima Daiichi NPP compared with those at Chernobyl.

The maps in Appendix I provide a useful high level overview of the deposition footprint. However, there is significant inhomogeneity at smaller scales. This is reflected in the designation of several hundred ‘Specific Spots Recommended for Evacuation’, which were defined by Japanese authorities outside of the two main evacuation areas. These are small areas, often just tens of square metres, where the annual dose from deposited radionuclides was expected to exceed 20 mSv.

Rates of deposition of radionuclides are known also to be strongly influenced by surface cover and structure and, hence, different land uses such as forests, agricultural lands, water bodies and urban settlements.

As a consequence of the accident at the Fukushima Daiichi NPP, there was significant deposition of radionuclides on agricultural land in the prefectures of Fukushima, Iwate, Miyagi, Ibaraki, Tochigi,

Gunma and Chiba. Agriculture systems including paddy fields for rice cultivation, fields for various agricultural products and livestock feed, and storage reservoirs were affected by deposited activity. In the period from the accident until the early summer 2011, direct deposition of ^{131}I, ^{134}Cs and ^{137}Cs on the surface of products, especially on leafy vegetables and trees, was observed. Owing to its short half-life, ^{131}I was not detected in agricultural products beyond that date, and radiocaesium incorporated in plants by root uptake became dominant. Agricultural lands with activity concentrations exceeding 1000 Bq/kg are found in a wide area in the eastern part of Fukushima Prefecture, in a narrow area in the central part of the prefecture, and widely scattered in areas of the northern part of Tochigi Prefecture. The distribution of radiocaesium concentration in the soil on agricultural lands is further described in Annex III.

As the accident occurred before the period of rice planting (which is usually carried out in May in Fukushima Prefecture), the national Government issued a policy of restrictions on planting and cultivating rice in paddy fields where concentrations of ^{134}Cs and ^{137}Cs in soil exceeded 5000 Bq/kg, as described in Technical Volumes 3 and 5. Although concentrations higher than 25 000 Bq/kg were found in fields within the evacuated areas, no activity concentrations exceeding 5000 Bq/kg were found in paddy fields outside these areas. Thus, rice planting and cultivation was restricted only within the evacuation zones.

Beef contaminated with radioactive caesium levels exceeding 500 Bq/kg, which was the provisional regulation value at the time, was found in July 2011. The cause of these high levels was found to be rice straw, which had been contaminated during outdoor drying and distributed to the market to feed beef cattle [74].

Kato et al. [75] measured the depth distribution of ^{137}Cs, ^{134}Cs and ^{131}I in Kawamata Town, 40 km north-west of the Fukushima Daiichi NPP. The results of this study demonstrated that, at the time of the measurements (April 2011), more than 86% of the total radiocaesium and 79% of the total ^{131}I were in the upper 2.0 cm of the soil profile. The relaxation mass depth (kg/m^2), which quantifies the radionuclide penetration into the soil (the greater the value, the deeper the penetration of the radionuclide), derived from the depth distribution of radiocaesium and ^{131}I in the soil profile at the study site were 9.1 kg/m^2 and 10.4 kg/m^2, respectively.

Tanaka et al. [76] carried out leaching experiments on different soil samples and revealed that most of the ^{137}Cs was attached to soil particles. In contrast, ^{131}I was leachable using an acidic solution, and the dissolved fraction of ^{131}I increased in an alkaline solution.

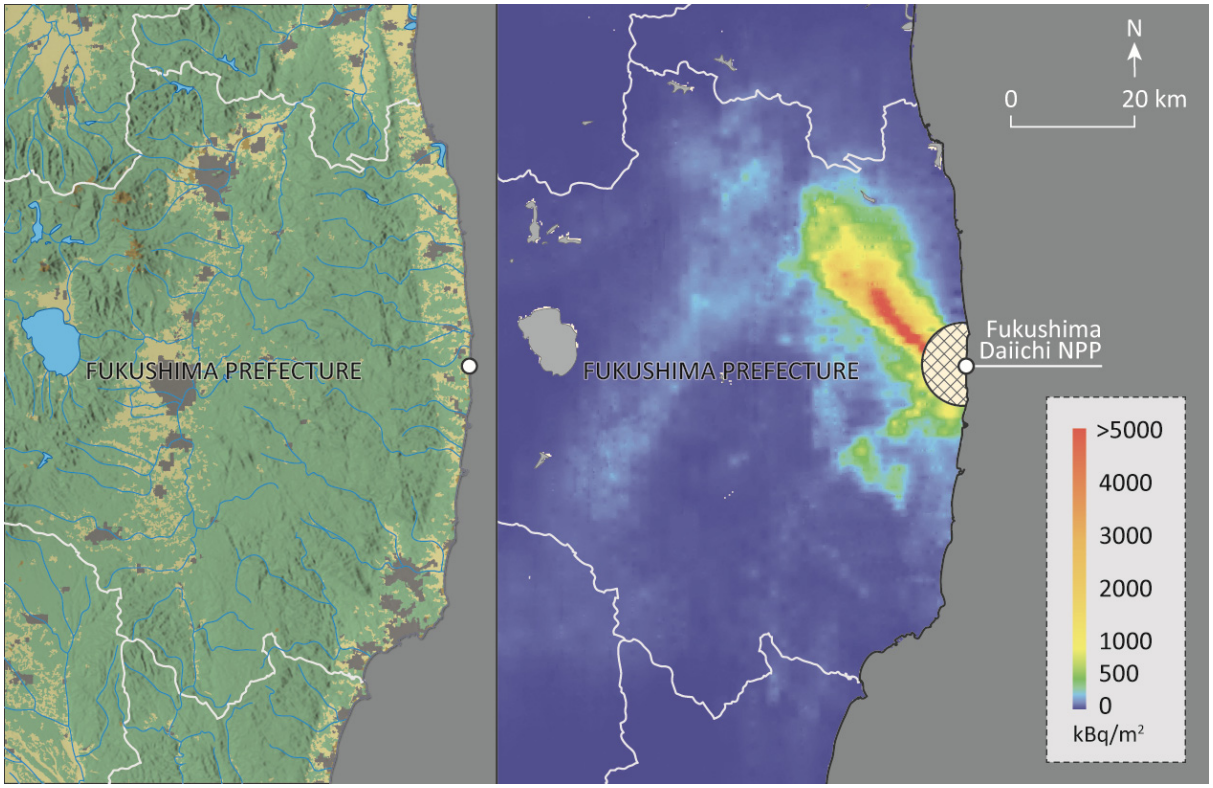
Relatively high levels of ^{137}Cs and ^{131}I were found in grass samples in Yagisawa (Iitate Village) just after the rainfall (snowfall) owing to direct deposition. However, for rice, the most important staple food in Japan, the major transfer process for radiocaesium is considered to have been uptake from the soil, because rice was not planted until after the main accidental releases from the Fukushima Daiichi NPP had ceased.

Forest covers approximately 70% of the land area of Fukushima Prefecture, so a significant part of the radionuclides deposited on the terrestrial environment entered the forest ecosystem. The surface of the canopy differs depending on the forest type and the season. At the time of the accident, deciduous forests were without leaves and deposition on the canopy was limited; radionuclides were deposited directly onto the litter and forest floor. However, analyses of ^{137}Cs, ^{134}Cs and ^{131}I in rainwater, throughfall and stemflow in coniferous forests indicated that more than 60% of the total deposited radiocaesium remained in the forest canopy after 5 months, while ^{131}I moved through the canopy with rainwater [75]. Ten months after the accident, radiocaesium was concentrated at the floor of coniferous forests, and high transfer factors were observed in undergrowth plants [77]. By 2014, around 99% of the total inventory of ^{137}Cs was found in soil within the top 10 cm, in which organic

matter content was greater than 10%. This suggests that subsequent distribution will be dependent on the turn-over of organic matter.

The distribution of radiocaesium in tree stems of a conifer (Japanese red pine) and a broad leaved species (Japanese konara oak) was investigated 1.5 years after the accident. The activity concentrations were highest in the outer bark, followed by the inner bark and the wood. The vertical distribution varied with species [78]. The impact of releases on the forests is described in more detail in Annex III.

The distribution of radionuclides in the environment is strongly influenced by topography. The deposition density of radiocaesium measured by an aerial survey in October 2011 [60] in the Tohoku and Kanto regions is shown in Fig. 4.1–16, adjacent to a topographical map of the area. Elevated levels can be clearly observed in the mountainous regions, i.e. the Ou Mountains, Iide Mountains, Echigo Mountains and Kanto Mountains. The mountains seem to have formed an effective barrier, preventing significant further transport of radioactive material further westward.



(a) (b)

FIG. 4.1–16. (a) Topographical map of Fukushima Prefecture; (b) map showing total deposition density of ^{137}Cs (kBq/m^2) estimated based on the results of aerial monitoring [60, 79](decay corrected to 13 October 2011) illustrating the influence of the mountains to the west of Fukushima Prefecture on deposition pattern.

4.1.3. Deposition and releases to the marine environment and radioactivity in the aquatic environment

4.1.3.1. Deposition and releases into the Pacific Ocean

As described in Technical Volume 1, Section 1.4, radionuclides were introduced to the Pacific Ocean from the Fukushima Daiichi accident. Several processes have contributed, or are still contributing, to levels of radionuclides in the ocean as a result of the accident:

— Deposition on the ocean surface of radionuclides released to and transported by the atmosphere (12–30 March 2011);
— Unintentional release of highly contaminated water from pit near the intake channel of Unit 2 (1–6 April 2011);
— Planned discharge of low level radioactive accumulated water from storage tanks (4–10 April 2011);
— Unintentional release of water containing moderate amounts of radionuclides (10–11 May 2011);
— Inflow of contaminated water (including groundwater and treated retained water from the site) (May 2011–present).

There is also likely to be runoff of deposited radioactive materials following rain, typhoons, tides and so on.

The most significant of these sources are thought to be atmospheric deposition on the ocean surface and the direct release of highly radioactive water from a pit adjacent to Unit 2. Key factors leading to radionuclides entering the marine environment are summarized below [5]. Further information on the events leading to these releases is given in Technical Volume 1 (Section 1.4).

Atmospheric deposition on to the ocean

Before 25–26 March, the most significant source of radionuclides in the ocean arising from the Fukushima Daiichi accident was deposition of radionuclides released to the atmosphere. For example, Ref. [80] considers that, before the end of March 2011, the concentrations of radioactive material in the sea were mainly influenced by deposition. As indicated in Section 4.1.1, the dominant weather pattern for much of the period when the larger releases from the Fukushima Daiichi NPP occurred was associated with westerly winds, i.e. moving eastwards and leading to the wet and dry deposition of the airborne radionuclides (notably ^{137}Cs, ^{134}Cs and ^{131}I) over the Pacific Ocean. There were no measurements of dose rate above the ocean surface during the first weeks of the accident (the first aerial survey over the sea took place on 5 April). The estimates of radioactivity deposited are therefore uncertain.

The amount of ^{137}Cs released to the atmosphere was estimated to have been between 7 and 20 PBq, of which between 0.18 and 10 PBq has been estimated to have been deposited onto the ocean [1, 81–84], as described in more detail in Technical Volume 1, Section 1.4. Atmospheric deposition of ^{137}Cs on land and ocean has been estimated with large scale atmospheric transference models in the intercomparison exercise [35] (see Annex IV).

For the purpose of the assessment in their 2013 report [5], UNSCEAR estimated the range of indirect releases to the ocean due to atmospheric dispersion and deposition to be between 5 and 8 PBq for ^{137}Cs and between 60 and 100 PBq for ^{131}I.

Direct release of contaminated water

There were no observations of the concentration of radionuclides in sea water until 21 March 2011, near the southern outlet of the NPP, and 23 March, near the northern outlet of the Fukushima Daiichi NPP. Therefore, it is difficult to evaluate the direct release from the site to the ocean during the first few weeks of the accident. The evaluated values of ^{137}Cs directly released to the ocean ranged from around 2.3 to 26.9 PBq [80, 84–88]. Additional information is presented in Annex IV.

The main source of the direct releases of radionuclides to the ocean was the large amounts of sea water injected to cool the reactors and the structural damage that some of the pressurized containment vessels had suffered. Progressively larger amounts of heavily contaminated water accumulated inside the reactor and turbine buildings over time. As of September 2013, the total radioactivity of water inside the basements, trenches, and shafts was evaluated at 12.6 PBq [89]. During 2011–2013, three main events led to direct releases of some of this water containing radionuclides to the ocean:

(1) The first event was discovered at around 09:30 on 2 April 2011, when TEPCO found that water with a dose rate reading of over 1000 mSv/h was leaking directly into the sea through a 20 cm crack in the wall of a pit that was storing electric cables, near the intake channel of Unit 2 [90]. During the following days, several measures were taken to stop the release of water, which was eventually achieved at 05:38 on 6 April. Based on the calculated leakage flow and sampling results, TEPCO assessed the total inventory of radioactive material released with water at 4.7 PBq [91].
(2) An outflow of contaminated water into the sea occurred through a leak from a pit near the intake channel of Unit 3 and was discovered at 16:05 on 11 May 2011. It was stopped at around 18:45 on the same day. The total amount of radioactive material discharged into the sea was estimated at 0.02 PBq.
(3) The third event was an intentional discharge of wastewater with relatively low levels of radionuclides into the ocean in April 2011. This was to prevent a possible leakage of radioactive wastewater with high levels of radionuclides, which had accumulated in the basement floor of the turbine building of Unit 2. TEPCO decided to discharge the low level radioactive water accumulated in the radioactive waste treatment facilities and sub-drains of Units 5 and 6 and replace it with the highly active radioactive wastewater from Unit 2. About 10 393 t were discharged from 4 to 10 April 2011. The total amount of radioactive material released to the ocean is estimated to have been about 1.5×10^{11} Bq [92].

The total quantity of ^{137}Cs released directly to the ocean has been estimated with oceanic dispersion simulation models in an intercomparison experiment (see Annex IV).

Based on the available information, UNSCEAR used a range for the direct discharge of ^{137}Cs to the ocean of 3–6 PBq and about 10–20 PBq for ^{131}I, noting that the larger range was based on other studies [5]. As described in Annex IV and Technical Volume 1, Section 1.4, the direct releases and discharges of ^{137}Cs are generally estimated to be 1–6 PBq, but there are assessments that have reported estimates of 2.3–26.9 PBq [35]. Measurements of activity concentrations in ocean water close to the Fukushima coast show that, although the release rate has decreased, radioactive materials are still entering the ocean. The possible sources of continued releases are likely to be the drainage of groundwater transferring radioactive materials from the basements of reactors or trenches or, to a lesser extent, leakage from storage tanks, as well as runoff of radionuclides from sediments and the ground during rain.

As explained above, a long term source of radionuclides released to the ocean is through the transfer of radionuclides to groundwater and to rivers and hence to the oceans. The levels released in this way are significantly lower than those discharged in March to May 2011 but these environmental transport

processes would be expected to continue for a period determined by radioactive decay and other physical and chemical processes.

4.1.3.2. Dispersion of radionuclides in the marine environment

The Fukushima Daiichi NPP is located adjacent to the Kuroshio-Oyashio Transition Area, which is the region of confluence of two wind-driven western boundary currents of the North Pacific: the Kuroshio, which transports warm, saline waters northwards along the south coast of Japan and then eastward; and the Oyashio, which transports cold, less saline water southwards [93]. The convergence of the two currents is marked by the creation of several intense mesoscale eddies. Another characteristic of the region is the Tsugaru Warm Current, flowing from the Sea of Japan through the Tsugaru Strait north of Honshu [94] and then southwards along the slope of its east coast.

Further information on the bathymetry and predominant currents during the time of the main release events in April 2011 are presented in Annex IV.

Marine dispersion and deposition

The dispersion of radionuclides released to the ocean depends on a number of factors, including the movement of the ocean currents illustrated above. Mixing of radionuclides with the ocean water is also influenced by the interaction of mesoscale structures and coastal waters where they meet on the shelf break, generating flows across the shelf break [85]. The dispersion in the shallow shelf waters is primarily driven by winds, tides and freshwater inputs. There are two regions with different dominant physical processes related to the dispersion of radionuclides released directly to the ocean. Before reaching the open ocean, where large scale currents and mesoscale structures will transport and disperse them, the radionuclides are transported by the coastal circulation on the continental shelf. The coast creates a blocking effect that reduces dispersion and induces a dominant alongshore transport. In 2011, during the three months following the Fukushima Daiichi accident, the strongest winds blew predominantly toward the south (south-east or south-west) and towards the north. In the first case, the wind induced downwelling, with surface waters pushed against the coast, and the emergence of a coastal jet flowing southwards. In the case of winds blowing north, the wind produced an upwelling. The resulting alongshore component of the transport was northward, but an additional perpendicular drift tended to spread coastal waters toward the external shelf and the slope. This dispersal favoured interaction with the offshore currents flowing southward along the slope, the Tsugaru and Oyashio Currents, as well as the residual tidal current.

Some 80% of the deposition of radionuclides from atmospheric releases from the Fukushima Daiichi NPP was spread on the ocean surface beyond the continental shelf [35]. Thus, these radionuclides were entrained by mesoscale structures characteristic of the region and by large scale currents, which enhanced their dispersion. The major surface current systems in the Pacific Ocean are the subpolar (subarctic) Gyre, the North Pacific Gyre and the South Pacific Gyre (Fig. 4.1–17). In the western North Pacific, the main currents are, as described above, the Oyashio and the Kuroshio, which are of primary importance for the dispersion of radionuclides released from the Fukushima Daiichi NPP. It has been shown that the North Pacific Current can transport radionuclides eastwards at a velocity of about 200 km/month [95]. In the eastern North Pacific, the main currents are the counter-clockwise Alaska Current in the north and the California Current, which is part of the North Pacific (subtropical) Gyre, flowing southwards along the western coast of North America. The Pacific equatorial current system is complex and consists of the North Equatorial Current, the North Equatorial Countercurrent and the South Equatorial Current. Significant equatorial subsurface flows include the Northern Subsurface Countercurrent, the Equatorial Undercurrent and the Southern Subsurface Countercurrent. Notwithstanding the complexity of the equatorial current system, the equatorial flow is predominantly eastward [96]. The dominant large scale structure in the South Pacific Ocean, the South Pacific

(subtropical) Gyre, includes the East Australian Current and the Peru Current. South of the Gyre, the Antarctic Circumpolar Current transports water eastwards.

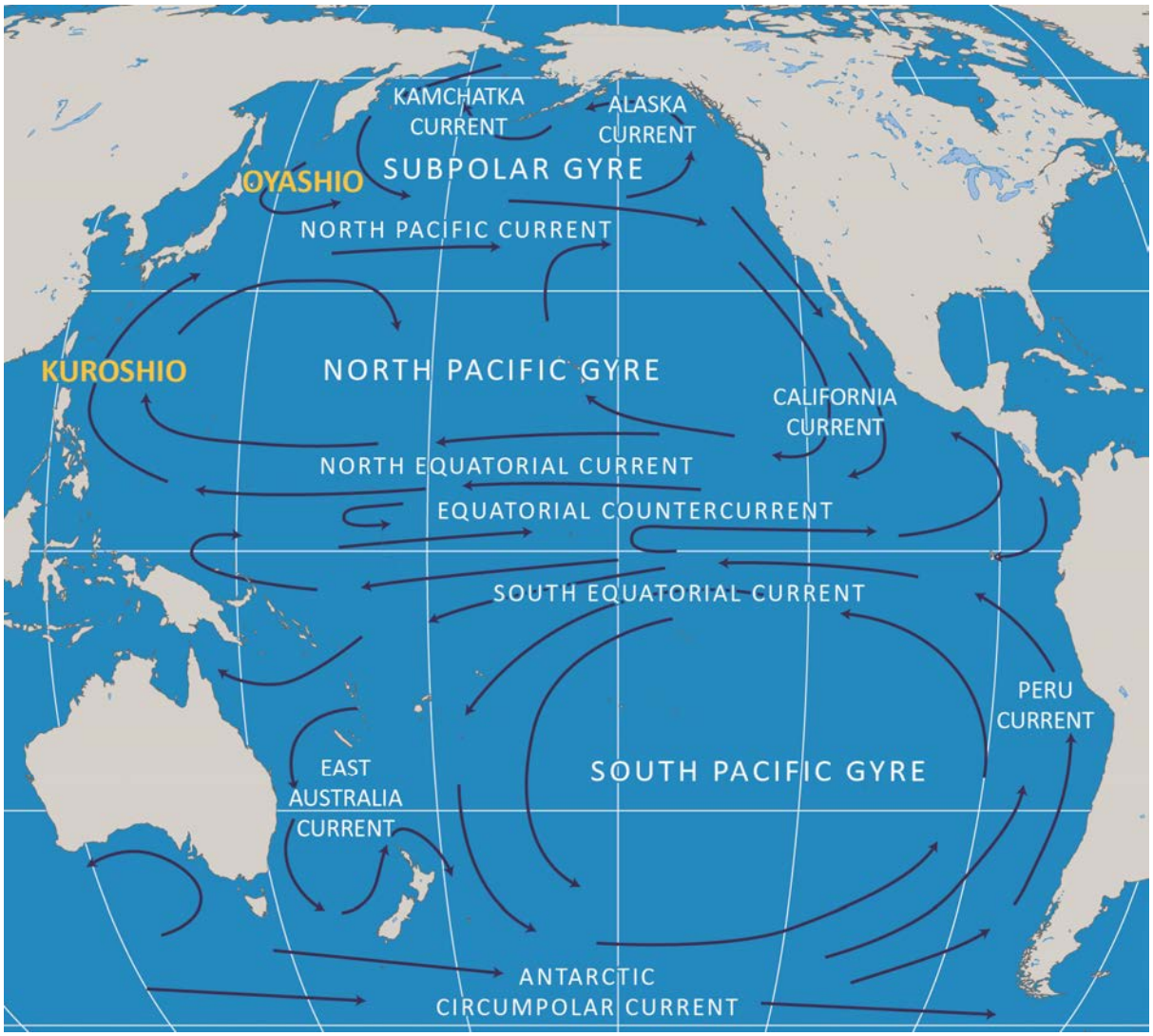


FIG. 4.1–17. The major surface currents in the Pacific Ocean (adapted from [99]).

The even larger scale global circulation (‘conveyor belt’ system) transports cold and salty Antarctic Circumpolar Bottom Waters from the South Pacific to the North Pacific, upwelling to shallower depths in the North Pacific Ocean. Warmer surface waters in the western North Pacific Ocean then move across the Pacific to the Indian Ocean through the Indonesian Straits [97].

The vertical profiles of temperature and salinity (density) in the ocean are indicators of vertical mixing processes and are a signature of the water masses at the respective point. A surface mixed layer with constant temperature and salinity, with a seasonally and geographically variable thickness of 10–200 m over most of the tropical and mid-latitude belts, results in downward mixing of any radionuclides deposited on the ocean surface. Relatively uniform distributions of radionuclides can be expected down to the bottom of the mixed layer (thermocline), followed by a sharp decrease below that. The mixed layer is deepest in winter, and further downward penetration of radionuclides originating at the surface can take place depending on the structure and flows of intermediate and deep water masses. In the North Pacific, besides the eastward transport of radionuclides by surface

currents, the formation and subduction of subtropical mode waters and central mode waters result in southward and westward subsurface transport [95, 98].

The mixing of waters brought by the Kuroshio and the Oyashio currents, formation of eddies and further sinking of surface water masses can also entrain different dispersal patterns for radionuclides released from the Fukushima Daiichi NPP.

There are a large number of rivers flowing into the coastal waters around the Fukushima Daiichi NPP. These rivers are drivers of coastal circulation, through their input of fresh, less dense waters. They also act as secondary sources of radionuclides initially deposited then later remobilized, washed off and entrained from the catchment area to the coastal waters. Radionuclides deposited on fine particles in various sections of rivers can also be entrained by high waters in the rainy or snowmelt seasons and reach the river mouth. Important geochemical and depositional processes take place at the mouths of the rivers (estuaries), where fresh and salty waters mix. This can result in areas with higher concentrations of radionuclides. The main rivers in the region are the Natori and Abukuma Rivers flowing into the Sendai Bay, to the north of Fukushima. Their average flows into the sea are 190, 17 and 67 m^3/s, respectively [85].

The interaction of radionuclides with sediments suspended in the water mass and with bottom sediments is a process that can deplete radionuclides from the water column and increase their inventories in bottom sediment. These processes are important for particle reactive radionuclides, especially in the coastal zone, where there are more particles in suspension. The degree to which radionuclides interact with sediments is influenced by the nature of the sediments (composition) and grain size; coarse sands and silts exhibit the lowest affinity for interaction, while fine clays have the highest. Movement of fine sediments on the seafloor because of the action of waves and currents, combined with the influence of the bottom topography, can result in a very patchy pattern of bottom sediment radioactivity, with areas of high concentration on the scale of 1–100 m [100]. Deposition and mixing through physical and biological processes can reduce the concentrations of radionuclides in the surface layer of bottom sediment.

The complexity of oceanographic processes combined with the complex source term (including direct liquid releases to the coastal ocean and atmospheric deposition further offshore) renders the understanding and the prediction of distributions and dynamics of radionuclides released from the Fukushima Daiichi NPP challenging. A number of models have been applied to estimate the dispersion of ^{137}Cs in the North Pacific Ocean and the results of some of these are illustrated in Fig. 4.1–18. This shows the estimated activity concentration of ^{137}Cs in water as a function of time and uses the original code of colours employed in each particular reference. As in the case of atmospheric dispersion, small changes in the degree or tone of the colours correspond to a one order of magnitude change in the activity concentration. This illustrates that the activity in the ocean decreased significantly with distance from the Fukushima Daiichi NPP. The first graphic, Fig. 4.1–18(a), presents an example of modelling the dispersion of ^{137}Cs in sea water from 21 March 2011 to 29 June 2012 [101, 102]. The second, 4.1–18(b), presents an example of simulated horizontal distribution of ^{137}Cs in surface waters between 14 and 26 April 2011 [103]. The third graphic, 4.1–18(c), presents an example of the horizontal distribution of the ^{137}Cs concentrations averaged over a ten day period from 21 to 30 April 2011 [35]. All models show that the activity of ^{137}Cs in the ocean was very low. Some further information on the models is given in Annex IV.

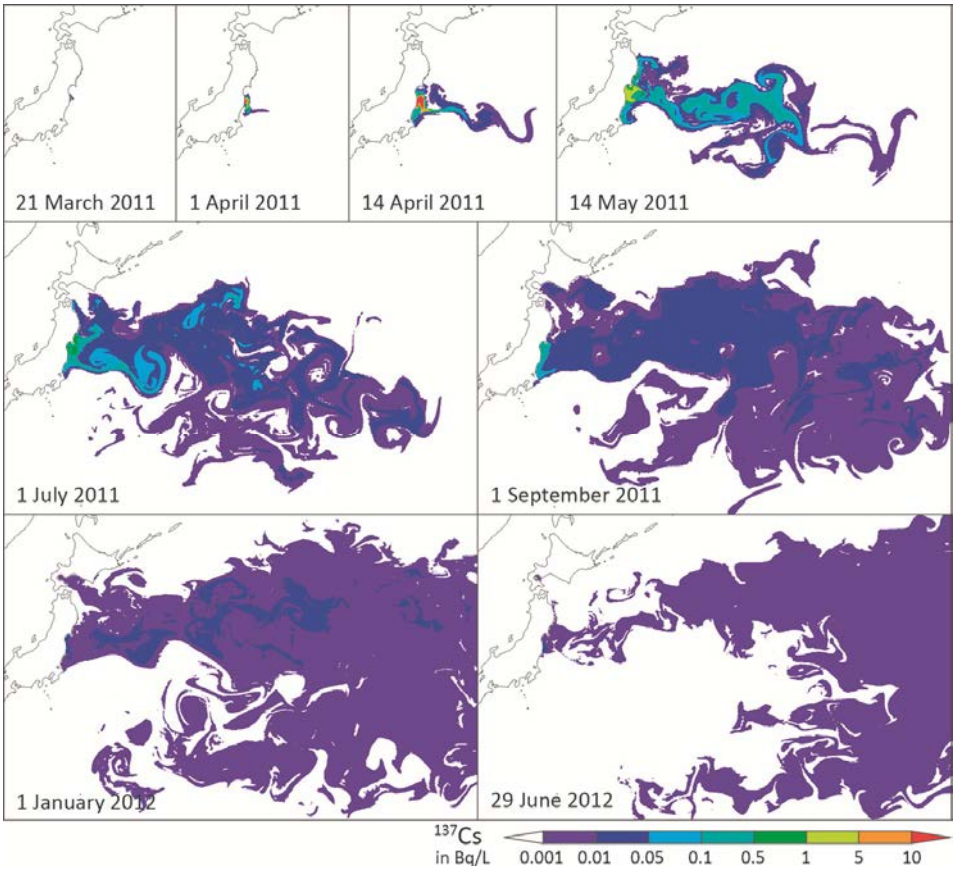


FIG. 4.1–18 (a). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from an oceanic model for the period from 21 March 2011 to 29 June 2012 [104, 105];

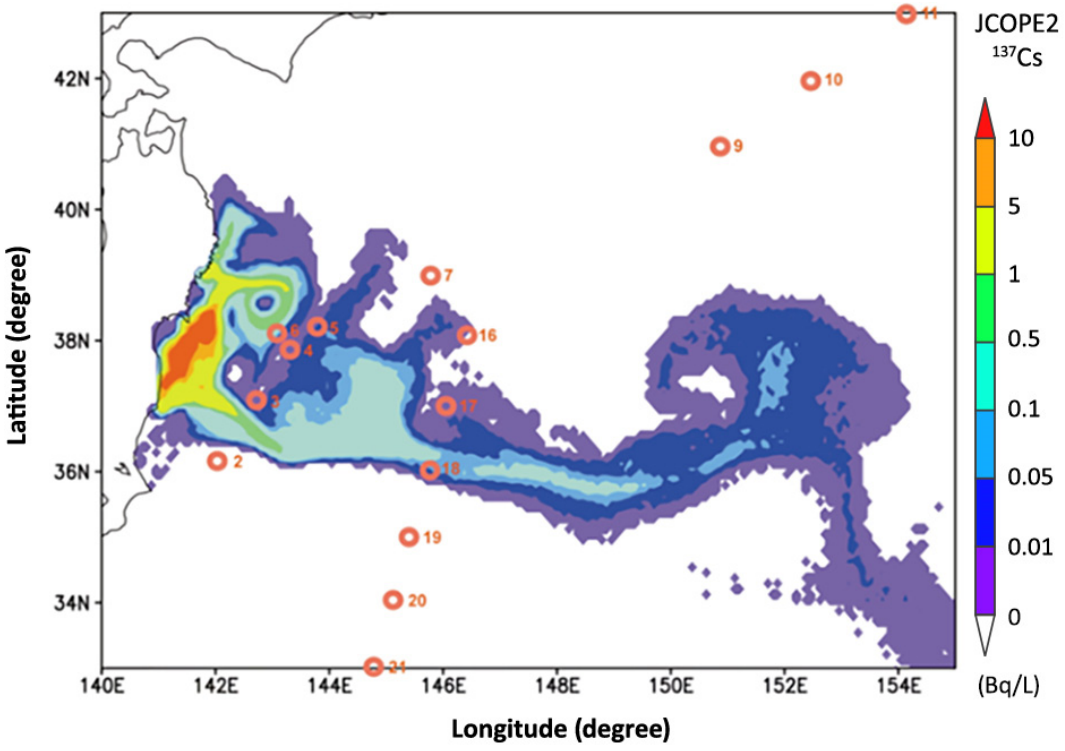


FIG. 4.1–18 (b). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from an oceanic model for the period 14 and 26 April 2011 [103].

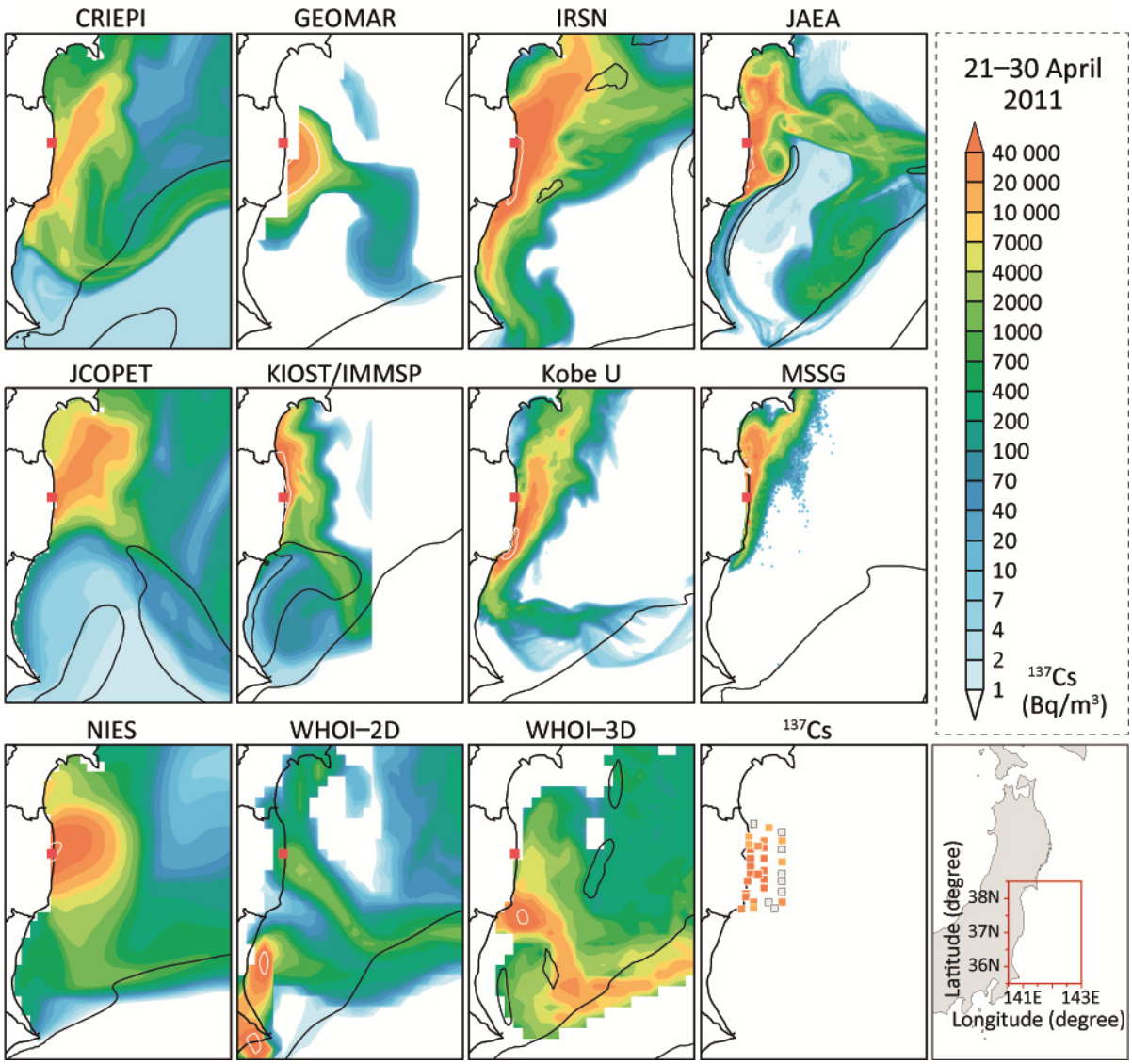
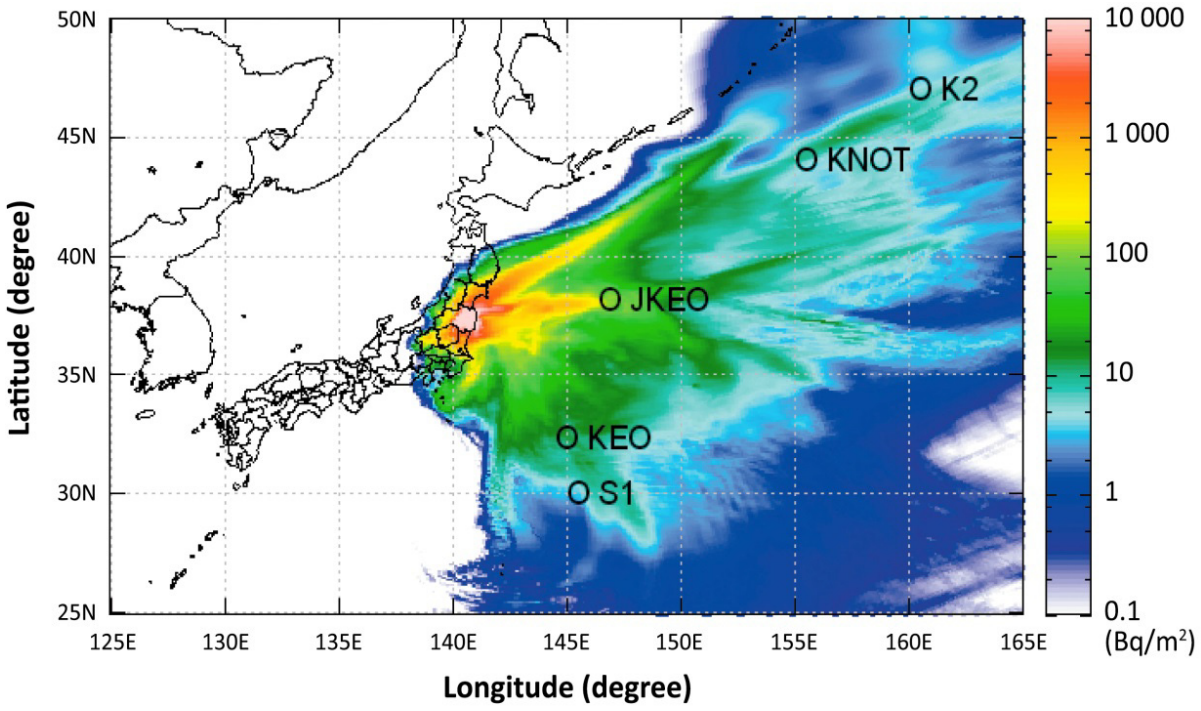
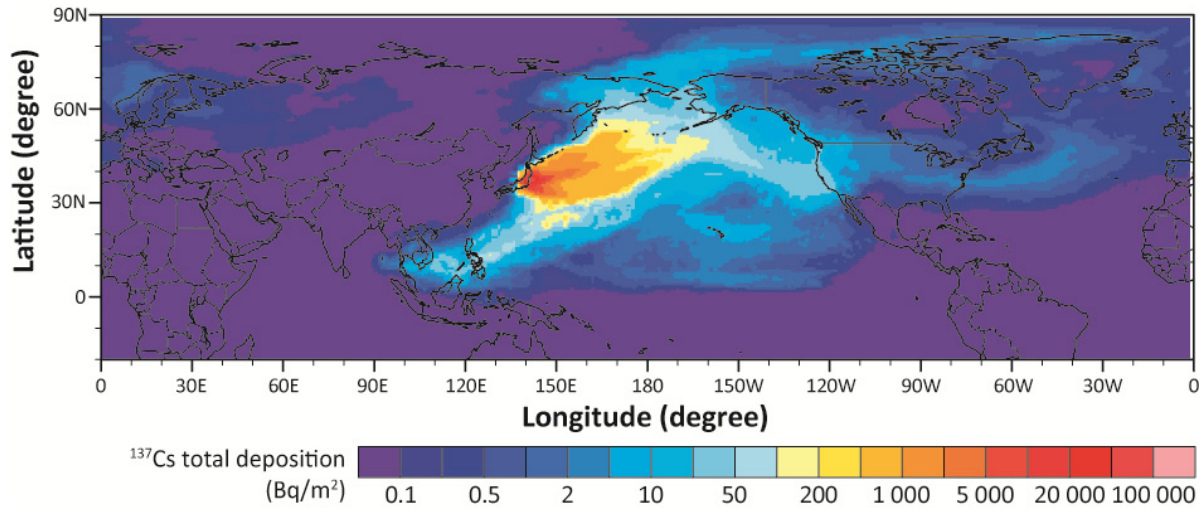


FIG. 4.1–18 (c). An example of the distribution of the activity concentration of ^{137}Cs in sea water obtained from oceanic models averaged over a ten day period from 21 to 30 April 2011 [35].

The deposition of ^{137}Cs onto the ocean has also been studied using various models. Figure 4.1–19 illustrates examples of modelling the cumulative Aeolian input (i.e. the accumulated deposition relating to or arising from the action of the wind) from 1 April 2011 [103] and of the ^{137}Cs deposition averaged over the estimates from a series of models from 11 to 31 March 2011 [35]. As explained above, it is challenging to produce an accurate estimate of the amount of the ^{137}Cs released to the atmosphere that was deposited on the ocean surface (see also Ref. [106]), but the results shown in Fig. 4.1–19 below illustrate the likely pattern of the deposition. The estimated total deposition of ^{137}Cs on the ocean surface due to the accident at the Fukushima Daiichi NPP is about 5–8 PBq, and this can be compared with the total global pre-accident deposition of ^{137}Cs (as of 1970), which is estimated as 290 ± 30 PBq, and the typical background level of ^{137}Cs in the North Pacific Ocean of about 69 PBq [43, 107].



(a)



(b)

FIG. 4.1–19. Various models have been used to estimate the oceanic deposition density of ^{137}Cs (the units used are Bq/m^2). (a) Modelling the cumulative Aeolian input up to 1 April 2011 [103]; and (b) an example of the ensemble averaged ^{137}Cs deposition (11–31 March 2011) [35].

4.1.3.3. Monitoring of radionuclides in the marine environment

The marine environment was thus affected by atmospheric releases and subsequent deposition of airborne radioactivity on the sea surface of the Pacific Ocean and by direct releases from the Fukushima Daiichi NPP. Despite these two pathways involving similar total activities, the atmospheric deposition has not led to significant concentrations, although it is detectable. The direct releases from the site caused high levels of radionuclides in the local marine environment. It is the nature of the huge ocean volume that persistent substances introduced into the oceans are dispersed

through the ocean currents over large distances and diluted accordingly to significantly lower concentrations (as described above).

Measurements of ambient dose equivalent

The aerial surveys of ambient dose equivalent, described in Section 4.1.2 and Appendix I, measured levels of radioactivity over the land and over the sea. Measurements over the sea are presented in Refs [108, 109]. Figure 4.1–20 illustrates the results of one such survey showing the pattern of the ambient dose equivalent rate over the Pacific Ocean near the Fukushima Daiichi NPP in April 2011.

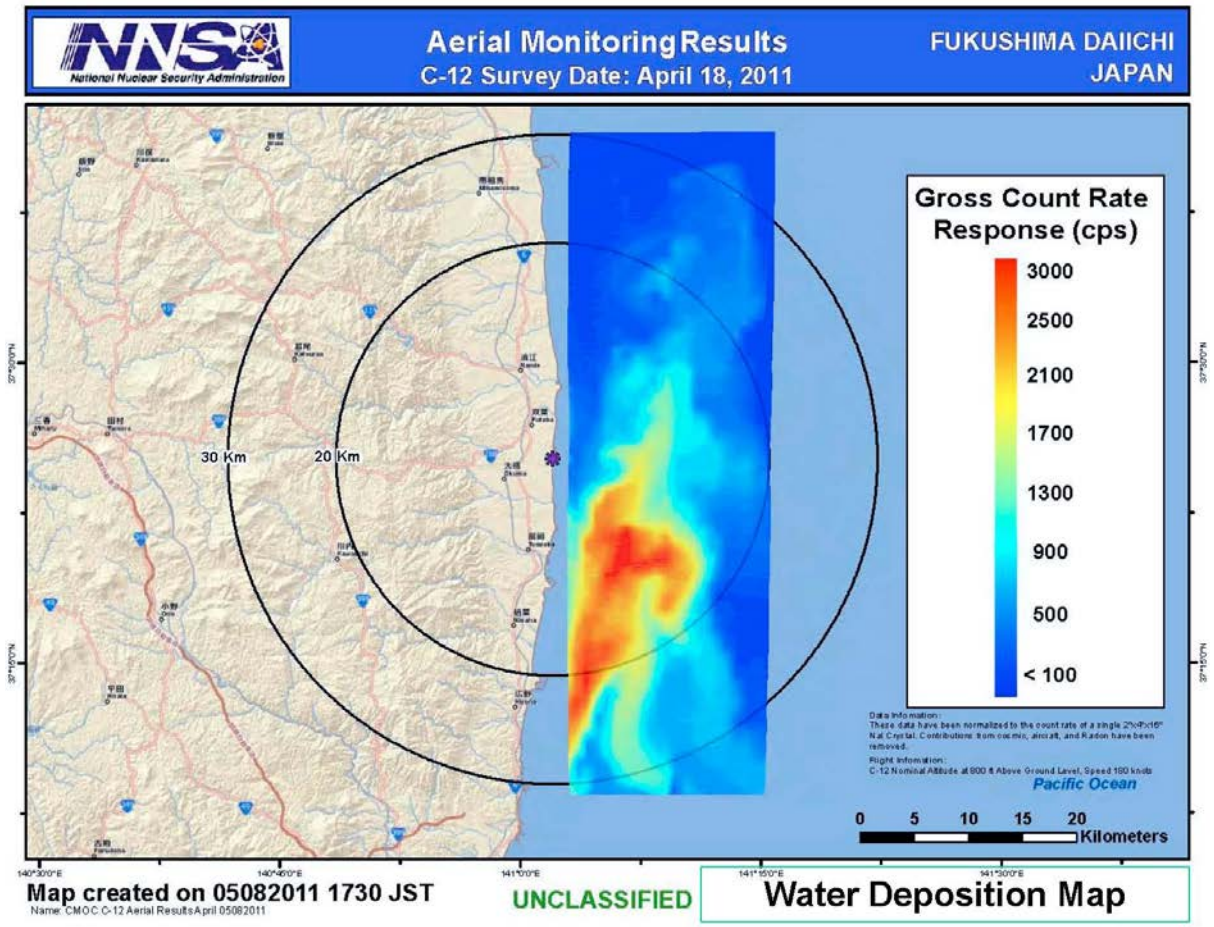


FIG. 4.1–20. The pattern of ambient dose equivalent rate over the Pacific Ocean as measured by aerial monitoring conducted by US DOE/NNSA, indicated by the gross count rate in counts per second [110].

After the initial phase of the accident and releases into the ocean, specific monitoring programmes were set up to follow the temporal and spatial trends of radionuclides in marine waters, sediments and biota.

Measurements of sea water

Marine monitoring began on 21 March 2011. On this date, radionuclides were detected in sea water around the discharge canal to the south of the Fukushima Daiichi NPP. This information was included in a press release on the following day [90] (see Table 4.1–4).

TABLE 4.1–4. INFORMATION INCLUDED IN THE TEPCO PRESS RELEASE OF 22 MARCH 2011

Time and date of sample collection	14:30, 21 March 2011			
Place of collection	Around the discharge canal (south) of Fukushima Daiichi NPP (approximately 330 m south of the discharge canal of Units 1–4)			
Manner of measurement	500 mL sample measured using germanium semiconductor detector			
Measurement time	1000 s			
Radionuclide	Measured activity concentration (Bq/cm^3)	Detection limit (Bq/cm^3)	Statutory limit[a] (Bq/cm^3)	Ratio of sample/statutory limit
^{58}Co	5.96×10^{-2}	3.35×10^{-2}	1	0.1
^{131}I	5.07	4.25×10^{-2}	4×10^{-2}	126.7
^{132}I	2.14	1.93×10^{-1}	3	0.7
^{134}Cs	1.49	4.03×10^{-2}	6×10^{-2}	24.8
^{136}Cs	2.13×10^{-1}	2.36×10^{-2}	3×10^{-1}	0.7
^{137}Cs	1.48	4.20×10^{-2}	9×10^{-2}	16.5

[a] The statutory limit is the allowable concentration of the listed nuclide in water discharged from the reactor.

The sea area within a 30 km zone of the Fukushima Daiichi NPP was monitored by TEPCO until 20 September 2011. After that date, TEPCO continued to monitor within a 20 km radius of the site, while other areas have been monitored by other organizations, including: the Nuclear Regulation Authority, the Ministry of the Environment, the Fukushima Prefectural Government, the Ministry of Land, Infrastructure, Transport and Tourism, Fisheries Agency and the Japan Coast Guard. Some research institutions and universities have also performed measurements of radioactivity in sea water, sediments and marine biota [111]. Marine monitoring results have been made available to international organizations and nuclear regulatory bodies [112], as well as on web sites of the monitoring organizations. These data indicate an improving situation in the sea areas over time (e.g. in sea water in coastal areas) [95, 98, 108, 113–117].

Relatively high levels of ^{137}Cs were detected close to the Fukushima Daiichi NPP directly after the accident and release in April 2011. The activity concentrations of ^{137}Cs in sea water at a range of monitoring points close to the Fukushima Daiichi and Daini NPPs and at a distance of 30 km offshore for the period 21 March–31 July 2011 are presented in Fig. 4.1–21. This figure also places these data within the context of the baseline activities in Japan in the period of 1960–2010 and peaks in activity in the Baltic and Black Seas resulting from the Chernobyl accident in 1986. The figure illustrates the relatively rapid decline in concentrations in the first few weeks. Since that time, there has been a continuous decrease in the activity concentrations of ^{137}Cs (see Annex IV). It also demonstrates that the radionuclide ^{131}I was only relevant and detectable during the first few months (until July 2011) in sea water [117].

Figure 4.1–21 indicates that the highest releases to the marine environment occurred from the end of March to the beginning of April 2011, resulting in concentrations of ^{137}Cs, ^{134}Cs and ^{131}I of up to 10^3 to 10^5 Bq/L in sea water near the reactors.

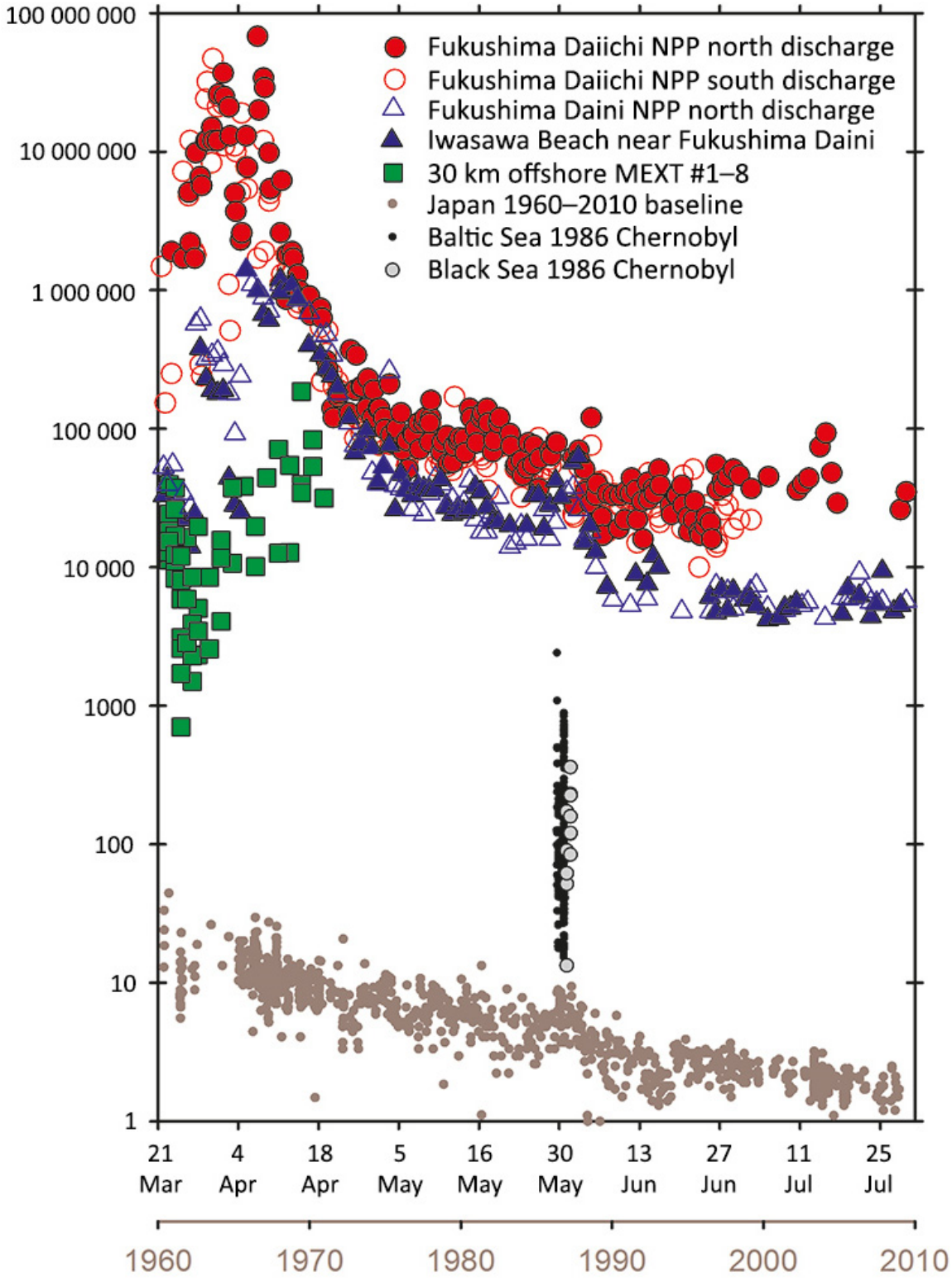


FIG. 4.1–21. Surface ocean concentrations of ^{137}Cs (in Bq/m^3) from 21 March to 31 July 2011 for two sites near the Fukushima Daiichi NPP, Fukushima Daini NPP, Iwasawa Beach near the Fukushima Daini NPP and 30 km offshore. These are compared on the lower x axis (1960–2010) to the historical record of ^{137}Cs off the east coast of Japan and to waters influenced by the Chernobyl accident in 1986 in the Baltic and Black Seas [118].

As explained earlier, following the initial phase of the accident, radionuclides released to the atmosphere were dispersed over the North Pacific Ocean. This activity, and the activity released directly to the sea from the Fukushima Daiichi NPP, is being transported along the Kuroshio

extension in an eastern direction across the Pacific Ocean and will be diluted to lower levels over the years to come. More information can be found in Annex IV.

An ongoing intensive sea area monitoring programme was established following the accident. The monitoring of the sea is routinely carried out in five areas[5], and the resulting measurements have been published [117]. This programme comprises collection and measurement of sea water, sediment and marine biota, primarily fish [119]. Recent results in the sea area around the Fukushima Daiichi and Fukushima Daini NPPs have indicated that the levels of radionuclides outside the port or in the open sea have been relatively stable at lower levels.

Measurements of marine sediments

Caesium can be adsorbed by suspended particulate matter in the water column to some extent and is therefore partly accumulated in the sediment. Contamination of sediments depends mainly on the type of the sediment and is therefore highly variable. Resuspension and mixing of sediments will decrease the initial activity in the surface layer, but the remobilization of radionuclides from the sediment near the Japanese coast will act as a source of ^{137}Cs to the water column during the coming years [120].

Monitoring of environmental radioactivity levels has been carried out by local governments, some research institutes and ministries and government offices in Japan since before the 1960s [121]. The temporal variation of ^{137}Cs concentrations in surface sediments collected from the Pacific Ocean off the Fukushima Daiichi NPP prior to 2011 (1984–2010) is shown in Fig. 4.1–22. The concentrations of ^{137}Cs measured after the accident were at most two orders of magnitude greater than those measured in 2010 at eight sampling stations off Fukushima Prefecture [122], and almost 1 Bq/kg (dry weight) just before the accident in 2011. The spatial and temporal variations of ^{137}Cs concentrations in sediments following the accident are shown in Fig. 4.1–23. Early in the sampling period (May–June 2011), the concentrations varied considerably with the sampling date, especially for the stations in the southern portion of the monitoring area. After September 2011, however, there was generally much less temporal variation [123] which suggested that radiocaesium is transported laterally by resuspended sediments.

The concentration of ^{90}Sr in surface sea water was measured from August to November 2011, and showed a two- to fourfold increase compared with pre-accident values. Strontium-90 was not detected in the sediments collected from May to July 2011. This may have been owing to the relatively high detection limit. Other detected nuclides were ^{95}Nb, ^{110m}Ag, ^{129}Te, ^{129m}Te and ^{125}Sb; however, the activity ratios of ^{137}Cs were less than 1 in sediments. There, activity ratios to that of ^{137}Cs varied, indicating fluctuations in the temporal profiles of their release into, and their transport through, the environment. The complexity of the variation of isotope ratios in the sediments may have been due to temporal changes in the activity ratios from the Fukushima Daiichi NPP and the fluctuating pathways by which these nuclides reached the sediments [124].

[5] Area 1: sea area close to the Fukushima Daiichi NPP; Area 2: coastal area; Area 3: offshore area; Area 4: outer sea area; Area 5: Tokyo Bay area.

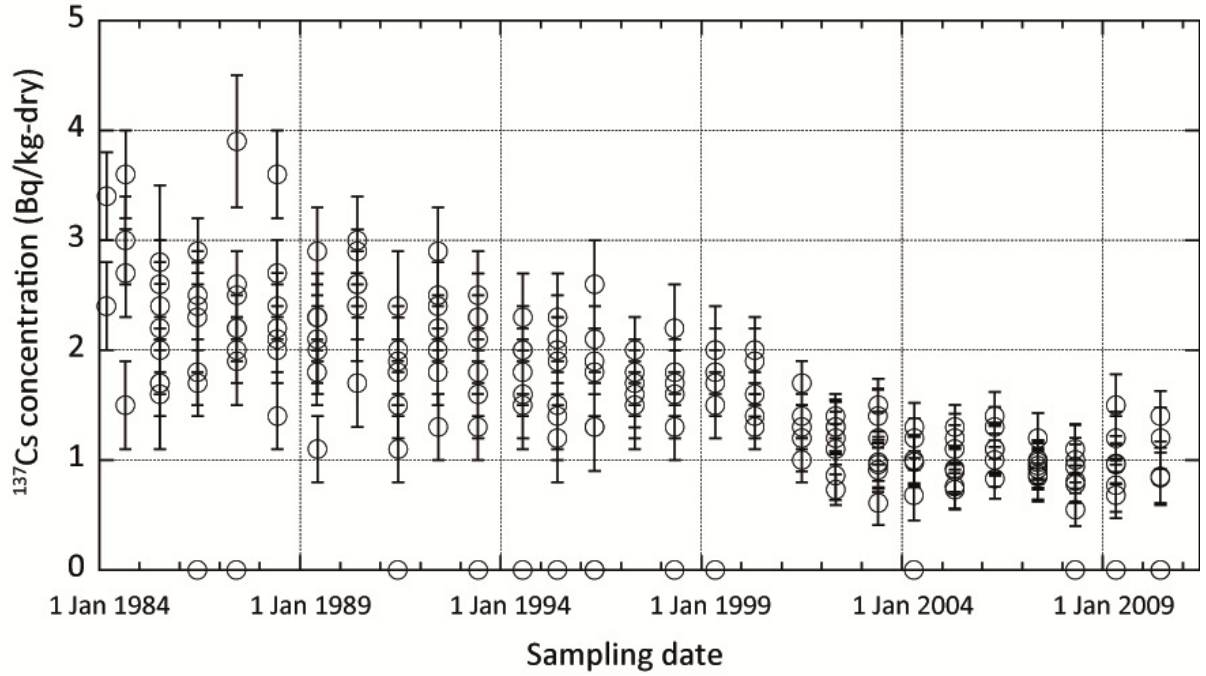


FIG. 4.1–22. Temporal variation of ^{137}Cs concentrations in surface sediments collected from the Pacific Ocean off the Fukushima Daiichi and Fukushima Daini NPPs prior to 2011 (1984–2009). The data plotted in the figure were obtained from the Ministry of Education, Culture, Sports, Science and Technology [125]. Eight sampling stations were located about 30 km off the coast. The open circles on the x axis indicate the concentrations that were below the detection limit [124].

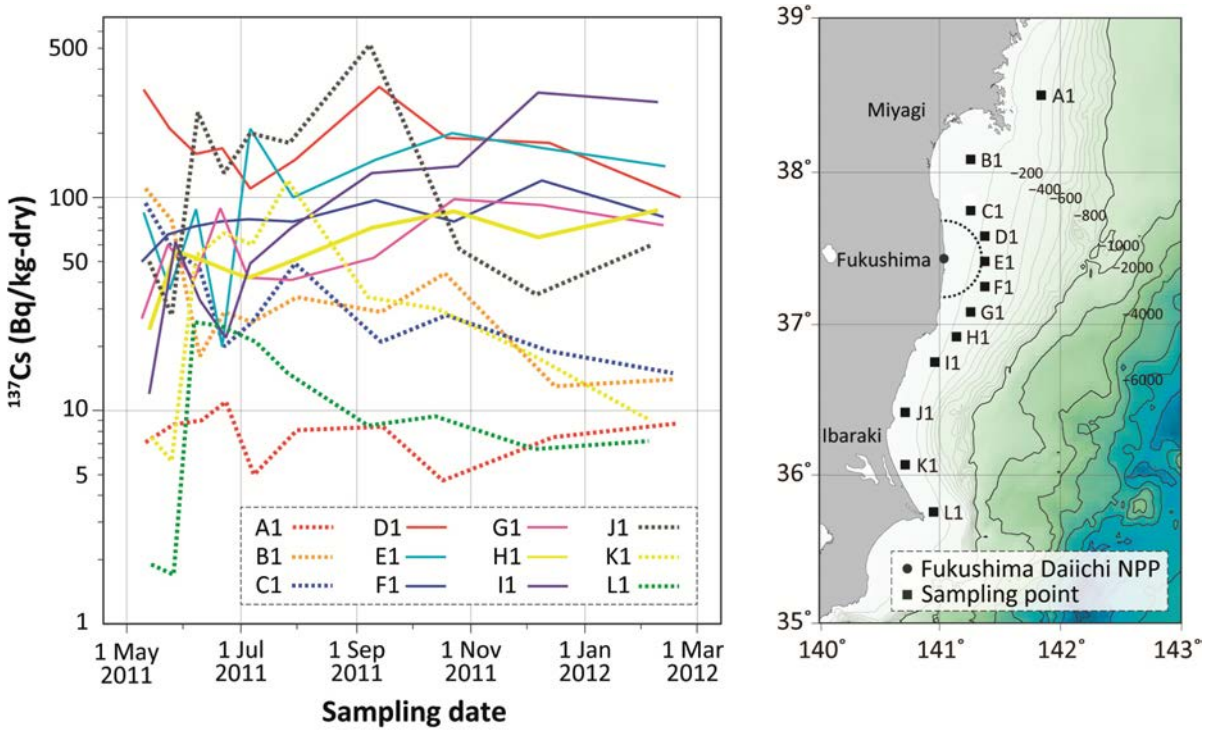


FIG. 4.1–23. Spatial and temporal distribution of ^{137}Cs concentrations in sediment samples collected on the dates indicated [124].

The activities of ^{239,240}Pu and ^{241}Pu in the sediments containing radiocaesium released from the Fukushima Daiichi NPP accident were low compared with the background level before the accident. Thus, the release of isotopes of plutonium from the accident to the marine environment was negligible [126].

A routine monitoring programme was established, on the basis of which monitoring results for sediment are presented for four areas[6] [127].

Measurements of marine biota

Surveys of radioactivity in fish and shellfish (as foods) were started after the detection of radionuclides such as ^{131}I, ^{134}Cs and ^{137}Cs in sea water around the Fukushima Daiichi NPP on 22 March 2011 [128]. All monitoring data from local governments, various research institutes and ministries and government offices are publicly available [129]. The main focus of measurements on marine biota as part of the monitoring programme has been on commercial fish species. As indicated in Section 4.3, Japan adopted a limit of 100 Bq/kg for combined ^{134}Cs and ^{137}Cs for food products on 1 April 2012, which also applies to the marine fishery products. The measurements of radionuclides in fish are described further in the section on food and drinking water below.

The levels of total caesium (^{134}Cs and ^{137}Cs) were found to have remained elevated one year after the accident in many fish collected in the coastal waters off Japan [129]. The levels in demersal, or bottom dwelling, fish close to Fukushima were particularly elevated, with over 40% exceeding the current Japanese regulatory limit of 100 Bq/kg (wet weight) in seafood, and no statistically significant decrease in caesium concentration was seen during 2011. However, in the analysis to the end of 2012, there is a slow reduction in caesium levels in these bottom dwelling fish off the coast of Fukushima Prefecture, equating to an ecological half-life of 330 days, much slower than initially predicted [130]. The activities of ^{134}Cs, ^{137}Cs and ^{110m}Ag in other marine biota off the coast of Fukushima Prefecture were investigated after the Fukushima Daiichi accident. Silver-110m was observed in many marine biota; Mollusca and Crustacea have a tendency to concentrate silver in the visceral parts. Fluctuations in the concentrations in plankton are a result of both radioactivity in sea water and sediment resuspension [131].

Overall, radiocaesium concentrations in marine products have decreased significantly since 2011. However, the time series trends differ greatly among taxa, habitats and spatial distributions. Higher concentrations have been observed in shallower waters south of the Fukushima Daiichi NPP. Radiocaesium concentrations decreased quickly or were below detection limits in pelagic fish and some invertebrates, and continue to decrease in seaweed, surf clams and other biota. However, in some demersal fishes, the declining trend was much more gradual, and concentrations above the regulatory limit (100 Bq/kg, wet weight) were frequently found, indicating continued uptake of radiocaesium through the benthic food web. The main continuing source of radiocaesium to the food web is expected to be detritus in sediment containing radiocaesium [132]. Comparison of ^{137}Cs concentrations in the invertebrates and those in sea water and sediments suggest that contaminated sediments are the major source of continuing contamination in benthic invertebrates, especially in Malacostraca and Polychaeta. Simulation studies using the data obtained, together with rearing experiments aimed at investigating invertebrates' mechanisms of ^{137}Cs uptake from contaminated sediments and further transfer from contaminated invertebrates to demersal fish, will be important to estimate how, and the degree to which, radioactive caesium near sediments moves up the benthic food web [133]. Information on the trend of ^{137}Cs activities in marine biota before the accident are presented in Ref. [134].

[6] Area 1: area close to the Fukushima Daiichi NPP; Area 2: coastal area; Area 3: offshore area; Area 4: Tokyo Bay area.

TEPCO installed a fence at the entrance of the port in the Fukushima Daiichi NPP in June 2013 to prevent the entry of fish from the coastal area [135]. Radiocaesium concentrations of more than 100 000 Bq/kg (wet weight) have been found in fish collected inside the port of the Fukushima Daiichi NPP [136]. Elsewhere in Fukushima Prefecture, only a small percentage exceeded the regulatory limit of 100 Bq/kg (wet weight) in November 2014 [129], and the highest ^{137}Cs activity in fish landed in Fukushima Prefecture in the period from June 2013 until November 2014 was 740 Bq/kg (wet weight) [137].

Madigan et al. [138] have reported that Pacific blue-fin tuna (*Thunnus orientalis*) have transported radionuclides derived from the release from the Fukushima Daiichi accident across the North Pacific Ocean at low levels. Gamma emitting radionuclides were found with ^{134}Cs concentrations of 4.0 ± 1.4 Bq/kg (dry weight) and ^{137}Cs concentrations of 6.3 ± 1.5 Bq/kg (dry weight) in 15 Pacific blue-fin tuna. These levels are very low, and the associated radiation dose from ingestion would be negligible compared with that dose from naturally occurring radionuclides, particularly ^{210}Po, in seafood.

4.1.3.4. Radionuclides in groundwater and surface freshwater systems

Rivers, lakes and reservoirs in Fukushima Prefecture have been described in detail in Section 4.1.1, which deals with the natural environment of the Fukushima Daiichi NPP. As mentioned above, numerous rivers flow into the coastal waters in the area around the plant.

Releases of groundwater and cooling water

As described in Technical Volume 1, from the early stages of the accident, water was injected into the reactor pressure vessels of Units 1–3 to provide cooling; at the time of writing, this process is still continuing. Some of this water drains into the lower levels of the reactor buildings and, as it comes into contact with melted fuel, it contains radionuclides. Currently, the flow rate of injected water is about 350–400 m^3 per day [136]. The topography of the Fukushima Daiichi NPP is such that groundwater flows from the hills to the west of the site down to the eastern shore of the Pacific Ocean. Some of this groundwater enters the reactor buildings and turbine buildings of Units 1–4 and also passes into auxiliary buildings. TEPCO estimates that the daily contribution of groundwater to the flooding of these buildings is about 400 m^3 [139].

These two sources of water (groundwater and cooling water) have resulted in large pools of water with ^{137}Cs activity concentrations of between 4 and 36 GBq/m^3 [140]. As reported in November 2013, the total volume of the water pool from all four units is approximately 75 000 m^3 [128]. The water flows into underground areas where, as reported in July 2013, there are approximately 11 000 m^3 of water with a ^{137}Cs activity concentration of 1.6 TBq/m^3, a beta activity concentration of 0.75 TBq/m^3 and a tritium activity concentration of 8.7 GBq/m^3 [141, 142]. These combined amounts of water are gradually infiltrating the ground through the layer of crushed stones, with radionuclides entering the clean groundwater that bypassed the basements of buildings; the contaminated groundwater is likely to flow toward the Pacific Ocean (see Fig. 4.1–24).

In order to reduce the infiltration of radioactivity into the groundwater and the ocean, TEPCO installed a water treatment and storage system coupled with a water injection system. It also built an impermeable wall along the harbour front, in an attempt to limit the discharge of contaminated groundwater into the ocean. The system includes the treatment of the stored water and its reuse as cooling water. However, owing to the additional groundwater entering the buildings, the total daily flow of water into the buildings (~800 m^3) exceeds the necessary flow rate to cool the reactors (~400 m^3), and each day a surplus of ~400 m^3 accumulates on the site. This excess of low level activity salt water is collected in tanks and stored on-site. As of January 2014, the total storage capacity of these tanks was approximately 410 000 m^3 and the volume of contaminated water stored

on-site was 350 000 m^3 [143]. The storage capacity is foreseen to double in the future (i.e. to 820 000 m^3), as the processing capacity of the current water treatment is approximately 750 m^3 per day.[7] Further information is presented in Technical Volume 5, Section 5.3.

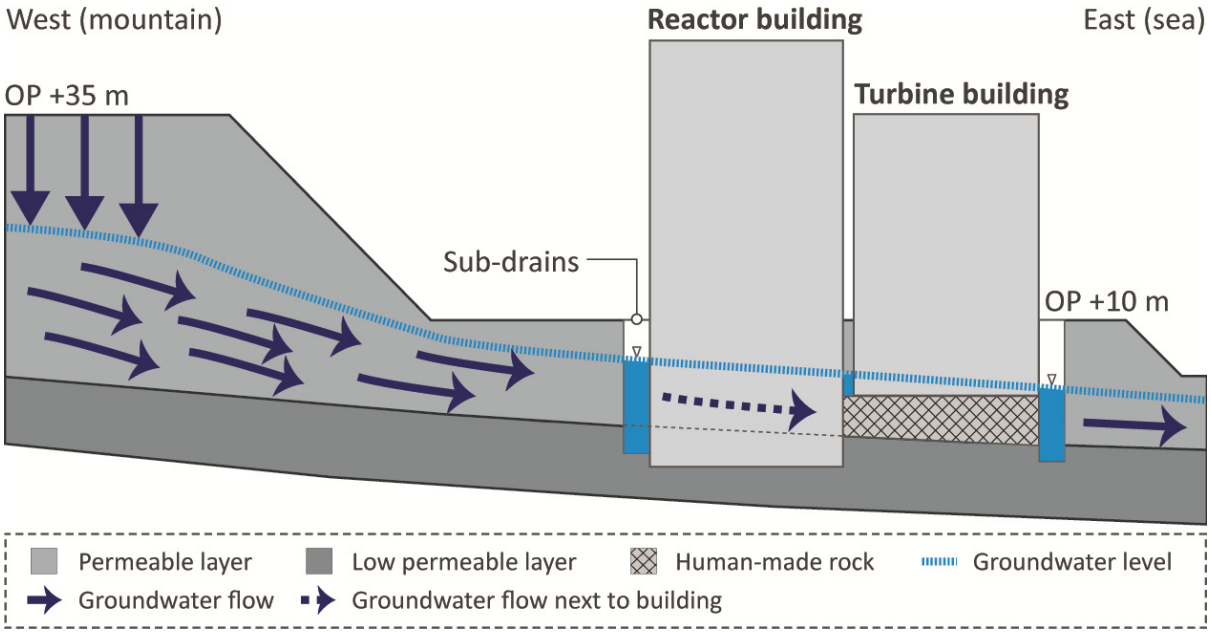


FIG. 4.1–24. On-site groundwater flowing in one direction from the mountain to the sea.

On two occasions, TEPCO announced the release of water containing radionuclides into the local on-site environment from the storage tanks. The first release was in August 2013 [144], and consisted of approximately 60 TBq of beta emitting radionuclides, 0.7 TBq of tritium and 0.06 TBq of combined ^{125}Sb, ^{134}Cs and ^{137}Cs [145]. A second leakage from a storage tank was announced by TEPCO in February 2014 [146]; it consisted of approximately 23 TBq of beta emitting radionuclides, an undisclosed amount of tritium and 6 GBq of combined ^{54}Mn, ^{60}Co, ^{125}Sb, ^{134}Cs and ^{137}Cs [146].

Measurements of activity in groundwater

With the exception of groundwater that flows through the Fukushima Daiichi NPP, groundwater bodies in Fukushima Prefecture have not been influenced by the radionuclides releases from the accident. The Ministry of the Environment has undertaken monitoring surveys of radionuclides (^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr) in groundwater in Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba prefectures and has found no radionuclides related to the accident in samples other than those at the Fukushima Daiichi NPP [147].

In order to monitor the on-site situation, multiple boreholes have been dug in locations between Units 1 and 4, storage tank locations and the harbour front. TEPCO has been reporting results for ^{90}Sr, ^{134}Cs, ^{137}Cs, gross beta and tritium levels in groundwater at these locations on a regular basis since 2013 [45]. The maximum ^{137}Cs results vary relatively widely with location, from values below 1 Bq/L to 93 kBq/L. There is a similar spread for gross beta (i.e. maximum values of below 20 Bq/L up to 3.1 MBq/L). For tritium, the corresponding range of maximum values is less than 200 Bq/L up to 0.6 MBq/L. Other reported radionuclides in groundwater are ^{90}Sr , ^{54}Mn, ^{60}Co, ^{106}Ru and ^{125}Sb. It is

[7] For a detailed description of these activities, see Technical Volume 5, Section 5.3 and Section 5.4.

important to note the relative differences between radionuclide ratios (e.g. the ^{137}Cs/tritium or ^{137}Cs/beta ratios) and activity concentrations (in some cases spanning several magnitudes) between locations relatively close together, suggesting an inhomogeneous distribution of the radioactive material, and multiple source terms.

Following the first of the reported leakages mentioned above, most of the sea water sampled near the Fukushima Daiichi NPP remained under the detection limits, and no significant changes were observed before and after the leakage. After the second event, the highest activity concentrations from water taken from these wells were measured in October 2013 for tritium and in November 2013 for all beta activity [148]. Significant levels of tritium in groundwater and sea water have been reported inside and outside the port of Fukushima Daiichi NPP. The activity concentration of tritium in groundwater collected in mid-April 2011 at the eastern side of the turbine building of Units 1 and 2 varied between less than 100 Bq/L and 270 000 Bq/L. The tritium concentration in sea water at the location near the water intake of Units 1 and 2 varied from about 100 Bq/L to about 3000 Bq/L during the monitoring period from June 2013 to April 2014. The concentrations in sea water collected in mid-April 2014 at a location outside the port ranged from less than 1.8 Bq/L to 6.5 Bq/L.

Measurements of radionuclides in rivers and other freshwater bodies

A series of surveys has been conducted to assess temporal variations in activity concentrations of radionuclides derived from the Fukushima Daiichi NPP in river water, riverbeds and suspended sediments [149].

Suitable sampling locations for ongoing monitoring were identified in 2011 using two selection criteria:

— Areas of relatively high radiocaesium deposition densities, determined by land based monitoring and aerial monitoring surveys;
— Locations with sufficiently high flow volumes to facilitate the assessment of the migration of radionuclides in the future.

Based on these criteria, 50 sampling locations were identified. River water sampling has been conducted over six periods in June 2011, August 2011, December 2011, February 2012, August 2012 and November 2012. The latter two sampling periods were selected specifically to assess activity concentrations before and after that year's typhoon season. In the initial surveys, river water samples were analysed at all 50 locations for the gamma emitting radionuclides ^{131}I, ^{134}Cs and ^{137}Cs. Samples from a subset of 10 locations that were evenly spread out were chosen for analysis of strontium (^{89}Sr and ^{90}Sr) and plutonium (^{238}Pu and ^{239,240}Pu) using low background beta ray counters and silicon semiconductor detectors, respectively, following radiochemical separation. In later surveys, samples were not analysed for plutonium or ^{89}Sr owing to the very low levels of these radionuclides measured previously. In 2012, samples were collected from an additional 7 locations in the vicinity of the Fukushima Daiichi NPP. The sampling locations and the distribution of activity concentrations of ^{137}Cs in river water in August 2012 are shown in Fig. 4.1–25.

The maximum activity concentrations of ^{134}Cs and ^{137}Cs measured were less than 5 Bq/kg, with some evidence of a general downward trend toward background levels over the period monitored [150]. The maximum activity concentration of ^{131}I was 0.15 Bq/kg. Measured activity concentrations of strontium and plutonium were much lower. Measured levels of ^{90}Sr were comparable with background levels measured before the accident [150].

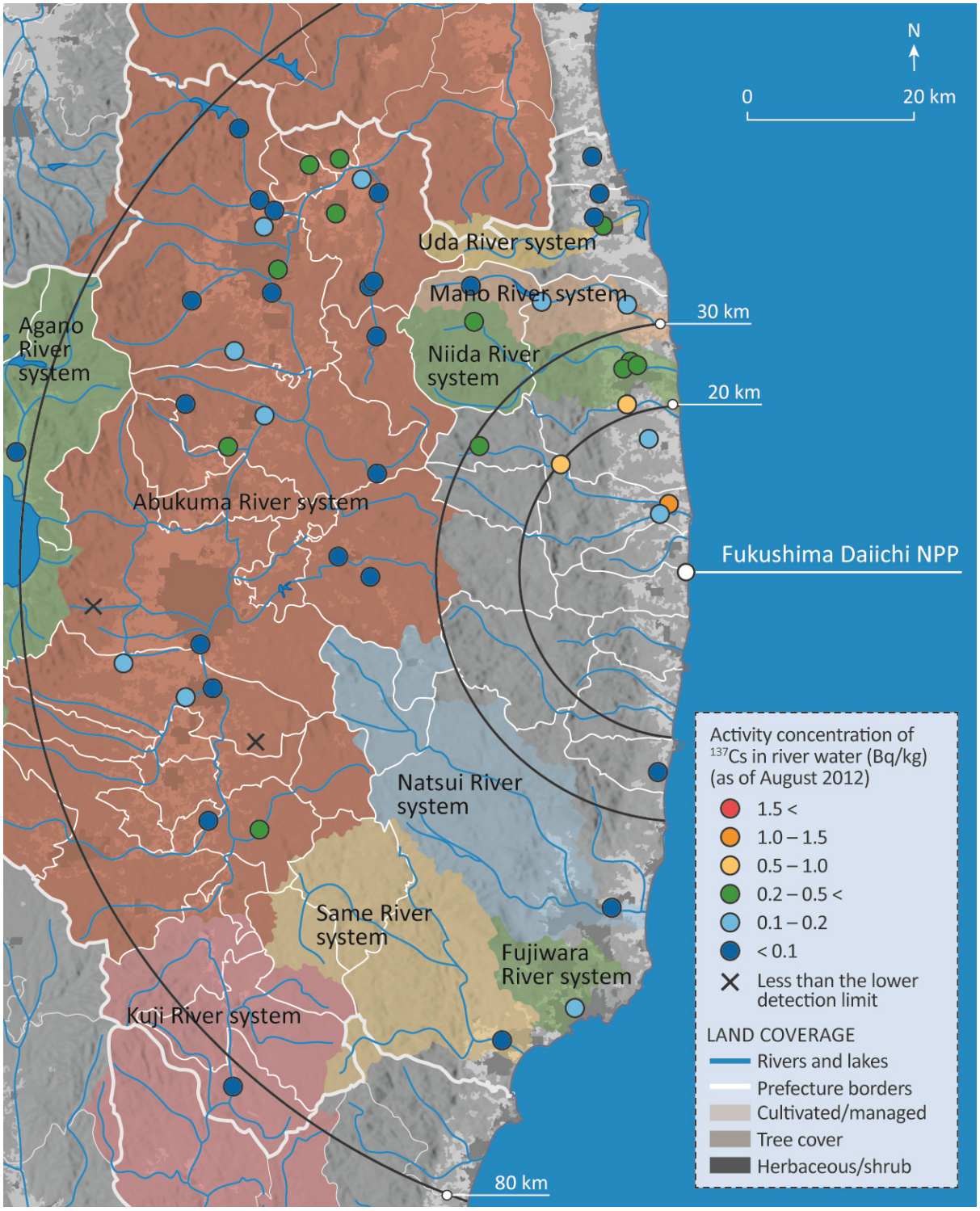
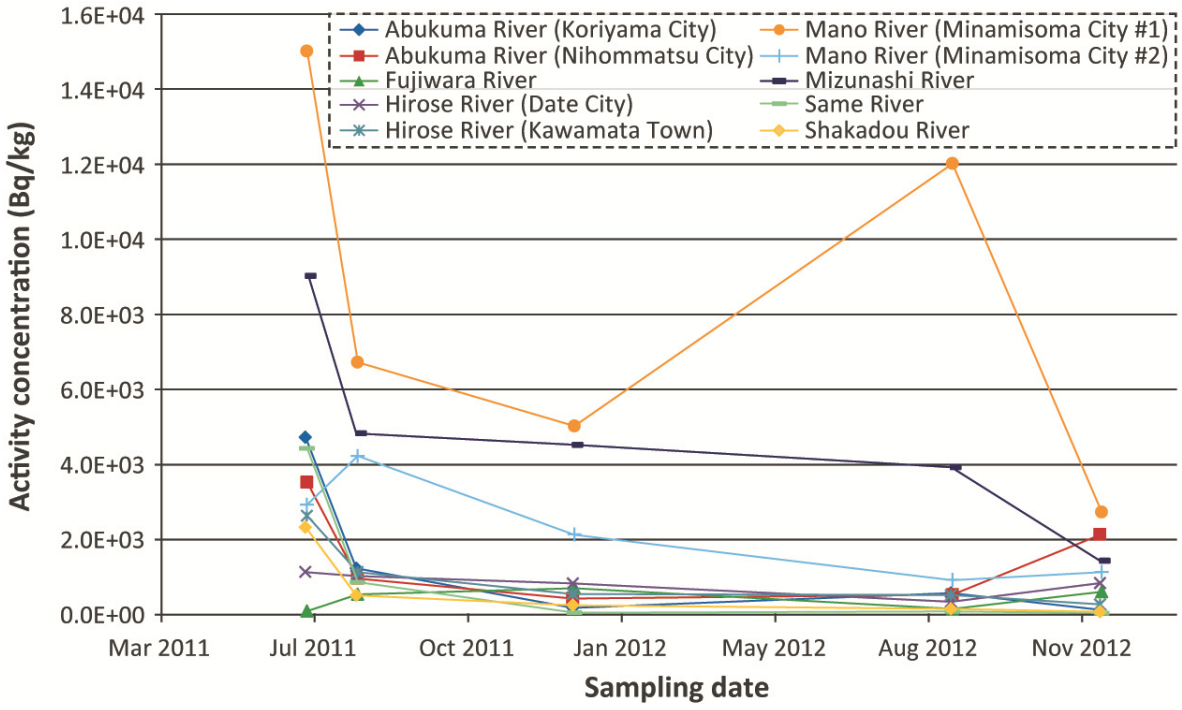


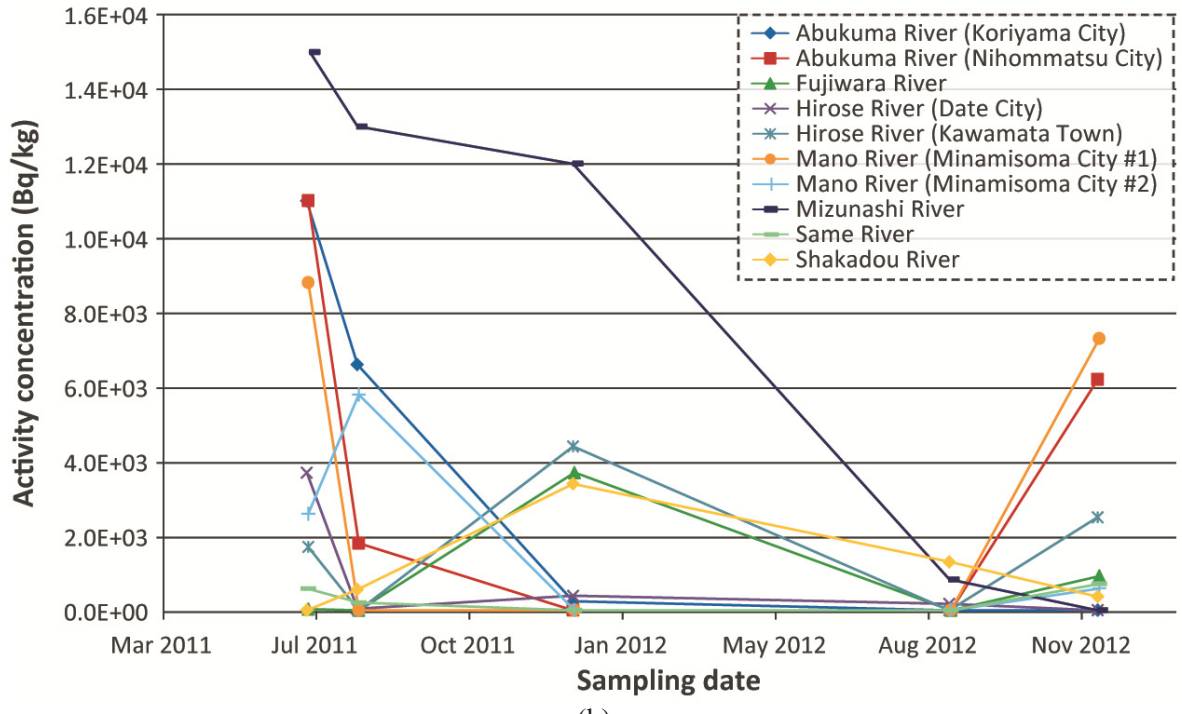
FIG. 4.1–25. Map of river sampling locations.

Riverbed sediment sampling has so far been conducted at the same ten locations from which river water samples were analysed for strontium and plutonium over five periods in July 2011, August 2011, December 2011, August 2012 and November 2012. As with the sampling of river water, the latter two sampling periods were selected specifically to assess activity concentrations before and after the typhoon season. The samples were analysed by HPGe gamma spectrometry for activity

concentrations of ^{131}I, ^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{129m}Te and ^{136}Cs. The results for ^{137}Cs and ^{131}I for the ten sampling locations are shown in Fig. 4.1–26.



(a)



(b)

FIG. 4.1–26. Results of measurements of (a) ^{137}Cs and (b) ^{131}I in riverbed samples for ten sampling locations in Fukushima Prefecture from July 2011 to November 2012 [151].

Suspended sediment sampling has been conducted over eight periods between August 2011 and February 2013. Samples were initially collected from the same ten locations as for riverbed samples

and analysed by HPGe gamma spectrometry for activity concentrations of ^{131}I, ^{134}Cs, ^{137}Cs, ^{110m}Ag, ^{129m}Te and ^{136}Cs. Between December 2012 and February 2013, five surveys were performed which included sampling at an additional 30 sites, mainly located near gauging stations in the Abukuma River basin and in the Hamadori area of Fukushima Prefecture. These samples were analysed for radiocaesium only.

Maximum activity concentrations measured in ^{137}Cs and ^{131}I were of the order of 15 000 Bq/kg and 20 Bq/kg, respectively.

The higher activity concentrations of radiocaesium in the sediments of the Abukuma River system (over 10 000 Bq/kg, dry weight) were usually observed in the same period (September-October 2011). However, 80% of the measurements of ^{137}Cs concentrations in the sediments of the rivers, and 60% in those of the lakes, of Iwate, Yamagata, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba Prefectures were less than 1 000 Bq/kg (dry weight). About 50% of the coastal sediment measurements were less than 50 Bq/kg (dry weight) [151].

Soil erosion and subsequent sediment transport in rivers play a major role in the global biogeochemical cycles and in the dispersion of contaminants within the natural environment. As with other particle borne pollutants, radionuclides emitted after the Fukushima Daiichi accident are strongly sorbed by fine particles, and they are therefore likely to be redistributed by hydro-sedimentary processes across catchments.

Various studies have estimated the amounts of radionuclides, particularly ^{137}Cs, from rivers where levels of radioactivity are affected by heavy rainfall and soil erosion. For example, in 2013, Nagao et al. [152] showed that heavy rain during Typhoon Roke on 21–22 September 2011 transferred large amounts of particulate ^{134}Cs and ^{137}Cs deposited on the land to river watersheds (namely, the Natsui and Same rivers) and coastal marine environments. The value of that flux was estimated to 0.020–0.026 TBq/d in the Natsui River and 0.007–0.009 TBq/d in the Same River. This amounts to 30–50% of the total annual flux for these rivers from 11 March to 31 December 2011. Kanda [153], estimated the discharge of ^{137}Cs from small rivers in April–September 2012 to be not more than 0.32 TBq/month. Larger rivers, such as the Abukuma River, would be a larger source of ^{137}Cs of up to 0.87 TBq/month [154].

Typhoons and snowmelt during 2011 and 2012 also led to intense soil erosion from hill slopes by runoff processes in the upper parts of water catchments, reservoirs, lakes, floodplains and outlets, with a selective export of fine particles containing radionuclides derived from the Fukushima Daiichi accident. The main dams are found in the upper parts of the Mano River and Ota River catchments, and their reservoirs form a potential sink for radioactive sediments. The ^{110m}Ag/^{137}Cs ratio provided a tracer for the dispersion of sediment in the Nita catchment area, which is affected by the areas with the highest levels of radionuclides. The system was very reactive to the succession of summer typhoons (2011) and spring snowmelt (2012). The 2012 typhoons were less violent than the ones in 2011 and led to less intense erosion; however, they were sufficiently powerful to increase river discharges and to export the sediment stored in the river channel [100, 155].

Measurements of radionuclides were also taken at 20 lakes and dams in Fukushima Prefecture; all results in water were below detection limits for ^{131}I, ^{134}Cs and ^{137}Cs. For sediments, some lakes and dams had activity concentrations above the detection limit. For three locations, measured values exceeded 100 Bq/kg at Lake Hatori and 1000 Bq/kg at Komachi Dam and Hokkawa Dam.

4.1.4. Levels of radionuclides in terrestrial and aquatic foods

The Ministry of Health, Labour and Welfare (MHLW) has responsibility for monitoring the levels of radionuclides in food and drinking water in Japan. On 4 April 2011, MHLW confirmed that

provisional regulation values for radioactive material in food and drinking water set on 17 March 2011 were effective in ensuring the safety for consumption, domestic distribution and export. At the same time, the Nuclear Emergency Response Headquarters issued policies for monitoring and enforcement of restrictions on the distribution and/or consumption of milk, vegetables, seafood, bottled water and other foods.[8]

4.1.4.1. Terrestrial food products

Extensive monitoring of food was carried out in Japan starting a few days after the initial accidental releases from the Fukushima Daiichi NPP, mainly by the municipalities under the Food Sanitation Law[9]. The monitoring was organized by the Ministry of Agriculture, Forestry and Fisheries (MAFF) and MHLW, and the information was used by the Food and Agriculture Organization of the United Nations (FAO) and the IAEA to compile a database in collaboration with MAFF and MHLW in Japan. This FAO/IAEA database includes data for over 500 types of food samples in all 47 prefectures and comprises activity concentrations in both terrestrial and aquatic foods. These measurements were mainly intended to ensure compliance with regulatory levels. Thus, the data do not provide information on the distribution of activity concentrations in food. The database only includes measurements for ^{131}I, ^{134}Cs and ^{137}Cs and contains data for immature crops and for areas where restrictions were in place; such foods would, therefore, not have been eaten. However, it is possible to select from the database results for those foods that were marketed and could have been consumed. Relatively high limits of detection were used in determining levels in food, and, in the database, it was assumed that any values below limits of detection were equal to 10 Bq/kg for each of the three radionuclides. However, for ^{131}I, this was only done for the first four months following the accident, and subsequently levels of ^{131}I below detection limits were taken to be zero. The information in the database formed the basis for the assessment carried out by UNSCEAR [5] of ingestion doses in the first year following the accident. Only results for foods as marketed were used in the assessment, and it was assumed that people obtained their food from a wide area, with doses estimated for Fukushima Prefecture, for five nearby prefectures (Miyagi, Tochigi, Gunma, Ibaraki and Chiba — using the means of all data for these prefectures) and for the rest of Japan. Rice is an important component of the Japanese diet, and, as a result, the database contains many measurements for immature crops. Therefore, in the UNSCEAR assessment, only measurements in rice taken six months or more after the accident were used to estimate the ingestion doses.

The initial concern following the accidental release of radionuclides to the atmosphere is the transfer of radionuclides to leafy vegetables through direct deposition from the atmosphere onto the edible part of the plant. Generally, the transfer of radionuclides, particularly ^{131}I, to milk is also of concern in the short term following accidental releases to the atmosphere, owing to the short transfer time for iodine from grassland to milk and the relatively high amounts of the radionuclide that reach milk. However, as the initial releases to atmosphere occurred in March, when cows would have been housed indoors and given stored feed, this transfer to milk was not as marked as it was following the accident at the Chernobyl NPP.

The results from the database show that ^{131}I was detected on edible leafy vegetables (cabbage, broccoli, lettuce and spinach) from eight prefectures in the first few months after the accident (Table 4.1–5). It should be noted that this includes all the measurement data and not just those from food that was marketed.

[8] For detailed discussions, see Technical Volume 3, Section 3.3, and Technical Volume 5, Section 5.2.

[9] Food Sanitation Law, Law No. 233, December 24, 1947, as amended by Law No. 87 of July 26, 2005 (Japan).

TABLE 4.1–5. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011 BY PREFECTURE [156]

Prefecture	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
Chiba	11	963	1 123	226	12	<10	3 500
Fukushima	85	1 799	3 670	79	22	<10	19 000
Gunma	27	410	660	98	7.6	<10	2 630
Ibaraki	30	8 867	11 484	1 291	21	<10	54 100
Kanagawa	12	299	467	28	13	<10	1 300
Miyagi	2	185	153	150	2.6	77	294
Nagano	21	7.5	12	5.6	1.7	<10	58
Saitama	38	231	467	22	9.0	<10	1 900
Tochigi	16	2 345	2 250	299	22	<10	5 700
Tokyo	10	135	410	8.7	5.8	<10	1 300
All values	252	1 954	5 222	74	19.4	<10	54 100

The highest levels were found for spinach (see Table 4.1–6) during March 2011. Activity concentrations on leafy vegetables decreased significantly in subsequent months, as is to be expected after an accidental release of ^{131}I, owing to its short half-life and the removal of activity from the surface of the plants by weathering processes (see Table 4.1–7). These results also confirm that no further significant release of ^{131}I to the atmosphere occurred after the first few days following the accident.

TABLE 4.1–6. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011, BY TYPE OF VEGETABLE [156]

Food tested	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
Broccoli	28	1587.857	3 565.347	82.001 63	20.317 71	<10	17 000
Cabbage	39	203.7949	851.4137	12.301 29	5.870 361	<10	5 200
Lettuce	28	61.1	213.9948	9.200 975	3.989 963	<10	1 100
Spinach	157	2 791.45	6 273.575	165.744 4	20.874 81	<10	54 100
All leafy vegetables	252	1 953.875	5 222.332	74.330 66	19.381 14	<10	54 100

TABLE 4.1–7. CONCENTRATION OF ^{131}I IN LEAFY VEGETABLES (Bq/kg) FROM MARCH TO MAY 2011, BY MONTH [156]

Period	*N*	Average	Standard deviation	Geometric mean	Geometric deviation	Minimum	Maximum
March	129	3 800.733	6 814.398	672.289 6	12.425 6	<10	54 100
April	41	39.482 93	59.998 02	14.790 05	3.939 035	<10	230
May	82	5.646 341	4.701 909	5.214 407	1.321 011	<10	46
All leafy vegetables	252	1 953.875	5 222.332	74.330 66	19.381 14	<10	54 100

About 2950 samples of milk and dairy products were analysed in the first year after the accident. Of the 2636 samples of cattle milk, 207 contained levels above the limits of detection, all from samples taken in March and April 2011, with the exception of the results of two samples in May, where a lower detection limit was used. The average concentration of ^{131}I in milk for samples above detection limits was 190 Bq/L (range: 0.1–5300). Detection limits, however, varied from 0.1 Bq/L to about 10 Bq/L among different prefectures and towns. Average values for results above detection limits were 247 Bq/L in March 2011, 10 Bq/L in April and 0.5 Bq/L in May; of these, about 65% were from Fukushima Prefecture. However, these samples represent only about 10% of measured samples and include samples from areas where milk was not marketed due to restrictions.

A summary of data on the concentration of radiocaesium in agricultural products provided by MAFF for different types of food is presented in Table 4.1–8 [129].

TABLE 4.1–8. SUMMARY OF COUNTRYWIDE MEASUREMENTS OF RADIOCAESIUM IN AGRICULTURAL PRODUCTS [129]

Product		Total number of reported samples	Per cent of vegetable samples		
			<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
March 2011–31 March 2012					
Wheat and barley		557		95.15	4.85
Vegetables		12 671		96.96	3.04
Fruits		2 732		92.31	7.69
Pulses	Soy bean	534		97.00	3.00
	Other pulses	155		100.00	0.00
Other cultivated plants		498		96.79	3.21
Mushrooms and wild edible plants		3 856		79.80	20.20
1 April 2012–31 March 2013					
Wheat and barley		1 818	100.00	0	0
Vegetables		18 570	99.92	0.05	0.03
Fruits		4 478	98.37	1.34	0.29
Pulses	Soy bean	4 069	97.75	1.68	0.57
	Other pulses	329	97.26	2.13	0.61
Other cultivated plants		3 094	96.77	2.78	0.45
Mushrooms and wild edible plants		6 588	82.21	8.61	9.18
1 April 2013–31 March 2014					
Wheat and barley		592	100.00	0	0
Vegetables		19 657	99.99	0.01	0
Fruits		4 243	99.34	0.66	0
Pulses	Soybean	4 716	98.37	1.19	0.45
	Other pulses	447	99.10	0.90	0
Soy bean harvested in FY 2012		1 564	85.49	12.08	2.43
Other cultivated plants		1 618	99.81	0.19	0
Mushrooms and wild edible plants		7 581	93.23	4.21	2.56

Rice is a staple food in Japan, and the FAO/IAEA database includes about 2800 results for rice in 2011. Of these, only 62 are above the detection limit of 20 Bq/kg. Two samples had concentrations greater than 100 Bq/kg, one in Fukushima City and the other in Nihonmatsu City, both in Fukushima Prefecture. In 2011, rice planting was restricted in paddy fields in which activity concentrations of radiocaesium in soil of 5000 Bq/kg or more were measured. However, close examination of the rice produced in that year revealed that radiocaesium concentrations in rice did not follow a simple proportional relationship to those in soils. Food restrictions and agricultural countermeasures are explained in more detail in Technical Volume 5, Section 5.2.

Radionuclides can be transferred to animal products by an animal's ingestion of grass, other vegetables and water, and also by inhalation. In addition, grazing animals may ingest radionuclides together with soil by inadvertent ingestion. A summary of data for the concentrations of radiocaesium in animal derived products is periodically reported by MAFF; a summary of these data is presented in Table 4.1–9 for raw milk and in Table 4.1–10 for meat and eggs [157].

TABLE 4.1–9. SUMMARY OF MEASUREMENTS FOR RADIOCAESIUM IN RAW MILK FOR ALL PREFECTURES IN JAPAN

Period	Total no. of samples	Per cent of samples in ranges		
		<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
11 March 2011–31 March 2011	173	95.38	4.05	0.58
1 April 2011–31 March 2012	1 764	100	0	0
1 April 2012–31 March 2013	2 453	100	0	0
1 April 2013–31 March 2014	2 052	100	0	0

TABLE 4.1–10. SUMMARY OF COUNTRYWIDE MEASUREMENTS OF RADIOCAESIUM IN MEAT AND EGGS FOR ALL PREFECTURES IN JAPAN

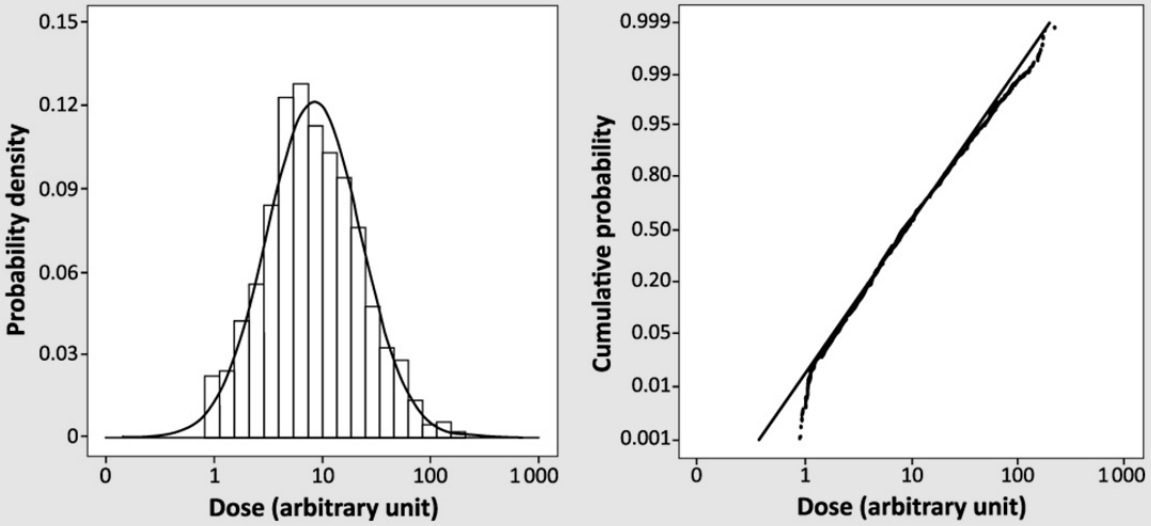
Period		No. of samples	Per cent of samples in ranges		
			<50 Bq/kg	50–100 Bq/kg	>100 Bq/kg
11 March 2011–31 March 2012	Beef	91 973		98.81	1.19
	Pork	538		98.88	1.12
	Chicken	240		100.00	0
	Egg	443		100.00	0
	Other	23		100.00	0
1 April 2012–31 March 2013	Beef*	74 168	99.97	0.02	0.01
	Beef**	113 008	99.99	0.01	0
	Pork	984	99.70	0.20	0.10
	Chicken	472	100.00	0	0
	Egg	565	100.00	0	0
	Other	99	97.98	1.01	1.01

* 1 April–September 2012
** October 2012–March 2013

Box 4.1–1. Statistical analysis of estimated and measured data

Some relevant data used in this report — notably data on personal doses and on activity in food — were analysed statistically. The values of the variable quantity (e.g. values of activity or dose) were classified according to their frequency distribution. For this, the whole range of data was *binned*, that is grouped together in *bins,* or a series of small interval ranges of numerical values, into which the data were sorted for analysis. The data in each bin were displayed adjacent to one another in a *histogram*. The histogram was then normalized, multiplying the values of the rectangles by a factor that makes the total area of the rectangles equal to 1. When sufficient data are available and the intervals become very small, the histogram tends towards a smooth curve termed *probability density function* that describes the relative likelihood for the quantity (e.g. the activity in food or the dose incurred by people) to have a given value.

While the most common distribution is the *normal* (or Gaussian) distribution, represented by a bell shaped probability density function that is symmetrical with respect to the maximum probability, the most relevant distribution for the purpose of the report is the *logarithmic-normal*, or *log-normal* distribution. The log-normal distribution is a probability distribution of a quantity, such as the activity or the dose, whose logarithm is normally distributed. Thus, the log-normal probability density function is symmetrical with respect to the maximum only when displayed as a function of the logarithm of the quantity (e.g. the logarithm of the activity or the logarithm of the dose) rather than as a function of the quantity. An example of such a log-normal probability distribution, showing an idealized histogram and its probability density function, is illustrated on the left hand side of the figure below.



The probability density function can be *integrated*, meaning that the values of the bins in the normalized histogram can be summed, from the lower to the higher values of the quantity. This summation, as a function of the quantity, is termed the *cumulative probability function* and describes the likelihood that a quantity with a given probability distribution will be found to be less than or equal to the value in question.

The *log-normal cumulative probability function* can be plotted as a straight line in a coordinate plane of abscissas representing the quantity (e.g. the dose) calibrated logarithmically versus ordinates representing the cumulative probability calibrated as a *normal* function. An example of such a representation is shown on the right hand side of the figure above, where the integral of the actual experimental data of the bins in the left figure is plotted vis-à-vis the straight line.

A statistical analysis was carried out on some of the data collected by FAO and the IAEA [156] of activity concentrations in different foods. Log-normal distributions were calculated using the approach described in Box 4.1–1. Figure 4.1–27 shows the log-normal probability distribution of ^{131}I in milk in the first month following the accident and in leafy vegetables in the first three months after

the accident. As noted earlier in relation to the data given in Table 4.1–5, the results shown in Figure 4.1–27 include all measurement data and not just those from food that was marketed. The calculated mean level of ^{131}I in leafy vegetables of 4.3 Bq/kg and in milk of 34 Bq/kg are well below the levels at which restrictions were required by the Japanese authorities. However, the 95th percentiles of 7300 Bq/kg for leafy vegetables and 1800 Bq/kg for milk show that it was important that the restrictions were introduced. However, the initial limiting values on activity concentrations in foods, established by the Japanese authorities, were subsequently reduced [158]. This cautious approach created difficulties for producers and consumers.

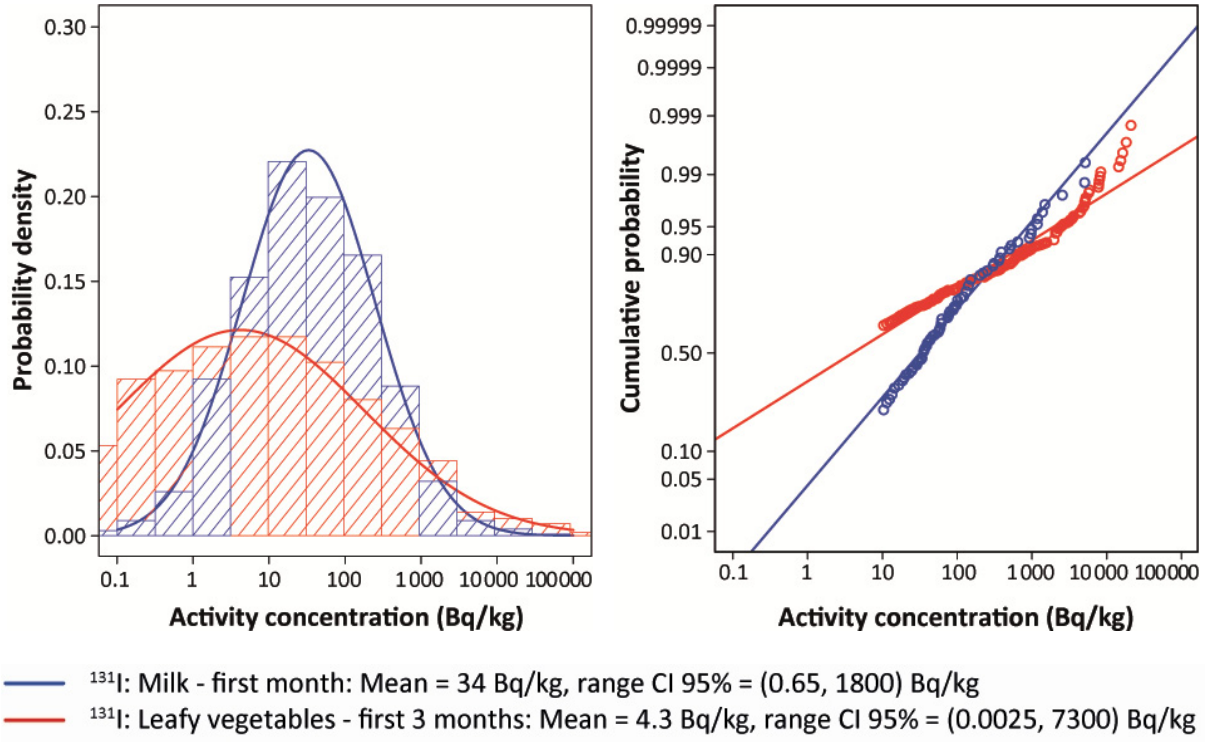


FIG. 4.1–27. Log-normal probability distribution of ^{131}I activity concentration in milk in the first month after the accident and in leafy vegetables in the first three months after the accident (normalized idealized probability density distribution and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used) (CI: confidence interval) [156].

4.1.4.2. Wild foods

In addition to the farmed foods listed above, wild foods may contain radionuclides released from the Fukushima Daiichi NPP. Measured activity concentrations are available for wild boar, other game animals, mushrooms and berries.

Levels of caesium isotopes were measured in adult wild boar hunted in Fukushima, Miyagi, Tochigi and Ibaraki prefectures between May 2011 and March 2012. The range of measured levels of ^{134}Cs and ^{137}Cs in the muscle of wild boar is shown in Fig. 4.1–28. The two highest levels measured were 14 600 and 13 300 Bq/kg; more than half of the measurements from boar captured in Fukushima Prefecture had levels >500 Bq/kg, as did many animals from the neighbouring prefectures [159]. The boar forages for small animals and plants by digging through the litter on the ground and in the soil, which contains relatively high levels of ^{134}Cs and ^{137}Cs, hence the greater levels in wild boar than in farmed animals.

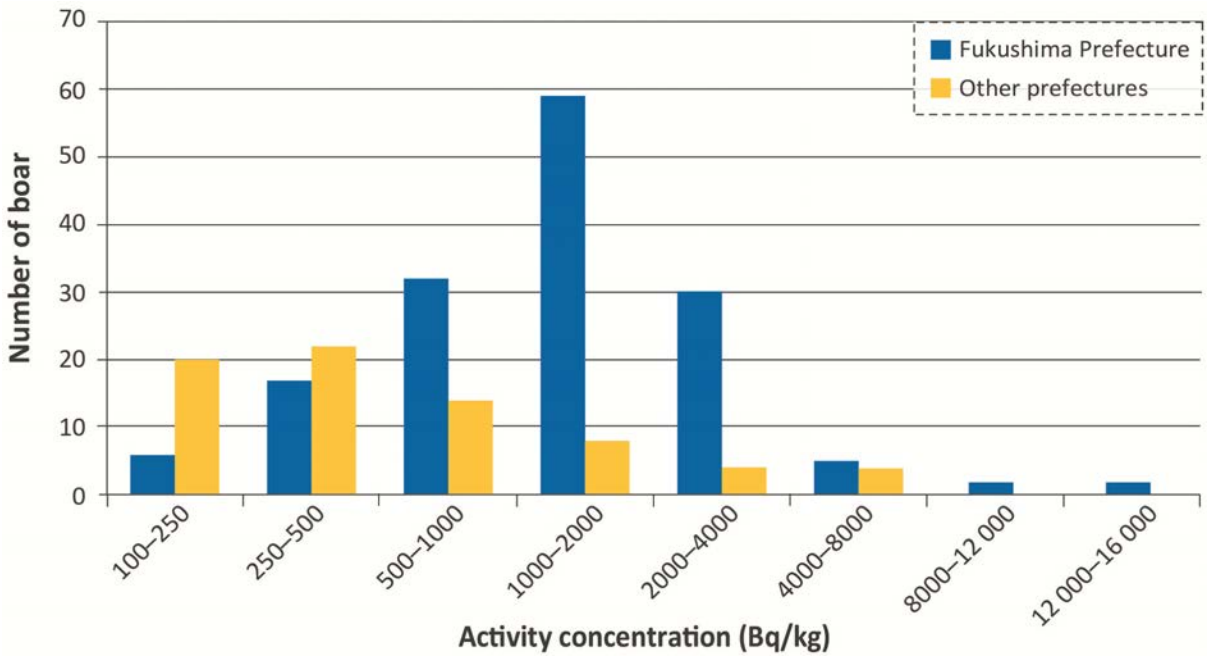


FIG. 4.1–28. Distribution of activity concentrations of radiocaesium in wild boar hunted in Fukushima, Miyagi, Tochigi and Ibaraki prefectures between May 2011 and March 2012 [159].

Concentrations of ^{134}Cs and ^{137}Cs were measured in about 400 samples of mushrooms from Fukushima Prefecture in the first year after the accident. A statistical analysis has been carried out of these measurement data, as shown in Fig. 4.1–29. Although the measurements fit a log-normal distribution, it can be seen from Fig. 4.1–30 that it was only after June 2011 that levels of ^{137}Cs started to be measurable (assumed detection limit about 10 Bq/kg). The concentrations reached a peak in September 2011 and then fell below the detection limit. In 2013, only three samples with concentrations above detection limits were found, with one sample having a concentration of ^{137}Cs of 9 Bq/kg. The average concentration in 2012 was below 15 Bq/kg. However, the number of samples is small, and the analysis of the annual change in radiocaesium concentration may be biased. It should be noted that this figure does not show the seasonal change of a single species, but presents the variation of species collected in different seasons of the year. The concentration of radiocaesium in wild mushrooms and wild edible plants is higher than in agricultural products. According to the food monitoring data, many samples exceeded 100 Bq/kg even after the first year (2.56%, as seen at the bottom of Table 4.1–8). This is consistent with the results of studies conducted after the Chernobyl accident. Collection, consumption and transportation of wild mushrooms are regulated in many areas of Fukushima Prefecture. From the analysis shown in Fig. 4.1–29, the calculated mean concentration of ^{137}Cs in mushrooms is 16 Bq/kg and there is a likelihood of around 90% that concentrations were below the Codex Alimentarius level for ^{137}Cs of 1000 Bq/kg (see Section 4.3 and Annex VIII for an explanation of the Codex Alimentarius). This figure illustrates the mean and 95% confidence interval (CI).

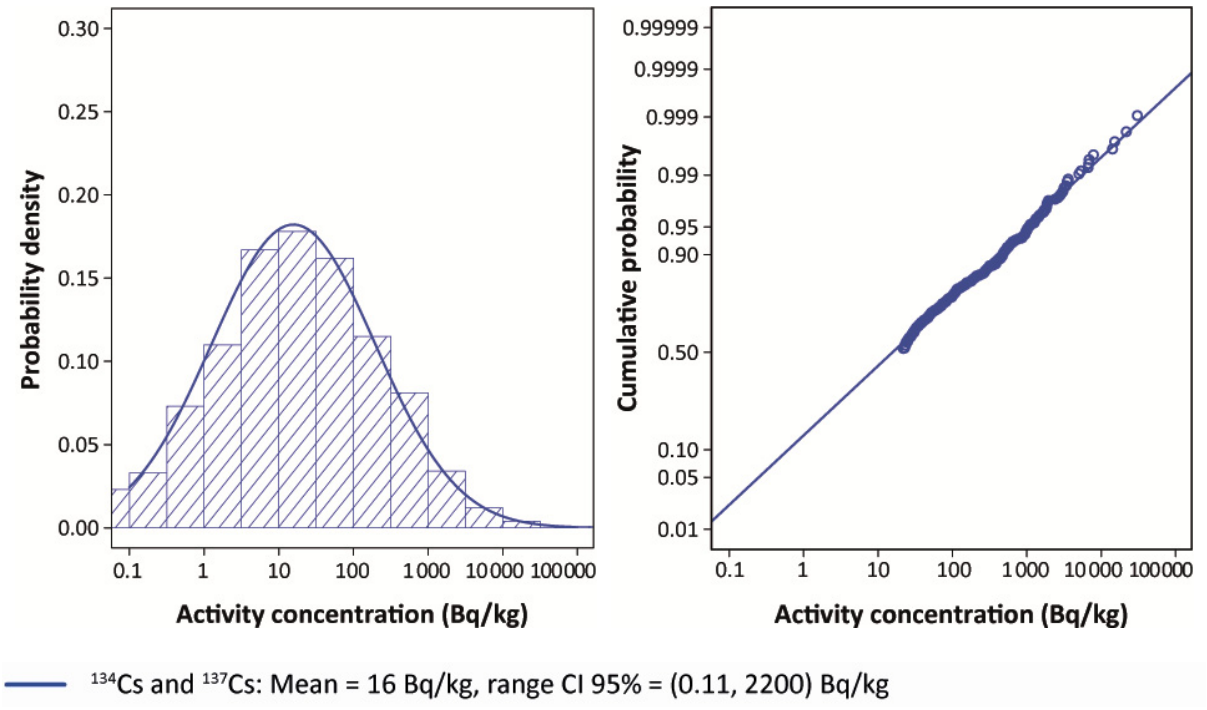


FIG. 4.1–29. Log-normal probability distribution of ^{134}Cs and ^{137}Cs activity concentration in mushrooms during the 12 months after the accident (normalized idealized probability density distribution and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used) [156].

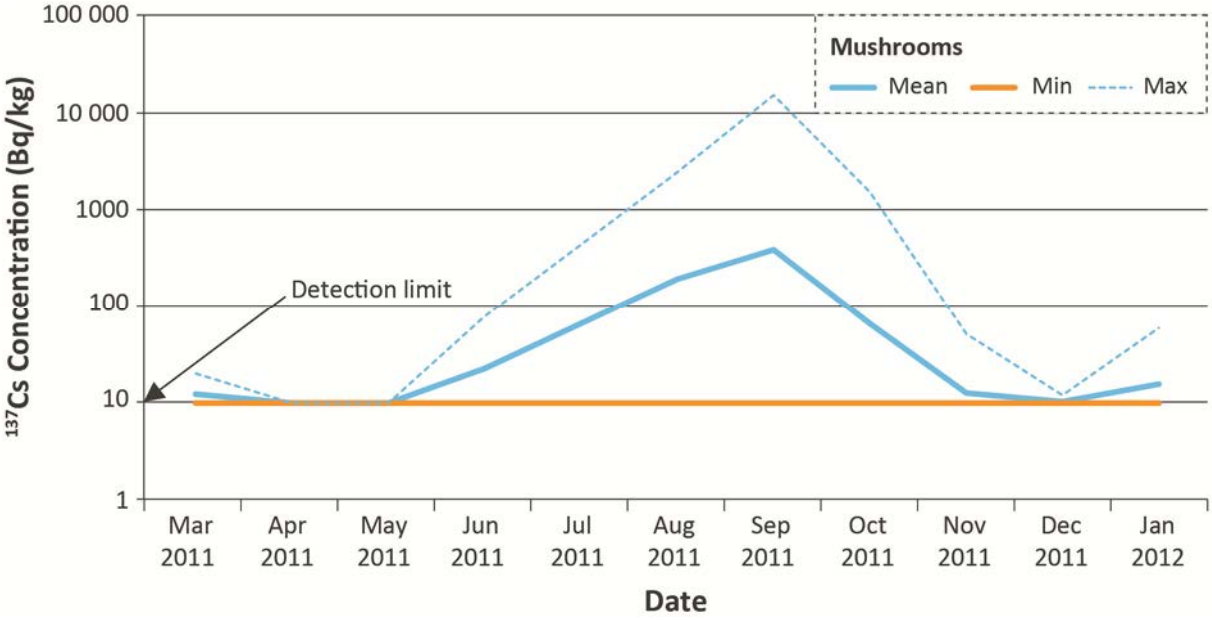


FIG. 4.1–30. Time trend of measured values of ^{137}Cs in mushrooms with different species collected in Fukushima Prefecture [156].

Only five samples in March 2011 contained measurable levels of ^{131}I, with an average concentration of 25 Bq/kg. Iodine-131 was not detected in any other sample, with detection limits varying from 5 to 10 Bq/kg.

From a total of nearly 250 samples of berries taken in the first year after the accident in Fukushima Prefecture, only 13 contained measurable levels of ^{131}I, with detection limits ranging from 5 to 10 Bq/kg. All these 13 samples were measured in March and April 2011. A statistical analysis of these data was carried out and is shown in Table 4.1–11.

TABLE 4.1–11. STATISTICAL SUMMARY OF CONCENTRATIONS OF ^{131}I IN BERRIES AT THE TIME OF MEASUREMENT [156]

Period	Number of samples	Arithmetical average	Standard deviation	Geometric average	Geometric deviation	Minimum[a]	Maximum
March 2011	23	92	293	18.4	3.7	10	1400
April 2011	22	18.0	23.6	13.0	1.9	10	110
2011–2012	247	18.4	91.0	10.8	1.6	10	1400

[a] Limit of detection assumed to be 10 Bq/kg, according to the FAO/IAEA database.

Although about 75% of samples contained levels below detection limits (about 10 Bq/kg), the monthly average activity concentrations were fairly constant during the first year after the accident, varying from less than 10 to 27 Bq/kg; some higher activity concentrations of ^{137}Cs were seen in March, July and October, as shown in Fig. 4.1–31. The highest measured concentration of ^{137}Cs was 170 Bq/kg. All samples taken in 2012 in Fukushima Prefecture had concentrations of less than the detection limits. The average concentration (arithmetical mean) of ^{137}Cs for the 240 samples of berries measured in the first year after the accident was around 18 Bq/kg, with a standard deviation of 24.

In addition to berries and mushrooms, wild plants such as ferns (collected mainly in the spring) are important forest products for people in Japan. The tendency for wild plants to accumulate caesium preferentially, compared with cultivated agricultural products, makes the monitoring of such products important. According to the food monitoring data, many of the samples exceeded 100 Bq/kg even after the first year (see Table 4.1–8). The collection and distribution of wild plants is regulated in areas of 12 prefectures in Japan.

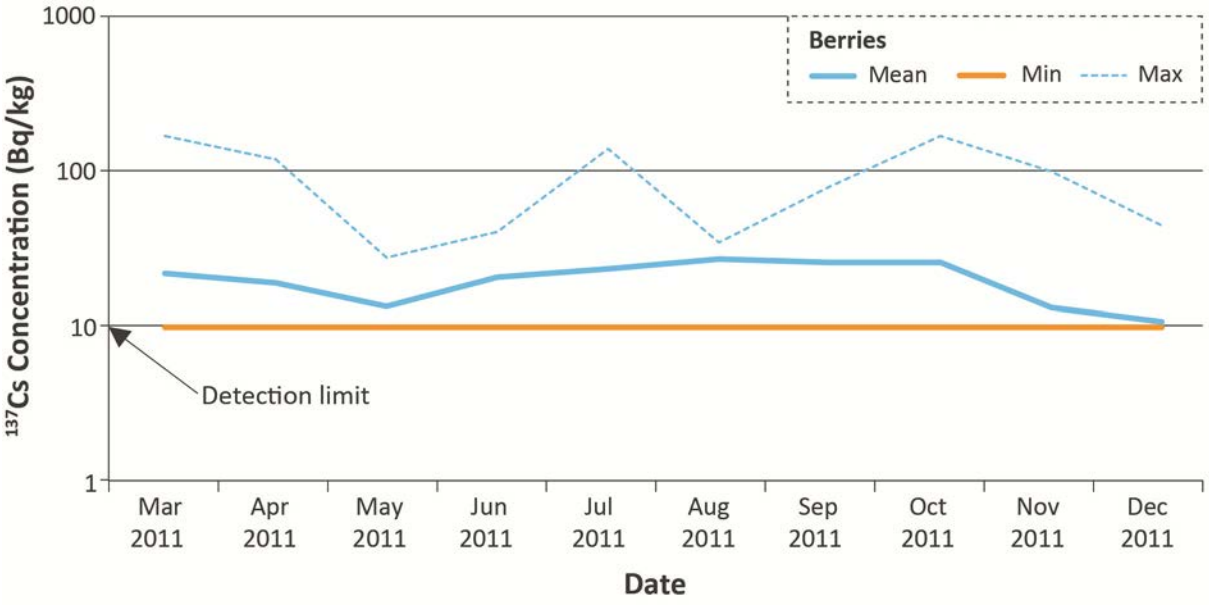


FIG. 4.1–31. Time trend of measured values of ^{137}Cs in berries in Fukushima Prefecture in 2011 [156]. These results may include data from the measurement of cultivated berries.

4.1.4.3. Fish

To supply safe fishery products to consumers, prefectural governments, in close cooperation with relevant ministries and industries, conducted monitoring of major marine fish species in each prefecture on a weekly basis [160].[10] If measurements approach the relevant standard, monitoring of the relevant products is strengthened [160]. The regulatory limits for combined ^{134}Cs and ^{137}Cs in food products also apply to seafood.

Commercial sea fishing activities were severely curtailed by the earthquake and tsunami, which damaged boats and ports. All sea fishing activities in Fukushima Prefecture were suspended for some time. A 20 km radius exclusion zone was established around the Fukushima Daiichi NPP, and some trial fishing beyond this area targeted 64 specific species, as of 30 April 2015 [129]. According to data published by the Fisheries Agency [129], 25 912 samples of marine fishery products were analysed from April 2011 to March 2015 in Fukushima Prefecture. Of these samples, 8% had a combined ^{134}Cs and ^{137}Cs level of more than 100 Bq/kg. The percentage of samples containing more than 100 Bq/kg dropped from 58% (average value for the period of April to June 2011) to 0.2% in the period of July to September 2014. In prefectures other than Fukushima, 32 852 samples of marine fishery products were analysed from March 2011 to March 2015 [129]. Only 0.5% of these samples had levels of combined ^{134}Cs and ^{137}Cs of more than 100 Bq/kg. The percentage of samples containing more than 100 Bq/kg in prefectures other than Fukushima dropped from 4.7% (average value for the period of March to June 2011) to effectively zero in the period of January to March 2015.

In the period of March 2011 to March 2012, the highest reported activity concentrations of ^{134}Cs and ^{137}Cs for freshwater fish in rivers and lakes was 18 700 Bq/kg (landlocked masu salmon, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish outside the 20 km radius exclusion zone in this period was 14 400 Bq/kg (Japanese sand lance; caught off the shore of Fukushima Prefecture) [161]. In the subsequent year (April 2012 to March 2013), the highest reported value for ^{134}Cs and ^{137}Cs was 1400 Bq/kg in fish in rivers and lakes (landlocked masu salmon, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish in this period was 3300 Bq/kg (Japanese black porgy; caught off the shore of Miyagi Prefecture) [162]. From April 2013 to March 2014, the highest reported values for ^{134}Cs and ^{137}Cs for fish in rivers and lakes was 600 Bq/kg (white spotted char, wild; Fukushima Prefecture). The highest reported value for oceanic fish in the period was 1700 Bq/kg (fat greenling caught off the shore of Fukushima Prefecture) [163]. In the period April 2014 to March 2015, the highest reported value for ^{134}Cs and ^{137}Cs in fish in rivers and lakes was 740 Bq/kg (white spotted char, wild; Fukushima Prefecture). The highest reported value for these radionuclides in oceanic fish was 510 Bq/kg (Japanese black porgy; caught off the shore of Fukushima Prefecture) [164]. However, inside the 20 km radius zone, and especially within the Fukushima Daiichi NPP harbour, much higher levels of ^{134}Cs and ^{137}Cs in fish were reported by TEPCO. To date, the highest reported value for these radionuclides in fish inside the harbour was 740 000 Bq/kg (greenling, caught in February 2013) [165], while outside the harbour, the highest value reported was 25 800 Bq/kg (greenling, caught in August 2012, 1 km offshore of the river Ota) [166]. TEPCO also reported values for other radionuclides (i.e. ^{110m}Ag and ^{90}Sr), mainly in shellfish, with levels not exceeding 69 Bq/kg and 1.5 Bq/kg, respectively [166]. As noted, these fish are not available for consumption.

If radioactive caesium close to or exceeding the standard is detected in a sample, fishermen stop the fishing and shipping of the species, and/or prefectural governments request distribution restrictions on the species. If any expansion of the contamination is observed (e.g. detection in more than one area in a prefecture of fishery products exceeding the standard), the Director General for the Nuclear

[10] In accordance with the relevant policies, including the 'Concepts of Inspection Planning and the Establishment and Cancellation of Items and Areas to which Restriction of Distribution and/or Consumption of Foods concerned Applies', established by the Nuclear Emergency Response Headquarters.

Emergency Response Headquarters (i.e. the Prime Minister) issues an instruction ordering the suspension of the distribution of the fishery products affected. For instance, in some prefectures, including Miyagi and Ibaraki, fishermen stopped the fishing and shipping of fishery products which exceeded or could exceed the standard, in accordance with the request from the prefectural government. In addition, the Director General of the Nuclear Emergency Response Headquarters instructed the relevant governor to order the suspension of the distribution of the fishery product that exceeded the standard.

As for the area off the shore of the Fukushima Prefecture, since the accident, all coastal and bottom fisheries have been suspended. The fishery products caught in the area after the accident were captured as samples for monitoring, and were not distributed at the markets (except for 55 species caught by trial fisheries on 30 November 2014). Skipjack and Pacific saury fisheries, on the other hand, are operated in the Pacific Ocean, including off the shore of Fukushima Prefecture, and the fish have landed at ports in the prefecture. These species migrate mainly through areas far from the Fukushima Daiichi NPP, where the effects of radioactive materials are considered to be small. This is confirmed by the results obtained from monitoring them.

Restrictive measures, including distribution suspension orders, have been introduced for fish in rivers and lakes where radioactive caesium exceeding the standard has been detected. Such information is publicized on the web sites of the national and prefectural governments [129].

4.1.4.4. Levels of radionuclides in drinking water

Monitoring of radionuclides in bottled and tap water began throughout Fukushima Prefecture on 17 March 2011, as described in more detail in Technical Volume 3, Section 3.3. Iodine-131 was detected in samples from a number of locations in Fukushima Prefecture in March and April 2011. The measured levels of ^{131}I exceeded the provisional regulation value (of 100 Bq/kg for radioiodine in drinking water for infants) in several locations in the first three weeks following the accident, which required restrictions on the intake of tap water to be imposed for this age group. The highest levels of ^{131}I were recorded in Iitate Village: the maximum activity concentration recorded was 965 Bq/kg in a sample taken from a small scale water supply on 20 March 2011. Restrictions on consumption of tap water were imposed for all age groups in this municipality. The levels of ^{131}I measured in water sampled from supplies in Fukushima Prefecture where restrictions on intake were imposed are shown in Fig. 4.1–32.

In total, the provisional regulation value for radioiodine in drinking water for infants was exceeded for 20 water supplies in six prefectures. The maximum levels of ^{131}I detected, and the period for which restrictions on intake were imposed, are summarized for these prefectures in Table 4.1–12.

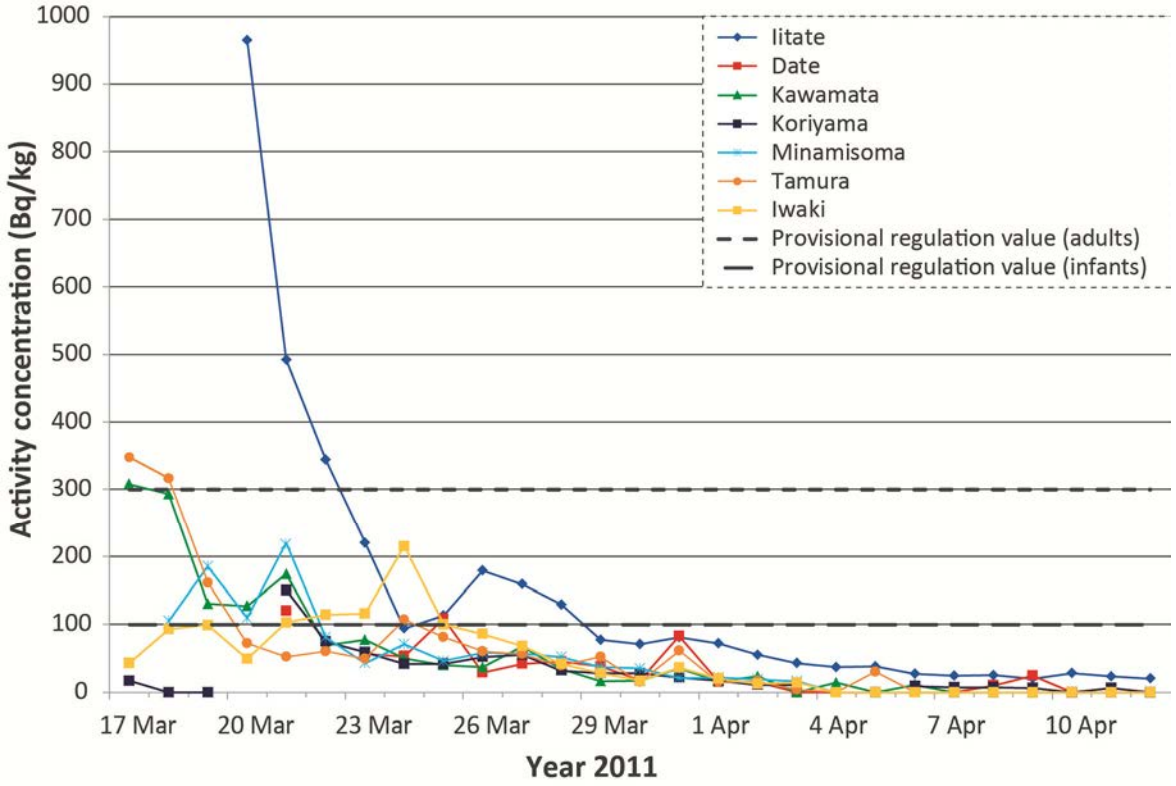


FIG. 4.1–32. Levels of ^{131}I measured in tap water supplies in Fukushima Prefecture [167].

TABLE 4.1–12. MAXIMUM LEVELS OF ^{131}I DETECTED IN DRINKING WATER[a] AND THE PERIOD FOR WHICH RESTRICTIONS ON INTAKE WERE IMPOSED
(adapted from Hamada and Ogino [168]).

Prefecture	Date ^{131}I levels first exceeded 100 Bq/kg	Maximum level of ^{131}I in tap water		Restrictions on consumption of drinking water by infants[b]	
		Activity concentration (Bq/kg)	Sample date	Date announced	Date lifted
Fukushima	16 March 2011	965	20 March 2011	21 March 2011	10 May 2011
Ibaraki	22 March 2011	298	23 March 2011	23 March 2011	27 March 2011
Chiba	22 March 2011	370	22 March 2011	23 March 2011	27 March 2011
Tokyo	22 March 2011	210	22 March 2011	23 March 2011	24 March 2011
Tochigi	23 March 2011	142	24 March 2011	25 March 2011	26 March 2011
Saitama	22 March 2011	120	22 March 2011	—	—

[a] These data relate to water available from the tap (not bottled water).
[b] In Iitate Village, restrictions for adults were also imposed. In Fukushima Prefecture, restrictions were lifted on 1 April 2011 in all locations except Iitate Village, where they were maintained in force until 10 May 2011.

The short lived radionuclide ^{132}I was also detected in a small number of samples taken from water supplies in Fukushima Prefecture in the first few days following the start of monitoring. The measured concentrations in tap water ranged from 50 to 150 Bq/kg. Radiocaesium was detected in a number of samples at levels far below the provisional regulation value of 200 Bq/kg. The highest levels were measured in samples taken on 31 March 2011 from water supplies in Date City (69 Bq/kg and 53 Bq/kg of ^{134}Cs and ^{137}Cs, respectively) and in Tamura City (60 Bq/kg and 81 Bq/kg of ^{134}Cs

and ^{137}Cs, respectively). Other radionuclides, including ^{51}Cr, ^{54}Mn, ^{58}Co, ^{59}Fe, ^{60}Co, ^{65}Zn, ^{95}Zr, ^{106}Ru and ^{144}Ce were monitored, but values were below detectable levels. Levels of other gamma emitting radionuclides, including ^{132}Te, ^{133}I, ^{134}I and ^{135}I, were not monitored. Levels of ^{89}Sr and ^{90}Sr were also not monitored. It is of interest to note that after April 2012, measured levels in Japan were below WHO guidance values for permissible levels of radionuclides in drinking water, although these are intended for normal circumstances (see Section 4.3).

Daily monitoring of tap water by prefecture was also undertaken from 18 March 2011 until the end of 2011 [169].

Samples from groundwater supplies (wells and springs) were collected at 101 locations in Fukushima Prefecture and at 9 locations in Iwaki City in June and July 2011. Levels of ^{131}I and radiocaesium ^{134}Cs and ^{137}Cs were monitored, but no values above the detection limit of 10 Bq/L were recorded [170].

Since early 2012, extensive surveys of tap water have been carried out for three month periods in all 47 prefectures. The detection limit is very low, about 1 mBq/L. Measurable values for ^{137}Cs were found in 12 prefectures, and the highest value measured was 0.012 Bq/L, which was measured in the period of July–September 2012 in Tochigi Prefecture. Apparently, there was a peak for most prefectures in the same period, as shown in Fig. 4.1–33, which gives a summary of the measured levels of ^{137}Cs in tap water for the periods of July–September 2012 and January-March 2013.

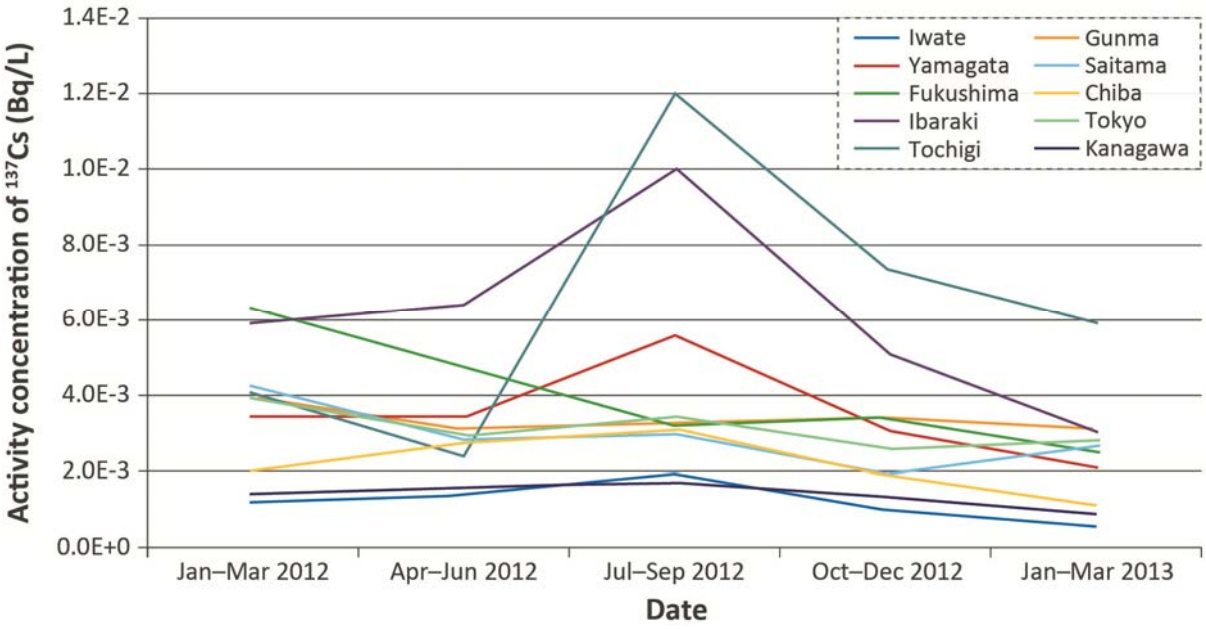


FIG. 4.1–33. Variation of ^{137}Cs activity concentration in tap water over time [171].

Although the concentrations of ^{137}Cs in tap water were very low, the increase from 2012 to 2013 observed in Fig. 4.1–33 may represent wash-off of radionuclides deposited on the land and transferred to surface waters used as a source for public supply (see Section 4.1.2).

Well water was also monitored. All the measurements made in July and August 2011 in about 80 wells in Fukushima Prefecture showed values below detection limits for ^{131}I, ^{134}Cs, ^{137}Cs, ^{89}Sr and ^{90}Sr [172], thus indicating that well water was not affected by the accident.

4.1.5. Levels of radioactivity worldwide

Radionuclides released to the atmosphere as a consequence of the Fukushima Daiichi accident were transported around the globe, resulting in very low but detectable concentrations above background levels in many regions. Atmospheric dispersion modelling results and environmental monitoring results, e.g. activity concentrations in air and rainwater, have been used to track the transport of the releases around the globe.

As explained in Section 4.1.2.2, radionuclides released to the ocean were also dispersed throughout the Pacific Ocean. Again, very low concentrations in sea water above the normal background have been detected, for example, in sea water sampled from the coasts of Alaska, Canada and California in 2013 and 2014.[11]

This section gives a brief overview of the global dispersion of the releases from the Fukushima Daiichi accident to the atmosphere and the resulting concentrations of radionuclides in environmental media.

4.1.5.1. Atmospheric transport modelling

A number of computer simulations have been carried out to model the dispersion of radionuclides released to the atmosphere from the Fukushima Daiichi NPP and to estimate the levels of radionuclides in other countries. Atmospheric dispersion modelling is subject to uncertainties in the amount of radionuclides released at different times and in other aspects of the source term as described in Section 4.1.2, together with the variable meteorological conditions and other factors affecting the modelling. The calculations suggest that the predominant long range transport of radionuclides was to the east of Japan, but that countries throughout the world received radionuclides from the Fukushima Daiichi accident releases, although at low levels. This long range transport was modelled in the preliminary dose estimation carried out by WHO in order to estimate global radiation exposures [173]. Calculations of the air mass trajectories were also performed by various other groups, using, for example, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model [174] and the global aerosol transport model SPRINTARS [33].

To illustrate the type of results obtained, Fig. 4.1–34, which is reproduced from Thakur et al. [13], shows calculated air mass trajectories initially starting at 500, 1000 and 1500 m above ground level, from 10:00 UTC[12] on 12 March 2011, approximately three hours after the first explosion. All of the trajectories were estimated to follow the winds from a westerly direction toward the Pacific Ocean and North America. The patterns of trajectories were then different, depending on the height of the release. It was estimated that the lower altitude trajectory followed a cyclonic system over the Bering Sea, reaching the eastern part of the Russian Federation on 16–17 March 2011 before entering north-eastern China. From 23 to 26 March, the air mass was transported from north-eastern China to the coastal region of southern China [13].

---

[11] CENTER FOR MARINE AND ENVIRONMENTAL RADIATION, WOODS HOLE OCEANOGRAPHIC INSTITUTION, Current Results (2015),

http://ourradioactiveocean.org/results.html

[12] Universal Time Coordinated, which is nine hours behind Japan Standard Time.

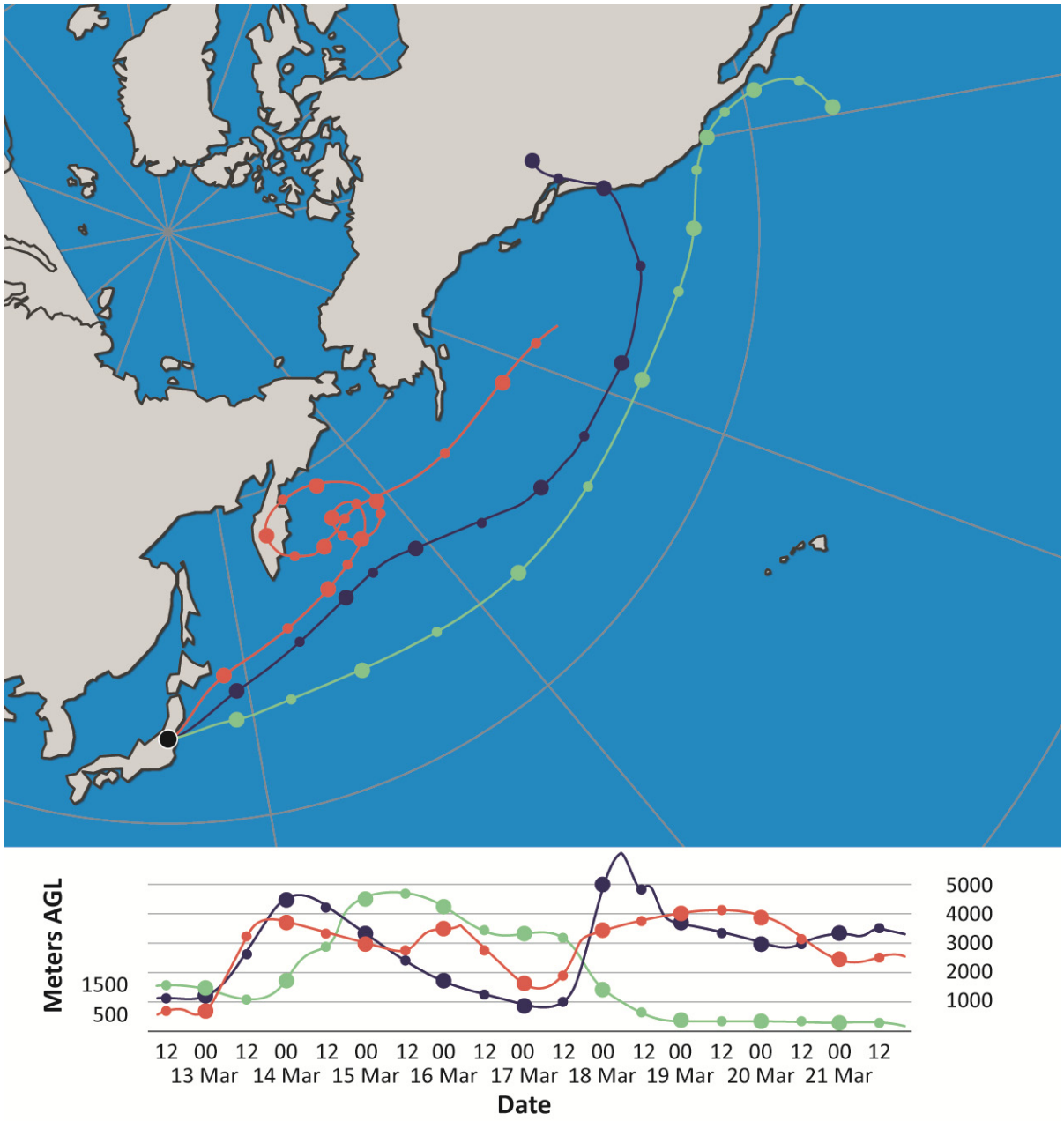


FIG. 4.1–34. Trajectories of air masses released from the location of the Fukushima Daiichi NPP calculated using the HYPSLIT model on the basis of GDAS Meteorological data and starting at 10:00 UTC on 12 March 2011 [13].

Similar results were obtained by Takemura et al. [33] using the SPRINTARS model to predict the long range transport of radioactive material from Fukushima Daiichi to the United States of America and to Europe within five days. These studies showed the importance of certain features, such as storms that lift material vertically, the action of jet streams and the removal of radionuclides by wet deposition. The results of the SPRINTARS model are illustrated in Fig. 4.1–35, which shows the global transport of material in air released continuously from the Fukushima Daiichi NPP for different periods (it should be noted that this does not reflect the actual releases). The complex nature of the dispersion can be seen, together with the possible mechanism by which radionuclides were dispersed to Europe. The model of Takemura et al. [33] also predicted the arrival of the radionuclides from the Fukushima Daiichi NPP in Asian countries in late March, as reported in various publications, including Refs [175, 176]. This suggests that the radionuclides were transported at two different altitudes along different trajectories with different speeds of transport.

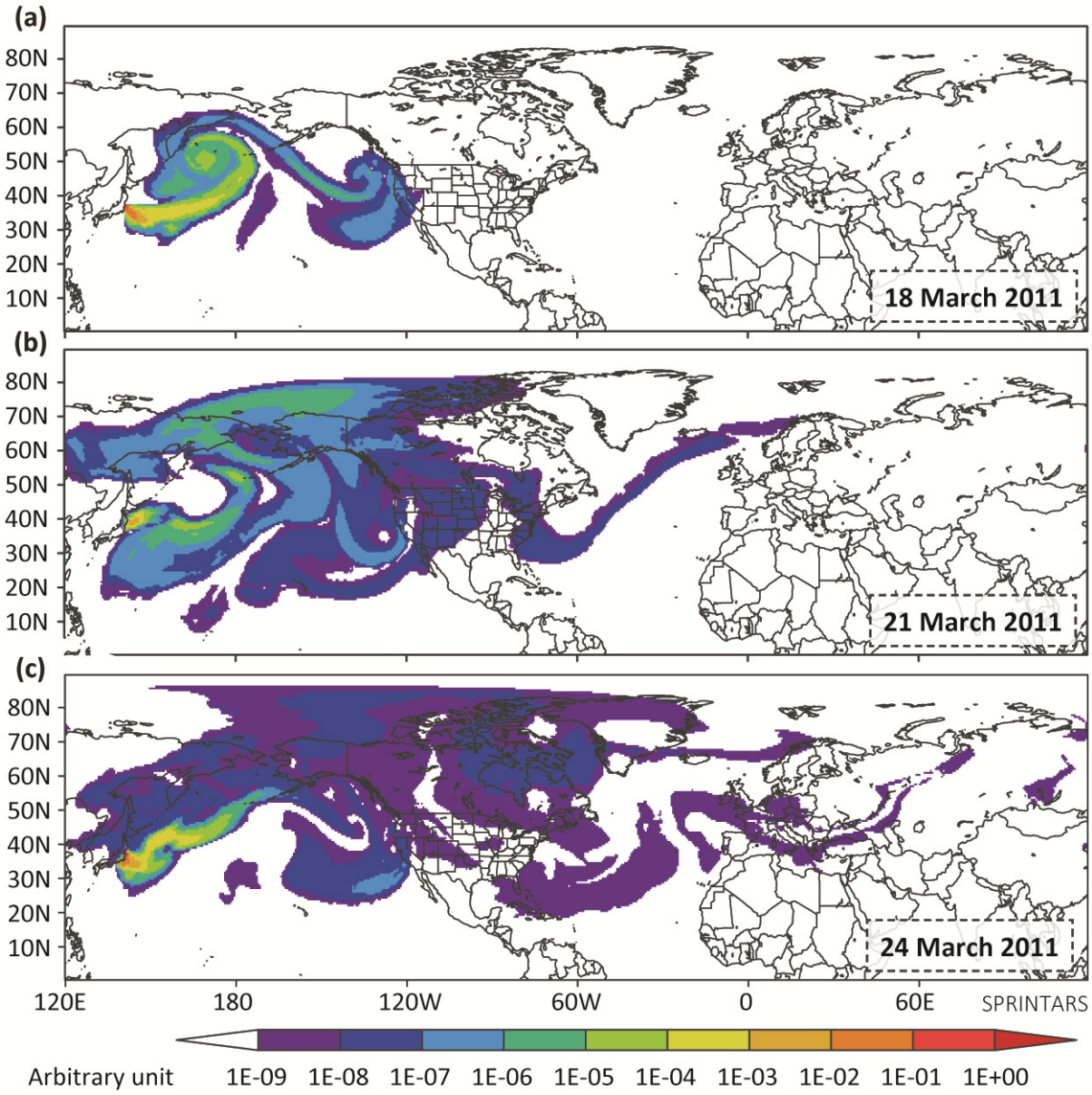


FIG. 4.1–35. SPRINTARS simulation of the global transport of material in near surface air masses emitted continuously from the Fukushima Daiichi NPP since 14 March, 12:00 UTC, for (a) 18 March, (b) 21 March and (c) 24 March 2011. The concentration indicated is relative to the concentration within a few tens of kilometres around the NPP. Each range of colour contours corresponds to one order of magnitude [33].

4.1.5.2. Global measurements of radionuclides released to the atmosphere

Following the events at the Fukushima Daiichi NPP in March 2011, the monitoring of radionuclides in the environment was increased throughout the Northern Hemisphere. The network of the CTBTO monitoring stations detected enhanced levels of isotopes of xenon, iodine and caesium in the air. Some additional radionuclides — isotopes of tellurium, ^{140}Ba/^{140}La, ^{90}Mo/^{99m}Tc, ^{110m}Ag and ^{111}Ag — were also detected in air samples collected across the USA and Europe. However, these measured activity concentrations were considerably (more than a thousand times) lower than the activity concentrations observed in Japan. Radionuclides from the releases from the Fukushima Daiichi NPP were detected in most of the countries in the Northern Hemisphere, but, as expected, there was little activity detected in the southern hemisphere, owing to the low exchange of air masses across the equator [13].

The measured activity concentrations in air throughout the Northern Hemisphere were evaluated by Thakur et al. [13]. They note that levels varied over time at the same location, reflecting the complex pattern of global dispersion, and also between locations. The measured activity concentrations in air were found to follow a log-normal distribution with higher values observed in North America, followed by countries in Asia, and lower values in Europe. They report that the highest activity concentrations in air measured outside Japan were 31 mBq/m^3 for ^{131}I; 8 mBq/m^3 for ^{134}Cs; and 10 mBq/m^3 for ^{137}Cs.

Radionuclides from the Fukushima Daiichi NPP were also detected in other environmental materials at many locations in the Northern Hemisphere, notably in rainwater, grass, milk and vegetables. Again, levels of these radionuclides were significantly lower than those measured in Japan. These measurements have been used to assess radiation exposures in many countries. UNSCEAR collected information from Member States on levels of radionuclides in environmental materials and on exposure assessments as part of a study to determine the levels and effects of radiation exposure due to the releases [5].

4.1.6. Summary

As a consequence of the Fukushima Daiichi accident, radioactive material was released into the environment, both to the atmosphere and into the ocean. This resulted in relatively high ambient radiation levels around the Fukushima Daiichi NPP. A proportion of the radioactive material reached the human habitat, including foods and drinking water. Some of this radioactive material was globally circulated.

The events leading to these releases were complex and variable. The main part of the releases occurred over a period of about one month and continued, albeit at very much lower levels. Of particular note were the releases that took place on 12 March 2011 following a hydrogen explosion in Unit 1, those on 14 and 15 March and those over the period from 20 to 23 March.

The radiological impact of the relevant releases to the atmosphere was dominated by the radionuclides of the elements caesium and iodine (including, ^{131}I, ^{134}Cs and ^{137}Cs). Different theoretical estimates of the releases have been performed by specialist institutions around the world. The estimates of the release of ^{131}I were in the range of 100–400 PBq. The amount of ^{137}Cs released is estimated to have been in the range of 7–20 PBq. A statistical analysis of the source term data using Bayesian techniques was carried out for the purposes of this report; it indicates that the mean of the distribution could be estimated to have been between 140 and 200 PBq for ^{131}I and between 12 and 16 PBq for ^{137}Cs.

One method of estimating an accident source term is to measure the levels of radionuclides deposited on the ground and calculate the amount of the release, using atmospheric dispersion models. However, in the case of the Fukushima Daiichi accident, part of the releases to the atmosphere took place when the wind was blowing in an eastward direction from the Fukushima Daiichi NPP towards the sea. Consequently, most of the radioactive material deposited onto the ocean and dispersed could not be measured, making it impossible to corroborate the amount of radionuclides released on the basis of measurement of deposition in the terrestrial environment. Nevertheless, it can be judged with sufficient confidence that the releases were lower than those from the accident at the Chernobyl NPP in 1986. The total release of ^{131}I is estimated to have been 20% of the release from the Chernobyl accident, while the total release of ^{137}Cs is estimated to have been 35% of the release from the Chernobyl accident. Unlike the Chernobyl accident, the Fukushima Daiichi accident is estimated to have led to only negligible releases of radionuclides such as ^{90}Sr and ^{239}Pu.

The weather conditions during the period of the releases were very variable, and, in spite of the fact that much of the released material was initially blown over the sea, some of the key releases were

blown over the land. Some of the released radioactive material encountered rainfall, leading to enhanced levels of deposition on land in some areas. The variable weather conditions and the complex nature of the releases led to a distribution pattern of radionuclides in the terrestrial environment that was very inhomogeneous, with some areas being affected to a greater extent than others. Notably, some areas to the north-west of the Fukushima Daiichi NPP were subject to the highest levels of deposition of radionuclides. A further factor that influenced the pattern of deposition in the terrestrial environment was the prevalence of different physical and chemical characteristics of the radionuclides of iodine and caesium.

Extensive monitoring of the terrestrial environment was carried out in Japan by the relevant national authorities, supplemented by international expertise. This monitoring provided information on the type and the levels of radioactive material in the environment in Japan. Of particular importance were the aerial surveys of ambient dose carried out jointly by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the United States Department of Energy (DOE), as well as the comprehensive measurements of radionuclides in soil across the whole of Japan. These two sets of measurements (which formed the basis for the UNSCEAR estimates of the consequences of the accident) confirmed the radiological significance of the radionuclides ^{131}I, ^{134}Cs and ^{137}Cs. Although other radionuclides were also detected during these measurements, they were found at relatively low levels. There is good agreement between the different measurements carried out by the Japanese authorities and other organizations, including measurements undertaken by the IAEA, which provides confidence in the results presented in this report.

Releases to the Pacific Ocean and levels of radionuclides in the aquatic environment

There were two main routes by which radionuclides reached the Pacific Ocean. Firstly, as mentioned above, because of the prevailing weather conditions, a component of the radionuclides released to the atmosphere was transported over the ocean and deposited on the ocean surface. Secondly, water containing radionuclides was released directly into the ocean. The direct releases took place in March and early April 2011. These two routes by which radionuclides reached the ocean seem to have been broadly similar in terms of the total amount released, although for direct releases of radionuclides to the ocean, there is a higher degree of uncertainty. Most estimates for the release of ^{137}Cs are in the range of 1–6 PBq; some estimates are as high as 27 PBq. The direct releases of ^{131}I are thought to have been in the range of 10–20 PBq. Other releases into the ocean included mainly ^{134}Cs and small amounts of other radionuclides, notably ^{90}Sr. Relatively low levels of radionuclides continue to be released to the ocean owing to transfer from groundwater and rivers.

The dispersion of radionuclides in the vast quantity of ocean water means that the levels of radioactive material measured in the Pacific Ocean were generally very low, although the radionuclides could be detected at large distances from Japan. The chemical characteristics of caesium are that it is soluble in sea water and is carried over very long distances by marine currents and widely dispersed throughout the water masses of the ocean. However, some of the caesium was bound to suspended particles and will eventually deposit on the sea floor.

Large volumes of water containing significant amounts of radionuclides are stored in tanks at the Fukushima Daiichi NPP. In addition, the damaged reactor buildings contain high levels of radionuclides, and large volumes of water have been transferred to the groundwater system around the site. As a consequence of the topography of the site, groundwater flows from the western side of the site to the eastern shoreline. Groundwater enters the damaged buildings and contributes to an increase in the amount of water containing radionuclides that needs to be treated, stored or discharged.

Radionuclides in food and drinking water

An extensive programme of monitoring of food and drinking water was implemented by the relevant authorities following the accident, and this programme is continuing. Measurements of ^{131}I, ^{134}Cs and ^{137}Cs on some terrestrial and aquatic foods identified levels that required restrictions on the sale and distribution of some foods. Measurements were also carried out on other sources of food, such as wild boar, mushrooms and berries, and, in the initial period after the releases, these were also found to have relatively high concentrations of the significant radionuclides.

Global circulation of radionuclides released from the Fukushima Daiichi accident

The transport of the atmospheric radioactive releases was directed mainly to the east and north of Japan, following the prevailing wind direction, and then around the globe. The transport of the releases to the Pacific Ocean is influenced by the complex recirculation patterns and the potential for the interaction of radionuclides with sediments and other physical and chemical processes.

Many countries have developed and implemented highly sensitive monitoring networks that can detect very low levels of radionuclides in the environment. The measurement results from these networks have been widely reported, and they have demonstrated that, although radionuclides have been detected at large distances from Japan, their levels have been extremely low and the impact of the Fukushima Daiichi accident on existing global levels has been negligible.

4.1.7. Observations and lessons

— **Prompt quantification and characterization of the amount and composition of radioactive material released to the environment are needed following an NPP accident. For significant releases, a comprehensive and coordinated programme of long term environmental monitoring is necessary to determine the nature and extent of the radiological impact on the environment at the local, regional and global levels.**
The quantification and characterization of the source term of the accident at the Fukushima Daiichi NPP proved to be difficult. Prompt monitoring of the environment provides confirmation of the levels of radionuclides and establishes the initial basis for protecting people. The results can be used to inform the public and to develop strategies for response and recovery activities. It is also important to continue environmental monitoring to verify that there are no further significant releases of radionuclides and to provide information to decision makers and other stakeholders on the possible redistribution of radionuclides in the environment over time.

— **Groundwater surveillance needs to continue.**
Radioactivity in groundwater is a local problem restricted to the Fukushima Daiichi NPP. However, continued surveillance is needed to confirm that this continues to be the case in the longer term.

4.2. RADIATION EXPOSURE

The assessment of radiation exposures of people is an important aspect of determining the radiological consequences of accidental events and releases of radioactivity. Information on the levels of radiation doses received by workers and members of the public is necessary to construct a picture of the pattern of exposures for different groups in order to determine whether there are likely to be any observable radiation induced health effects among the population. Furthermore, it is important to determine the different routes of exposure, and the time dependence of the exposures, when using them as inputs for the planning and implementation of appropriate protection measures and for emergency planning and response purposes.

This section provides dose estimates that are as accurate as currently possible, making use of direct personal measurements where available. It builds on previous assessments, particularly the most recent international assessment, which was completed by UNSCEAR in 2014 [5]. It takes into consideration additional measurement data that have become available since that assessment was undertaken. Particular attention is paid to personal measurements from dosimeters worn by individuals and the results of thyroid measurements and whole body counting. This information has been provided by the Japanese Government, TEPCO and from available reports and sources collected up to December 2014.[13]

Section 4.2.1 focuses on occupational exposures and summarizes the doses received by workers in the more than three years since the accident. Section 4.2.2 provides a review of effective doses and thyroid equivalent doses incurred by the public in Fukushima Prefecture and neighbouring prefectures. Where possible, effective doses and thyroid equivalent doses are categorized by the appropriate location, namely the municipality in which the residents were living before the accident, and by the appropriate time period. Not all data for all prefectures are contained in this report. However, the data presented provide information for a range of municipalities for which such data were available.

4.2.1. Occupational exposures

This section provides a summary of the radiation doses received by workers engaged in on-site and off-site emergency work activities during and immediately following the accident at the Fukushima Daiichi NPP. It also provides information on the doses subsequently reported for on-site workers who have been involved with longer term stabilization and cleanup activities since the accident, for the period until December 2014. In order to place this information in context, it is helpful to provide some introductory information on the limits in place, the protective measures available at the time of the accident and the methods used to assess doses.

4.2.1.1. Dose control and dosimetry

To protect workers, other responders and the public, countries and organizations have established exposure guidelines, which are explained in greater detail in Section 4.3. Regulations and guidelines typically provide exposure limits for emergency workers that are different from those for normal radiation workers or the public. These guidelines balance the risks and benefits, considering the individual's training, the duties that require the individual to be close to radiation or radioactive sources, and the activities that need to be undertaken. The guidelines may differ between countries; they can also be changed. During the response to the Fukushima Daiichi accident, the Japanese guidelines evolved over time.

As explained further in Section 4.3, an effective dose limit of 100 mSv was initially applied for male workers involved in the radiation emergency.[14] This value was increased to 250 mSv with effect from 14 March 2011 to allow emergency workers to undertake tasks that it was necessary to perform, in particular tasks relating to controlling and stabilizing the reactors [177]. The lower level was reinstated for new workers after 1 November 2011, except for those working on reactor cooling and release suppression systems, where the higher value was retained for those workers who were already on-site [178, 179] (see Section 4.3 and Technical Volume 3 for more details). TEPCO staff and contractors and members of the police, firefighters and the Japan Self-Defense Forces (SDF) were also involved in on-site emergency activities.

[13] In some cases, information was available for the period until May 2015. This information was included in this volume, where possible.

[14] An effective dose limit of 5 mSv over three months remained in place for female workers.

Workers from the various emergency services and from other organizations were also involved in off-site emergency activities, including within the evacuation zone. Information on the doses reported for each of these groups of workers during the emergency is presented where it is available. Male SDF workers and firefighters were subject to an annual limit of 50 mSv effective dose (100 mSv in 5 years), while female workers with reproductive capacity (i.e. those who did not complete a form declaring that they did not have reproductive capacity) who served as emergency workers were subject to the normal effective dose limit of 5 mSv over three months. Other workers who offered assistance were typically subject to the guidelines of the agency for which they worked.

Table 4.2–1 shows the different organizations that responded and the organizations that had authority to issue exposure guidelines. The different sources of guidance can lead to different guidelines, as is also shown in Table 4.2–1. Note that the dose limits are associated with specific activities, reflecting the need to balance risks and benefits.

TABLE 4.2–1. RESPONDING ORGANIZATIONS AND THE ENTITIES ESTABLISHING APPLICABLE EXPOSURE GUIDELINES

Responding organization	Regulatory organization	Dose limits and criteria
TEPCO	Ministry of Health, Labour and Welfare (MHLW)	250 mSv (limiting effective dose criterion for emergency action) [a] 100 mSv (limiting effective dose criterion for emergency action)
SDF	Ministry of Defense	50 mSv/year, (100 mSv/5 years) (male); 5 mSv/3 months (female) [180]
Police	National Public Safety Commission and National Police Agency	50 mSv/1 year (100 mSv/5 years) (male), 5 mSv/3 months (female)
Fire Department	Ministry of Internal Affairs and Communications (MIAC)	50 mSv/year (100 mSv/5 years) (male); 5 mSv/3 months (female)
Municipal workers	Fukushima Prefecture	—
IAEA	IAEA Safety Standards	50 mSv/year
Australian military, urban search and rescue	Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)	50 mSv/year (in ARPANSA RPS1) [181]
US urban search and rescue	US Occupational Safety and Health Administration	50 mSv/year
US Department of Energy (DOE)	DOE	50 mSv/year
US military	United States Pacific Command (USPACOM), derived from United States Nuclear Regulatory Commission occupational limits	3 mSv during Operation Tomadachi response[182]; ≤10 mSv but documentation of mitigating factors necessitated; only upon approval by Unit Commander; >10 mSv only with USPACOM approval
Volunteers (i.e. the public)	MHLW	1 mSv/year

[a] Applicable to a limited number of workers over a short period of time.

Different guidelines among responders from other countries and international organizations created challenges for personnel from different organizations working together.

4.2.1.2. Measurements of external dose

Worker protection, and the associated legal requirements, generally necessitates the use of dosimeters or other forms of workplace instruments to measure the external exposure that individuals receive. A variety of dosimeters are available; some provide real time information (known as electronic personal alarm dosimeters (PADs) or electronic personal dosimeters (EPDs)), while others capture the information for later retrieval (passive dosimeters). The former type of dosimeter enable individuals to act on the information in real time and to modify their activities or leave the exposure situation on the basis of the information provided. However, passive dosimeters can be more accurate and are more commonly used to provide a record of exposure.

Before the accident, TEPCO used EPDs for radiation dose measurements for the purposes of both dose control and for statutory monitoring and reporting. Immediately after the tsunami, many of the EPDs were damaged by flooding and were rendered inoperable. As a result of the shortage of EPDs, a single EPD was provided per work group during the period 15–31 March 2011 [183], when groups were working under conditions where exposure was expected to be almost constant. The reactor operators were provided with individual PADs, where possible, although they were not available on an individual basis in the main control rooms. During the first month, external doses for workers inside the seismic isolation building were estimated on the basis of measured external exposure rates in the work area and worker occupancy times. From 1 April 2011, a sufficient number of dosimeters of different types were available [184, 185].

A number of organizations involved in off-site assistance activities also used EPDs of various types for tracking doses in real time and for record keeping purposes.

4.2.1.3. Measurements of internal dose

During the immediate response to the accident, TEPCO estimated internal worker doses on the basis of assessments of external exposure and assuming an intake of gamma emitting radionuclides. However, no bioassays[15] were performed by TEPCO for workers during the emergency phase. The release was known to consist predominantly of iodine and caesium. Since these radionuclides are easily measured with a whole body counter (WBC), TEPCO decided to determine internal dose from the WBC measurements. This process, later approved by MHLW, is described in detail on the TEPCO web site [186]. When an individual incurred an external dose of 100 mSv, a WBC measurement was performed and the internal dose was estimated.

WBCs are widely used to measure the amount of radioactivity in people. The principles governing their use are presented in Annex I. High background radiation levels and elevated levels of contamination at the Fukushima Daiichi NPP meant that on-site WBC equipment could not be used to monitor workers. Other WBC facilities were therefore used, as described in Annex I.

In addition to WBC measurements, in vivo measurements of radionuclides in the thyroid were also carried out. These measurements started in 22 March 2011. However, owing to emergency response activities and a lack of WBCs, many workers were not measured until mid to late May 2011, with the exception of three of the most highly exposed workers, for whom measurements began in mid-April [185]. As indicated below, this delay increased the uncertainty in the assessment of doses from ^{131}I and other short lived radioisotopes of iodine and tellurium.

TEPCO later instituted a policy to detect internal contamination and exposure to beta emitting radionuclides in certain areas of the Fukushima Daiichi NPP (e.g. the reactor building area and

[15] A bioassay is a measurement of the concentration or potency of a substance by its effect on living cells or tissues.

contaminated water storage tank locations) where the total beta and gamma exposure was expected to exceed the gamma-only exposure by approximately four times. Each worker wore an EPD (which measured gamma and beta radiation)[16] and a full face respirator in these areas. When workers left the work area, they were screened. If contamination was detected on the nose or mouth, a nasal smear was conducted. If the nasal smear was positive, the intake of beta nuclides was estimated and if the estimated committed effective dose exceeded 2 mSv, a bioassay was required. Workers with doses exceeding 250 mSv were referred to the National Institute of Radiological Sciences (NIRS) for detailed dose assessment and checkups. NIRS performed cytogenetic biodosimetry, usually by dicentric chromosome assay (DCA).

DCA is an accurate, yet time consuming, method which involves taking a blood sample, processing it in a laboratory, looking at it under a microscope, and counting chromosomal abnormalities, which can be calibrated to indicate radiation exposure. The process takes approximately two days. By the end of 2013, NIRS had performed assays for 12 workers for dose assessment purposes; ten of these workers agreed for their data to be incorporated in the study [187], and their data indicated that the estimated doses for all individuals were lower than 300 mGy, with a mean value of about 100 mGy. The results by DCA were consistent with those obtained by physical dosimetry based on personal measurements and thus primarily provided reassurance and confirmation to workers of their assessed exposures.

4.2.1.4. Protection measures

Time, distance and shielding can protect workers from external exposure. However, internal exposures tend to arise from intakes of radionuclides from ingestion or inhalation, which can lead to exposures over extended periods following intake. Personal protective equipment (PPE) is generally used to protect workers from receiving such intakes. Following the release of radioactive material from the Fukushima Daiichi NPP, virtually all of the on-site workplaces were contaminated with airborne or particulate radioactivity; thus, the greatest source of intake of radionuclides was through inhalation. Airborne contamination remained elevated until approximately the end of July 2011, as demonstrated by measurements of activity concentrations in air at the site perimeter. Emergency workers used a range of respiratory protection equipment, from filtering respirators to self-contained breathing apparatus. However, in the main control rooms, charcoal filtering PPEs were not properly distributed and used during the early phase of the accident [185, 188].

In addition to respiratory protection, gloves, shoe covers and protective suits were issued to on-site workers, depending on workplace conditions. For many off-site workers, shoe covers and gloves provided sufficient protection, although some used full PPE for particular operations such as decontaminating aircraft. Some assistance workers were measured using WBC and bioassay in their country of origin after completion of their work in Japan.

As explained in more detail in Technical Volume 3, from 13 March 2011, potassium iodide tablets were provided to some emergency workers, for the purpose of blocking the uptake of radioactive iodine by the thyroid.

4.2.1.5. Training

From the time of the accident until around 30 May 2011, TEPCO and the primary contractors conducted training for newcomers at J-Village (the coordination centre for response action located in the south of Fukushima Prefecture). The half-hour course developed by TEPCO covered worker training and education on the effects of radiation, how to control radiation dose, and the use of PPE.

[16] Since 1 July 2013, all on-site radiation workers, including those conducting decommissioning activities, have worn dosimeters that measured both beta and gamma radiation.

The course was originally designed for 20–30 participants at a time, but with an increasing number of emergency workers, revisions to the TEPCO educational and training programme were made beginning on 19 May 2011 [183]. Later, on 8 June 2011, a special education programme was initiated at J-Village for both TEPCO staff and contractors. TEPCO started a compulsory seven hour training course in the summer of 2011, approximately five months after the accident [185].

Table 4.2–2 identifies some of the organizations that participated in the response to the Fukushima Daiichi accident and their general levels of radiological awareness and dosimetry. Many of the responders had been trained to work in environments with elevated levels of radiation or contamination. They typically worked under informed consent, their exposure was tracked, and they followed exposure guidelines.

Apart from TEPCO employees, only personnel from the SDF, police, Fire Department and Nanmei Kosan (a private firefighting company and a subsidiary of TEPCO) worked on-site. Firefighters from the municipalities were involved in the off-site response. The Tokyo firefighters were members of a specially trained unit who received annual refresher training in radiation protection. These individuals wore dosimeters and their dose was recorded.

However, some firefighters, specifically the employees of Nanmei Kosan, did not receive radiation protection training. During the accident, this group operated fire engines and other equipment on-site.

TABLE 4.2–2. OVERVIEW OF ORGANIZATIONS AND RADIOLOGICAL AWARENESS (11 MARCH 2011–16 DECEMBER 2011)

Organizations	No. of workers on-site	No. of workers off-site	Radiation safety training	Dose tracking
TEPCO (including contractors)	~20 000	—	Extensive	Required
TEPCO subsidiary Nanmei Kosan	~20 (15 March) ~130 (16 December)	—	No training	Required
Firefighters –Municipal off-site	—	Varied	Awareness	Available
Police	13	Varied	Awareness	
SDF	147	~100 000	Awareness	Required
Medical personnel	—	Varied	Awareness for those who received just in time training; otherwise, none	Unknown
IAEA	—	16	Extensive	Required
Australian military, urban search and rescue	—	72	Awareness	Required
DOE	—	100	Extensive	Required
US military	—	~90 000 (~1000 within 45 km)	Awareness; extensive for some	Required
US urban search and rescue	—	150	Awareness; extensive for subset	Required
Other volunteers	—	Varied	Varied	Varied

Police officers, firefighters, members of the SDF and other first responders were an essential component of the response, facilitating evacuations and providing assistance and performing other tasks off-site. In conducting these activities, they often entered areas with elevated levels of radioactivity which residents were being asked to leave, thus increasing their potential for radiation

exposure. Their training was typically designed to give them the knowledge to minimize their exposure.

Many volunteers participated in the response and recovery work. Some of them were experienced radiation workers and others were not, but they were not designated workers. They included central and local government workers, staff at medical institutions, construction workers, university staff (e.g. Kyoto University Research Reactor Institute) and non-profit organization workers (e.g. Safecast, Greenpeace). The majority were from the affected area, but several hundred people came from other parts of the country or from other countries.

Individuals responding to the Fukushima Daiichi accident and the earthquake and tsunami performed a range of activities, including reactor stabilization, search and rescue, evacuation, medical treatment, environmental monitoring, decontamination, and providing support for these activities.

Specific on-site operations in the early phase included diagnosing the plant conditions and maintaining the important safety functions of criticality control, cooling and confinement. Initially, these were performed by TEPCO employees, with TEPCO contractors providing more support as time progressed. After the on-site situation had stabilized and major releases had ceased, the intermediate phase activities involved restoring enough control to the site to facilitate on-site operations, performing off-site contamination surveys and mapping, and mitigating the flow of heavily contaminated water into the sea. The recovery phase began in December 2012[17] and is continuing. Recovery activities include site restoration, cleaning heavily contaminated water in the basement of the plants, limiting the flow of contaminated groundwater to the sea, carrying out surveys to refine the off-site contamination maps, and decontaminating of residential areas off-site. These activities may lead to radiation exposure or contamination; thus, it is important that the people performing these activities have appropriate training, protection, and exposure monitoring. Tables 4.2–1 and 4.2–2, in combination, provide information on the people who performed the tasks, their level of training and the protection levels applied.

4.2.1.6. Reported doses to on-site workers

This section presents an overview of the reported doses to on-site workers during the emergency phase and, in the longer term, until December 2014. These data have been provided by TEPCO through the Japanese Government for the purposes of this technical volume. These data have not been independently validated. However, it should be noted that, in their 2013 report, UNSCEAR reviewed the methodologies used in Japan for assessing doses and undertook independent assessments of the doses for defined groups of workers, which were then compared with the reported values [5], as is described in more detail in Section 4.2.1.3.

Figure 4.2–1 shows the variation and decline in the annual effective doses (external plus internal dose) to on-site workers (TEPCO and contractors) from March 2011 to October 2014.

[17] As explained in Technical Volume 1, on 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a 'cold shutdown state' had been achieved in Units 1–3. This officially brought the accident phase to an end, according to the criteria set by the Government of Japan at the time.

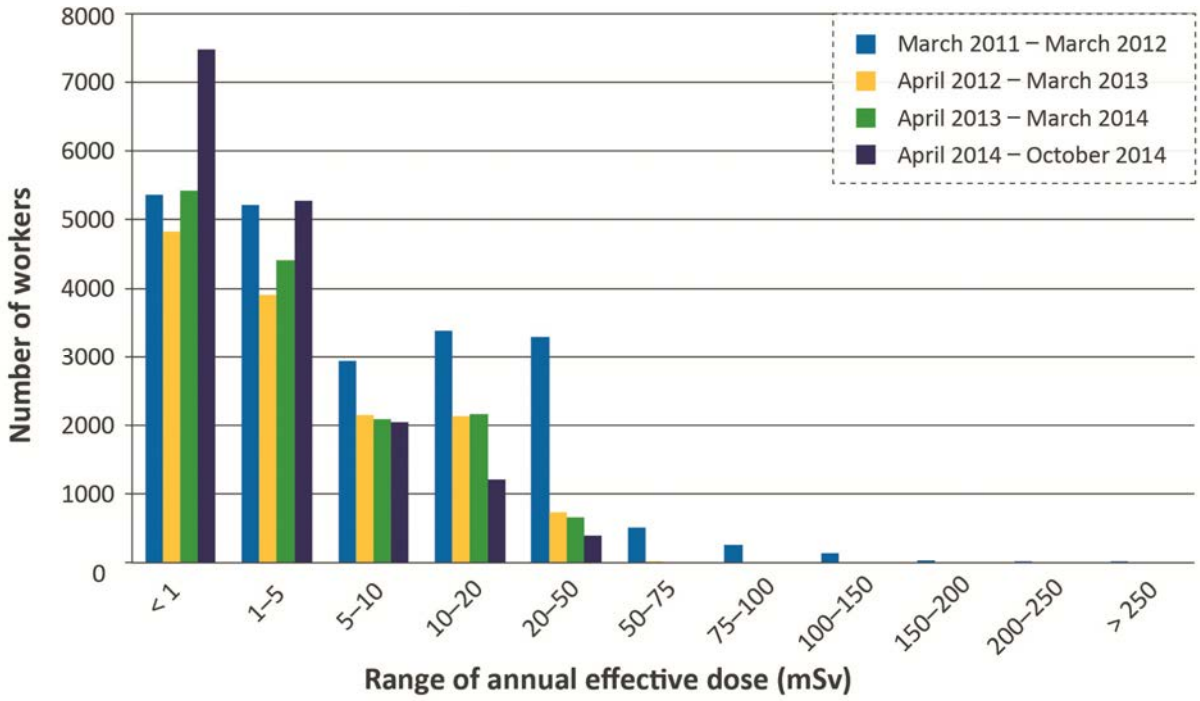


FIG. 4.2–1. The annual effective dose to workers between March 2011 and October 2014 [101].

In March 2011, 3971 workers were involved in the early on-site response, half of whom were TEPCO employees and the other half contractor employees. The number increased quickly to reach a peak workforce approaching 8000 in July 2011. Most of the additional workers were contractors who worked on a range of activities, from site restoration to technical work on the plant systems. The number of workers per month decreased gradually and remained at around 6000 for the following two years. The number increased towards the end of 2013, with a total of about 8000 workers employed at the end of March 2014 (see Fig. 4.2–2).

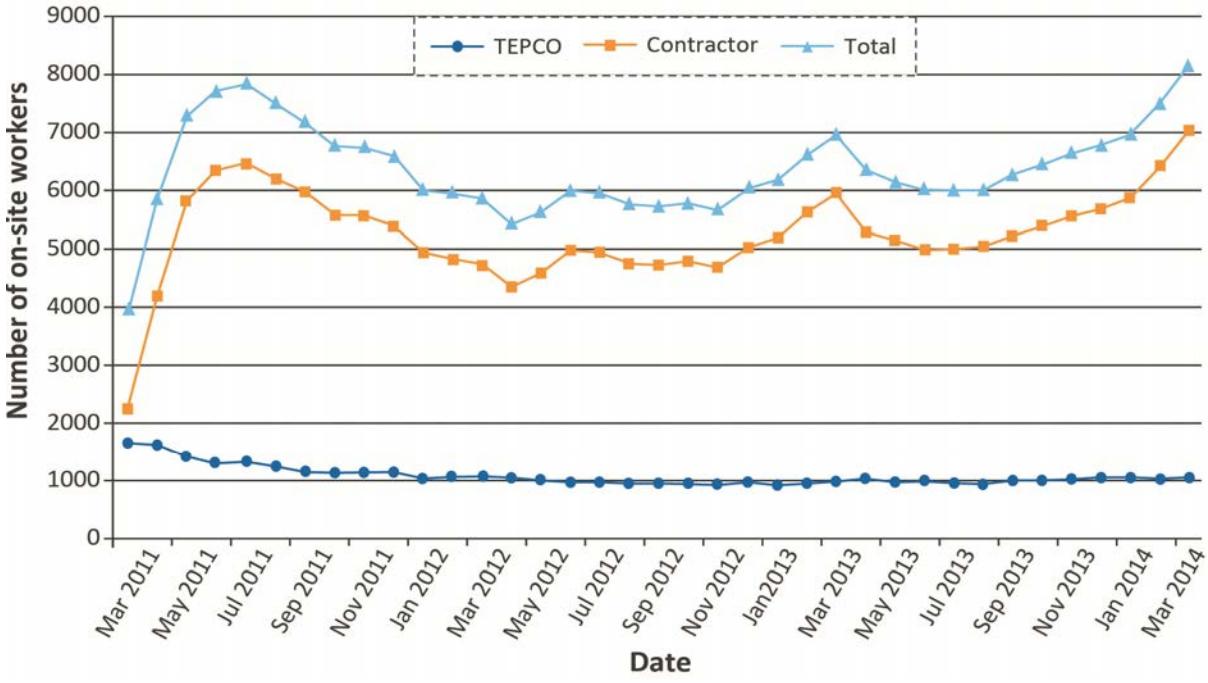


FIG. 4.2–2. The number of on-site workers after the accident [101].

On-site workers were subjected to the harshest work conditions and the highest radiation fields during the accident. Under these circumstances, six TEPCO workers exceeded the temporarily revised annual effective dose limit for emergency workers of 250 mSv, and 174 workers in total exceeded the original 100 mSv emergency dose limit during 2011. The reported external effective doses to TEPCO workers and contractors over the period March 2011–December 2014 are presented in Table 4.2–3. The reported committed effective doses from internal exposures in the period March 2011–March 2012 are presented in Table 4.2–4. In subsequent years, all reported committed effective doses were in the lowest dose category (2 mSv or less). As Table 4.2–3 indicates, no workers exceeded either of these dose limits in subsequent years and one worker exceeded an annual effective dose of 50 mSv in the period from March 2012 to December 2014.

Figure 4.2–3 illustrates the distribution of cumulative doses for the period from March 2011 to June 2014 by age groups for the on-site workers (TEPCO employees and contractors). The reference year of age is 2013. This figure illustrates that the higher doses were not reported for workers in the younger age groups. It also shows that most of the on-site workers were, and continue to be, between the ages of 30 and 60.

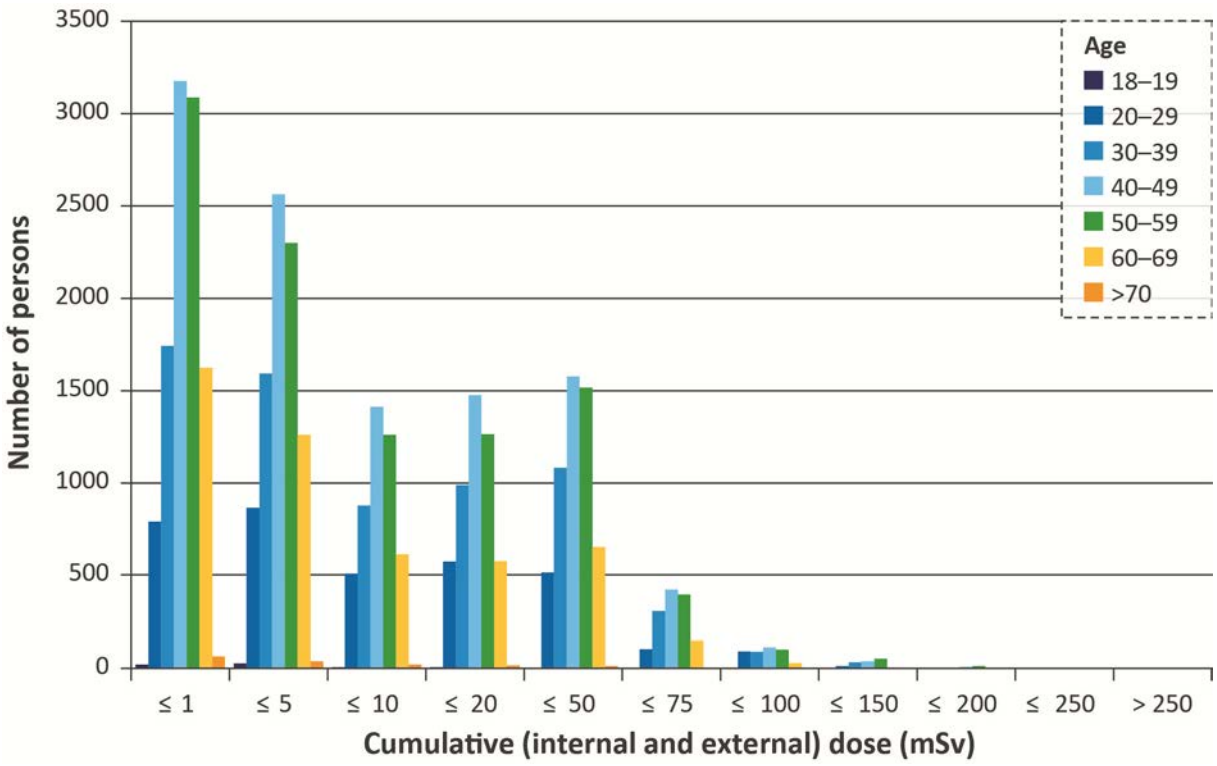


FIG. 4.2–3. Age and dose distribution of occupational exposure at the Fukushima Daiichi NPP for all workers (TEPCO employees and contractors). Cumulative (internal and external) dose from March 2011 to 30 June 2014.

TABLE 4.2–3. EFFECTIVE DOSE (EXTERNAL EXPOSURE) DISTRIBUTION TO TEPCO AND CONTRACT WORKERS (MARCH 2011–DECEMBER 2014) [189]

Classification (mSv)	March 2011–March 2012			April 2012–March 2013			April 2013–March 2014			April 2014–December 2014		
	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total	TEPCO	Contract workers	Total
Over 250	0	0	0	0	0	0	0	0	0	0	0	0
200–250	0	0	0	0	0	0	0	0	0	0	0	0
150–200	7	3	10	0	0	0	0	0	0	0	0	0
100–150	58	8	66	0	0	0	0	0	0	0	0	0
75–100	107	29	136	0	0	0	0	0	0	0	0	0
50–75	231	195	426	1	0	1	0	0	0	0	0	0
20–50	674	2 457	3 131	62	675	737	31	629	660	5	604	609
10–20	554	2 845	3 399	129	2 000	2 129	95	2 067	2 162	17	1 651	1 668
5–10	428	2 586	3 014	266	1 875	2 141	195	1 897	2 092	130	2 340	2 470
1–5	599	4 734	5 333	579	3 326	3 905	670	3 739	4 409	573	5 015	5 588
1 or less	758	4 852	5 610	588	4 240	4 828	701	4 722	5 423	898	6 954	7 852
Total	3 416	17 709	21 125	1 625	12 116	13 741	1 692	13 054	14 746	1 623	16 564	18 187
Max. (mSv)	188.14	199.42	199.42	54.10	43.30	54.10	41.90	41.40	41.90	24.18	39.85	39.85
Average (mSv)	19.14	9.16	10.77	4.49	5.90	5.74	3.24	5.51	5.25	1.74	4.27	4.05

TABLE 4.2–4. COMMITTED EFFECTIVE DOSE (INTERNAL EXPOSURE) DISTRIBUTION TO TEPCO AND CONTRACT WORKERS (MARCH 2011–MARCH 2012) [189]

Classification (mSv)	TEPCO	Contractor	Total
Over 250	5	0	5
200–250	1	0	1
150–200	1	0	1
100–150	7	0	7
75–100	11	11	22
50–75	27	17	44
20–50	191	125	316
10–20	399	311	710
5–10	280	411	691
2–5	223	685	908
2 or less	2 271	16 149	18 420
Total	3 416	17 709	21 125
Max. (mSv)	590.00	98.53	590.00
Average (mSv)	6.00	0.90	1.73

[a] Sum of effective dose from external radiation and the committed effective dose.

Table 4.2–5 summarizes the details relating to the doses received by the six on-site workers, out of a total of several hundred working in the elevated radiation exposure environment of the main control rooms, who exceeded emergency dose limits. In all cases, internal exposure from the intake of radionuclides was the predominant contributor to doses received. This was a consequence of challenges associated with respiratory protection during the emergency phase of the operations, notably with the availability and functioning of appropriate respiratory protection. Some issues with the fit of protective equipment were also noted [185, 188].

After the early phase of the recovery work in March 2011, workers were examined by WBCs operated by TEPCO. The six workers who had been involved in emergency work from 11 March were referred to the NIRS. The first worker visited the NIRS clinic on 30 May 2011 and the sixth worker came to NIRS on 1 July 2011, around 11 to 15 weeks after the estimated period of exposure to radionuclides. They are being followed up medically, including checking of their thyroid using ultrasound. Results at the time of writing indicate that none had developed deterministic effects such as hypothyroidism, as explained in more detail in Section 4.4.

To put these numbers in context, among the 20 most highly exposed workers, 11 received a total dose (internal and external dose) of less than 200 mSv. For this larger group, exposure from intake of radionuclides was not always the predominant contributor. This may reflect the nature of the work undertaken and the availability and functioning of proper respiratory protection in these cases [5].

TABLE 4.2–5. EXPOSURE OF SIX TEPCO EMERGENCY WORKERS IN THE MAIN CONTROL ROOMS (MCRs) OF UNITS 1–4 THAT EXCEEDED EMERGENCY DOSE LIMITS OF 250 mSv
(from Ref. [40])

Worker	Total effective dose[a]	Work period	Respiratory protection	Potassium iodide administration	Duties
A	680 mSv (590 mSv committed effective dose)	11 March–14 April	Particulate only until the Unit 1 explosion, and charcoal thereafter	No record	Plant operation and data collection in the MCR
B	650 mSv (540 mSv committed effective dose internal)	11–15 March	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total:10 tablets 14 March: 2 2 May: 2 3 May: 1 12 May: 2 20 May: 2 21 May: 1	Plant operation and data collection in the MCR
C	350 mSv (240 mSv committed effective dose)	11–31 March	Charcoal	Total: 3 tablets after 14 March	Plant operation and data collection in the MCR
D	310 mSv (260 mSv committed effective dose)	11 March–15 June	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total: 2 tablets after 28 March	Instrument restoration in the MCR (Units 1 and 2)
E	480 mSv (430 mSv committed effective dose)	11 March–4 June	Particulate only until the Unit 1 explosion, and charcoal thereafter	Total: 2 tablets after 21 March	Instrument restoration in the MCR (Units 1 and 2)
F	360 mSv (330 mSv committed effective dose)	11 March–7 June	Charcoal	Total: 15 tablets after 24 March	Instrument restoration in the MCR (Units 1 and 2)

[a] Rounded to 2 significant figures.

Absorbed dose to the thyroid

The reported dose results from the WBCs revealed that inhalation of ^{131}I was the predominant contributor to the internal doses of the workers at the Fukushima Daiichi NPP [190, 191]. Table 4.2–6 shows the reported internal doses to those most highly exposed group of workers, where $E50_{all}$ and $E50_{I\text{-}131}$ denote the committed effective doses from all radionuclides detected and from ^{131}I only, respectively. The fact that the values of the ratio $E50_{all}/E50_{I\text{-}131}$ are close to 1 indicates that ^{131}I is by far the most important component of the internal exposure. Absorbed doses to the thyroid can therefore be roughly estimated from the committed effective dose given in Table 4.2–6 by applying the tissue weighting factor for the thyroid of 0.05. This implies that the highest absorbed doses to the thyroid received by two emergency workers at the Fukushima Daiichi NPP are estimated to be around 10 Gy [192].

TABLE 4.2–6. COMPARISON OF COMMITTED EFFECTIVE DOSES FROM ALL RADIONUCLIDES AND FROM ^{131}I ONLY TO THE WORKERS MOST HIGHLY EXPOSED TO INTERNAL RADIATION*

Worker ID	Reported dose (mSv)		Ratio
	$E50_{all}$**	$E50_{I\text{-}131}$**	$E50_{all}/E50_{I\text{-}131}$
1	590	580	0.98
2	540	540	1.00
3	433	433	1.00
4	328	327	1.00
5	260	259	1.00
6	242	240	0.99
7	166	166	1.00
8	137	136	0.99
9	120	120	1.00
10	120	119	0.99
11	117	116	0.99
12	101	100	0.99
13	110	109	1.01
14	137	100	1.37

* This table includes information from a re-evaluation of TEPCO worker doses.
** $E50_{all}$: committed effective dose from all nuclides detected; $E50_{I\text{-}131}$: committed effective dose from I-131 only.

The reported total absorbed doses to the thyroid for 19 561 workers who worked on the Fukushima Daiichi NPP from 11 March–31 December 2011 are summarized in Table 4.2–7. The majority of these workers (17 804) were estimated to have received absorbed doses to the thyroid of less than 100 mGy, including those for whom measurement results were below the limit of detection. Some 1757 workers received thyroid equivalent doses above 100 mGy, among whom 17 workers were considered to have exceeded an absorbed dose to the thyroid of 2000 mGy (equivalent to 100 mSv effective dose if the contribution from other radionuclides and organs is not included), while two workers received thyroid equivalent doses in excess of 12 000 mGy [101]. All of these workers were performing emergency activities related to reactor stabilization operations [102]. The higher equivalent doses were a consequence of intake; 75 workers were estimated to have received an external dose to the thyroid exceeding 100 mSv (and in the range of 100–200 mSv).

TABLE 4.2–7. DISTRIBUTION OF TOTAL ABSORBED DOSE TO THE THYROID FOR WORKERS FROM 11 MARCH 2011 TO 31 DECEMBER 2011 [101][a]

Classification of dose (D) (mGy/y)	Internal dose		External dose		Total[a]	
	TEPCO employees	Contract workers	TEPCO employees	Contract workers	TEPCO employees	Contract workers
15 000 < D	0	0	0	0	0	0
10 000 < D ≤ 15 000	2	0	0	0	2	0
2 000 < D ≤ 10 000	13	0	0	0	15	0
1 000 < D ≤ 2 000	39	13	0	0	44	13
500 < D ≤ 1 000	109	64	0	0	129	67
200 < D ≤ 500	233	260	0	0	286	305
100 < D ≤ 200	338	383	64	11	416	480
≤100	2 549	15 558	3 219	16 267	2 391	15 413
Total	3 283	16 278	3 283	16 278	3 283	16 278

[a] Total dose (internal + external)[18].

TEPCO analysed the contributions of ^{131}I, ^{132}Te/^{132}I, ^{137}Cs and ^{134}Cs to effective dose [186]. The contribution from ^{132}Te/^{132}I was considered by TEPCO to be negligible, and the contribution from ^{133}I was not considered [193, 194]. UNSCEAR estimated that the additional contribution to effective dose from the intake of short lived radionuclides (such as ^{132}Te and ^{133}I, "may have been in the order of 20% relative to the contribution of ^{131}I" [5]. There are thus uncertainties associated with the dose contribution from short lived radionuclides.

4.2.1.7. Dose verification and re-evaluation

There are several uncertainties associated with the estimates of the workers' radiation doses due to internal exposure, particularly the thyroid equivalent doses. There was some time lag in undertaking thyroid measurements owing to the emergency operations and conditions. In addition, the estimated doses are dependent on the scenario that was assumed for the incorporation of radionuclides into the body (e.g. the timing). MHLW has since investigated the significant discrepancies between the internal dose assessments of emergency workers made by TEPCO and those reported by primary contractors. MHLW conducted a re-evaluation of internal dose assessments from March to June 2013 and concluded that some of the internal dose assessments of committed doses of 479 workers had been adjusted [193, 194]. In addition, TEPCO voluntarily re-evaluated the doses of hundreds of employees [195].

UNSCEAR undertook an independent evaluation of the 12 TEPCO employees with the highest reported internal exposure and a sample of workers with lower internal exposures who were randomly selected. In those cases where it had been possible to measure ^{131}I in the thyroid, the internal doses estimated by UNSCEAR were in reasonable agreement with those reported by TEPCO. For example, the largest absorbed dose to the thyroid was estimated to be 12 Gy by TEPCO, while the UNSCEAR independent assessments by different institutions ranged from 9.7 to 12.6 Gy, with the variation

[18] The thyroid equivalent dose was evaluated as follows: 20 × internal effective dose (^{131}I) + internal effective dose (^{134}Cs) + internal effective dose (^{137}Cs) + external effective dose. When the internal radionuclides were not identified, the thyroid equivalent dose was assumed to be equivalent to 20 × internal effective dose + external effective dose.

depending on the assumptions made, particularly the timing of the main intakes of ^{131}I. However, for many of the other workers considered (TEPCO and contract workers), ^{131}I was not detected in the thyroid owing to the time between exposure and the measurement and resulting radioactive decay. UNSCEAR identified the uncertainties associated with using a ratio approach to estimate doses to the thyroid in these cases, with the possibility that the resulting total effective dose "could, in extreme, have been underestimated by a factor of up to about 30, or overestimated by a factor of up to about 5" [5]. The reliability of assessments for those workers where ^{131}I was not detected in the body could not be confirmed, as it was considered that the two methods used did not provide a reliable estimate of the true intake and there was a significant uncertainty associated with the results, including that due to the influence of a high level of background doses in early whole body measurements. The delay in starting WBC or thyroid monitoring also meant that it would not have been possible to detect short lived radionuclides such as ^{132}Te and ^{132}I; the additional contribution to the effective dose from these radionuclides may have been of the order of 20%, but there could be large variations between individuals [5].

Since March 2014, MHLW has closely examined data for 6245 emergency workers, excluding those covered by the previous re-evaluation, from a total of 7529 emergency workers engaged in the period March–April 2011. This examination revealed that the data for 1536 emergency workers may have been obtained by methods other than the standard assessment methods. TEPCO and its primary contractors have re-evaluated these data and the committed effective doses for 142 emergency workers were revised accordingly [196].

Organizations in Japan are working to reduce further the existing uncertainties in the occupational dose assessment, specifically in the internal exposure assessments. In its re-evaluation of internal dose, MHLW recognized that, given the uncertainty of the chemical form of ^{132}Te, the contribution from ^{132}Te to the committed effective dose may be up to approximately 10% of the contribution from ^{131}I. However, given the conservative assumption of the intake date as the first work day and the use of the acute intake scenario, this contribution from ^{132}Te to the committed effective dose contribution was assumed to be within the margin of safety of conservative estimation [194].

4.2.1.8. Statistical analysis of recorded dose information

Further analysis has been carried out of the data available on worker doses as part of this study. In particular, log-normal distributions have been fitted for the different sets of data. The approach adopted is described briefly below. The results of this analysis are then presented.

Analysis approach using log-normal distribution

When a population is exposed to radiation, it is important to estimate the 'dose distribution', namely how many people are exposed to a certain amount of radiation. The whole range of the data can be binned by grouping data together in intervals (or bins) covering a specific range of doses. The approach used is described in more detail in Box 4.1–1 in Section 4.1.4. As indicated earlier, the probability density illustrates the probability that a member of the exposed population will incur a certain dose. If the curve is approximately bell shaped, it approximates the normal distribution.

The analysis of dose distribution in the exposed population can be taken further by summing the tops of the bars as the dose increases and then representing the resulting partial summations as a function of the dose. The ensuing function is termed cumulative probability because it represents a summation of probabilities that a certain dose incurs as a function of the dose. Figure 4.2–4 illustrates, in orange, a probability density function, f(x), and, in blue, the corresponding cumulative probability function, F(x), both versus variable values of dose, x. It can be observed that, as the dose, x, increases, the cumulative probability function approaches a value of 1, which corresponds to a probability of 100%, because it is certain that above a given doseall people will incur a dose lower than such a value.

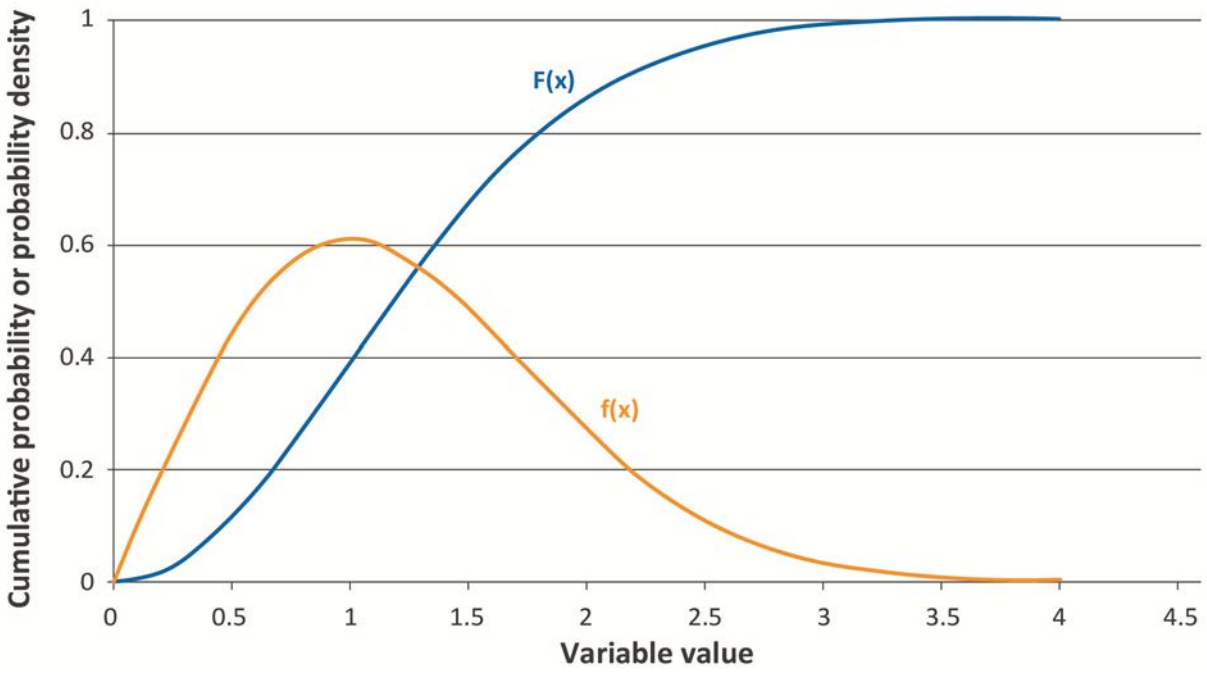


FIG. 4.2–4. Illustration of the relationship between the probability density function (orange) and the cumulative probability function (blue).

There is a large quantity of data at the international level on how the doses incurred by exposed populations are statistically distributed among their members, namely on the more common probability density and cumulative probability functions. This experience has been applied to the statistical analysis of dose data of exposed people as a result of the accident at the Fukushima Daiichi NPP. The relevant previous knowledge is from the UNSCEAR dose estimates and also from the analyses of public doses from the Chernobyl accident (which were performed by international organizations, including the IAEA). This experience has shown that, when the exposures are reasonably uniform, the distribution of doses follows a log-normal function.

Many radiation dose distributions exhibit a log-normal distribution, which can be identified as a straight line in a cumulative probability distribution. These log-normal graphs show the median value of the doses, along with an understanding of their distribution around the median such as the doses associated with a cumulative probability of 95% and 5%.

Data provided by the Japanese authorities were analysed following this approach and were often a reasonable fit to a log-normal distribution. There were, however, some issues with assigning log-normal distributions, which are summarized in Box 4.2–1.

Box 4.2–1. Issues with log-normal distribution of the data

While the binning of datasets usually results in a relatively smooth distribution, for some datasets this was not the case. For these datasets, the bin distributions appear distorted, usually owing to the accumulation of a large amount of data in a particular bin. For instance, in some datasets all the data near the detection limit were accumulated in one (initial) bin without discrimination while higher data were properly discriminated. In some of the statistical analyses, the decision was made to distribute this misleadingly accumulated data according to a probability density distribution derived from the actual data (using its relevant statistical values, such as mean and standard deviation) and, on this basis, building up a conjectural, randomly created, distribution including a larger number of bins. The result is a conceptual histogram which is tailored to the statistical values of the real data and to which a smooth density probability curve can be fitted. This idealized probability density function, which illustrates how the distribution would look if the data were sufficiently detailed and discriminated, is then presented together with the cumulative probability function in the relevant figures of the report. In some cases, the actual distribution of bins is also presented for comparison.

While exact adherence to the log-normal distribution may be not observable across the full range of data, explanations of the deviations, in particular, deviations from the straight line in the cumulative probability, can usually be elaborated, and they form an important part of the analysis. A cause of deviation is uncertainty originating both in the measurements themselves and in the statistical nature of the sampling process. A particular problem in the analyses of incurred doses, which is typical of accident situations, was the likely inhomogeneous nature of the cohorts of exposed people. Other causes included constrained distribution in the data; for instance, at high doses, there might be higher than expected cumulative probability (namely, fewer people than expected are incurring high dose) with the most likely explanation that dose restrictions have been applied successfully. If the cumulative probability is higher than expected in the low dose range (namely, more people than expected are incurring low doses), a plausible explanation is that a dose equal to the detection limit has been (misleadingly) assigned to all people with doses below these levels. Conversely, if the cumulative probability is lower than expected, it might mean that a zero dose has been assigned (again misleadingly) to all those with doses below the detection level. Sometimes deviations from the straight line became ostensible due to the high level of inconsistency in the local data; for example, when two different population groups were mixed, such as evacuees with residents that remained in the area, there may be evidence of the change in the slope of the cumulative probability distribution, with each sector reflecting the doses received in each area. Sometimes the collection of information was protracted and this distorted the data, for example, owing to radioactive decay over time. Deviations from linearity in a log-normal cumulative probability plot may be used to make plausible inferences about the underlying data.

Analysis of worker doses

Figures 4.2–5 to 4.2–7 show the normalized idealized probability density and cumulative probability plots for different doses to workers at the Fukushima Daiichi NPP [101].

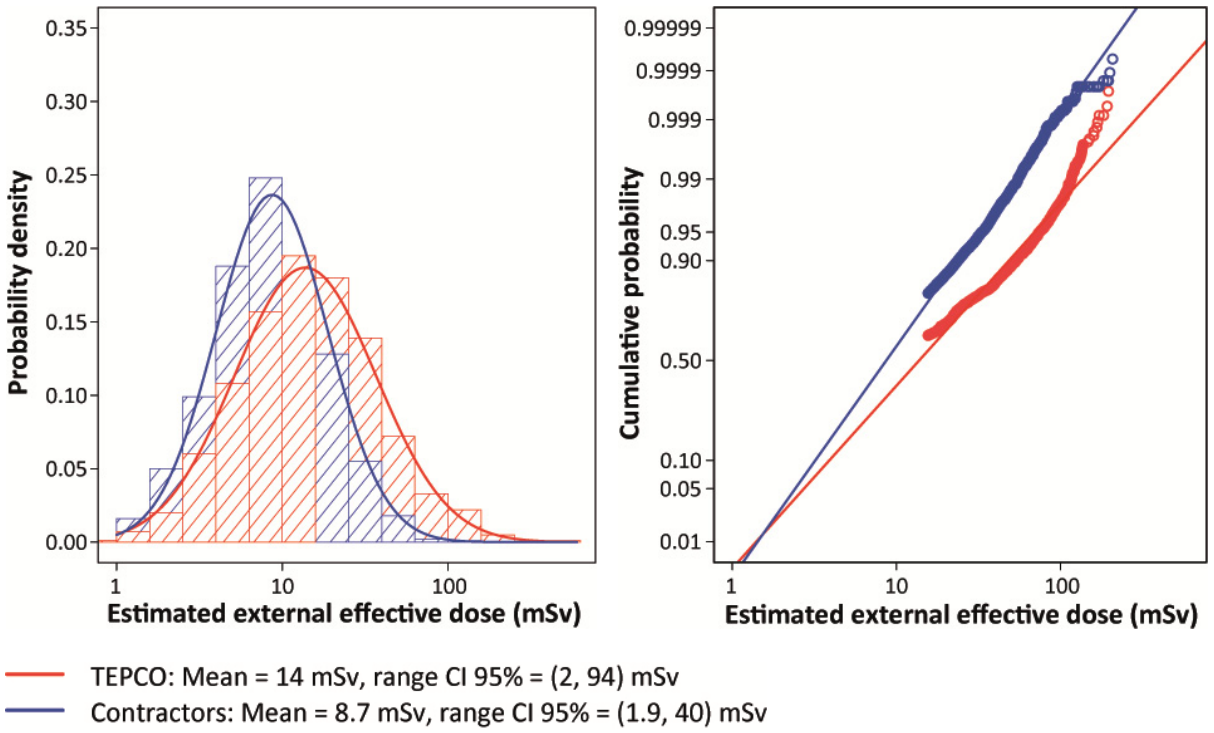


FIG. 4.2–5. Normalized idealized probability density distribution and cumulative probability distribution of personal dose equivalent monitored for workers from TEPCO and contracted workers for 2011 [101].[19]

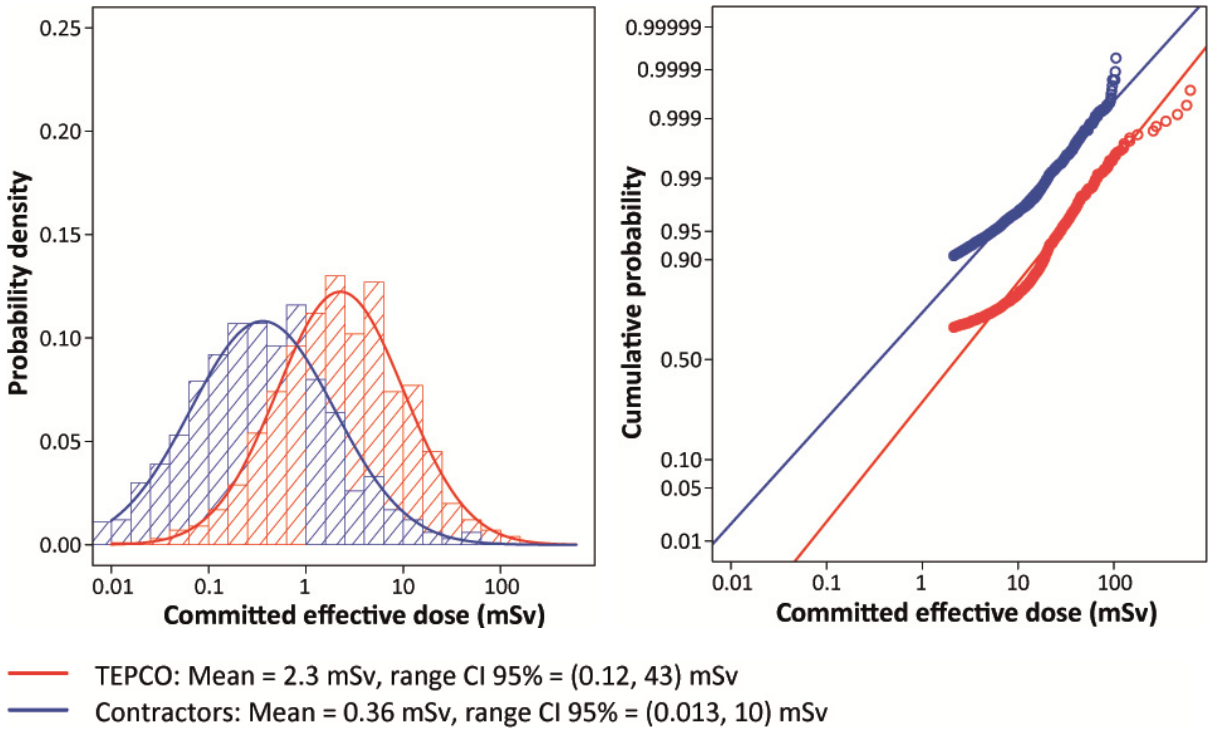


FIG. 4.2–6. Normalized idealized probability density distribution and cumulative probability distribution of committed effective dose from internal exposure [101].

[19] The effective doses from external exposure are estimated on the basis of personal dose equivalent, Hp(10), factually monitored in the exposed population, assuming that Hp(10) may be used as an approximation of the effective dose from external exposure to penetrating radiation.

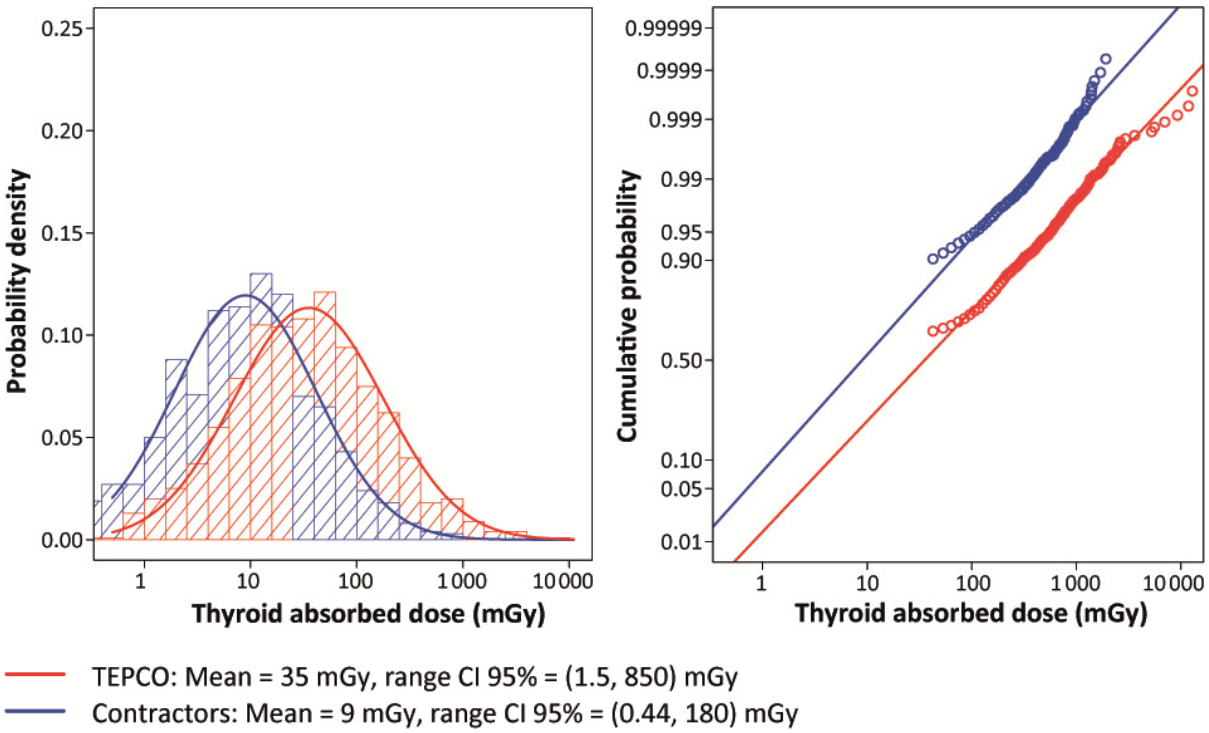


FIG. 4.2–7. Normalized idealized probability density distribution and cumulative probability distribution of thyroid absorbed dose [101].

These statistical analyses support the reported levels of radiation doses received by on-site workers presented above. Cumulative probability distributions for internal and external doses in subsequent years are presented in Appendix II.

4.2.1.9. On-site exposure of firefighters

From 18 to 25 March 2011, 260 firefighters engaged in on-site operations associated with cooling the spent fuel pools. The Fire and Disaster Management Agency (FDMA) has made available information on the range of doses received by this group for the purposes of this report. External doses received by this group were generally below 5 mSv, as indicated in Fig. 4.2–8.

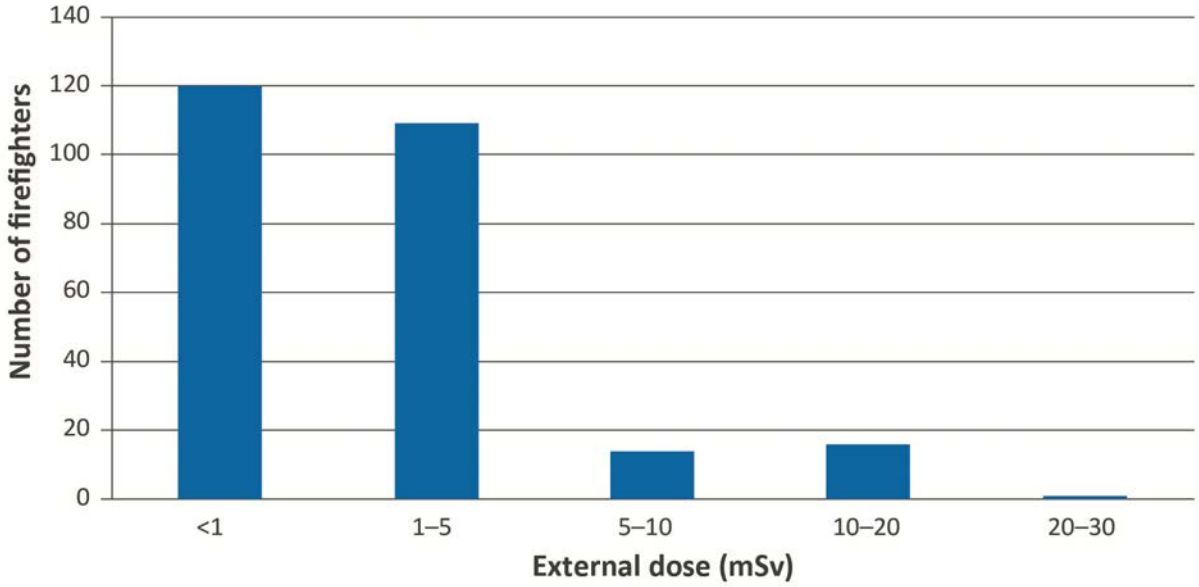


FIG. 4.2–8. Reported external doses of firefighters involved in on-site emergency activities from 18 to 25 March 2011 [197].

Of this group, 259 agreed to provide their internal exposure data for this report. The committed effective dose due to internal exposure was less than 1 mSv in all cases. The effective doses received by the firefighters working on-site were thus significantly lower than the dose limit values presented above.

All the firefighters working on-site during this period wore personal protection equipment, including a full face mask, gloves and fire boots with shoe covers. In making their assessment of doses to the skin and the lens of the eye, FDMA did not take account of these protective measures. The estimates presented in Fig. 4.2–9 are therefore likely to be conservative. These dose estimates were based on the personal dosimeter readings, modified for the depth of the skin and the lens of the eye and the relative height of the eye and the most exposed area of skin above the ground [197].[20] UNSCEAR considered that there was insufficient information on beta irradiation to make an assessment of doses to the lenses of the eyes of workers [5].

[20] Heights and depths assumed: Dosimeter height, 130 cm; lens of the eye, 160 cm, and skin 50 cm above the ground (above the height of boots). The depth assumptions: dosimeter 10 mm, lens 3 mm, skin 0.07 mm dose. The modification factors for gamma and beta dose equivalent to the lens of the eye applied were 0.1 and 0.95, respectively. For skin, the modification factors for gamma and beta dose equivalent were 10 and 1.2, respectively.

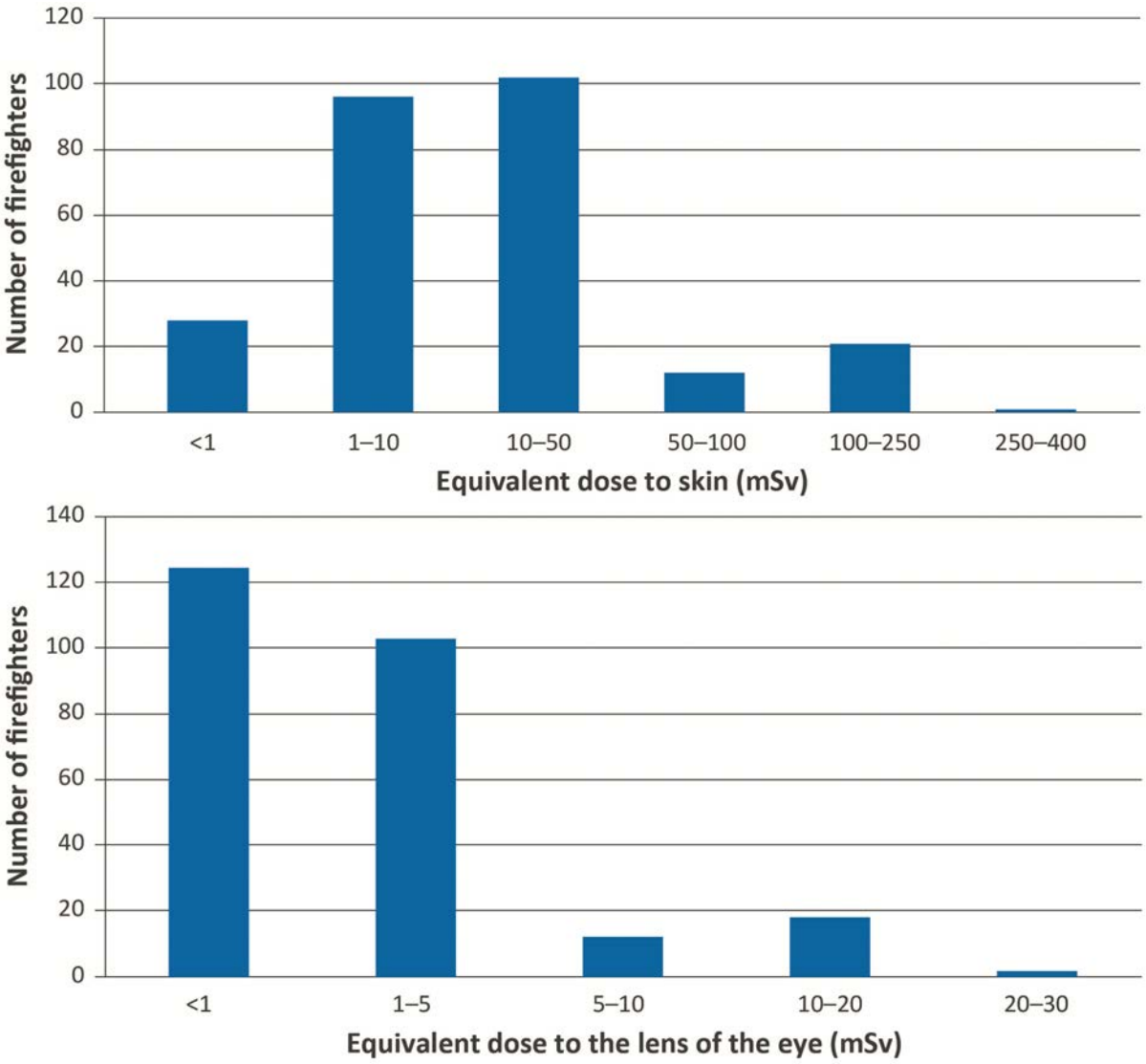


FIG. 4.2–9. Estimated equivalent doses to the skin and the lens of the eye of firefighters involved in on-site emergency activities from 18 to 25 March 2011 [197].

Japanese regulations concerning the prevention of radiation hazards due to ionizing radiation stipulate that exposure limits of workers to the skin and eye lens are 500 mSv/year and 150 mSv/year, respectively. However, in the case of an emergency, those limits are raised to 1 Sv/year for skin and 300 mSv for the lens of the eye. It can be seen from the data above that the reported doses received were significantly below these values [198].

4.2.1.10. On-site exposures of police and SDF personnel

A total of 13 police officers were involved in on-site operations related to the cooling of the reactor. The cumulative doses received by members of this group in the period until 17 March 2011 were less than 10 mSv.

UNSCEAR additionally presented reported doses to the 147 members of the SDF personnel, provided by the Government of Japan. No members of this group received an effective dose greater than 100 mSv, and 132 of this group received doses of less than 10 mSv [5].

4.2.1.11. Off-site workers

As explained previously, many organizations participated in a variety of activities during the immediate response. However, these activities were not considered to be emergency work, so dose limits for emergency work were not applicable to these activities. Personnel of some of these organizations were highly trained to work in radiation environments and operated under higher dose guidelines. Some workers were considered volunteers and operated under dose guidelines established for the public. Although different dose guidelines governed their activities, the workers remained well within the applicable limits, which were set as internal rules corresponding to the dose limits for radiation workers, which are prescribed in law.

As mentioned earlier, a number of police officers were also involved in off-site response activities in Fukushima Prefecture during 2011. A total of 290 000 person-days were spent in Fukushima Prefecture on such work in the period until 31 December 2011. The maximum external dose reported for this group was less than 5 mSv in the period up to 30 June 2011. During the period 21 July–23 August 2011, 33 police officers were monitored by whole body counting and the maximum committed effective dose recorded was around 10 μSv [199].

Information on the effective doses received by 8458 SDF personnel working off-site was provided by the Government to Japan to UNSCEAR. Of this number, five received doses in excess of 10 mSv, within a range of 10–20 mSv [5].

Almost 99% of the approximately 350 officials of Fukushima Prefecture involved in aiding various emergency measures for whom dose data are available received a dose of less than 1 mSv. The maximum dose recorded for this group was around 2.3 mSv [199].

Among the United States personnel who assisted or performed environmental monitoring in the Fukushima area, the maximum effective dose received was 0.12 mSv for the US military personnel [200] and around 0.07 mSv for personnel from the DOE. A total of 21 IAEA staff members participated in environmental monitoring and the provision of advice on nuclear safety and food restrictions. One member of this group received an effective dose of around 2.5 mSv from external exposure, while the mean dose was around 0.5 mSv.

4.2.2. Public exposures

In this section, the main routes by which people are exposed to radiation following an accidental release of radionuclides to the environment are reviewed. In addition, the estimated effective doses and thyroid equivalent doses incurred by adults and children in Fukushima and neighbouring prefectures are analysed.

4.2.2.1. Background and exposure pathways

The main exposure pathways relevant to a nuclear accident, such as that at the Fukushima Daiichi NPP, are illustrated in Fig. 4.2–10.

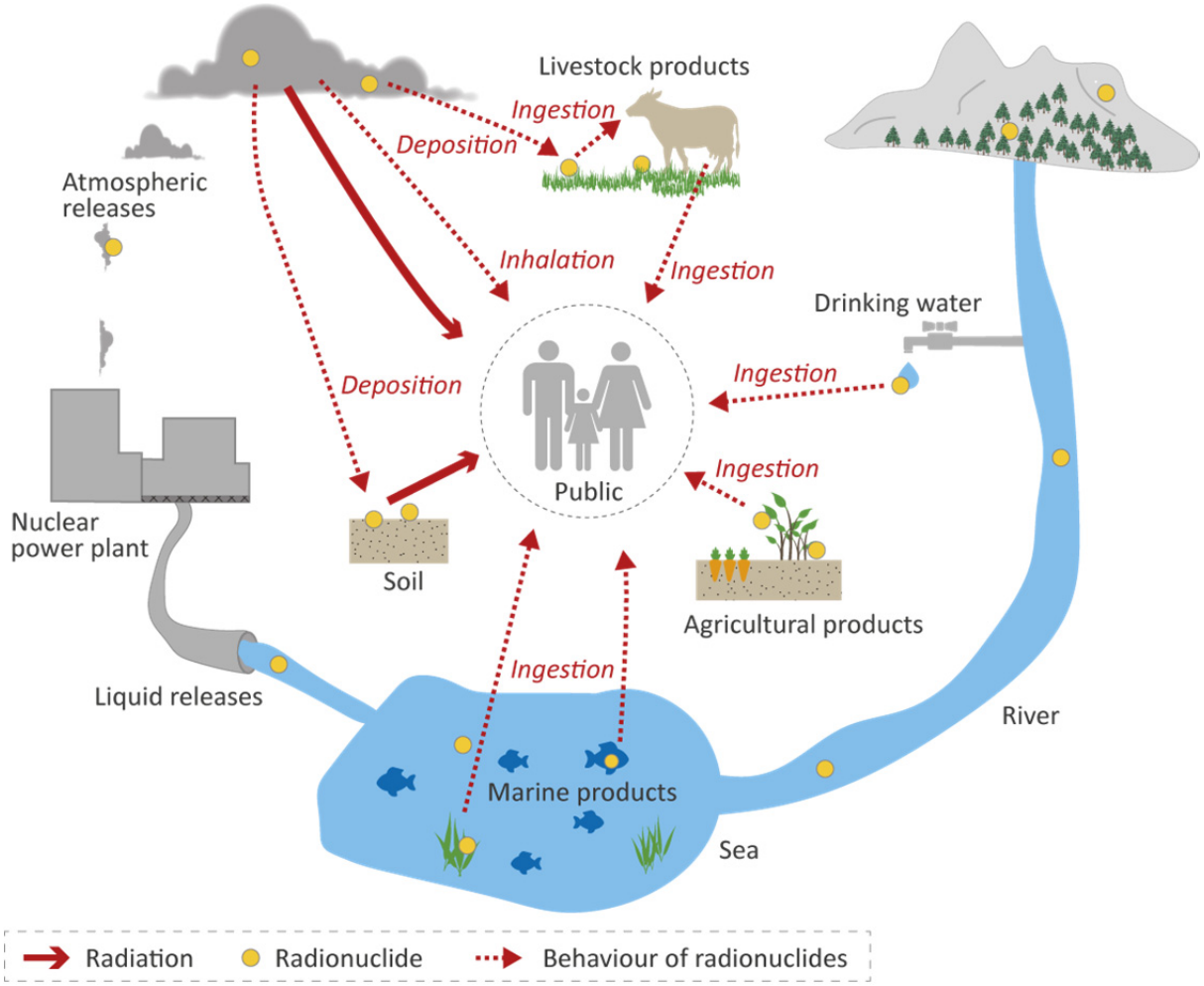


FIG. 4.2–10. Main exposure pathways relevant to a nuclear accident.

The most important exposure pathways are:

— External exposure from immersion in elevated concentrations of radioactive material in the air;
— External exposure from radionuclides deposited on the ground following the passage of radioactive material in the air;
— Internal exposure from inhalation of radioactive material in the air;
— Internal exposure from ingestion of radionuclides in food and drink.

The assessment of doses to the public from each of these main exposure pathways is explained in the following sections.

The focus of this report has been on gathering and interpreting data that have become available since the publication of previous assessments by WHO and UNSCEAR [5, 173]. The assessments by WHO and UNSCEAR were undertaken using the progressively more extensive databases that have become available (covering the time until September 2011 and March 2012, respectively).

Where possible, dose estimates in the present report have been based on direct measurements of people: measurements of external exposure rate, measurements of radionuclides incorporated in people (by whole body counting) and assessment of ^{131}I in the thyroid (by measurements of the dose rate close to the thyroid). This includes newly obtained data provided to the IAEA for this report by

Japanese Government institutions, and publicly available reports and sources collected up to December 2014.[21]

The general approach is to summarize doses by appropriate locations, for example, for the municipality in which residents were living before the accident, and by appropriate time periods. Where possible, these results have been compared with those in the most recent and comprehensive assessment, undertaken by UNSCEAR [5]. For ease of reference, background information on the two major international assessments of doses to the public arising from the Fukushima Daiichi accident is presented before further analysis of dose information.

Previous international assessment of dose to the public from the Fukushima Daiichi accident

WHO assessment of public exposures

WHO published two reports on the Fukushima Daiichi accident: Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, in 2012; and Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, in 2013 [173, 201]. These reported estimated potential health consequences of human exposure to radiation during the first year after the Fukushima Daiichi accident. The assessment covered infants, children and adults living in Fukushima Prefecture, nearby prefectures, the rest of Japan, neighbouring countries and the rest of the world.

To the extent possible, measurements of radioactive material in the environment (e.g. levels of different radionuclides on the ground) and activity concentrations in foods were used. The estimated doses relied on measurements available in the first few months after the accident (until mid-September 2011). When direct monitoring data were not available, estimates based on simulations were used as input for dose models. The approach used for assessing doses within Fukushima Prefecture is summarized briefly below.

Surface activity densities were the environmental measurement data used as the primary input to the assessment, and gamma dose rates were also available from a wide range of monitoring locations in Fukushima Prefecture. External doses from the radioactive cloud were reconstructed by modelling, because measured dose rates were not available for sufficient locations for the first few days after the release; ground deposition levels were therefore converted to time integrated activity concentrations in air. These values were also used for assessing intakes by inhalation. External effective and thyroid doses from radionuclides deposited on the ground were based on measured ground deposition levels (surface activity densities).

The assessment of doses resulting from the ingestion of food containing radionuclides requires estimates of activity concentrations in food as a function of time, together with levels of consumption of the various foods for different age groups. Several scenarios were used in this assessment to estimate the dose from food consumed during the first year. WHO assumed that the measured activity concentrations in each food category were representative of the entire food market for Fukushima and neighbouring prefectures. Analytical results for radionuclides of iodine and caesium reported to be below the limit of detection were assumed to be 10 Bq/kg, except for ^{131}I, which was assumed to be close to zero after four months. Three scenarios were considered for the population living in Fukushima Prefecture, using median, mean and 90th percentiles of the distribution of concentrations in food in the prefecture for each of the relevant food categories.

[21] In some cases, notably for the results of the Fukushima Health Management Survey, information up to May 2015 was available and was included in this volume.

Given the limited information available at the time, it was acknowledged that the assessment contained a number of conservative assumptions, for example radioactive cloud composition and dispersion, time spent indoors/outdoors, consumption levels and the implementation of protective measures, leading to an overestimate of doses. The committed effective doses during the first year for individuals in two locations (Namie Town and Iitate Village) were estimated to be within a dose band of 10–50 mSv; in other areas of Fukushima Prefecture, doses in the range 1–10 mSv were estimated. Within Fukushima Prefecture, external exposure from deposited radionuclides was found to be the major contributor to the effective dose.

The typical thyroid doses in most locations in Fukushima Prefecture were estimated to be within a dose band of 10–100 mSv. In one particular location, the assessment indicated that the characteristic thyroid dose to one year old infants would be within a dose band of between 100 and 200 mSv, with the inhalation pathway being the main contributor to the dose. Thyroid doses in the rest of Japan were within a dose band of 1–10 mSv, and in the rest of the world, doses were estimated to be below 0.01 mSv and usually far below this level.

The WHO health risk assessment concluded that no discernible increase in health risks from the Fukushima Daiichi accident was to be expected outside Japan [201]. With respect to Japanese residents, the WHO assessment estimated that the lifetime risk for some cancers might be somewhat higher than baseline rates in certain age and sex groups that were in the areas most affected. This was based on assessment models that were derived from previous radiation events and experience, which did not match the pattern of exposure seen following the Fukushima Daiichi accident, owing to the generally conservative approach taken in the WHO preliminary dose estimation [173].[22]

UNSCEAR assessment of public exposure

The UNSCEAR evaluation of exposure and dose for the public [5] made use of a wide range of measurements of radionuclides in the environment, together with the necessary modelling to link these measurements to the doses received. Some limited measurements of radionuclides in people were also used for comparison purposes. UNSCEAR assessed doses to various groups of people living in different regions of Japan and also provided exposure information for other countries. Three different age groups were considered: one year old children, ten year old children and adults. Consideration was also given to doses to fetuses and breast-fed infants, but these were not explicitly evaluated as they would be similar to the doses to the other age groups. The four groups of people considered in Japan were: members of the public who were evacuated in the days and months after the accident; members of the public living in the non-evacuated districts of Fukushima Prefecture; members of the public living in Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate prefectures; and members of the public living in the remaining prefectures of Japan. The emphasis was on estimating the exposures of individuals who were representative of the average of the population, assuming typical habits such as average food intakes. Radiation doses were estimated for the first year following the accidental releases from the Fukushima Daiichi NPP and also integrated over the period of the first ten years. Committed doses were assessed for three age groups by integrating doses from incorporated radionuclides to age 80. Effective doses were estimated, together with absorbed doses to the thyroid and some other organs, notably the breast and the red bone marrow. The UNSCEAR report also described the variability in radiation doses for the public together with the main uncertainties in the assessment.

In later sections of this volume, the different aspects of assessing doses to members of the public are described, and a brief overview of the UNSCEAR assessment is given, together with further analysis

[22] Given the limited information available at the time, the assessment contained a number of conservative assumptions. WHO indicated that "All efforts were made to avoid any underestimation of doses" and that "some possible dose overestimation may have occurred" [173].

based on direct measurements of people carried out for the present volume. The key results of the UNSCEAR dose assessment of the public are reproduced in Annex V to provide some overall context for comparison with personal dosimetry information presented later in this volume.

The UNSCEAR report also provided estimated doses to people who were evacuated, taking into account the doses that were received before and during the evacuation and the doses at the evacuation destination from all exposure pathways to obtain estimated settlement averaged effective doses and absorbed doses to the thyroid for the first year following the accident. The results are presented in detail in Annex V and indicate that, in the evacuated areas with the highest average estimates, the effective dose estimated to have been received by adults before and during the evacuation was, on average, less than 10 mSv, and about half of that level for those evacuated early. Adults living in Fukushima City were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated effective doses to one year old infants were about twice as high. Those living in other areas within Fukushima Prefecture and in neighbouring prefectures were estimated to have received comparable or lower effective doses; even lower effective doses were estimated to have been received elsewhere in Japan. However, UNSCEAR emphasized that there was considerable variation between individuals around this value, depending on their location and the type of food they had consumed.

Doses from releases of radionuclides to the marine environment were low due to the restrictions on fishing and access to the shore-line near the Fukushima Daiichi NPP. For the first year, marine foods were included in the estimated ingestion doses, but made a minor contribution [5]. In subsequent years, the doses from radionuclides in the marine environment were estimated to be very low (less than 1 μSv/y), and they were lower than those from radionuclides in the terrestrial environment.

Doses were also estimated by UNSCEAR for exposure over future years, which found that generally the district average or prefecture average effective doses integrated over ten years were likely to be up to twice the first year's effective dose, while the effective dose integrated to age 80 was likely to be three times higher than the first year's effective dose. UNSCEAR estimated the average lifetime effective doses to adults in Fukushima Prefecture to be of the order of 10 mSv or less [5]. However, this estimation did not make any allowance for the effects of remediation, and it was therefore recognized that in many cases the actual doses could be lower. The effectiveness of remediation is discussed further in Technical Volume 5. UNSCEAR also considered doses to other countries and concluded that the average effective doses to populations living outside Japan were less than 0.01 mSv in the first year.

Approach adopted in this assessment

As noted, the focus of this assessment was to gather further information to assess radiation doses for the public using personal dosimetry data, where available. These values were then compared with those estimated by UNSCEAR, where possible. To do this, a distinction was made between external and internal radiation exposure pathways (see Fig. 4.2–10). The emphasis was on the doses to those people who were evacuated following the start of the accident at the Fukushima Daiichi NPP and those living in the areas with elevated levels of radionuclides in Fukushima and other prefectures.

External exposures of people can be assessed directly by the use of personal dosimeters[23] or from measurements of external dose rate in the environment (using in situ dose rate meters or instruments mounted on vehicles or aircraft). In the latter cases, doses need to be reconstructed by accounting for an individual's location and movements. Following the accident at the Fukushima Daiichi NPP, a

[23] Personal dosimeters are those worn by individuals and which allow the external dose received during the period they are worn to be measured.

large number of residents were evacuated and therefore moved, sometimes a number of times, to different locations, which complicates assessments of external doses. In the first few months following the accident, personal dosimeter results were not available for the public, and therefore an approach based on environmental measurements had to be used.

A questionnaire, distributed in the context of the Fukushima Health Management Survey (FHMS) (see Section 4.4.2.1), provided information that is relevant here [202]. Around 2 056 000 residents and visitors in Fukushima Prefecture from 11 March 2011 were contacted to provide information on their movements in the four months following the nuclear accident. Around 26% of the total population (about 532 000 people) had responded to the postal survey by 31 March 2014, but response rates were higher in areas of greater radionuclide deposition. In the Soso area[24], the response rate was 45.1%.

In order to estimate the exposure levels of the external doses to the residents, NIRS developed a series of 18 representative evacuation scenarios to model the movement of residents from different locations following the accident [203]. These scenarios were also used in the UNSCEAR study to estimate doses for people in the evacuated communities.

Detailed studies were carried out later focusing on people living in specific locations in Fukushima Prefecture using personal dosimeters, which also allowed the results from the two approaches to be compared.

For assessing internal exposures, there are three main measurement methods for determining the intake of radionuclides to the body and hence estimating radiation doses. These are whole body counting, thyroid monitoring (primarily for radioiodine uptake) and analysis of radionuclides in urine. Annex I gives further information on these techniques. The key points are summarized here. In addition to these measurement methods, atmospheric dispersion simulations are also useful to construct maps of radionuclides in air for different times and locations for use when the available data are not sufficient.

WBCs are widely available and have the advantage that the levels of some radionuclides present in the body are measured directly and the results are available quickly. They are used for determining the levels of radionuclides that emit gamma radiation of sufficient energy to be measured. Following the releases from the Fukushima Daiichi NPP, whole body counting examinations were used primarily to detect ^{134}Cs and ^{137}Cs. These counters cannot differentiate between internal and external contamination, so care must be taken to ensure that individuals are free from external contamination on the body or clothing before measurements are performed.

For accidental releases of radioiodine, such as that following the Fukushima Daiichi accident, thyroid monitoring was also conducted to directly measure ^{131}I content in the thyroid. Calibration factors were developed to convert measured count rates to activity in the thyroid for children and adults. Factors were also developed to convert the measured count rate to committed effective dose and thyroid dose equivalent for various age groups. With regard to whole body counting, it is necessary to take into account the time and route of intake. Because of the short half-life of ^{131}I of eight days, it is desirable for measurements to be taken as soon as possible after intake. It is again important that individuals are free from external contamination before measurements and that suitable allowance is made for background radiation levels, which is not always straightforward.

[24] An area in eastern part of Fukushima Prefecture, consisting of Soma City, Minamisoma City, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Kazurao Village, Namie Town, Shinchi Town, Iitate Village, many of which were within the designated evacuation zone or the Deliberate Evacuation Area.

The estimation of doses from incorporated activities obtained from WBC or thyroid measurements requires knowledge of the time and route (i.e. whether by inhalation or ingestion) of intake. If such knowledge is not available, assumptions need to be made regarding these factors. Some uncertainty arises in the dose estimate if the mode and timing of intake are not well known.

As described in the following sections, a number of studies have been carried out which produced results used in this assessment. However, there are some limitations of the measurements used to estimate public exposures, including the fact that:

— Measurements were carried out by many different organizations and public bodies without a common monitoring protocol. In particular, there were different approaches to dealing with low doses below the limits of detection. In some cases, they were ignored, while in others they were all grouped together (e.g. in a range of 0–1 mSv).
— Measurements were carried out at different times, over different periods and using different measurement techniques. However, measurements were carried out in many, but not all, affected areas.
— Results above limits of detection were sometimes grouped by dose ranges, which might not be ideal for a subsequent log-normal analysis.
— An average background dose was usually subtracted from the measurement data, which were often close to background. For statistical analyses, it may be better to report the total doses and then the likely range in background doses for comparative purposes.

These limitations reflect the fact that the majority of the measurements were carried out for screening purposes that aimed to reassure the public and not to generate data for subsequent dose assessment studies.

Laboratory measurements may also be performed to determine if radioactive material has been absorbed, ingested or inhaled. This typically involves collecting samples of urine to determine the presence of a particular radionuclide. For individuals who received higher radiation exposures in a very short period of time, blood tests such as chromosome analyses may be conducted to determine if any biological effects from exposure, such as abnormalities in chromosomes, are detected. Such techniques are only appropriate for relatively high doses, and they were not appropriate for members of the public following the accident at the Fukushima Daiichi NPP. Some chromosome analyses were performed for a number of workers considered to have received the highest doses, as described in Section 4.2.1.

4.2.2.2. Assessment of external exposures

External doses from Fukushima Daiichi NPP releases to the atmosphere have two components: irradiation from radionuclides in the air and irradiation from radionuclides deposited onto the ground. Any measurements of ambient dose equivalents made during the period when releases were continuing included doses from both components. Personal dosimetry of members of the public is not normal practice, and the nature of the reactor accident and tsunami made such measurements particularly difficult. Estimates of external doses to the public have been based on a combination of modelling, particularly for the early period, and personal measurements, where such data are available. The studies that are of particular relevance for external doses are summarized in Table 4.2–8. The results of these studies are presented below.[25]

[25] The results of these studies have not been independently validated for the purposes of this volume.

TABLE 4.2–8. STUDIES TO DETERMINE EXTERNAL DOSES

Item	Survey type	Dates/locations/subjects	Key points	References
1	Personal dosimetry		— Glass badge (Chiyoda Technol. Corporation; radio photoluminescence) used in Fukushima City and Date City — Quixel badge (Nagase Landauer Ltd; optically stimulated luminescence) used in Nihonmatsu City, Tamura City and Koriyama City — Detection limit 0.01 mSv — Summary of measurements, measurement periods, results, etc. (see Table 2 of Ref. [204]) — Fukushima City: o 36 767 infants, schoolchildren, pregnant women o 1 September–30 November 2011 o Frequency distribution of individual accumulated external doses for three month period o 87.2% < 0.5 mSv; 99.7% < 1 mSv — Date City o Accumulated doses to 9 443 residents of all ages over three months by district o 1 September–30 November 2011 o Lowest: Yanagawa District (0.17 mSv) o Highest: Ryozen District (0.72 mSv) — Tamura City o Accumulated doses to 4 559 children up to junior high school age and pregnant women over 103 days gestation by district o 30 September 2011–10 January 2012 o Lowest: Ohgoe, Takine (0.1 mSv) o Highest: Miyakoji (0.17 mSv) — Nihonmatsu City o Accumulated doses to 8 725 pregnant women over three months gestation and children by age group o 1 September–30 November 2011 o Dose range 0.28–0.41 mSv	Results of individual doses as cited in Ref. [204] (in Japanese): Date City [205] Nihonmatsu [206] Tamura City [207] Koriyama City [208] No source for residents of Fukushima City Results of measurements made using personal dosimeters in 22 municipalities omitting names of cities, towns and villages [209]

TABLE 4.2–8. STUDIES TO DETERMINE EXTERNAL DOSES (cont.)

Item	Survey type	Dates/locations/subjects	Key points	References
			— Koriyama City o 24 115 school children o 7 November 2011–9 January 2012 o Frequency distribution of individual accumulated external doses for a 64 day period o 91.9% in range of 0.01–0.29 mSv o Maximum dose: 1.31 mSv; average dose: 0.17 mSv	
2.	External dose estimate, behaviour logging (FHMS)	12 March–11 July 2011	NIRS external dose estimation system — maps of gamma dose rate by MEXT and calculations by the System for Prediction of Environmental Emergency Dose Information (SPEEDI) combined with behaviour data derived from survey. 554 241 residents (27.0%) of a total of 2 055 383 residents who resided in Fukushima Prefecture at the time of the accident responded to the questionnaire. External doses in four months were estimated for 477 121 residents: o 279 118 (62.2%) < 1 mSv o 421 462 (93.9%) < 2 mSv o 446 059 (99.4%) < 3 mSv o The maximum dose was 25 mSv Results of individual external doses for four months in the Soso area: o 55 144 (77.6%) < 1 mSv o 67 521 (95.0%) < 2 mSv o 1 647 (97.3%) < 3 mSv o The maximum dose was 25 mSv	Fukushima Medical University [210] See also Ref. [203] for methods.

Assessment of external doses based on measured ambient dose equivalents

NIRS developed an external dose estimation system for residents of Fukushima Prefecture after the Fukushima Daiichi accident. The system has been used for the basic FHMS. In this system, the external exposures of the residents can be calculated based on information on the movements of the residents after the accident as recorded in the survey sheets, and on the dose rate maps of days in the four months following the accident, constructed from the measured dose rates and simulation data. Information on the shielding effects of houses or buildings from the radioactive plumes and from the radionuclides on the ground was based on Ref. [211]. The background exposure before the accident was estimated based on the available data and was subtracted from the calculated external exposures. For babies or children, the smaller body sizes compared with those of adults were considered, and the conversion coefficients for effective doses were applied.

As noted above, in the basic FHMS (see Section 4.4.2.1), information was collected on locations of residences, dates of moving and patterns of activity of Fukushima Prefecture residents and, combined with environmental dose rate maps, the individual integrated external exposures in the first four months following the accident were estimated. To examine the range of doses, 18 evacuation scenarios for the residents were assumed by considering actual evacuation information, as described above.

The doses to the residents from the Deliberate Evacuation Area were elevated compared with those from the area within the 20 km radius of the Fukushima Daiichi NPP. The estimated cumulative effective doses from external exposure for the four month period between 11 March and 11 July 2011 have been published on the Fukushima Prefecture's web site. Ninety-five per cent of residents were estimated to have received doses of less than 2 mSv. Natural radiation background of an average of 0.03 μSv/h (about 0.27 μSv/y) was subtracted from the estimated external exposure rates.

The estimated individual effective doses from external pathways received in the first four months following the accident have been published [212] and the results for Fukushima Prefecture are shown in Fig. 4.2–11. It can be seen that for the majority of people in Fukushima Prefecture external doses are low. A number of estimates of the individual effective doses due to external exposure in the first four months have been published [204, 210, 213, 214]. For example, in the Soso area (which includes the evacuation zone and the Deliberate Evacuation Area), these doses were below 5 mSv for 98.7% of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and the Deliberate Evacuation Area, the doses were below 3 mSv for 99.4% of the residents surveyed [210].

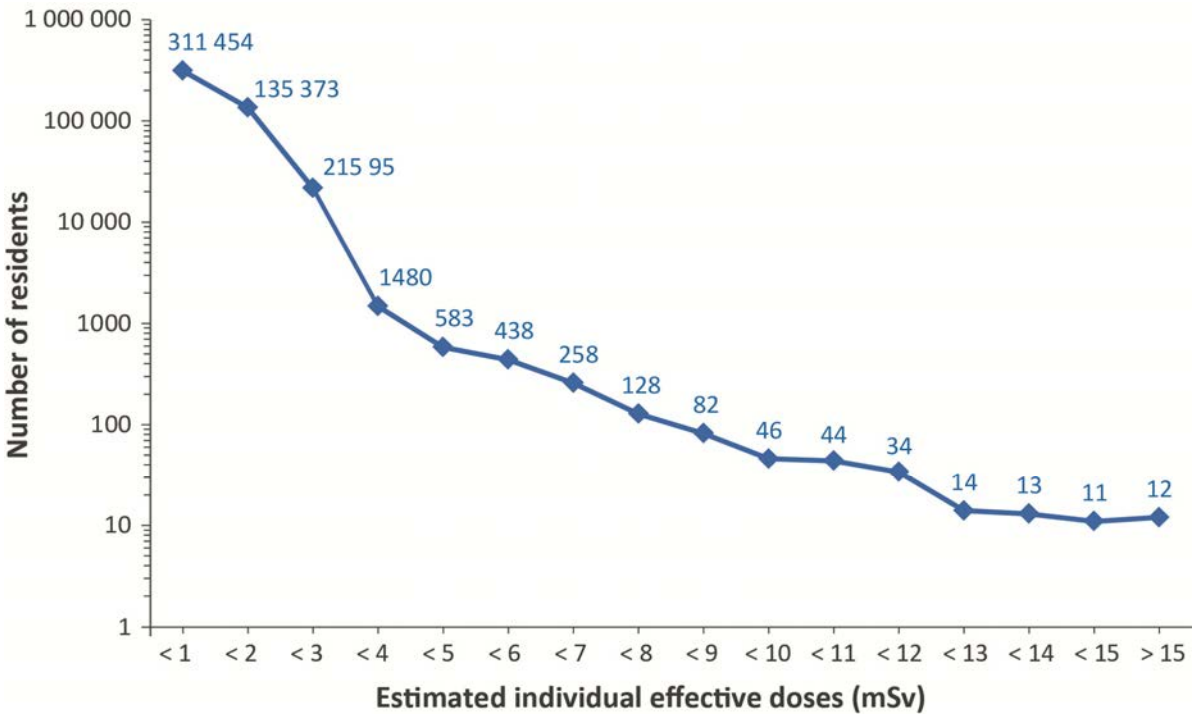


FIG. 4.2–11. Estimated individual effective doses from external radiation for all residents of Fukushima Prefecture for the first four months following the accident [212].

These results were further analysed using a log-normal fitting process (see Section 4.2.1.8 for details of this process), as illustrated in Fig. 4.2–12 for some settlements. The upper figures are for cities located within 20 km of the Fukushima Daiichi NPP, while the lower figures are for cities outside this area. This analysis took account of the fact that:

— Some measurements were aggregated in such a way that the datasets reflected the number of people who received a dose within specific intervals (bins).
— For many datasets, the majority of measurements were either around or below the limit of detection.

Therefore, a probability density function as well as the cumulative distribution were calculated. The measurements that were below the limit of detection (1 mSv) were particularly marked for Hirono Town and Iwaki City, where 97% and 99%, respectively, of the data were 1 mSv or less. The resulting distribution for Hirono Town was affected to such an extent that it is not included in Fig. 4.2–12. There were other difficulties in interpreting the data as discussed earlier, particularly the treatment of background radiation and the approach adopted for dealing with low doses. Nevertheless, it is possible to obtain useful information from these measurements and the analysis.

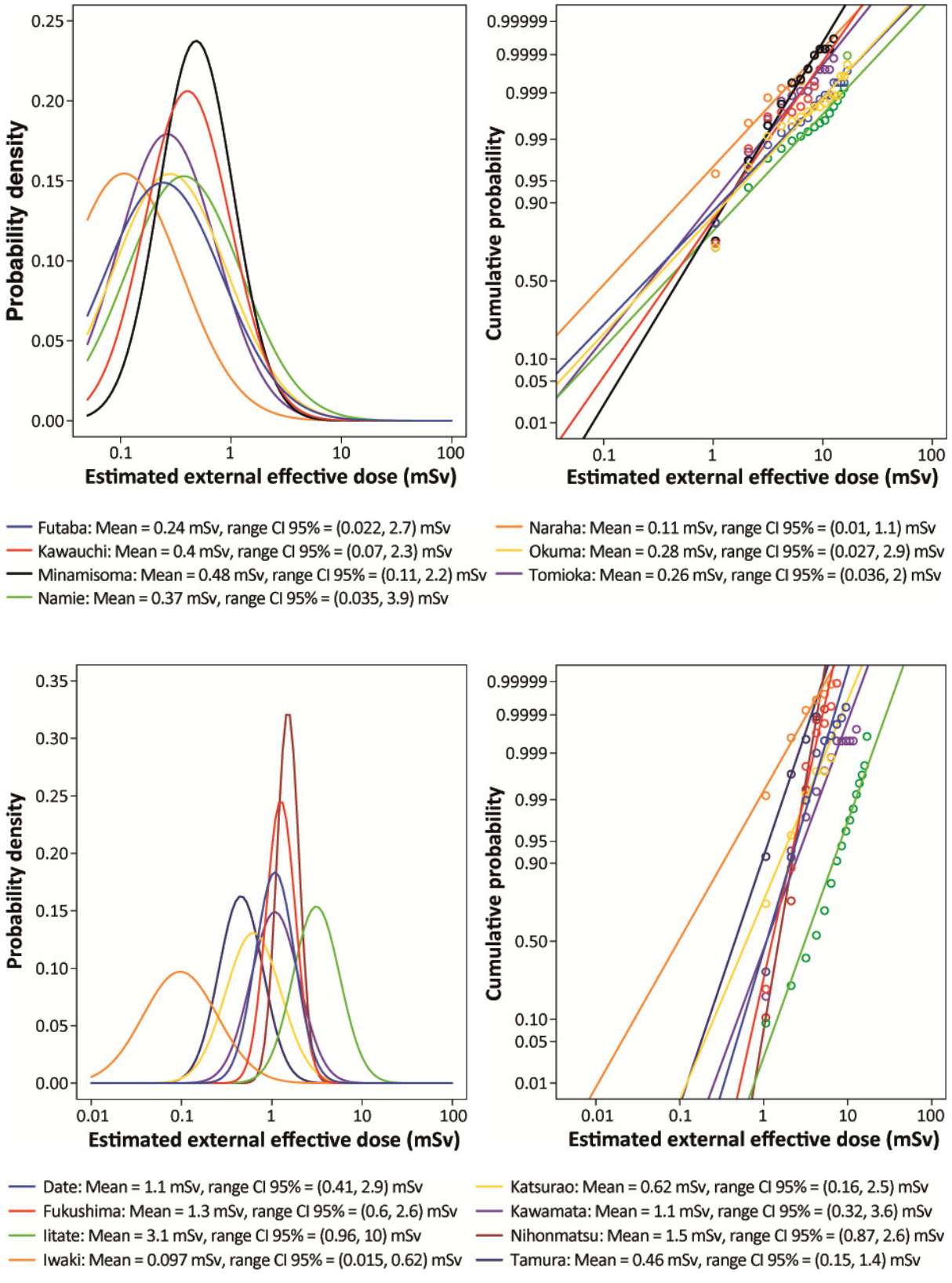


FIG. 4.2–12. Log-normal normalized idealized probability density and cumulative probability distributions of the estimated external effective doses in various cities, towns and villages of Fukushima Prefecture for the four months following the accident on the basis of Fukushima Health Management Survey data. The upper part of the figure presents the analysis for places located in the area within the 20 km radius and the lower part of the figure for places outside this area.

For people originally located within 20 km of Fukushima Daiichi NPP (the upper part of Fig. 4.2–12), the estimated mean doses range from 0.24 mSv to 0.4 mSv in the first four months after the accident. The highest 95th percentile dose is estimated to have been 3.9 mSv in Namie Town. As seen from lower part of Fig. 4.2–12, the estimated doses tend to be higher outside the 20 km zone, reflecting the effects of the prompt protective actions within 20 km. There is also a greater range in doses for people living outside the 20 km area, as would be expected from the variation in levels of radioactivity at different locations. For these cities and towns, the estimated mean doses range from 0.46 mSv in Tamura City to 3.1 mSv at Iitate Village (excluding Hirono Town and Iwaki, where the estimated mean doses are lower but where there are difficulties with the analysis as explained above). The highest estimated 95th percentile dose was about 10 mSv for Iitate Village, where evacuation took place later than in other locations [215]. The estimated 95 percentiles for other cities and towns ranged from 1.4 mSv for Tamura to 3.6 mSv for Kawamata Town (excluding Hirono Town and Iwaki City).

It should be noted that the spread of doses at Namie Town is wider than for other municipalities. This appears to be because the evacuation from Namie Town took place in two stages about a week apart, so that part of the population was exposed in the locality for a longer period, giving rise to an overall dose distribution which is effectively the combination of two distributions [215].

The results illustrated in Figure 4.2–12 are all reasonable fits to a log-normal distribution following the normalization process described in Section 4.2.1.8. Differences between the various locations reflect the extent and timing of evacuation as well as the levels of radioactivity experienced. The results within the 20 km zone tend to show wider distributions than the locations outside 20 km. This is due to the effects of evacuation of the same community to different locations and the further movements that took place in many cases. This complicated pattern was modelled by NIRS using 18 evacuation scenarios, as explained earlier. Appendix II presents some additional analysis of the data for various locations.

Despite significant inhomogeneity in the mean doses estimated for the individual municipalities, the distribution obtained for the Soso area as a whole is also well described by a log-normal probability density function. These results can be compared with those estimated by UNSCEAR using the same 18 scenarios and a similar methodology for estimating external doses, but with a different dispersion model and source term. These dose estimates also included other exposure pathways. For example, for Iitate Village, UNSCEAR estimated a total dose before and during evacuation of 5.7 mSv, which includes contributions from inhalation and ingestion. This is higher than the mean dose given above, but lower than the 95th percentile. UNSCEAR compared the external doses with the results obtained by NIRS and found that the two sets of doses were reasonably consistent [5]. UNSCEAR also estimated lower doses for those people who were evacuated in the first few days following the start of the accident than for those who were evacuated later.

Assessment of external doses from personal dosimetry

There are uncertainties associated with the use of interviews with residents, environmental measurement and dose estimation models for assessing public doses. Personal radiation monitoring of members of the public is therefore important for a reliable reconstruction of radiation doses. Personal dosimeters were distributed to large numbers of people living in different regions, as summarized in Table 4.2–8. Residents in Fukushima City were provided with dosimeters to be worn for a three month period from September 2011. The results were summarized by Nagataki et al. in 2013 [204]. For 36 767 infants, schoolchildren and pregnant women in Fukushima City, the accumulated dose in the three month monitoring period was less than 1 mSv in 99.7% of the measurements. The results are presented in the form of log-normal cumulative probability plots in Appendix II.

Further analyses have been carried out on the data for Date City[26] and Iwaki City[27], for which annualized doses derived from measurements in two settlements towards the end of 2011 and early 2012 are available. The results are presented in Fig. 4.2–13 [216–218].

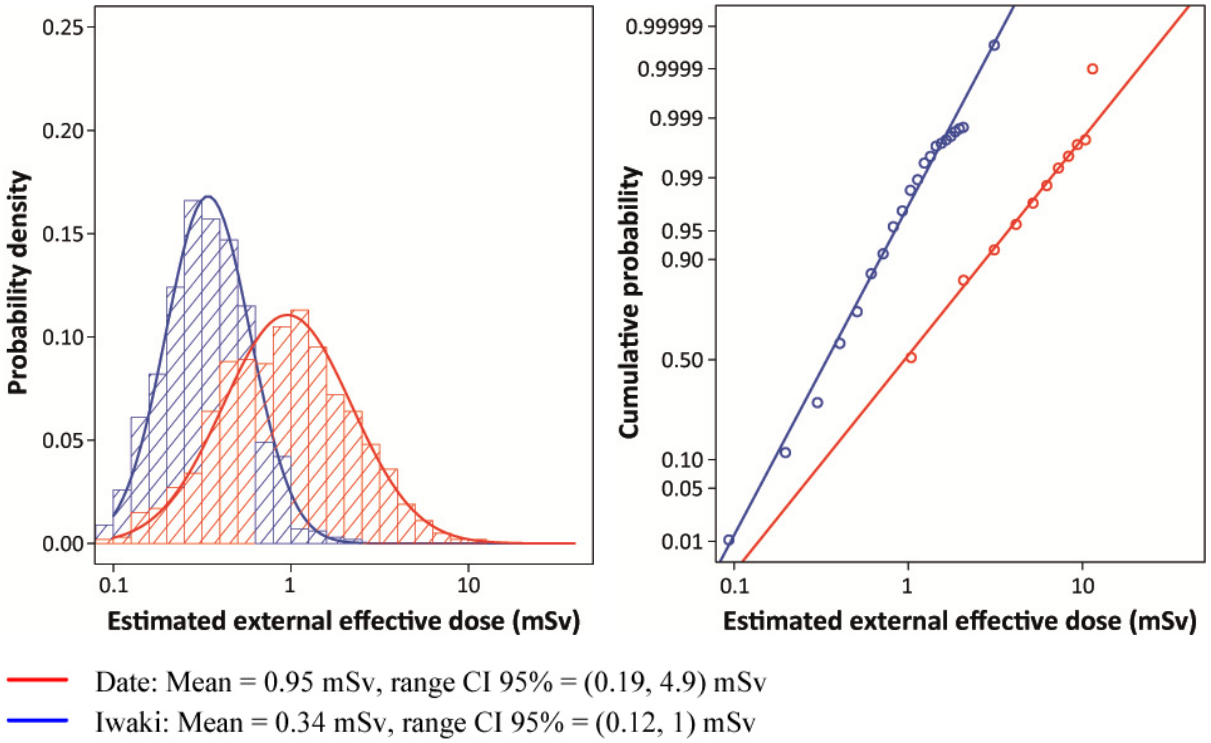


FIG. 4.2–13. Probability distribution of monitored personal dose equivalents of members of the public during 2011 for two cities in the affected area, Date City and Iwaki City, for which annualized data were available.The normalized idealized probability density function and the cumulative probability distribution is illustrated for each city.

Figure 4.2–13 indicates that personal dose equivalents received by members of the public in these two cities were low, with averages below 1 mSv per year, providing 95% confidence that individuals who incurred effective doses in those cities sustained doses below 5 mSv [216–218]. For Date City, the estimated mean external personal dose equivalent is 0.95 mSv for the first year following the accident with the 95th percentile being 4.9 mSv [216]. For Iwaki City, external doses are lower, reflecting the lower levels of radioactivity in the area. The estimated mean personal dose equivalent was 0.34 mSv in the first year and the 95th percentile is 1 mSv [217].

A number of studies were carried out in Date City with people in various locations within the area being provided with dosimeters to be worn over the period September 2011 to February 2012. Additional information is presented in Appendix II.

In Date City, personal dosimeters were also provided for a large number of schoolchildren attending various schools over the period April–June 2012. The average doses measured over the period ranged from 0.4 to 0.9 mSv, but the variation for different schools was greater (0.4–1.4 mSv) [216]. A further

[26] For Date City, individual dose measurement with personal dosimeters (glass badges) was carried out for six months from September 2011 to February 2012. The cumulative dose was doubled to calculate the annualized dose, as described in Ref. [216].

[27] For Iwaki City, personal dose measurements were carried out for three months, from November 2011 to January 2012. The cumulative dose was multiplied by 4 to calculate the annualized dose, as described in Ref. [217].

set of measurements was obtained during the period from July 2012 to June 2013, and for these a comparison was carried out between the results of the personal dosimeters and estimates of external doses based on measurements of ambient dose equivalent. This is shown in Fig. 4.2–14 [219].

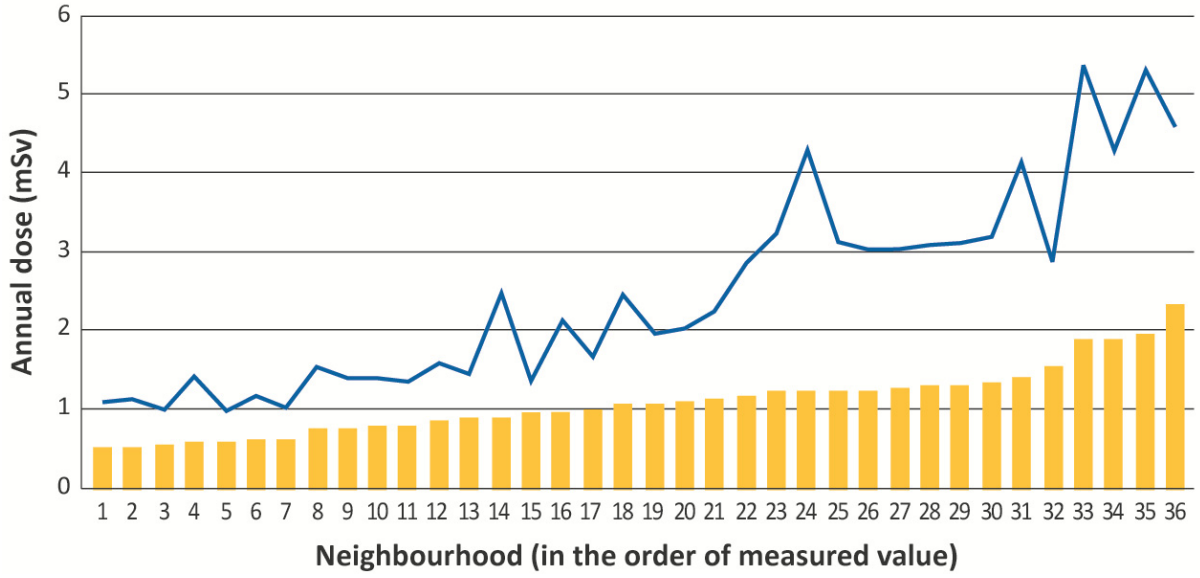


FIG. 4.2–14. Comparison of external individual dose estimates with measurements in Date City between July 2012 and June 2013. The effective doses are assessed by estimation (line), assuming indoor occupancy and shielding for 16 h, outdoors for 8 h, and by personal monitoring (bar) of personal dose equivalent, in various neighbourhoods of the city (numerated) [219].

These results indicate that the doses based on data from personal dosimetry are lower than those based on measured ambient dose equivalent rates, habit information and modelling. It is also possible to compare the results with those obtained using the UNSCEAR method for projecting external doses over time. From the beginning of April 2012 to the end of March 2013, the UNSCEAR assessment approach would imply a district averaged external dose of 1.2 mSv for a representative person[28] living in the wider Date City area, which is consistent with the dosimeter results [216].

Log-normal distributions were also produced for some other locations where the available information is sufficiently detailed to obtain ranges in external doses, and this information is presented in Appendix II.

Comparison with UNSCEAR estimates of external dose

Although measurements of external doses using personal dosimetry are generally performed for a maximum period of three months, these data may be used to derive a rough estimate of the dose in one year that can be compared with the projected additional annual effective doses from external pathways, estimated using the UNSCEAR methodology. This involved using time weighted district averages of soil measurements performed in 2011 to determine initial dose rates. Projections of the additional external dose rates at subsequent times were then estimated using information on the reduction in dose rate with time arising from natural processes, such as radioactive decay and weathering, from post-Chernobyl studies.

[28] A representative person is an individual receiving a dose that is representative of the dose to the more highly exposed individuals in the population [220].

Figure 4.2–15 shows the estimated reduction with time of external dose rates due to gamma emitting radionuclides from 2012 to 2015, with no allowance for any remediation of the land [221]. Thus, over the three year period 2012–2015, the external doses would be projected to decline by a factor of 4 owing to radioactive decay, natural weathering from surfaces and vertical migration in soil.

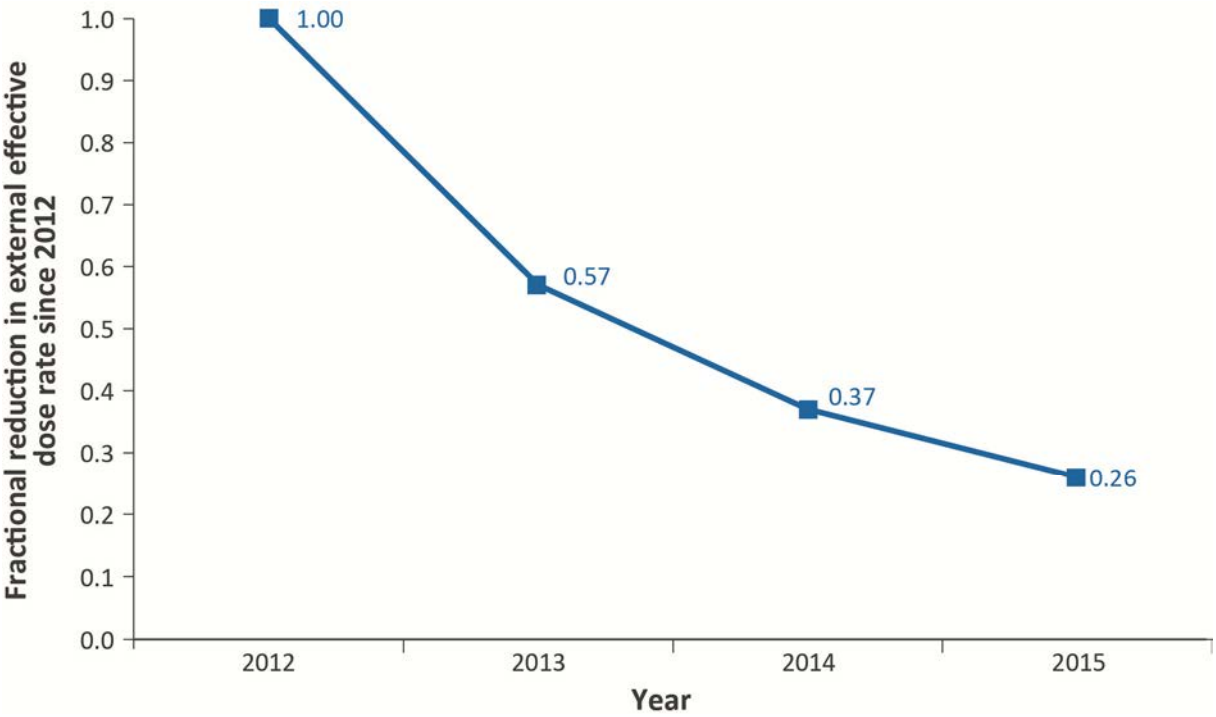


FIG. 4.2–15. Fractional reduction in external effective dose rates relative to 2012 from gamma emitting radionuclides. [221].

The projected external effective doses estimated for 2012 indicate that the district averaged doses to a representative person would have been less than 1 mSv in all prefectures except Fukushima Prefecture. Figure 4.2–16 is a map of the projected district averaged external effective doses for the representative person in Fukushima Prefecture in 2012. The projected annual effective dose in 2012 for representative persons returning to an area currently evacuated was estimated to be 10–17 mSv, in Okuma Town, Futuba Town and Namie Town, and below 6 mSv in the remaining areas of Iitate Village, Katsurao Village and Kawauchi Village. By 2015, this approach would suggest that the maximum district averaged effective dose to a representative person would be less than 5 mSv in that year based on natural processes and assuming no remediation. These district averaged estimates do not allow for spatial variation in radiocaesium deposition within each municipality. Actual doses will therefore vary below and above the district averaged estimate. For comparison with the effective doses to a typical person reported above and by UNSCEAR [5], the dose to a representative person, based on district average dose rate information, is estimated to be within a factor of 1.4 to 1.5.

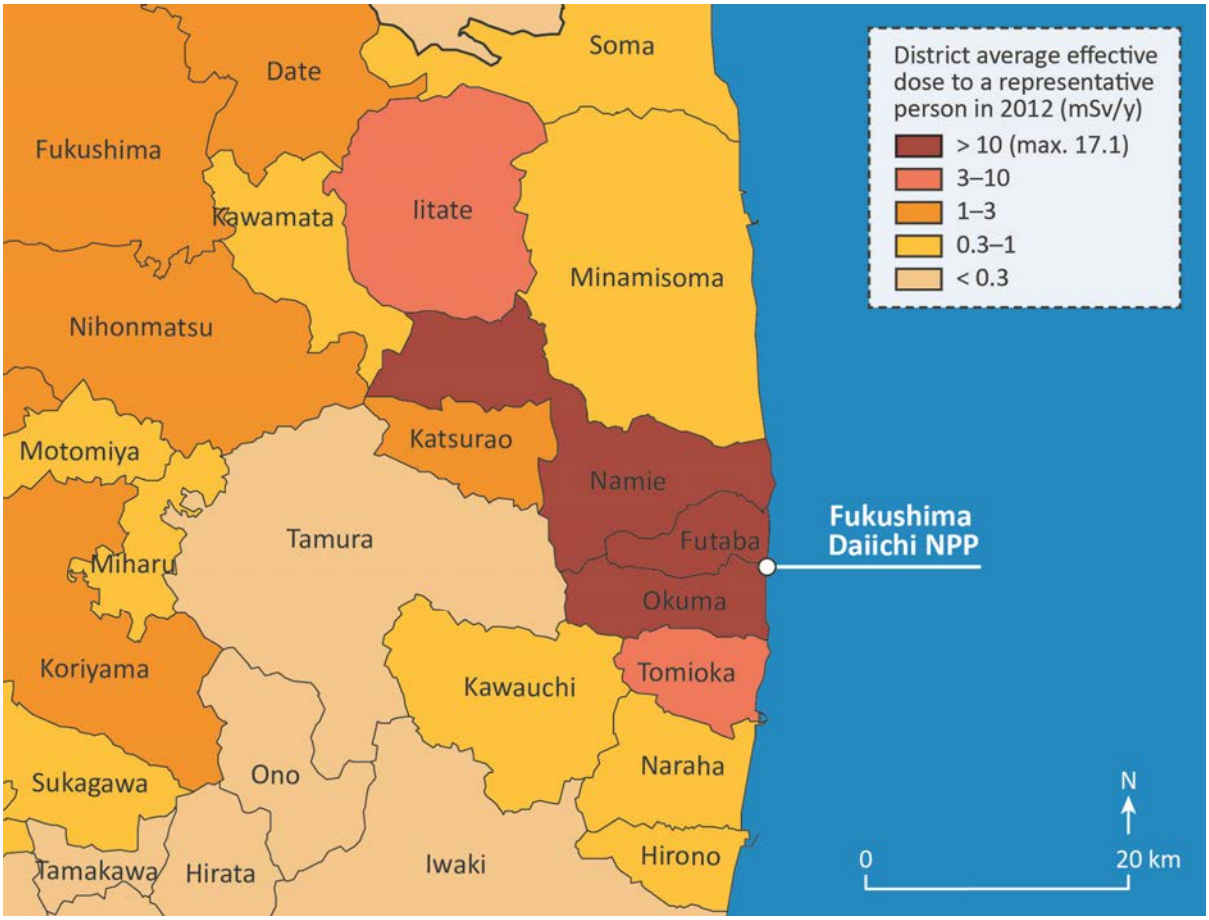


FIG. 4.2–16. Predicted district average external effective dose for a representative person in 2012.

Table 4.2–9 presents a comparison of personal dosimetry results with the projected additional external effective doses in 2012 from deposition measurements performed in 2011, using the methodology applied in the UNSCEAR assessment. Projected doses are generally assessed for the purpose of prospective decision making and do not reflect the doses received by any individual. By their nature, such estimates are based on some form of environmental and dosimetric modelling and are subject to the associated uncertainties. Dose estimates based on personal dosimetry represent more closely those received by individuals, but are also subject to the uncertainties associated with such measurements.

Although the measurements and modelled doses are of a different nature and cover different time periods, they are generally in good agreement. However, it is clear that there will be variability in individual doses, due to local variations in deposited activity together with variations in people's behaviour. It should be further noted that the modelled values presented in Table 4.2–9 are intended to be representative of those who are likely to receive higher doses (the representative person), while the measured values presented in this table are mean values and therefore more indicative of typical exposures.

TABLE 4.2–9. COMPARISON OF PERSONAL DOSIMETRY RESULTS WITH EXTENDED ANALYSIS USING UNSCEAR METHODOLOGY FOR ASSESSING PROJECTED ADDITIONAL EXTERNAL DOSE FROM DEPOSITION

Location	Measurement period	Doses estimated from measurements (mSv)		Annual doses (mSv)	
		Mean	Range[a]	Measured mean	Projected dose[b]
Fukushima City	1 Sep. 2011–30 Sep. 2011	0.06	0.01–0.26	1.2	1.8 (2012)
Fukushima City	1 Oct. 2011–30 Nov. 2011	0.11	0.03–0.46		
Fukushima City	1 Nov. 2012–31 Jan. 2013	0.08	0.02–0.33	0.3	1.0 (2013)
Iwaki City[c]	1 Nov. 2011–31 Jan. 2012	0.34[d]	0.12–0.99	0.34	0.2 (2012)
Tamura City	30 Aug. 2011–30 Sep. 2011	0.04	0.02–0.13	0.5[d]	0.28 (2012)
Tamura City	30 Sep. 2011–10 Jan. 2012	0.12	0.04–0.36		
Tamura City	11 Jun 2012.–11 Sep. 2012	0.07	0.02–0.24	0.28	0.28 (2012)

[a] The range is the 5th and 95th percentile; a simple method of multiplication by the number of months is not applicable, and comparison with data for 2012 is not strictly appropriate.
[b] Projected additional effective dose to the representative person based on environmental measurement data from 2011.
[c] Measured values for schoolchildren.
[d] These are annualized doses and not for the three month period of the measurement.

4.2.2.3. Assessment of exposures from intake of radionuclides

As explained in Section 4.2.2.1, there are two main routes for exposures from intakes of radionuclides: inhalation of radionuclides released to air and ingestion of radionuclides in food and drinking water. It is possible to assess the doses arising from intakes from either direct measurements of the body content of radionuclides, where such measurements are possible, or by an estimate of intake and the use of dose coefficients based on biokinetic models. The results of each type of analysis are presented below.

Assessment of committed effective doses by measurement of incorporated radionuclides

The measurement of radionuclides in people provides a direct source of information on their internal exposures. Two main sets of data are available, the first from measurements of ^{131}I in the thyroid and the second from whole body measurement for ^{134}Cs and ^{137}Cs. In order to assess dose from internal exposure of incorporated radionuclides, assumptions have to be made regarding when and where intakes took place and how much of the intake was by inhalation and how much by ingestion. The use of whole body counting does not take into account, or provide any measure of, any external radiation exposures.

The number of measurements of people in the vicinity of the Fukushima Daiichi NPP immediately after the accident is quite limited owing to the severe effects of the tsunami, organizational and transportation difficulties, elevated background radiation and contamination of radiation measuring devices. However, a large number of WBC measurements were later carried out at different settlements. Information on these was provided by the municipalities, through the Government of Japan, for this study and was also obtained from other published sources.

A summary of the distribution of committed effective doses among residents of Fukushima Prefecture, measured by WBC, is presented in Table 4.2–10.

TABLE 4.2–10. COMMITTED EFFECTIVE DOSE DISTRIBUTION OF FUKUSHIMA PREFECTURE RESIDENTS MEASURED BY WBC IN INDIVIDUAL MUNICIPALITIES FROM 27 JUNE 2011 TO 31 JANUARY 2012 [222]

Municipality	Committed effective dose (mSv)				Total
	<1	1–1.5	1.5–2.5	2.5–3.5	
Kawamata	632	0	0	0	632
Namie	3 043	5	2	0	3 050
Iitate	1 425	0	0	0	1 425
Hirono	645	0	0	0	645
Naraha	1 067	1	2	0	1 070
Tomioka	1 814	0	1	0	1 815
Kawauchi	302	0	1	0	303
Okuma	1 960	3	1	0	1 964
Futaba	1 155	2	2	2	1 161
Katsurao	181	0	0	0	181
Soma	2	0	0	0	2
Minamisoma	21	0	0	0	21
Date	1 208	2	1	0	1 211
Iwaki	799	0	0	0	799
Tamura	200	0	0	0	200
Shirakawa	10	0	0	0	10
Fukushima	430	0	0	0	430
Sukagawa	490	0	0	0	490
Total	15 384	13	10	2	15 409

The data presented in Table 4.2–10 were measured using a WBC with sodium-iodine detectors installed at NIRS, JAEA and other organizations. The measurements conducted by NIRS were measured using a bed type WBC with four sodium iodide detectors. The measurement time was 3 minutes [223]. The minimum detectable activity was 320 Bq ^{134}Cs and 570 Bq ^{137}Cs.

Some additional information was provided by the municipalities, through the Government of Japan, for the purposes of this assessment, as indicated in Table 4.2–11. It generally was not possible to undertake detailed statistical analyses of these data; most measurements were at or below the limits of detection.

As can be seen from Table 4.2–11, WBC measurements were carried out on tens of thousands of people from various locations, particularly in Fukushima Prefecture. Where it was possible to convert measurements to dose, making assumptions about the timing and nature of the intake, the estimated effective dose commitments from measurements of ^{134}Cs and ^{137}Cs were reported to be lower than 1 mSv for 99% of residents [204]. The aim of many of the studies was for screening or public reassurance purposes. Many measurements were below detection limits and serve to demonstrate that doses were less than 1 mSv. However, it is not possible to carry out any detailed statistical analyses, such as fitting log-normal distributions, for these data.

In many cases, the WBC measurements were carried out several months or more after the accident and therefore provide information on the levels of ^{134}Cs and ^{137}Cs incorporated, but do not provide information on ^{131}I, which would have decayed by this time. Given the importance of intakes of ^{131}I

both by inhalation and ingestion in the first month following the accident, this makes comparison between the measurement data and the dose assessment carried out by UNSCEAR difficult.

Inhalation doses varied from place to place and included a component arising from the intake of ^{131}I, which would not have been detected in many of the WBC measurements. The highest estimated effective doses measured were 1 mSv, corresponding to an absorbed dose to the thyroid of 20 mSv (mGy). Without information about the locations in Fukushima Prefecture where the people monitored spent their time and the time of the measurement, it is not possible to compare these results in detail with those estimated by other organizations, although the overall magnitudes may be compared. UNSCEAR estimated that the committed effective dose from inhalation of the population of Fukushima Prefecture who were not evacuated was between about 0.01 mSv and 0.3 mSv, depending on location [5]. The first month's committed effective dose from ingestion for an adult was estimated to be about 0.8 mSv. These results are broadly consistent with those presented above.

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT

Study	Survey type	Dates/locations/subjects	Key points	References
1	WBC thyroid and urine analysis	27 June and mid-July 2011 Residents of Iitate Village, Namie Town and Yamakiya District of Kawamata Town (from Deliberate Evacuation Area) 122 subjects	— Pilot study performed by NIRS — Results reported for 109 of 122 residents — Significant levels of radiocaesium detected in 50% of subjects (max values 3 100 and 3 800 Bq of ^{134}Cs and ^{137}Cs, respectively) Ref. [224] — ^{134}Cs detected in 47.8% of subjects, ^{137}Cs in 29.4% and both in 23.9% — Estimated combined dose from radiocaesium (^{134}Cs and ^{137}Cs) <1mSv — ^{131}I not detected	Ref. [224]
2	WBC	11 July 2011–end January 2012 (reported here — measurements continuing) Residents of 11 municipalities in Fukushima Prefecture (at time of accident) 9 927 subjects aged 4–adult	— JAEA measurements of residents started — Measurements build on pilot study (item 3) and form part of the Fukushima Prefectural government's study, Health Examination for Citizens in Fukushima Prefecture — Details on efficiency calibrations/phantoms provided — Maximum concentrations for children <8 years and for adults were 2 700 and 14 000 Bq, respectively — 99.8% of committed effective dose (CED) estimates below 1 mSv (but does not include contribution from short lived radionuclides ^{131}I, ^{132}I, ^{132}Te) — 22 subjects had CED estimated >1 mSv; maximum CED = 3 mSv. All children or teenagers apart from one adult (who had worked at the damaged Fukushima Daiichi NPP) — ^{134}Cs/^{137}Cs ratio 0.89–0.79	Refs [224, 225]
3	WBC	June 2011–February 2013 118 930 residents of Fukushima Prefecture at the time of the accident (includes current residents and evacuees in Niigata Prefecture)	— Report entitled Health Examination for Citizens in Fukushima Prefecture — Estimated committed effective dose of 118 904 (99.9%) residents <1mSv based on the assumption that intake was by inhalation in March 2011 — Maximum estimated committed effective dose: 3 mSv	Monthly updates of statistics based on results of this WBC initiative are published (in Japanese) on the Fukushima Prefectural government web page. The monthly results as of February 2013 were used. See Refs [224, 226] up to end of January 2012 and Refs [204, 226] for results up to February 2013.

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
4	WBC	7 October 2011–30 November 2012 Residents of Fukushima and neighbouring prefectures 32 811 subjects aged 4–93	— Distinct from the Fukushima Prefectural government measurement campaign (Item 3) — No information provided on efficiency calibration of WBC — Initial measurements (11 026 subjects between October 2011 and February 2011) eliminated owing to possible surface contamination of clothes — Of the remaining measurements (21 785 subjects between March 2012 and November 2012), $^{134}Cs/^{137}Cs$ detected in 1.0% of adults and 0.09% of children ≤15 years — $^{134}Cs/^{137}Cs$ ratio approximately 1, gradually decreasing with time — High concentrations in small groups of elderly subjects (maximum 184 Bq of ^{137}Cs; 108 Bq of ^{134}Cs) who had eaten banned wild foods — Possible sampling bias investigated and discounted	Ref. [227]
5	WBC	26 September 2011–31 March 2012 9 484 residents of Minamisoma City (including returned evacuees)	— WBC of residents (offered to all, 24% were measured) — Radiocaesium detected in 34.6% of subjects (16.4% of children, 37.4% of adults) — 1 432 children aged 6–15: 210–2 953 Bq (median 590 Bq); 2.8-57.9 Bq/kg (median 11.9 Bq/kg) — 3 051 adults 210–12 771 Bq (median 744 Bq); 2.3–196.5 Bq/kg (median 11.4 Bq/kg) — All doses <1 mSv in all but one resident	Ref. [228]
6	WBC	15 March 2011 onwards 173 subjects who were in Fukushima Prefecture between 11 March and 10 April 2011	— ^{131}I, ^{134}Cs and ^{137}Cs detected in >30% of subjects — ^{132}I and ^{132}Te detected in some measurements — Measured ranges: • ^{131}I: 0.42–140 kBq • ^{134}Cs: 0.13–16 kBq • ^{137}Cs: 0.13–16 kBq — Maximum dose estimated assuming acute inhalation of three radionuclides (levels from SPEEDI estimates) = 1 mSv (maximum thyroid dose, 20 mSv) — Reconstruction of doses for 16 evacuees for whom ^{131}I, ^{134}Cs and ^{137}Cs were detected by Matsuda et al. (2013) [229] and comparison with SPEEDI predictions of airborne activity concentrations	Ref. [229]; additional information in Ref. [230]

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
7	WBC	2011–2013 residents of Date City 9 305 children and pregnant women to the end of 2011 6 377 (to end of September 2012) 17 577 in 2013	In 2011, 99.96% received <1 mSv; 33 of group from areas in spots recommended for evacuation — In 2012, 1091: 4–6 years old; 119 pregnant women 5167 people >19 years old from four districts — All <1 mSv — 1091: 4–6 years old; 2 779 students of elementary and junior high school; 507 high school students; — 13 765 people >19 years — All <1 mSv	Newsletter published on 26 July 2012 [231] (Municipality in Fukushima Prefecture)
8	WBC	Residents of Fukushima City, measurements for 2011–2013 117 measurements from 25 November 2011 to 20 December 2011 (no age information available) 24 598 measurements of adults and children in 2012 41 258 measurements of adults and children in 2013	— 2011: All ^{134}Cs levels were below detection limits and only ten ^{137}Cs levels were above detection limits — 2012 levels nearly all below detection limits — 2013 levels nearly all below detection limits	Ref. [226] (Municipality in Fukushima Prefecture)
9	WBC	Residents of Hirono Town for 2012–2014; September–December 2012, (1044 measurements) January 2013–January 2014, (514 measurements)	— Summary of WBC measurements — data not presented — 90% not detected, 2% only ^{134}Cs detected, 5% only ^{137}Cs detected and 3% both Cs isotopes detected. Distribution of effective dose where caesium was detected presented	Ref. [226] (Municipality in Fukushima Prefecture)
10	WBC	Koriyama City 2013 only	— 14 data points that exceeded detection limit (age and gender; with the exception of one man of 29 years, all >59 years) — CED between 0.009 and 0.07 mSv	Ref. [226] (Municipality in Fukushima Prefecture)

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
11	WBC	Motomiya City In 2011, 3 035 children (by school type) and 81 pregnant women In 2012, 11 281 people, including 43 pregnant women, 416 workers (restorative construction), 7 986 general public — rest schoolchildren In 2013, 4 799 (1 584 general public), remainder children (by school age)	— No doses >1 mSv found	Ref. [232] (Municipality in Fukushima Prefecture)
12	WBC	Namie Town 26 April 2012–29 March 2013, 7 645 subjects (age information available) 1 April 2013–18 March 2014, 4 470 subjects	— Raw individual data — body burden and estimated effective dose (assumed to be derived from chronic ingestion) — Most measurements below limits of detection and all doses estimated to be less than 1 mSv	Ref. [226] (Municipality in Fukushima Prefecture)
13	WBC	Tamura City Raw data, 7361 subjects, June 2012–9 March 2014 Raw data for 4 681 subjects for 27 August–14 January 2014	— Body burden and effective dose from radiocaesium assuming chronic ingestion — Most measurements below limits of detection and all doses estimated to be less than 1 mSv	Ref. [226] (Municipality in Fukushima Prefecture)
14	WBC	Iwaki City, total of 62 071 measurements in the period November 2011–27 February 2014	— In the year March 2011–March 2012, 490 people were measured, with a detection rate of 28.8% — In 2012 and 2013, over 30 000 measurements were performed, with a detection rate of 2.3% and 0.3%, respectively	Ref. [226] (Municipality in Fukushima Prefecture)
15	Thyroid screening (scintillation survey meters)	26–30 March 2011 Iwaki City, Kawamata Town, Iiate Village 1 080 children, 0–15 years at time of accident	— Screening survey of children living in areas where thyroid doses were predicted to be high — Chronic intake rates and constant calibration factor used — Screening level of 0.2 μSv/h corresponds to a thyroid equivalent dose of 100 mSv (1 year old) — No significant signal detected in 55.4% of cases (<0.01 μSv/h) — Maximum thyroid equivalent dose measured was 43 mSv (1 year old)	Ref. [233] See also Ref. [234]

TABLE 4.2–11. SUMMARY OF THE WHOLE BODY COUNTER (WBC), MEASUREMENTS CARRIED OUT (cont.)

Study	Survey type	Dates/locations/subjects	Key points	References
16	Thyroid screening (scintillation survey meters)	12–16 April 2011 Residents of Namie Town (Tsushima district) Evacuees from coastal areas including Minamisoma City 62 subjects aged 0–83 years	— Thyroid measurements of 62 residents/evacuees — ^{131}I detected in 46 subjects — Mean thyroid doses for children and adults were 4.2 mSv and 3.5 mSv, respectively — Maximum thyroid doses for children and adults were 23 mSv and 33 mSv, respectively	Ref. [235]
17	WBC and thyroid measurements	196 residents and short term visitors to Fukushima, 11 March–20 April 2011	— Thyroid doses and effective doses were estimated using the measurement results from WBC — ^{131}I, ^{134}Cs and ^{137}Cs detected in 49 of the 196 people — Committed effective doses from caesium <1 mSv — Maximum thyroid equivalent dose was 18.5 mSv — Mean thyroid dose 3 mSv and committed effective dose of 0.06 mSv estimated	Ref. [230]
18	WBC, thyroid	734 Russian citizens in Tokyo in three trips in 2011–2012, the first one was from 8 to 20 April 2011	— In April 2011, 3 of 268 people exceeded the minimum detectable level of ^{131}I in the thyroid (100 Bq of ^{131}I) — Maximum estimated dose equivalent to the thyroid was 2 mSv for an adult and 4 mSv for a 1 year old child — Average thyroid equivalent dose estimated as 0.2 mSv for an adult and 0.4 mSv for a 1 year old child — None of 784 people exceeded the minimum detectable level of 1 800 Bq ^{137}Cs and ^{134}Cs in the body	Ref. [236]
19	Urine analysis	15 residents of Iitate Village and Kawamata Town between 54 and 78–85 days after 11 March 2011	— Estimated equivalent doses to the thyroid were between 27 and 66 mSv	Ref. [237]

Other assessments of doses from intake of radionuclides from ingestion

The assessment of exposure from the possible ingestion of radionuclides in food and drinking water requires information on the concentrations of radionuclides detected in food and drinking water over the period of assessment, as well as on the appropriate age dependent intake rates and dose coefficients of the radionuclides. Information on the average quantity of particular foods consumed per capita of the population, based on surveys carried out in Japan, has been provided by the Government of Japan. The most extensive data were available for adults, but these data also include information for infants and children.

Market basket analyses

Data on concentrations of ^{134}Cs, ^{137}Cs and ^{131}I in foods and in drinking water are described in Section 4.1.4. Market basket samples in more than ten areas across Japan were surveyed in September–October 2012, and the estimated annual committed effective doses for radiocaesium were derived from standard meals. Foods were purchased in 15 areas in Japan, including three areas in Fukushima Prefecture. Locally grown products were selected wherever possible. Using this approach, the annual committed effective doses from radiocaesium in food were found to be less than 0.01 mSv/y, as shown in Table 4.2–12. Subsequent surveys showed that doses continued to be less than 0.01 mSv/y. From the information given in Annex V, this is consistent with the estimated doses from ingestion beyond the first year given in the UNSCEAR study.

A detailed study of early doses due to the ingestion of radionuclides is being carried out by the Mitsubishi Research Institute, Inc., for the Ministry of the Environment, and some findings have been reported [238]. Field research was conducted to collect data on food distribution in the period following the accident and the intakes of food and water by the population during evacuation. Concentrations of radionuclides in water and foods were determined and ingestion doses calculated taking into account the quantities consumed for the period to the end of March 2011, when ^{131}I concentrations in water fell to below 10 Bq/L. Consumption of water is understood to be the primary contributor to ingestion doses. Concentrations in water were measured or assessed from ground deposition measurements. Owing to disruption in the distribution of food supplies, it is likely that few of these foods would have been eaten by the people who were evacuated.

The researchers confirmed that exposure from the consumption of milk was expected to be very low, as locally produced milk was not distributed. In addition, researchers determined that only bottled water was used to make infant formula food, as parents were concerned about the potential health effects of using tap water. Exposure from consumption of vegetables was noted to be low as very few vegetables were growing outside (owing to the cold weather at that time of the year) and that effectively the only locally produced vegetables consumed were those grown in greenhouses [239].

On 5 September 2013, the Fukushima Prefectural Government published ^{90}Sr radioactivity concentrations in food in Fukushima [240]. Strontium-90 was detected in 3 of 78 samples. The measured levels were 0.016 Bq/kg, in the diet of a child from 1 to 12 years of age, residing in the northern part of Fukushima Prefecture; 0.034 Bq/kg for a person over 13 years of age in the same area; and 0.026 Bq/kg for a child from 1 to 12 years in the central part of Fukushima Prefecture. The contribution of ^{90}Sr to doses is minor compared with that from ^{137}Cs and ^{134}Cs.

The concentrations of radionuclides in foods included marine species. Only foods available in markets complying with government standards were included.

TABLE 4.2–12. ANNUAL RADIATION DOSE FROM RADIOCAESIUM IN MARKET BASKET SAMPLES OF FOODS (COMMITTED EFFECTIVE DOSE BASED ON DIETARY SAMPLES) [241]

Area (Prefecture)	^{134}Cs and ^{137}Cs (mSv/year)
Hokkaido	0.0010
Iwate	0.0040
Miyagi	0.0057
Fukushima (Hamadori)	0.0018
Fukushima (Nakadori)	0.0038
Fukushima (Aizu)	0.0038
Tochigi	0.0032
Ibaraki	0.0035
Saitama	0.0024
Tokyo	0.0022
Kanagawa	0.0021
Niigata	0.0017
Osaka	0.0012
Kochi	0.0013
Nagasaki	0.0009

Assessment of thyroid equivalent doses from thyroid uptake measurements

A limited number of direct measurements of ^{131}I activity in the thyroid were reported for the weeks following the accident. These are summarized in Table 4.2–11, and a description of these studies is given in Annex VI.

A thyroid dosimetry survey was performed from 26 March to 30 March 2011 using a NaI (Tl) scintillation survey meter. The screening level was set under the assumption that a reading of 0.2 μSv/h on the survey meter corresponds to 100 mSv in the case of one year old infants, which is based on experiments by NIRS [233]. Using this method, the radiation doses to 1080 children under the age of 15 were measured in Iwaki City (134 children), Kawamata Town (631) and Iitate Village (315) in Fukushima Prefecture on the advice of the Nuclear Safety Council (NSC). None of the children showed a level of 0.2 μSv/h or higher, and the highest level was 0.1 μSv/h. Of these children, 55% showed background levels, and 99% had levels of less than 0.04 μSv/h [242]; data were expressed later as mSv with the intake (inhalation) scenario from 12 March to the day before measurement [233].

Figure 4.2–17 shows the distribution of measured thyroid equivalent doses estimated from the screening survey.

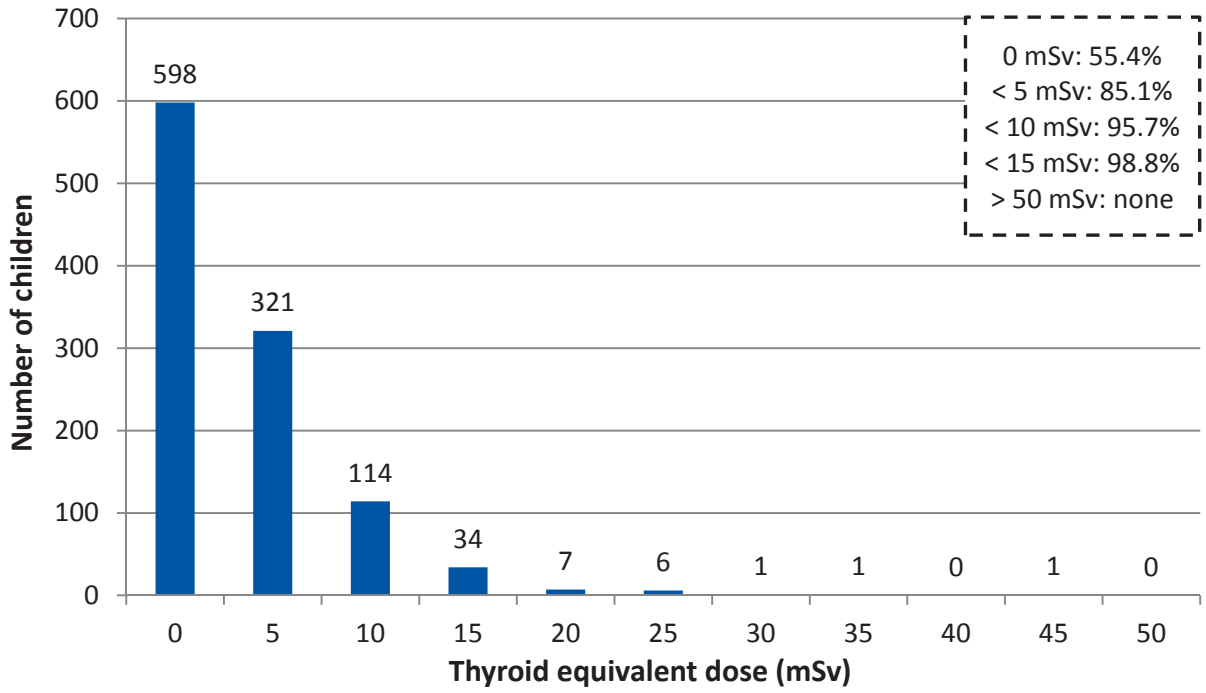


FIG. 4.2–17. Distribution of thyroid equivalent doses estimated by the results of the screening survey and intake scenario from 12 March 2011 to the day before measurement [233].

These doses indicate the range in the measurements and the fact that for the majority of the children the dose rates from the thyroid were low (less than 5 mSv).

For the purposes of this assessment, the data from this study were analysed further to investigate the relationship between the ratio of ^{131}I content in the thyroid derived from these measurements and those associated with theoretical assumptions on intakes by inhalation and ingestion. A comparison of the data for Iwaki City (see Fig. 4.2–18) clearly indicates that the measured data are closer to those for intakes by inhalation than ingestion, suggesting that the former was the predominant route of intake in this case. This analysis is presented in more detail in Annex VII.

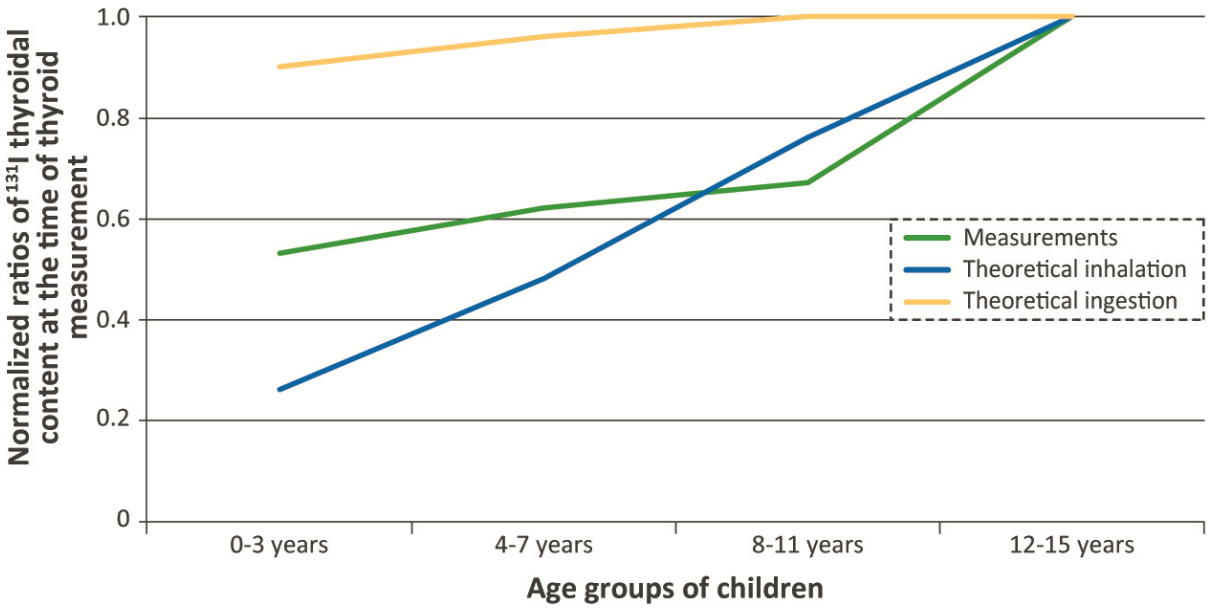
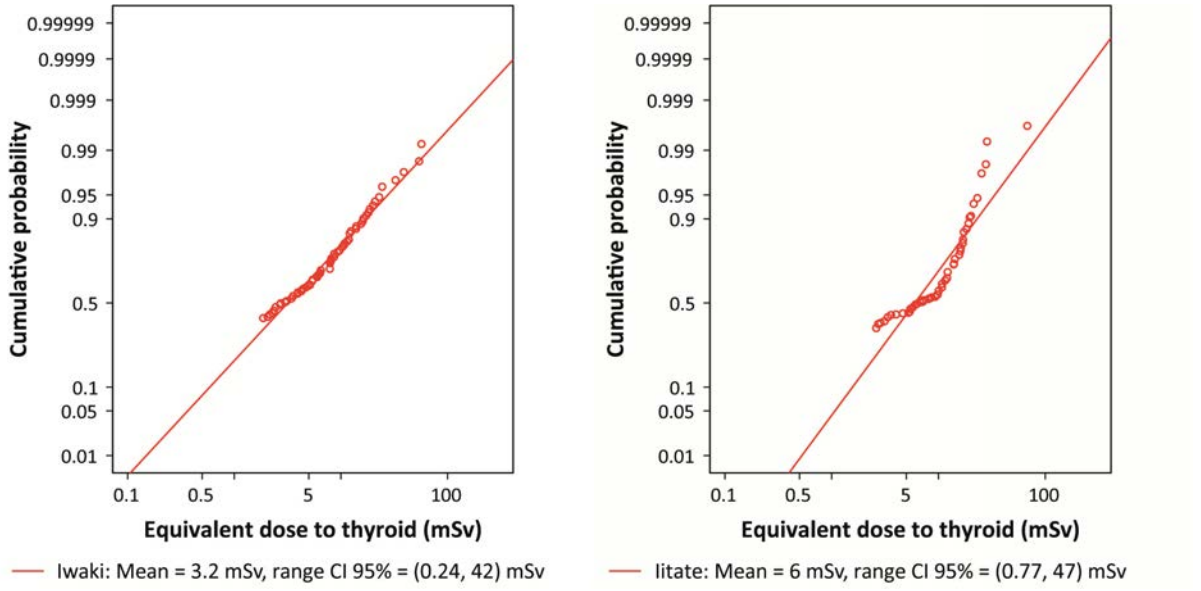


FIG. 4.2–18. Ratios of the estimates of the ^{131}I thyroidal content derived from direct thyroid measurements (green) and theoretically calculated on the basis of the assumption of (1) only inhalation intake (blue) and (2) only ingestion intake (yellow) in the form of normalization to the ^{131}I thyroidal content of group of older children for Iwaki City.

As a described in Annex VII, thyroid doses were estimated based on the assumption that inhalation occurred on 15 March 2011. The uncertainties associated with these data are described in Annex VII. It is necessary to recognize these uncertainties in interpreting the data and the corresponding cumulative log-normal probability distributions for Iwaki City and Iitate Village presented in Fig. 4.2–19. This figure suggests that the data for Iwaki City conform to a log-normal distribution, while those for Iitate Village do not. The distribution of individual doses in this village may include people who experienced different radiological conditions.



(a) (b)

FIG. 4.2–19. Log-normal cumulative probability distribution of individual thyroid dose estimates for children of (a) Iwaki City and (b) Iitate Village, derived from direct thyroid measurements assuming inhalation intake.

A detailed analysis of the available direct thyroid measurements for the 1080 children aged up to 15 years from three settlements in Fukushima Prefecture indicated that inhalation intake of ^{131}I was the dominant intake pathway. This was partly a consequence of the fact that intakes by ingestion were largely avoided owing to the prompt notification and implementation of restrictions on foods by the Japanese authorities. This resulted in an average equivalent dose to thyroid from intakes of ^{131}I of the order of a few mSv among those children.

These results are in contrast to the situation following the Chernobyl accident, where ingestion was the dominant intake pathway of ^{131}I for children living in contaminated areas, mainly owing to consumption of fresh milk from cows grazing on pasture. People living in the contaminated areas were not immediately aware of the accident and continued to drink locally produced milk. This resulted in average equivalent doses to the thyroid of up to a few thousand mSv (with a maximum value of 50 000 mSv based on direct thyroid measurements).

It is important to recognize that the consumption of fresh cows' or goats' milk is potentially the most significant of the various ingestion pathways leading to intakes of ^{131}I. A cow grazing on pasture typically eats about 50 kg of grass (wet weight) per day. If this grass is contaminated with ^{131}I, the cow will produce milk that has higher volumetric activity of ^{131}I than that in grass. Furthermore, the typical daily intake of cows' milk is greater than that of leafy vegetables (by a factor of 10–100).

It was reported that thyroid equivalent doses determined in March 2011 using an NaI (Tl) scintillation survey meter in children in the evacuation zone and the Deliberate Evacuation Area were lower than around 10 mSv in 95.7% of children (with a maximum of 43 mSv) [233]. Effectively, all doses were lower than the generic optimized intervention value for iodine prophylaxis of 100 mGy of avertable committed absorbed dose to the thyroid due to radioiodine, established in the 1996 International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources:[29] [243], which were valid at the time of the accident, and lower than the projected dose of 50 mSv in the first seven days for iodine thyroid blocking established in the currently valid International Basic Safety Standards [220]. In comparison, the absorbed doses to the thyroid of children following the Chernobyl accident ranged up to several thousand mGy [244, 245], a factor of nearly 100 to 1000 times higher.

Thyroid radiation doses of evacuees from Fukushima Prefecture were determined by Hirosaki University. The thyroid dose was determined by NaI (Tl) scintillation spectrometer at the neck of the examinees during the period from 12 to 16 April 2011. The median thyroid equivalent dose in 62 evacuees was estimated to be 4.2 mSv for children and 3.5 mSv for adults, and the maximum values were 23 and 33 mSv, respectively. Five children under the age of 9 and a total of 8 under the age of 20 were included [235]. In Nagasaki, the internal radioactivity in evacuees and short term visitors to Fukushima was measured by WBC beginning on 15 March 2011. Internal radioactivity was measured in 173 people who stayed in Fukushima Prefecture between 11 March and 10 April 2011. The average length of stay was 4.8 days. Iodine-131, ^{134}Cs and ^{137}Cs were detected in more than 30% of examined individuals. The maximum committed effective dose and thyroid equivalent dose were 1 mSv and 20 mSv (mGy), respectively [229]. For comparison, the estimated dose range for thyroid dose to the evacuees from the Chernobyl accident was about 500 mGy (with individual values ranging from less than 50 mGy to more than 5000 mGy). For the more than six million residents of the contaminated areas of the former Soviet Union who were not evacuated, the average thyroid dose was about 100 mGy, while for about 0.7% of them, the thyroid doses were more than 1000 mGy [246].

[29] Generally referred to as the International Basic Safety Standards (or by the acronym BSS).

Contribution to thyroid exposures of other short lived radionuclides

The contribution to thyroid exposures from short lived radioiodines (primarily from ^{133}I and ^{132}I due to intake of ^{132}Te) may be important, especially in the case of intakes by inhalation during the first few weeks following an accident. The contribution of short lived radioiodines to the thyroid equivalent dose to the public following the Fukushima Daiichi accident has been estimated by considering the ratio of the dose to the thyroid from short lived radioiodines to that from ^{131}I from inhalation. This contribution depends on three factors:

— Relative time integrated concentrations in the ground level air of radioisotopes of iodine in the form of gaseous and particulate aerosol;
— Relative time integrated concentrations in ground level air of ^{131}I, ^{133}I, and ^{132}Te;
— Age dependent ratios of the committed thyroid dose coefficients for inhalation for ^{131}I, ^{133}I and ^{132}Te.

Values for input parameters to assess thyroid exposures from short lived radioiodines as well as the estimates of the contribution of other short lived radioiodines to the thyroid doses from inhalation was not explicitly included in the thyroid dose estimates from radioiodines presented in the UNSCEAR study [5]. Table 4.2–13 presents separate assessments of the contribution of these short lived radionuclides based on input data used by UNSCEAR. The approach adopted takes account of the different deposition velocities of tellurium and iodine in aerosol form and iodine in its elemental form[30], as outlined in detail in Ref. [247].

TABLE 4.2–13. ASSESSING THYROID EQUIVALENT DOSES TO INFANTS FROM SHORT LIVED RADIOIODINES ASSUMING INHALATION INTAKE ON 15 MARCH 2011 [247]

Radionuclide		^{131}I	^{133}I	^{132}Te
Ratio to ^{137}Cs in soil (adjusted to 15 March 2011)*	All Japan except for the south trace***	11.5	1.39**	8
	South trace	74	8.95**	59
1-year-old child inhalation dose coefficient (Sv/Bq)	Particulate+	1.4×10^{-6}	3.5×10^{-7}	5.3×10^{-8}
	Elemental	3.2×10^{-6}	8.0×10^{-7}	—
Dose ratio to ^{131}I thyroid dose of 1-year-old child	All Japan except for the south trace	1.00	0.03	0.096
	South trace	1.00	0.03	0.11

* According to [5].
** Assuming a ratio of ^{133}I/^{131}I equal to 2.1 in the three reactors at time of shutdown (at 14:46 on 11 March 2011) [248].
*** UNSCEAR referred to a narrow region along the coast to the south of the Fukushima Daiichi NPP as the 'south trace'. This area was characterized by ratios for ^{129m}Te and ^{131}I that were significantly elevated.
\+ The ratio of particulate to gaseous/elemental forms of radioiodine in air is equal to 0.67 (40% in particulate and 60% in gaseous forms) [247].

For the releases that occurred on 15 March 2011, the estimated additional contribution from short lived radionuclides is within 15% of thyroid equivalent doses to members of the public, which were calculated to have resulted from ^{131}I. The exposure to the thyroid from ^{132}I produced from ^{132}Te in the body is relatively more important than that due to ^{133}I (by a factor of up to 3) [247]. However, the

[30] Tellurium is assumed to be in aerosol form; 40% of iodine is assumed to be in aerosol form and 60% in its elemental form. The deposition velocity of elemental iodine is a factor of 10 greater than the aerosol form of iodine and tellurium.

contribution of short lived radioiodines to thyroid exposures decreases with time compared with that from ^{131}I.

The contribution of short lived radioisotopes of iodine to thyroid equivalent doses to the public in the case of inhalation intake that might have occurred as early as 12 March 2011 might be as great as 30–40% of that from ^{131}I. In this case, the relative importance of thyroid exposure from ^{133}I is greater than that from ^{132}I by a factor of up to 2 [247]. However, thyroid exposures from releases on 12 March would be much lower than those from releases on 15 March, because the amount of iodine released on 15 March was substantially higher and directed north-west, while on 12 March, the releases were primarily directed to the east (ocean).

For comparison with the situation following the Chernobyl accident, the contribution of short lived radioiodine to thyroid exposures for the vast majority of the public in the contaminated areas following the Chernobyl accident was much lower and did not exceed about 1–2% [244] because the primary intake pathway for those individuals was ingestion of locally produced cows' milk. Intake of radioiodines with contaminated milk following the Chernobyl accident resulted in much higher thyroid equivalent doses from ^{131}I (up to 50 Sv) than those following the Fukushima Daiichi accident [244, 245]. The thyroid equivalent doses from ^{131}I resulting from the Fukushima Daiichi NPP accident were lower than those at Chernobyl primarily because of government restrictions on food, and particularly milk products.

The results of the thyroid equivalent doses estimated from direct measurements performed on people from different age groups are summarized in Table 4.2–14. Where possible, the estimates from the UNSCEAR dose assessment have also been added for comparison (see Annex V for information on the UNSCEAR assessment).

TABLE 4.2–14. THYROID EQUIVALENT DOSES FROM DIRECT MEASUREMENTS

Dates and mode of measurement	Location of subjects	Number of subjects	Doses calculated from measured activities (mSv)	Reference and UNSCEAR estimates for comparison
26–30 March 2011 Thyroid uptake	Iwaki, Iitate, Kawamata	1080 children	Mean 2, Maximum 43	Ref. [233] 37–63 mGy during evacuation for a 1 year old
12–16 April 2011 Thyroid uptake	Namie, Minamisoma	62, aged 0–83 years	Median 4.2 for < 20 years, 3.5 for adults	Ref. [235] 6.4–52 mGy during evacuation for a 1 year old
Urine collection 54 and ~80 days after 11 March 2011	Iitate, Kawamata	15 adults	Maximum 27–66	Kamada et al. [237] 6.4–63 mGy during evacuation for a 1 year old
8–20 April 2011 Thyroid uptake	Tokyo	268 children and adults	Maximum 2 for adults Average 0.4 child, 0.2 adult	[236] For areas including Tokyo the ranges are: 0–0.4 adults external + inhalation + 0.5 ingestion 0–0.8 for 1 year old external + inhalation and 2.6 ingestion
11 March–20 April 2011 WBC	Residents in Fukushima and short term visitors in Fukushima	196	Committed effective dose: Median: ^{137}Cs: 0.004, ^{134}Cs: 0.003, Maximum: ^{137}Cs: 0.067, ^{134}Cs: 0.098; Thyroid: Median: 0.67, Maximum: 18.5	[230] Range for districts not evacuated Adult 0.1–9.6 external + inhalation plus 7.8 ingestion

Maximum thyroid equivalent doses in children in the more heavily exposed communities, based on these measurements, are several tens of mSv, with mean doses of a few mSv. The highest estimated dose was 66 mSv based on limited data. The most extensive dataset [233] found a 95th percentile dose of about 8 mSv [249] and a maximum recorded value of about 43 mSv. These doses would increase by 10–15% if contributions from shorter half-life iodines were included. It is difficult to compare these results with the estimates from UNSCEAR [5], but from the information presented above, there are no major differences between the two sets of estimated doses.

It is difficult to compare the estimated doses presented above with one other and with the UNSCEAR assessment as there are differences in the locations, the time periods considered and the exposure pathways included. There are also uncertainties in the results of all studies. For the results based on measurements of people, the numbers measured are often small compared with the total population, many of the early measurements were taken for screening purposes and there can be difficulties in accounting adequately for background radiation.

Assessments based on multiple pathways

Takahashi et al. [225] adopted a probabilistic approach to dose assessment based on the measurement data of the surface activity concentrations of ^{137}Cs and the results of the NIRS behavioural patterns of the population groups living in Fukushima Prefecture. The study assessed the doses to adults from external exposure to radionuclides deposited on the ground and radionuclides in the radioactive cloud, as well as the doses caused by internal exposure through inhalation of radionuclides from the radioactive cloud. Internal radiation doses from ingestion pathways were not included. The 95th percentile of the effective dose received by the inhabitants evacuated was mainly in the 1–10 mSv dose band in the first year after the accident. However, the 95th percentile of the dose received by some outdoor workers and inhabitants evacuated from highly contaminated areas was in the range of 10–50 mSv. It was assumed in the calculations that other protective actions such as sheltering and stable iodine uptake were not carried out.

4.2.3. Summary

Occupational exposures

Despite the accident and extreme work conditions, exposure and levels of contamination, doses beyond accepted limits were rare among the many emergency workers, first responders, and other workers. Of the approximately 23 000 workers on the site in the period from March 2011 to December 2011, six TEPCO workers exceeded the temporarily revised annual effective dose limit for emergency workers of 250 mSv, and 174 workers in total exceeded the initial 100 Sv emergency dose limit during 2011. No workers exceeded either of these values in subsequent years, and only one worker exceeded an annual effective dose of 50 mSv in the period of March 2012–June 2014. This worker was working under the emergency dose limit 100 mSv for those conducting troubleshooting tasks, such as those related to reactor cooling. Internal exposure from the inhalation of radionuclides was the predominant contributor to doses received by the six on-site workers who exceeded the emergency dose limit in 2011. This was a consequence of challenges associated with respiratory protection during the emergency phase of the operations.

The reported results of WBC measurements indicate that the internal doses to the workers at the Fukushima Daiichi NPP were mostly from inhaled ^{131}I. The highest absorbed doses to the thyroid received by two emergency workers at the Fukushima Daiichi NPP are estimated to be in the region of 10 Gy. However, there are uncertainties associated with these estimates (and the contribution from other short lived radionuclides) due to the high background levels associated with early WBC measurements, the delay in undertaking thyroid measurements and the lack of bioassay information.

Firefighters, police officers and SDF personnel were also involved in a range of on-site emergency activities. No members of this group received effective doses in excess of 100 mSv and the majority received doses of less than 10 mSv.

Of the more than 8000 members of the SDF personnel who worked off-site, and for whom dose information was available, 5 received effective doses in excess of 10 mSv, but less than 20 mSv. The maximum effective dose recorded for police officers working off-site was less than 5 mSv.

Public exposures

Following the accident at the Fukushima Daiichi NPP, the highest radiation exposures for the public occurred in the first months owing to external irradiation from deposited material, inhalation and, possibly, ingestion of foods. At later times, radiation exposures decreased significantly, and external irradiation from deposited material became the most significant exposure pathway. Effective doses received by the majority of people in Japan were less than 1 mSv in the first year following the accident and are estimated to be significantly less than this in subsequent years. For the people who were evacuated or who lived in the areas where levels of radionuclides in the environment were highest, effective doses in the first year are estimated to have ranged up to 10 mSv, and again, all indications are that doses in subsequent years are significantly lower. These estimated doses are low and generally comparable with the range of effective doses incurred owing to global levels of natural background radiation. Global natural background radiation delivers an annual average effective dose of 2.4 mSv, with a typical range of 1–13 mSv, and with sizeable population groups incurring up to 10–20 mSv, and in extreme cases, up to around 100 mSv [250].

In some locations with relatively high levels of radionuclides on the ground, people have been issued with personal dosimeters to measure their external radiation dose over extended periods. Although these measurements are very limited in the early period, they are generally in reasonable agreement with the estimates of the UNSCEAR 2014 study. Further calculations carried out using the UNSCEAR methodology demonstrate that external doses are falling significantly with time owing to radioactive decay, natural weathering and migration down the soil column. Remediation will reduce these doses further (see Technical Volume 5).

Internal doses were highest in the first month or so following the accident and are thought to be mainly due to the inhalation and possible ingestion of ^{131}I. There is also a contribution from the inhalation of short lived radionuclides. Later, when intakes by inhalation directly from radionuclides released to the atmosphere had ceased, intakes by ingestion became the most important source of internal exposure. However, the restrictions placed by the Japanese authorities on the distribution and marketing of food means that doses from ingestion of food are very low after the initial period. This is found both in the UNSCEAR assessment of doses and the analysis of measurements of caesium radionuclides in people by WBC and on measurements of the thyroidal content of ^{131}I in 1080 children carried out on 26–30 March 2011.

In the initial period after the accident, there were limited measurements directly on the levels in people, and the purpose of these measurements was to provide screening rather than for detailed dose assessment. However, from the limited measurements available, there is some indication that the doses estimated by UNSCEAR for the initial period for the people who were evacuated may have been overestimated, at least for the average person. Nevertheless, much depends on whether people ate locally produced food in the first few days after the accident, before restrictions were fully implemented, and whether tap water was consumed. As these doses were mainly due to intakes of ^{131}I, which has a half-life of eight days and therefore could not have been measured in the later measurements, uncertainties in the doses will remain.

The exposures to the public in the period immediately following the Fukushima Daiichi accident appear to have been dominated by the inhalation pathway, in contrast to the situation following the Chernobyl accident, when ingestion was the main contributor to dose.

4.2.4. Observations and lessons

— **Personal radiation monitoring of representative groups of members of the public provides invaluable information for reliable estimates of radiation doses and needs to be used together with environmental measurements and appropriate dose estimation models for assessing public dose.**
The early estimation of doses was based on environmental dispersion modelling, resulting in some conservative assumptions on doses incurred and projected.
Personal monitoring of ^{131}I in the thyroids of children needs to be undertaken as soon as possible following radioiodine releases to the environment, owing to the short half-life (eight days) of this radionuclide. Personal monitoring of external radiation and the internal presence of the longer lived radionuclides (e.g. ^{137}Cs) needs to be undertaken as soon as feasible and to continue over time, as appropriate.
In the absence of personal radiation measurements, modelling of environmental and ambient data may be needed to estimate the radiation doses incurred by individuals. In these cases, the uncertainties associated with the assumptions used in the models need to be clearly explained, particularly if the results are being used to inform decision making on protective measures and actions or to estimate the potential for radiation induced health effects.

— **While dairy products were not the main pathways for the ingestion of radioiodine in Japan, it is clear that the most important method of limiting thyroid doses, especially to children, is to restrict the consumption of fresh milk from grazing cows.**
The estimates of thyroid doses to children following the accident were low. This was the result of a combination of factors, including the time of year (before the growing season), agricultural practices in Japan, low consumption of cows' milk by infants and the controls on milk consumption that were immediately introduced. These factors contributed to the low level of intake of ^{131}I. This is in contrast to the situation following the Chernobyl accident, where the dominant intake pathway of ^{131}I for children living in contaminated areas was ingestion intake, mainly due to consumption of fresh milk from cows grazing on pasture. People in contaminated areas were not immediately aware of the accident and continued to drink locally produced milk. This resulted in average equivalent dose to the thyroid of up to a few thousand mSv.

— **A robust system is necessary for monitoring and recording occupational radiation doses, via all relevant pathways, particularly those due to internal exposure that may be incurred by workers during severe accident management activities. It is essential that suitable and sufficient personal protective equipment be available for limiting the exposure of workers during emergency response activities and that workers be sufficiently trained in its use.**
Early and continued direct measurements of the radiation exposure and the levels of radionuclides incorporated by emergency workers are the most valuable approach for obtaining information for estimating radiation risks and potential health effects and for optimizing protection. There is a need to monitor and register occupational radiation doses through a robust system of personal dosimeters and measurements. Monitoring of ^{131}I in the thyroid needs to be undertaken as soon as possible.
Immediately following the Fukushima Daiichi accident, the provision of personal protective equipment for restricting the exposure of workers and monitoring was difficult.

— **Clearer guidelines on occupational medical management of potentially overexposed workers would be beneficial. It is necessary that people responsible for workers' health have a clear understanding on how, when, for how long and to whom protective therapies need to be administered.**
The timely application of potassium iodide for blocking the thyroid gland is helpful for controlling workers' thyroid doses. For some workers, taking potassium iodide is thought to have

significantly reduced their thyroid exposures from inhalation of radioiodine. However, many workers used potassium iodide long after their intake had ceased.

— **Following an accident, it is essential to provide personal radiation monitors to the affected population, because direct personal measurements are much more reliable than reconstructing such doses through environmental modelling and assumptions about personal behaviour.**
Early and follow-up direct measurements of levels of dose and incorporation of radionuclides in members of the public are the most valuable way of obtaining information on the radiological impact of an accident and for providing public information. In particular, measurements of ^{131}I in thyroid should be taken as soon as possible following releases to the environment, owing to its short half-life. If direct measurements are not available, modelling and assumptions of transfer parameters may be required to estimate the doses received as long as its limitations in accuracy are recognized. When estimating doses using modelling techniques that are based on environmental measurements and estimates of the amount of radionuclides released, the relatively large uncertainties associated with these estimates should be recognized and clearly explained.

— **The comparisons of assessments from various organizations would be simplified if a common monitoring protocol were developed which included ranges of doses to report, how to report doses below detection limits and how to take background radiation into account**.

4.3. RADIATION PROTECTION

Over many decades, an international system of radiation protection and safety has evolved based on scientific information, recommendations and standards developed by a number of organizations. A distribution of responsibilities has been established in which UNSCEAR, established in 1955 by the United Nations General Assembly, assesses and reports levels and effects of ionizing radiation. Taking account of such information, ICRP produces recommendations on radiological (or radiation) protection, primarily on its principles and aims. Guided by UNSCEAR estimates and ICRP recommendations, safety standards are set by a number of United Nations and international bodies, in particular by the IAEA.

Several international conventions were agreed through the International Labour Organization (ILO) and by the IAEA. The International Basic Safety Standards are developed under the aegis of the IAEA and co-sponsored by the Food and Agriculture Organization of the United Nations (FAO), the ILO, the United Nations Environment Programme and the World Health Organization (WHO), as well as by several non-United-Nations bodies. In addition, FAO and WHO jointly issue food standards through the Codex Alimentarius Commission, and WHO establishes drinking water guidelines.

The information, recommendations, conventions and standards of these various bodies comprise the system of radiation protection and safety, which is reflected in national legislation worldwide. The Fundamental Safety Principles [251], developed by the IAEA and other international organizations, specify that “The fundamental safety objective is to protect people and the environment from harmful effects of ionizing radiation” [251]. The currently valid International Basic Safety Standards (BSS) state that “the system of protection and safety aims to assess, manage and control exposure to radiation so that radiation risks, including risks of health effects and risks to the environment, are reduced to the extent reasonably achievable” [220].

Planning, preparedness and response for nuclear and radiological emergencies are determined by radiation protection and other considerations. The International Emergency Preparedness and Response (EPR) Framework that was in place at the time of the Fukushima Daiichi accident comprised international legal instruments, IAEA safety standards and operational arrangements, as described in detail in Technical Volume 3. This included requirements for the Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2 [252],

which was jointly sponsored by the FAO, IAEA, ILO, the OECD Nuclear Energy Agency (OECD/NEA), the Pan American Health Organization (PAHO), the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), and WHO.

Like many countries, Japan has its own system of radiation protection, implemented by national legislation and regulations, which takes account of the international system. Japan is a signatory to a number of legally binding international conventions that address radiation protection issues. Furthermore, Japan is a Member State of the IAEA, the ILO, UNSCEAR and WHO, and Japanese experts participate in the work of the ICRP, UNSCEAR and the standard setting organizations.

As described in Technical Volume 3, the accident at the Fukushima Daiichi NPP severely tested the system of radiation protection and emergency preparedness and response arrangements. There were many contributing factors, including the fact that decisions regarding urgent protective actions had to be taken in the context of the destruction resulting from the preceding earthquake and tsunami.

This section is structured as follows. Firstly, the major relevant elements of the international system of radiation protection that were in place at the time of the accident are set out. The information, recommendations, standards and guidance available from UNSCEAR, the ICRP and international intergovernmental organizations, notably the IAEA, are outlined. The most important aspects of Japan's system are then introduced. Finally, specific aspects of radiation protection of workers and of members of the public related to the response to the accident in Japan are described. Issues that emerged during the emergency and recovery phase are identified, and lessons learned that may be of interest to the wider radiation protection community are described.

4.3.1. International organizations, recommendations and standards

4.3.1.1. UNSCEAR

The mandate of UNSCEAR is to assess and report on the levels and effects of exposure of people to ionizing radiation. The reports of UNSCEAR constitute an important input to the recommendations of the ICRP and to the international safety standards, developed under the aegis of the IAEA. Several of its recent reports are directly relevant to the analysis of the Fukushima Daiichi accident. This applies in particular to the ICRP's annex on hereditary effects in the UNSCEAR 2001 Report [253], the annex on epidemiological studies of radiation and cancer in the 2006 Report [254], the annex on health effects due to radiation from the Chernobyl accident in the 2008 Report [246] and the summary of low dose radiation effects on health in the 2010 Report [250]. An annex on the levels and effects of radiation exposure due to Fukushima Daiichi accident was published in April 2014 as part of UNSCEAR's 2013 Report [5]. The present volume was produced in close consultation with UNSCEAR in order to utilize the information compiled in that annex.

The UNSCEAR 1996 Report included a compilation [255] of the effects of radiation on non-human biota. This was updated in the 2008 Report [246], showing that information on the effects of ionizing radiation on non-human biota has accumulated over the years, although many investigations are limited to external radiation and high dose rates. The results from studies performed in areas contaminated by accidental releases of radionuclides, such as the Chernobyl accident, are valuable for understanding the long term impact of the Fukushima Daiichi accident on the natural environment. The April 2014 annex of UNSCEAR's 2013 Report [5] reviewed the consequences of the accident until March 2012 based largely on measurements performed in the environment.

4.3.1.2. Recommendations of the ICRP

The ICRP is an independent, non-profit-making advisory body that develops radiation recommendations and principles. The recommendations of the ICRP are a key input to international standards and national regulations addressing radiation protection.

Aims and principles of the ICRP recommendations

The recommendations of the ICRP aim at contributing to an appropriate level of protection for people and the environment against the detrimental effects of radiation "without unduly limiting desirable human actions" associated with such exposure [256]. The human health objectives of this aim are to prevent deterministic effects[31] and to reduce the probability of stochastic effects[32] to the extent reasonably achievable (see Section 4.4 and Annex X on health consequences). The environmental protection objective is to achieve negligible radiation impact on the maintenance of biological diversity, the conservation of species, and the health and status of natural habitats, communities and ecosystems.

Fulfilling these aims and objectives requires scientific knowledge on radiation exposure and its health and environmental effects, consideration of societal and economic aspects of protection, and making value judgments about the relative importance of different kinds of detrimental effects and about the balancing of detriments and benefits.

For instance, there may be a trade-off between controlling radiation doses to members of the public and controlling occupational radiation doses, for instance, in an emergency exposure situation. Remediation after an accident may also raise questions concerning the distribution of potential health effects between population groups and between generations.

The System of Radiological Protection developed by the ICRP contains three basic principles, described as follows in the 2007 ICRP Recommendations [256]:

Two principles are source related and apply in all exposure situations[33]:

— *Justification*: Any decision that alters the radiation exposure situation should do more good than harm;
— *Optimization of protection*: The likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors.

The remaining principle is related to the individual and applies in planned exposure situations:

— *Application of dose limits*: The total dose to any individual from regulated sources in planned exposure situations, other than medical exposure of patients, should not exceed the appropriate limits.

---

[31] Deterministic effect: a health effect of radiation for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose. Such an effect is described as a severe deterministic effect if it is fatal or life threatening or results in a permanent injury that reduces quality of life.

[32] Stochastic effect: a radiation induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose.

[33] In its 2007 Recommendations, the ICRP defined the following exposure situations: planned (involving the planned introduction and operation of sources of radiation), emergency (e.g. as an unexpected development of a planned situation) and existing (where the radiation is already present when decisions on control are being contemplated).

The system of radiation protection applies to all ionizing radiation exposures from any source, whether natural or human-made, and to all exposure situations. However, dose limits can only apply in planned situations. In some cases, neither the source of radiation nor the pathway from the source to doses to individuals can be controlled (e.g. natural ^{40}K in the human body). Such exposures are *excluded* from regulatory control. In some other cases, the effort to control exposures would be unwarranted and excessive compared with the associated probability of detrimental health effects; such exposures are *exempted* from some or all regulatory requirements.

The ICRP recommendations are reviewed and revised at intervals of about 15 years and supplemented with more specific recommendations provided in several reports each year. New recommendations generate reviews and revisions of the documents of standard setting bodies such as the IAEA, a process that usually takes several years.

At the time of the Fukushima Daiichi accident, legislation related to radiation protection in Japan and worldwide was generally based on the 1990 ICRP Recommendations [192] and was generally aligned with the safety standards of the IAEA, in particular the 1996 International Basic Safety Standards (BSS) [243]. However, a new set of ICRP Recommendations was issued in 2007 [256]; revised international safety standards were in the final stages of being completed at the time of the accident. These standards were approved in September 2011, and an interim version of the revised BSS was published in November 2011 [257].

The 1990 and 2007 ICRP Recommendations are based on the three fundamental principles listed above, but in 2007, the principles had been condensed and simplified to the wording above, in order to clarify their scope and validity to different exposure situations. The 1990 Recommendations used a process based on distinction between *practices* (that add doses) and *interventions* (that reduce doses). The 2007 Recommendations evolved from the previous process based protection approach (using practices and intervention) to an approach based on the exposure situation.

The 2007 ICRP Recommendations reinforced the principle of optimization of protection subject to restrictions on individual doses and risks (i.e. probabilities of exposure): dose and risk constraints for planned exposure situations, and reference levels for emergency and existing exposure situations. Constraints and reference levels are not intended to be interpreted as (legally enforceable) limits.

Recommendations on protection of the environment

The principles of environmental protection derived from, among other things, the Rio Declaration of 1992 [258], have been laid down through multilateral environmental agreements defining the general objectives of environmental protection and how it may be achieved. Protection of the environment is now recognized as an integral part of sustainable development, and strategies are formulated for that purpose. One of the aims of protection of the environment[34] identified in ICRP Recommendations is "the maintenance of the integrity of ecosystems, which depends on surviving and reproducing populations". The 2007 ICRP Recommendations [256] endorsed this aim and subsequently provided practical guidance in a series of reports on the subject [259, 260] (see Annex VIII). Thus, people are protected at the level of the individual, while the living components of the environment (flora and fauna) are generally protected at the population level.

[34] Protection of the environment includes the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services such as the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media such as soil, water and air; and natural processes such as carbon, nitrogen and water cycles [220].

ICRP recommendations at the time of the accident

The dose limits for planned exposure situations recommended by the ICRP were the same in 2007 as in 1990 (Table 4.3–1). These limits refer to the total (additional) dose from regulated sources (in addition to natural background) to any individual in planned exposure situations other than the medical exposure of patients.

TABLE 4.3–1. DOSE LIMITS RECOMMENDED FOR PLANNED EXPOSURE SITUATIONS [192, 256]

Type of limit	Occupational	Public
Effective dose	20 mSv per year, averaged over defined periods of five years, and not exceeding 50 mSv in any single year[a]	1 mSv in a year (in special circumstances a higher value could be allowed in a single year provided that the average over five years does not exceed 1 mSv per year)
Annual equivalent dose to the:		
Lens of the eye[b]	150 mSv	15 mSv
Skin (averaged over 1 cm[b])	500 mSv	50 mSv
Hands and feet	500 mSv	—

[a] Additional restrictions apply for pregnant women.
[b] Reduced in 2011 [261, 262] for occupational exposure to 20 mSv in a year averaged over defined five year periods, with no single year exceeding 50 mSv.

Accidents, by definition, are not controllable, nor are they planned exposure situations. Consequently, dose limits do not apply. The ICRP presented principles for intervention for protection of the public in a radiological emergency in its Publication 63 [263]. It included recommended intervention levels as a range of optimized intervention values. Subsequently, in 1999, the ICRP published recommendations on the protection of the public in situations of prolonged exposures [264] (which could result from accidents). Generic reference levels for intervention were provided. They established a range from a total existing annual dose of ~100 mSv, above which intervention would almost always be justifiable, to ~10 mSv, below which intervention was not likely to be justifiable.

These *generic reference levels* of *existing annual dose* were specified for intervention in prolonged exposure situations. This position was based on several considerations, including natural background radiation levels and the detriment expected at such radiation levels. It is acknowledged that sometimes intervention will be justified below an annual dose of 10 mSv, and that radiation protection considerations are one input to decision making.

Concerning occupational exposures in emergency exposure situations, the ICRP recommends no dose restrictions for informed volunteers in life saving actions. For other urgent rescue operations, the 1990 ICRP Recommendations suggested an intervention level of about 500 mSv, while the 2007 Recommendations indicated reference levels[35] of at most about 1000 or 500 mSv, depending on circumstances. Reference levels of dose for other rescue operations should, according to the 2007 Recommendations, be selected at or below 100 mSv. Additional advice on occupational exposure in emergencies is given in ICRP Publication 96 [265]. Reference levels are not dose limits (see Section 4.3.2.1 concerning the use of dose limits in Japanese regulations). However, it is recommended that those undertaking recovery and restoration work in a later phase, after the termination of an emergency, should be protected according to normal occupational radiation

[35] Reference levels are defined in the 2007 ICRP Recommendations as: "the level of dose or risk, above which it is judged to be inappropriate to plan to allow exposures to occur, and below which optimization of protection should be implemented" [256].

protection standards, i.e. for such occupational exposure, the recommended dose limits for planned exposure situations should apply.

The various dose criteria recommended for public exposure in emergency exposure situations are complicated, because they refer to a multitude of different exposure pathways and possible actions (some of which are disruptive) to reduce exposures. Pertinent ICRP reports are enumerated in Annex VIII. The 2007 ICRP Recommendations suggested that, in planning for emergency situations, a reference level for the highest planned residual doses[36] in emergency situations would be selected typically between an acute or annual effective dose of 20 and 100 mSv, depending on the situation.

The existing exposure situation that develops after an emergency poses challenging questions concerning public exposures. Even if it is technically possible to reduce doses due to accident residues to below the public dose limit of 1 mSv/y, the actions required could be prohibitively disruptive. Thus, the ICRP does not recommend that the dose limit for the public be applied to existing exposure situations.

In Publication 82 [264], the ICRP concluded that interventions to reduce doses after an emergency event were unlikely to be justifiable, in the radiation protection sense, for existing doses (i.e. the total dose due to the accident and due to other causes) to members of the public below about 10 mSv/year. Interventions would almost always be justifiable for doses approaching 100 mSv/year. The 2007 ICRP Recommendations proposed that in existing exposure situations, a reference level of *residual dose* (after the application of protective strategies) to members of the public be selected between 1 and 20 mSv/year, according to the situation. The main factors to be considered for setting the reference levels are the feasibility of controlling the situation and past experience with the management of similar situations. While this allows for optimized actions that are adapted to the prevailing situation, regulatory authorities as well as members of the public often tend to favour the lowest number in any dose band. ICRP Publication 111 [266] suggested that a typical long term reference level of residual dose would be 1 mSv in a year. However, it is also recommended that the prevailing circumstances should be taken into account and that intermediate reference levels be adopted to improve the situation progressively.

These reports stress, in general terms, the importance of the optimization of radiological protection. Techniques are well developed for balancing the adverse health effects of radiation and different kinds of costs of protective measures [267–269]. However, little international guidance is available on optimization in emergency and existing exposure situations. Such situations will usually require the assessment of possible adverse health effects associated with the actual protective actions, and the cost implications will usually go beyond the expertise of radiation protection specialists. Further details concerning the 1990 and 2007 ICRP Recommendations, and several guidance reports supplementing these two sets of recommendations, are provided in Annex VIII.

4.3.1.3. International safety standards issued by the IAEA

The IAEA safety standards have their foundation in the IAEA's Statute, which authorizes the organization:

> "to establish or adopt, in consultation and, where appropriate, in collaboration with the competent organs of the United Nations and with the specialized agencies concerned, standards of safety for protection of health and minimization of danger to life and property ... and to provide for the application of these standards" [270].

[36] Residual dose: the dose expected to be incurred after protective actions have been terminated (or after a decision has been taken not to take protective actions) [220].

A decision by the IAEA Board of Governors in 1960 states that:

> "The Agency's basic safety standards ... will be based, to the extent possible, on the recommendations of the International Commission on Radiological Protection (ICRP)." [271]

The standards include the International Basic Safety Standards (BSS) [220, 243, 257] established jointly by several United Nations and other international bodies and published by IAEA; the IAEA safety standards; and standards from other standard setting organizations, including FAO, the ILO and WHO.

The IAEA safety standards are a system of fundamental safety principles, safety requirements (including the BSS) and safety guides. As the primary publication in the IAEA Safety Standards Series, the Fundamental Safety Principles establishes the basic safety objectives and principles of protection and safety for ensuring the protection of the public and the environment, now and in the future, from the harmful effects of ionizing radiation. Safety requirements publications, such as the BSS, establish the requirements that must be met to ensure the protection of people and the environment, both now and in the future, in accordance with the objective and principles of the Safety Fundamentals. Safety guides provide recommendations and guidance on how to comply with the safety requirements, indicating an international consensus on the measures recommended.

While regulating safety is a national responsibility, international standards and harmonized approaches to safety promote consistency, help to provide assurance that nuclear and radiation related technologies are used safely, and facilitate international technical cooperation, commerce and trade. The methodology used in this and other technical volumes is to use IAEA safety standards in force at the time of the accident as the basis of assessment; they are considered to represent international consensus regarding requirements and guidance that is necessary to ensure radiation protection and nuclear safety. However, the use of these standards does not imply that Member States are required to follow them or that they are the only means of ensuring protection and safety.

The IAEA Statute makes the safety standards binding on the IAEA in relation to its own activities. They are not by default binding on Member States, but any State entering into an agreement with the IAEA concerning any form of IAEA assistance is required to comply with the requirements of the safety standards that pertain to the activities covered by the agreement. Many States chose to use the IAEA safety standards as templates for their own legislation and regulations. Many other States, including Japan, use legislation and regulations adapted to their own situation and traditions. While Japanese regulations are not explicitly based on the BSS, the regulations related to radiation protection at the time of the Fukushima Daiichi accident were consistent with the 1996 BSS then in force [243], which reflected the ICRP 1990 Recommendations [192].

IAEA safety standards in force at the time of the accident

The key safety standards addressing radiation protection and emergency response in place in March 2011 were:

— The Safety Fundamentals, IAEA Safety Standards Series No. SF-1: Fundamental Safety Principles [251];
— Safety Requirements: Safety Series 115: International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [243] (now superseded by GSR Part 3 [257]);
— Safety Requirements: IAEA Safety Standards Series No. GS-R-2: Preparedness and Response for a Nuclear or Radiological Emergency [252];

— Safety Guide: IAEA Safety Standards Series No. GS-G-2.1: Arrangements for Preparedness for a Nuclear or Radiological Emergency [272].[37]

The Fundamental Safety Principles, established by the international organizations mentioned above and issued by the IAEA, underpin the relevant safety conventions and were formulated following the previous ICRP Recommendations, including their basic principles of justification, optimization and limitation [251].

A relevant fundamental safety principle is that of emergency preparedness and response, which require that arrangements must be made for emergency preparedness and response for nuclear or radiation incidents. According to this principle, the primary goal of emergency preparedness is to ensure that arrangements are in place for a timely, managed, controlled and effective response at the scene, and at the local, regional, national and international level to any nuclear or radiological emergency [252].

The BSS in force at the time [243] were published in 1996 and were based primarily on the 1990 ICRP Recommendations. The BSS established basic requirements for the protection of people and the environment against the risks of exposure to ionizing radiation, and for the safety of sources that deliver such exposure.

The 1996 BSS incorporated the concepts of practices and interventions from ICRP Publication 60. They included emergency situations and requirements for intervention. The radiation protection requirements for intervention include justification of intervention; optimization of intervention; and action levels of dose, as explained in more detail in Annex VIII.

An intervention is justified if it is expected to achieve more good than harm, with regard to health, social and economic factors. Regarding the protection of workers undertaking an intervention, the 1996 BSS required that:

> "When undertaking intervention…, all reasonable efforts shall be made to keep doses to workers below twice the maximum single year dose limit, except for life saving actions, in which every effort shall be made to keep doses below ten times the maximum single year dose limit in order to avoid deterministic effects on health. In addition, workers undertaking actions in which their doses may approach or exceed ten times the maximum single year dose limit shall do so only when the benefits to others clearly outweigh their own risk." [243]

The Safety Requirements on Preparedness and Response for a Nuclear or Radiological Emergency [252] were published in 2002 and were sponsored by the FAO, IAEA, ILO, OECD/NEA, OCHA, PAHO and WHO . These standards establish requirements for an adequate level of preparedness and response for a nuclear or radiological emergency in any State. They provide a structure and comprehensive details for all the requirements relating to emergency preparedness and response established in other IAEA safety standards. The Safety Guide on Arrangements for Preparedness for a Nuclear or Radiological Emergency [272] is intended to assist Member States in the application of the Safety Requirements [252] and to help in fulfilling the IAEA's obligations under the Convention on Assistance in the Case of a Nuclear or Radiological Emergency.

Further details on the international framework on emergency preparedness and response in the event of a nuclear or radiological emergency are given in Technical Volume 3.

[37] General Safety Guide: IAEA Safety Standards Series No. GSG-2: Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency [273] was available on the IAEA website on 17 March 2011.

At the time of the Fukushima Daiichi accident, the 1996 edition of the BSS [243] was in the final stages of revision. The revised BSS was published in November 2011 as an interim version [257] (see Annex VIII). The final version was published in 2014 [220]. The Safety Guide on Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency (GSG-2) [273] was published on 17 March 2011, after the accident. The generic approach and criteria in this Safety Guide are consistent with GSR Part 3 (2014 BSS).

4.3.1.4. Radiation protection issues in international treaties and conventions

A number of international conventions are implicitly or explicitly connected to the international radiation protection standards established by relevant international organizations. For example, the ILO Radiation Protection Convention (ILO 1960 [274]) sets out legally binding requirements on occupational exposures to radiation. The Convention on Early Notification of a Nuclear Accident (Early Notification Convention) [275] and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Assistance Convention) [276] were adopted in 1986, and place legally binding obligations related to nuclear and radiological accidents on the parties to these conventions and on the IAEA. Article 16 of the Convention on Nuclear Safety [277] and Article 25 of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (the Joint Convention) [278] establish legally binding obligations related to emergency preparedness for the parties to the conventions, while other articles relate to other aspects of radiation protection and safety.

Japan, like many other countries, is a signatory to a range of international conventions pertaining to radiation issues and is thus subject to certain obligations. More information is provided in Annex VIII. Information on the conventions directly related to emergency preparedness and response, notably the Early Notification and Assistance Conventions, is provided in Technical Volume 3.

ILO Radiation Protection Convention

The ILO is a specialized agency of the United Nations that promotes social justice and human and labour rights. Its structure is unique in that it is the only tripartite United Nations agency, with employer and worker representatives in addition to government delegations. Radiation protection is a component of the ILO mandate to protect workers against sickness, disease and injury arising from employment. Several requirements were established in its 1960 Convention Concerning the Protection of Workers against Ionizing Radiations (ILO Radiation Protection Convention) (Annex VIII) [274].

This convention sets out requirements: for ensuring the effective protection of radiation workers and other workers from exposure to ionizing radiation; for setting and reviewing dose limits and limits of intake; and for providing adequate warnings and information on potential health hazards due to radiation. It also defines requirements for follow-up action in the event of significant exposures of workers, including medical examinations, notification of competent authorities, workplace inspections and remedial actions. When assessing compliance with the convention's requirements, the ILO refers to the BSS.

Japan has been bound by the terms of the ILO Radiation Protection Convention [274] since 1973. Its Competent Authority for this convention is MHLW.

Convention on Nuclear Safety

The Convention on Nuclear Safety (CNS) [277], for which the IAEA is the Secretariat, is an incentive instrument based on the common interest of its Contracting Parties to achieve higher levels of safety. It obliges participating States operating land based nuclear power plants to submit reports for discussion at periodic review meetings of the Contracting Parties.

The obligations of the Contracting Parties are based to a large extent on the principles contained in the Fundamental Safety Principles (IAEA Safety Standards Series No. SF-1) [251]. The convention's criteria related to radiation protection are established in Article 15 (see Annex VIII) and include the principle that exposures to workers and the public from the nuclear installation be kept as low as reasonably achievable and that individual doses not exceed national dose limits. The convention also includes the requirement to "prevent accidents with radiological consequences and to mitigate such consequences should they occur" [277].

Japan has been bound by the terms of the CNS since 1996. For reporting purposes, the Competent Authority was the Nuclear and Industrial Safety Agency (NISA) and is now the Nuclear Regulation Authority (NRA). [38]

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management

The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (the Joint Convention) [278], for which the IAEA is the Secretariat, focuses on the management of spent fuel and radioactive waste resulting from civilian nuclear reactors and applications. It also applies to spent fuel or radioactive waste from military or defence programmes, if so declared by the Contracting Party, and if and when such materials are transferred permanently to and managed within exclusively civilian programmes. The convention also applies to discharges, i.e. planned and controlled releases into the environment of liquid or gaseous radioactive material from regulated nuclear facilities, and radioactive waste management as defined by the Convention.

Relevant requirements are provided in Articles 24 and 25 of the convention (see Annex VIII). Article 24 relates to the safety of spent fuel management facilities and to the prevention and mitigation of unplanned and uncontrolled releases of radioactive material into the environment. In Article 25, the convention establishes the necessity of implementing and exercising adequate on-site and off-site emergency plans in spent fuel management facilities. The convention also makes reference to protection of the environment in Articles 4, 6, 11 and 13, as outlined in more detail in Annex VIII.

Japan has been bound by the terms of the Joint Convention since 2003. Its Competent Authority is the Ministry of Foreign Affairs.

4.3.2. Radiation protection regulations in Japan at the time of the accident

The Japanese legislation on radiation protection comprises primarily the Atomic Energy Basic Act [279], the Act concerning Prevention from Radiation Hazards due to Radioisotopes, etc.(hereinafter referred to as the Prevention Act [280]), and the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (hereinafter referred to as the 'Reactor Regulation Act') [281] (see Annex VIII). Several additional laws apply to the operation of nuclear installations (see Technical Volumes 1 and 2), for instance, the Act on Special Measures Concerning Nuclear Emergency Preparedness [282] and the Industrial Safety and Health Act [283]. Regulations and legislation applicable to the national emergency preparedness and response (EPR) system in Japan prior to the accident are described in Technical Volume 3.

[38] In June 2012, the Establishment of the Nuclear Regulation Authority Act was passed. This established the NRA as an independent commission in charge of all of the nation's nuclear regulatory functions. The NRA replaced the organizations previously responsible for nuclear safety regulation, including NISA. This restructuring separated the government's nuclear regulatory function from that of nuclear power promotion. The reform also established the Nuclear Emergency Preparedness Commission under Japan's cabinet and required the new regulatory body to incorporate the latest scientific and technical knowledge into the nation's nuclear regulatory basis.

The Atomic Energy Basic Act [279] establishes a general framework for the regulation of nuclear activities, deferring specific aspects to subsequent separate acts. Radiation protection issues are governed by the Prevention Act and the Reactor Regulation Act.

The Prevention Act [280] authorizes the issuing of ordinances on radiation protection, prescribes occupational and public dose limits for facilities where radioactive material is used, and for the handling of radioactive material. The Reactor Regulation Act and other relevant legislation also prescribe regulations on radiation protection for facilities where nuclear materials are used. They were supervised at the time of the accident by NISA and the Ministry of Education, Culture, Sports, Science and Technology (MEXT); they are now supervised by the NRA, which also prescribes dose limits for ionizing radiation. The Regulation Law authorizes the issue of ministerial ordinances on radiation protection, such as the Ordinance on Dose Limits, which sets out occupational dose limits for personnel under the Industrial Safety and Health Act (staff of NPP operators and contractors working on-site). People working for public agencies had occupational radiation limits defined in specific regulations; for example, the Prefectural Nuclear Emergency Plans defined dose limits for off-site responders.

This set of laws, acts, ordinances, and other regulatory instruments defines the application of the system of radiation protection in Japan. It is not based explicitly on the international standards, but is generally aligned with them and with the recommendations of the ICRP.

4.3.2.1. Occupational exposures

Dose limits for occupational exposure to ionizing radiation during normal operation, i.e. in what is now termed planned exposure situations, are given in the MHLW Ordinance on Prevention of Ionizing Radiation Hazards [198] and, in the case of NPPs, the Ministry of Economy, Trade and Industry (METI) Ordinance on Installation of Commercial Nuclear Power Reactors [284], the METI Notification for Dose Equivalent Limits on the Basis of the Ministerial Ordinance [285] and the National Personnel Authority Rules 10–5 (Prevention of Radiation Injuries in Staff) [286]. They are in line with the 1990 Recommendations of the ICRP [192]. For example, a limit on effective dose of 20 mSv averaged over defined five year periods is stated, with the added provision that the dose must not exceed 50 mSv in any single year. Additional restrictions apply, as in the 1990 ICRP Recommendations, to equivalent dose in the lens of the eye, the skin and to female workers who have declared a pregnancy.

The regulations include an additional restriction on the effective dose rate to female workers who could potentially become pregnant of 5 mSv every three months, with the purpose of reducing the probability of the fetus receiving a dose in excess of 5 mSv [287]. This provision reflects older international recommendations issued at a time when the effective dose limit was 50 mSv/y. The 1990 ICRP Recommendations, as well as the 2007 ICRP Recommendations, considered that no special occupational dose limit was required for women in general [192, 256].

For emergency situations, the ordinance laid down a dose limit for workers of 100 mSv in an event. This was more restrictive than the ICRP Recommendations of 1990 [192] or 2007 [256], or the BSS of 1996 [243] and 2011 [257]. The ICRP Recommendations point out that dose limits are not intended for emergency situations. It may not be possible in a serious accident to undertake justified work within the dose limits permitted in normal conditions, and some relaxation of controls can be permitted without lowering the long term level of protection.

The ICRP recommendations and the 2011 Interim BSS [257] provide a reference level or guidance values for effective dose of up to 100 mSv.[39] While the numerical value equals the Japanese dose limit, the concepts are different, since exceeding a reference level is not necessarily an infraction of any laws or regulations. International guidance recognizes that there are situations where higher exposures could be justifiable, for example, if the exposure is unavoidable or occurs in exceptional situations, such as to save life or prevent serious accidents. For such situations, the guidance is that every effort should be made to keep effective doses below 500 mSv.

TEPCO had, and continues to have, a comprehensive set of internal rules and guidelines on radiation protection matters. These describe the applicable legislation and set out in detail the steps that TEPCO workers must follow in order to ensure compliance with the official regulations. They also cover legal requirements on the operator with respect to public exposures (see Annex VIII).

4.3.2.2. Public exposures

A dose limit for members of the public of 1 mSv in a year[40], consistent with ICRP Recommendations and the BSS, is provided for exposures due to radioactive sources in the Ordinance of the Prevention Act. The dose limits associated with nuclear installations are stipulated in the Ordinance of the Reactor Regulation Act. Discharge authorizations for nuclear installations in planned exposure situations, aimed at keeping doses to members of the public below 1 mSv in a year, were issued by NISA and are now issued by the NRA [288].

4.3.3. Aspects of radiation protection relevant to the response

This section discusses specific aspects of radiation protection associated with the accident at the Fukushima Daiichi NPP related to the limitation of doses to members of the public, limitation of doses to emergency workers and radiation protection lessons learned.

As indicated above, international safety standards addressing emergency preparedness and response and the transition from the emergency phase to an existing exposure situation were in place, notably in IAEA Safety Standards Series No. GS-R-2 [252], published in 2002. However, in their response to the accident, notably in the transition phase, the Japanese authorities decided to apply the recent ICRP recommendations in making radiation protection decisions. As explained above, around one year before the accident, the ICRP had issued specific recommendations for the application of the ICRP Recommendations to the protection of people in emergency exposure situations [289] and of people living in long term contaminated areas after a nuclear accident or a radiological emergency [289]. At the time of the accident, this guidance had not been applied in practice.

4.3.3.1. Radiation workers and others engaged in radiation emergency situations

There were major challenges encountered in the monitoring and controlling of doses for on-site emergency workers. These challenges were resolved in a staggered manner over an extended time period, which is described in detail in Technical Volume 3, Section 3.2. For example, electronic personal dosimeters (EPDs) and dose reading devices were unusable for a time, and appropriate personal protection equipment (such as protection masks) were not always available or were improperly used, resulting in workers receiving enhanced inhalation exposures (Section 4.2.1).

---

[39] A guidance value of 100 mSv is specified for restricting exposure of emergency workers involved in tasks to avert a large collective dose [257].

[40] Additional dose, excluding background.

For workers engaged in a radiation emergency situation, a dose limit was specified in the pertinent ordinances of MHLW [198] and the Notification for Dose Equivalent Limits on the Basis of the Ministerial (METI) Ordinance, at an effective dose of 100 mSv, at an equivalent dose of 300 mSv for the lens of the eye and at an equivalent dose of 1 Sv (1000 mSv) for the skin. As indicated in Section 4.3.5, this differs from (and is more restrictive than) the approach included in international guidance, which recommends reference levels rather than dose limits.

The dose limit for workers engaged in a radiation emergency situation was revised from 100 mSv owing to the need to undertake specific tasks to prevent further worsening of the nuclear accident. An increased emergency dose limit of 250 mSv was selected in several successive decisions, with the overriding aim of keeping doses as low as reasonably achievable while still permitting required emergency actions to be carried out.

The details of the decisions are as follows:

— Through an Exemption Ordinance issued on 15 March 2011[41], the emergency dose limit was raised from 100 mSv to 250 mSv to allow necessary activities to continue on-site and within a radius of 30 km of the Fukushima Daiichi NPP [177, 290].
— On 1 November 2011, the Exemption Ordinance was revised. For workers who were first engaged in emergency work after this date, the emergency dose limit was decreased to the original 100 mSv level, except for certain tasks as specified by MHLW. These concerned work on troubleshooting tasks for reactor cooling systems and radioactive material release suppression systems, for which the 250 mSv level was retained [178].
— The 250 mSv level was also retained as a transitional measure for workers who had been engaged in emergency work before 1 November 2011.
— On 16 December 2011, the Exemption Ordinance was abolished. This meant that the dose limits for planned exposure situations applied to most workers, as recommended by international standards [290].
— Workers engaged in maintaining the functions of reactor cooling systems and radioactive material release suppression systems were still subject to emergency dose limits, but at the original 100 mSv level.
— The 250 mSv level was retained until 30 April 2012 for a group of some 50 TEPCO workers with highly specialized knowledge and experience of the cooling and release suppression systems. These workers had been engaged in emergency work before 1 November 2011 and had accumulated doses exceeding 100 mSv [290].

These decisions were in line with the reference levels suggested in the ICRP recommendations and generic criteria in the BSS. However, it would not have been necessary to change regulatory provisions during the accident had the approach and levels proposed in the BSS and ICRP Recommendations been adopted in advance.

MHLW issued administrative guidance on radiation doses for workers previously engaged in emergency work who were then engaged in non-emergency work, which nevertheless exposed them to radiation [291]. Also, the national Government issued instructions to TEPCO regarding exposure and dose management for workers, including internal exposure, through the implementation of temporary health examinations, and so on, as decided in the Policy for Immediate Actions for the Assistance of Nuclear Sufferers by the Nuclear Emergency Response Headquarters on 17 May 2011. The Government has also required TEPCO to report periodically on the implementation status [184].

[41] Retroactive to 14 March 2011.

In addition, certain emergency operational work is required to be reported in advance to the Labour Standards Inspection Office to have provisions for exposure control for workers confirmed. Moreover, the policy requires that a database be created for tracking doses over the long term for all workers who were engaged in emergency work, even after they leave their current jobs, for conducting long term health management [292]. On 20 May 2011, MHLW established the Promotion Office for the Measures for the Health Management of Workers of TEPCO Fukushima Daiichi NPP to promote the above measures.

Members of the SDF. The SDF are the unified self defense forces of Japan. By an order of the Minister of Defense on 12 March 2011, the SDF were engaged in a nuclear disaster relief mission. As such, the MHLW Ordinance on dose limits does not apply to national Government staff (including the SDF). However, the SDF have their own regulations with the same dose limits as those given in the MHLW Ordinance.

Members of the firefighting teams. Firefighters are local government employees and are subject to the MHLW Ordinance. However, the relevant supervisory organization is the personnel committee of the local government. The dose limits specified in the MHLW Ordinance for planned exposure situations were not exceeded (see Technical Volume 3 for more information).

4.3.3.2. Members of the public

As explained in Section 4.3.1, dose limits for the public do not apply during an emergency exposure situation or in the exposure situation following an accident. It may be impossible to keep doses following an accident below the limits for planned situations, or actions required to keep doses below limits might be unjustifiably disruptive and/or associated with other adverse impacts. In an emergency exposure situation, countermeasures (or protective actions) are implemented as described below, based on the dose averted by different actions (Tables 4.3–2 and 4.3–3). This may be complicated and disruptive in practice [256].

The protective actions applied to reduce exposures of members of the public, and the basis for decisions, are described in detail in Technical Volume 3. The doses received by members of the public after the Fukushima Daiichi accident are presented in Section 4.2.2 of this volume.

Urgent protective actions: Sheltering, evacuation, stable iodine intake, food restrictions

In the emergency phase, urgent protective actions may need to be considered in order to mitigate the exposure of members of the public. International recommendations on criteria for urgent protective actions have been published by the ICRP [192, 256] and, in the form of international safety standards, by the IAEA (co-sponsored by other international bodies) [243, 252]. At the time of the accident, the guidance used in Japan was expressed in terms of projected dose. Those recommendations are summarized in Tables 4.3–2 and 4.3–3. The actions taken in Japan are presented in Technical Volume 3, Section 3.2.

Sheltering involves remaining indoors while the radioactive plume is passing, with doors and windows closed, and ventilation systems shut off, to reduce inhalation and external irradiation doses from the radioactive plume and from radioactive material deposited on the ground. Sheltering can reduce external radiation doses by an order of magnitude or more. For example, sheltering in cellars can reduce inhalation doses by a factor of about 2 [263].

Evacuation involves the temporary removal of persons from a contaminated or potentially contaminated area to one which is free of contamination or contaminated to a lesser extent. Effective evacuation can prevent exposures from all significant pathways, including external exposure, and inhalation of airborne radionuclides. Evacuation is not recommended for a period of much longer than

one week. For longer term protection, temporary relocation or permanent resettlement may be required.

TABLE 4.3–2. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON SHELTERING AND EVACUATION

Countermeasure	Organization	Intervention level[a] (mSv)	Integration time
Evacuation	IAEA[b]	50	No more than 1 week
	ICRP[c]	50–500	<1 week
Sheltering	IAEA[b]	10	No more than 2 days
	ICRP[c]	5–50	2 days

[a] Avertable dose (the dose that could be averted if a countermeasure or set of countermeasures were to be applied)
[b] IAEA, GS-R-2, (2002) [252]
[c] ICRP, Pub. 63 (1991), [263], ICRP, Pub. 103 (2007) [256]

National emergency arrangements at the time of the accident envisaged that decisions on protective actions would be based on estimates of the projected dose to the public that would be calculated when a decision was necessary using a dose projection model — the System for Prediction of Environmental Emergency Dose Information (SPEEDI). However, estimates of the source term could not be provided as an input to SPEEDI owing to the loss of on-site power (see Techical Volume 3, Section 3.3). Initial decisions on protective actions were made on the basis of plant conditions although the arrangements at the time did not envisage that decisions on urgent protective actions for the public would be based on predefined specific plant conditions, as recommended in IAEA safety standards such as Ref. [252].

Stable iodine tablets (prophylaxis) taken before the arrival of the radioactive plume or within a few hours of the arrival of the plume, can effectively reduce uptake of radioactive iodine by the thyroid following inhalation[42], and thus significantly reduce the probability of thyroid cancer [263]. This is particularly important if the normal diet is poor in stable iodine (as was the case in Chernobyl, but not in Japan).

TABLE 4.3–3. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON STABLE IODINE INTAKE

Countermeasure	Organization	Intervention level (mSv)[a]
Stable iodine intake	IAEA–WHO [252]	100 mSv
	ICRP [263]	50–500 mSv

[a] Equivalent dose to the thyroid [252, 263].

Restrictions on foods

Protective actions to restrict the distribution and sale of contaminated food aim to reduce its consumption and any consequential detrimental radiation health effects, especially to children. This involves preventing contaminated food from entering supply chains by restricting the harvesting, collection and distribution of affected food at the point of production and, if necessary, withdrawing foods from sale. These protective actions also ensure the availability of food supplies with measured

[42] Food restrictions, e.g. withholding contaminated milk, may be more effective in reducing exposure from radioiodine.

or predicted activity concentrations less than pre-defined action or guideline levels, and they assist in maintaining public confidence in the commercial food supply. Similar restrictions could apply to the public water supply and other drinks; to animal feed, for reasons of public health rather than animal welfare; and to non-edible commodities.

The control of activity concentrations in this range of commodities associated with international trade is governed at the international level by a complex set of standards and guidelines from different organizations.

The Codex Alimentarius Commission (a body set up jointly by FAO and WHO) has recommended guidance levels (GLs) for the maximum activity concentrations in food acceptable as commodities in international trade (see Annex VIII). The Codex General Standard for Contaminants and Toxins in Food and Feed [293] includes revised guideline levels that apply to radionuclides contained in foods destined for human consumption and traded internationally following a nuclear or radiological emergency. They apply to food after reconstitution or preparation for consumption, i.e. not to dried or concentrated foods, and are based on a dose criterion for ingestion of 1 mSv in a year. When radionuclide levels in food do not exceed the corresponding GLs, the food should, as far as radiation protection of consumers is concerned, be considered safe for human consumption [293]. When the GLs are exceeded, national governments may decide whether and under what circumstances the food should be distributed within their territory or jurisdiction. National governments may wish to adopt different values for internal use within their own territories where the assumptions concerning food distribution that have been made to derive the GLs may not apply, for example in the case of widespread radioactive contamination. For foods that are consumed in small quantities, such as spices, which represent a small percentage of the total diet and hence a small addition to the total dose, the GLs may be increased by a factor of 10.

Generic action levels for foods to be used within the Accident State, based on earlier (1991) Codex guidelines [294], are provided in IAEA Safety Standards Series No. GS-R-2, which was jointly sponsored by the pertinent international and United Nations organizations [252]. It should be noted that action levels serve a particular purpose in an intervention following an emergency and are not the same as GLs, although for coherence, they were made numerically consistent with the GLs current at that time. These action levels differ from the revised Codex GLs in the following respects:

— The use of the GLs was originally intended to be limited to the first year after a nuclear emergency (in 1991, the Codex agreed that the applicable timespan for these GLs should be extended for an indefinite period after an emergency) [294].
— The GLs are based on a dose criterion of 5 mSv in a year (the generic action levels for foods originate from optimized intervention levels based on considerations of the benefits and detriments for the withdrawal and substitution of foodstuffs) [295].
— The GLs only apply to food in international trade and assume an annual consumption rate of 550 kg/y for adults or 200 kg/y for infants, with only 10% of food derived from affected countries and containing radionuclides.

The 1996 BSS [243] include the same Codex guidelines. However, the 2011 version of the BSS [257] requires Member States to develop food intervention levels, taking into account the current 2006 Codex guidelines.

ICRP Publication 63 [263] recommends both restrictions on the consumption of contaminated water and actions limiting the transfer of radionuclides into the food chain (such as housing grazing animals). According to the ICRP, for any single food, an intervention level that is almost always justified is an averted effective dose of 10 mSv in a year. If alternative food supplies are not readily available, intervention may be justified only at much higher levels of projected dose.

WHO has issued guidelines for drinking water quality, the fourth edition of which was published in 2011 [296]. However, the WHO GLs for radionuclides do not apply to drinking water supplies contaminated during emergency exposure situations.

Guidance on commodities (other than foods and drinking water) is provided by the IAEA in Safety Standards Series No. RS-G-1.7 [297]. It includes specific values of activity concentration for both radionuclides of natural origin (table 1 in Ref. [297]) and those of artificial origin (table 2 in Ref. [297]) that may be used for bulk amounts of material for the purpose of applying exclusion or exemption. It also elaborates on the possible application of these values to clearance.

The Japanese restrictions on food are described in more detail in Technical Volumes 3 and 5. A discussion of the approach applied is provided by Hamada and Ogino [168].

Early protective actions: Relocation

Relocation differs from evacuation mainly in terms of the time over which this action is taken. It may be undertaken as an extension to evacuation or it may be introduced weeks or months after an accident to reduce doses from deposited radionuclides and to allow remedial measures to be carried out. The duration of relocation may be permanent or for a limited period.

International guidance at the time of the Fukushima Daiichi accident on intervention levels of avertable dose for relocation and resettlement is shown in Table 4.3–4.

TABLE 4.3–4. SUMMARY OF INTERNATIONAL RECOMMENDATIONS ON RELOCATION AND RESETTLEMENT*

Countermeasure	Intervention level of avertable dose (mSv)	Integration time
Initiating temporary relocation	30	1 month
Terminating temporary relocation	10**	1 month
Permanent resettlement	1000	lifetime

* Refs [243, 252]; ICRP Pub. 96 (2005) [265])
** from IAEA, GS-R-2 (2002) [252]

A generic effective dose criterion of 100 mSv per year (projected dose) is included in the revised BSS (2014) [220] and in IAEA Safety Standards Series No. GSG-2 [273] for taking early protective actions, such as temporary relocation, decontamination and replacement of food, milk and water, and for public reassurance.

Inconsistencies concerning commodities

The various criteria described in the previous section have given rise to questions among the Japanese public. For example, the WHO drinking water reference level for ^{137}Cs is 10 Bq/L [296], but the Codex Alimentarius GL for foods (including fruit juice, for example) is 1000 Bq/kg (Annex VIII, Table VIII-6) [293]. This variation is due to the different circumstances in which these levels are intended to be used. For example, drinking water is essential and cannot always be replaced (the WHO guidelines for drinking water are not applicable in an emergency), while the Codex values relate to foods and liquids that can be replaced and that are traded internationally. There are more examples of criteria and restrictions, the logic of which is not immediately clear and which could have benefitted from more explicit explanations or supplementary recommendations (see, for example, González et al. [298]).

4.3.4. Reactions to the situation for radiation protection in Japan and globally

In the aftermath of the accident, many radiation protection questions were raised, not only by members of the public and their representatives but also by specialists, including those in the radiation protection community. Thus, soon after the accident, the ICRP convened a Task Group to compile the lessons learned with respect to the system of radiological protection. Its report [299] is aimed at the ICRP itself rather than the radiation protection community.

The ICRP report [299] does not discuss in depth the level of protection to be selected for protection of the public in an existing exposure situation, although other ICRP documents consider different arguments on this issue. Arguments in favour of using the high end of the pertinent dose band (>1–20 mSv) for public dose reference levels (i.e. emphasizing the reasoning advanced in ICRP Publication 82 [264]) are put forth by Hedemann-Jensen and McEwan [300], who also point to some inconsistencies in ICRP guidance that may warrant updating. Several papers also stress the confusion caused by public misunderstanding of the concept of reference levels and their application (e.g. Kai [301] and Sakai [302]).

Issues encountered in remediation after the accident are described in Technical Volume 5, Section 5.2. Remediation also generates radioactive waste, as indicated in Technical Volume 5, Section 5.4 (see also Annex VIII).

Section 4.3.5 below demonstrates that the evacuation and temporary relocation efforts entailed significant adverse effects. An optimization assessment in order to alleviate these side effects may indicate that generic criteria for relocation should be set above 20 mSv effective dose received in the first year following an accident. According to the 2014 BSS, the optimization of a protection strategy including relocation should be considered with a reference level in the range of 20–100 mSv residual effective dose [252].

4.3.5. Social issues associated with protective actions

As described in earlier sections, a range of protective actions were taken by authorities in Japan after the Fukushima Daiichi accident. These actions were generally successful in reducing doses to those living and working in the vicinity of the Fukushima Daiichi NPP, but in many cases, they impacted negatively on the daily lives of individuals and on communities.

4.3.5.1. The impact of evacuation and sheltering

As described in detail in Technical Volume 3, Section 3.3, there were many practical issues associated with implementing the evacuation of a large number[43] of people [215] at the same time as dealing with the consequences of the earthquake and tsunami. Infrastructure — roads, railways, public transportation, telephone and internet, electricity, gas, drinking water, supplies of food, petrol, heating oil, and so on — was significantly damaged. This affected transport, communication and coordination activities. There were difficulties in arranging the transportation and accommodation of hospital patients.

The implementation of evacuation, especially within the 20 km zone, was stressful for many of the evacuees. Traumatic situations and deaths of hospital patients during the transport out of the 20 km zone were documented [303], as described in detail in Section 3.3 of Technical Volume 3. Healthy people also suffered. The evacuation orders, together with the earthquake and tsunami damage to the

[43] At the peak, in June 2012, around 160 000 people were involved, including people from a number of different evacuation areas.

road and railway systems, led to an effective suspension of the supply and distribution of goods. Many evacuees were accommodated in temporary shelters, such as large school auditoriums or other local municipal buildings. Many evacuees lived in uncomfortable conditions for several months, as illustrated in Fig. 4.3–1(a).



(a)



(b)

FIG. 4.3–1. The initial evacuation led to crowded conditions in shelters. (a) A senior TEPCO executive apologizes to evacuees at an evacuation centre on 22 March 2011 (Photograph courtesy of Koichi Nakamura/AP Images/picturedesk.com); (b) the normal living conditions of the people who were relocated were greatly affected (Photograph courtesy of Dr Yujiro Kuroda/Fukushima Medical University).

Sheltering is normally considered to be less disruptive than evacuation, and different dose criteria are consequently applied. However, it is also generally considered to be a short term measure, extending for a period of two days [252]. Following the accident at the Fukushima Daiichi NPP, sheltering continued for a longer period, during which living standards of residents deteriorated as a consequence of isolation and lack of supplies. More information is provided in Technical Volume 3, Section 3.3.

4.3.5.2. Impacts of relocation

The deliberate evacuation affected Iitate Village and parts of Katsurao Village, Kawamata Town and Minamisoma City, and amounted to about 10 000 residents. The inhabitants living in these areas were allowed around six weeks to move from their homes. This enabled people and the communities to be better prepared, and some employees and elderly people were permitted to remain.

Construction of temporary housing began in the summer of 2011, leading to an improvement in living conditions; however, as illustrated in Fig. 4.3–1 (b), these conditions were still not ideal. In addition, there is the continued isolation of evacuees from their home community life. Opportunities for employment and for participation in community activities have been limited, and the temporary and uncertain situation has made planning for the future very difficult. As a consequence, evacuees have suffered psychologically and physically. More information on these issues is provided in Section 4.4.

Long term evacuation has also affected family structures. Before the accident, many residents lived in large farmhouses, often with three generations living together. After the accident, the number of households increased, because temporary housing units are generally too small to accommodate all family members. More information is presented in Technical Volume 5.

Local communities effectively disintegrate when their members move. Additionally, relationships within a community can and have been affected by inequities in the application of measures within it,

due to zoning and the monetary compensation policies [304, 305] (see Technical Volume 5 for further information on compensation policies).

4.3.5.3. The impacts of applying remediation criteria

The two level nature of internationally recommended reference levels has led to some confusion among local residents in the affected areas. An effective dose criterion of 20 mSv/y (residual dose) was specified for lifting evacuation orders [306], but the existence of a lower reference level that was numerically equivalent to the annual effective dose limit of 1 mSv[44] for planned exposure situations appeared to imply that the situation was not safe. There was also a lack of clarity in international advice on long term residual doses (see Section 4.3.3). The choice to return to the evacuated and relocated areas may imply accepting that radiation doses are higher than before the accident. It may be possible to improve the situation on return by following guidance to avoid radiation exposure by avoiding hot spots and foods that exceed the established criteria. See Technical Volume 5 for more information.

4.3.5.4. Food safety standards and their impacts

Prior to the accident, there were no specific regulatory limits that applied to radionuclides in foods produced in Japan, but the guidelines of food and water restrictions in the Nuclear Safety Commission Regulatory Guide [307] were broadly consistent with international guidance. However, these levels had not been adopted in the regulations prior to the accident, as explained in detail in Technical Volume 3. Many local governments were not equipped and some were reluctant to perform the necessary tests on food owing to concerns about the possible harm to their reputation. There were thus differences in monitoring programmes instituted by different local governments. Some private sector companies began to perform tests voluntarily and some retailers adopted voluntary standards that were lower than the standards set by the Government [215]. Although restrictions on products for public consumption were important and necessary, they caused economic damage and social disruption to local producers.

Four years after the accident, the level of radiocaesium in the food produced in Fukushima Prefecture has decreased to close to background levels; no radiocaesium has been detected in most commercially available food produce in Fukushima Prefecture. However, a substantial fraction of the general public still refuses to buy food produced in Fukushima Prefecture [308].

4.3.6. Summary

There is an internationally accepted system for the protection of people and the environment from the harmful effects of ionizing radiation. It is founded on basic principles formulated in the system of radiological protection recommended by the ICRP, which have been established by international intergovernmental standards. These principles include:

— Justification of facilities and activities, namely that facilities and activities giving rise to radiation risks must yield an overall benefit so that actions that might alter the extant radiation exposure situation should produce more good than harm;
— Optimization of radiation protection, namely that protection be the best under the prevailing circumstances;
— Limitation of risks to individuals, namely that measures for controlling radiation risks ensure that no individual bears an unacceptable risk of harm.

[44] Additional dose, excluding natural background.

The principles embed an overarching principle of protection of present and future generations, namely that people and the environment, present and future, must be protected against radiation risks.

An international framework of agreements and standards related to radiation protection and safety exists that is based on international legally binding undertakings, international safety standards and international provisions for the application of those standards. The exposure and risk estimates undertaken by UNSCEAR provide the scientific basis for these standards. The recommendations and guidance of the ICRP also provide an input to many international safety standards developed, under the aegis of the IAEA and specialized organizations of the United Nations system. The recommendations of the ICRP have influenced the development of many international safety standards.

At the time of the accident, international requirements related to preparedness and response for a nuclear or radiological emergency were available in the form of IAEA Safety Standards Series No. GS-R-2 [252], which covered both the emergency phase and the transition from the emergency to long term recovery. However, at the time of the accident, the general requirements on radiation protection (the international Basic Safety Standards, BSS) were being revised to take account of, among other things, the recently revised recommendations of the ICRP. A draft version of the new standards had been available since 2009. The interim version of the new BSS was not available until November 2011, several months after the accident. The Government of Japan decided to apply the ICRP recommendations in making decisions related to the transition phase.[45]

Radiation protection measures taken after the Fukushima Daiichi accident helped to limit the radiation doses to the public, but the complex nature of the distribution of doses across communities, within and beyond the 20 km evacuation zone, demonstrate the influence of evacuation timing, location and destination on the doses received. Furthermore, these measures have also had a variety of effects on the well-being of individuals and communities in the affected areas and severely disrupted the daily life of people. The impact of these protection measures may not always be commensurate with the benefits achieved by the protection.

4.3.7. Observations and lessons

— **Relevant international bodies need to develop explanations of the principles and criteria for radiation protection that are understandable for non-specialists in order to make their application clearer for decision makers and the public. As some protracted protection measures were disruptive for the affected people, a better communication strategy is needed to convey the justification for such measures and actions to all stakeholders, including the public.**

There is a recognized need for simple explanations of a number of radiation protection issues, including:

- Differences between the concepts of dose limits and reference levels and the associated rationale;
- Criteria for the justification of protective measures and actions aimed at averting radiation doses in the long term, in particular when they involve significant disruptions to normal life;
- Specific situations relating to the radiation protection of emergency workers.

The principles of radiation protection are based not solely on science but also on value judgements based on ethical principles. In some circumstances, protective measures and actions involve protracted social disruption. Under these circumstances, the potential benefit from

[45] NUCLEAR SAFETY COMMISSION, Provisions for a Deliberate Evacuation Area and an Evacuation-prepared Area (2011),
http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110410advise_1.pdf

avoiding radiation doses must outweigh the individual and social detriment caused by the protective measures and actions themselves. It is important to explain to stakeholders the justification for long standing radiation protection measures and actions.

— **Conservative decisions related to specific activity and activity concentrations in consumer products and deposition activity led to extended restrictions and associated difficulties. In a prolonged exposure situation, consistency among international standards, and between international and national standards, is beneficial, particularly those associated with drinking water, food, non-edible consumer products and deposition activity on land.**
The current international system for controlling radioactivity in consumer products is governed by distinct guidance, e.g. the Codex Alimentarius for food (including bottled water) in international trade, IAEA safety standards for food and drinking water for use in an emergency, WHO guidelines for drinking water in existing exposure situations and IAEA safety standards for non-edible products for exemption purposes. There is a need for harmonization among the international standards for acceptable levels of radioactivity in products for public consumption in order to facilitate their application by regulatory bodies and their understanding by the public. National standards need to be in line with international standards, where this is feasible. Moreover, there is a need for criteria for dealing with the protracted presence of radionuclides on land.
Guidance also needs to be developed for international trade to control of contaminated non-edible commodities. There is a need for transparency in the derivation and implementation of reference levels of activity in food and other commodities to facilitate understanding. The terminology used needs to be clarified. Moreover, existing guidelines do not fully address commodities assessed by measuring surface activity (there is a need for criteria in terms of Bq/cm^2). A review is needed to identify any gaps in existing international standards and to identify the work necessary to achieve an international consensus on such standards.

— **Education and training in radiation protection should be continuous for all stakeholders and should be regularly updated.**
There is always room for even more preparation in radiation protection. While radiation protection was successful, given the scale of the earthquake and tsunami and the concomitant nuclear accident, some gaps in procedures occurred; the experience needs to be used to achieve further improvements and resilience should accident an accident occur in the future.

4.4. HEALTH CONSEQUENCES

Since the Fukushima Daiichi accident, one of the foremost concerns for the people of Japan has been the possible health consequences that might arise from the release of radioactive material from the damaged reactors. This concern has been especially important for those in the regions surrounding the Fukushima Daiichi NPP who have been directly affected by evacuation, and/or for workers from the plant who were present at the time of the accident or who have participated in emergency or remedial actions. This section provides a description of the possible health consequences of the accident in the light of the information available at the time of writing.

According to the WHO, *health* is "a state of complete physical, mental and social well-being, not merely the absence of disease" [309]. This section thus addresses two types of possible consequences: detrimental (physical) health effects that may be caused by exposure to radiation; and indirect effects arising from experiences due to the situation during and following the accident, including reactions to the presence of radiation, such as effects on mental well-being. The first type of effect is reviewed extensively in this section and the supporting annexes. However, only a preliminary discussion of information on the second type of health effect is available at the time of writing and can therefore be provided here. Societal consequences, as distinct from health consequences, are reviewed in Sections 4.3.5 of this volume and in Technical Volume 5, Section 5.5.

As indicated in Section 4.2 above, there have been two earlier international assessments of the possible health consequences of the Fukushima Daiichi accident: one by WHO [201] and one by UNSCEAR [5]. These are described in Section 4.4.1.

Section 4.2 of this report provides estimated radiation doses to workers and to the public as a result of the accident. In order to appreciate the health significance of these exposures, it is important to be aware of the current extent of scientific knowledge concerning the relationship between radiation dose and possible harmful consequences that can be attributed to radiation. Annex X summarizes the known effects of radiation on human health and how assessments of possible future risk from radiation exposure are made.

The health of people living in the regions surrounding the Fukushima Daiichi NPP and of workers who were engaged in emergency or remedial work following the accident is being monitored through ongoing studies. Section 4.4.2 reviews post-accident studies in Japan, including the FHMS, which is tracking the health of members of the public and the results of surveys of the health of workers at the Fukushima Daiichi NPP.

Section 4.4.3 presents the evidence on observable health effects of the accident, and Section 4.4.4 describes surveys of thyroid effects. The possibility of thyroid malignancies arising from exposure to ^{131}I released from the NPP is the most significant potential radiation related health issue associated with the accident. This is being dealt with in depth using primarily thyroid ultrasound surveys. Some background material to assist in understanding possible thyroid effects is given in Annex IX.

The possibility of delayed effects on health in the future is explained in Section 4.4.5. This is based on the dose estimates presented in Section 4.2 and modelling of risks as described in Annex X. A preliminary consideration of the effects of the accident on mental health is presented in Section 4.4.6, recognizing that there are consequences of the earthquake and tsunami in addition to those arising from the Fukushima Daiichi accident. Finally, the assessment of health consequences is summarized in Section 4.4.7, with observations and lessons presented in Section 4.4.8.

4.4.1. Previous international assessments

This technical volume builds on earlier publications by WHO [201] and UNSCEAR [5] and is able to make assessments based on information that has become available since the publication of these reports. To clarify the relationship between these international assessments, the earlier reports are summarized here. The WHO report was initiated soon after the accident in order to provide advice on potential human health consequences as early as practicable, based on radiation dose estimates available at the time. The UNSCEAR decision to conduct an assessment of the levels of exposure and radiation risks attributable to the accident was endorsed by the United Nations General Assembly in December 2011. The present technical volume originated from an undertaking by the IAEA Director General that the IAEA would prepare a report on the Fukushima Daiichi accident. He stated that this would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned" [310].

4.4.1.1. Assessment by WHO

Soon after the Fukushima Daiichi accident, WHO initiated a health risk assessment "to support the identification of needs and priorities for public health action and to inform Member States and the public" [201]. Its declared aim was to estimate "at global level the potential health consequences of human exposure to radiation during the first year" [201] after the accident. It was designed to cover "infants, children and adults living in the Fukushima prefecture, nearby prefectures, the rest of Japan, neighbouring countries, and the rest of the world" [201].

Because the health risk assessment required estimates of radiation doses received by the population, WHO first established an International Expert Panel "to make an initial evaluation of radiation exposure of people both inside Japan and beyond, as a result of the accident". The panel's report, issued in May 2012 [173], while taking into account all major pathways of exposure, was based on the monitoring data that was available for about the first six months following the accident, and projections derived therefrom. As a result, it is acknowledged to be a preliminary assessment and subject to refinement as further information becomes available.

This technical volume, based on more extensive monitoring data collected over a longer period, has shown that doses incurred by the population affected by the accident are lower than the estimates of the WHO preliminary report. WHO issued a health risk assessment of the Fukushima Daiichi accident in 2013 based on its 2012 dose assessment report [173, 201]. The assessment was conducted by independent international experts who were selected by WHO for their expertise and experience in relevant scientific and public health disciplines, including radiation dosimetry and radiation risk modelling.

The WHO risk assessment involved the following elements:

— The lifetime risk of cancer was modelled for all solid cancers combined (not including leukaemia), and separately for the individual cancer sites most closely associated with radiation exposure and with a known dependence of the magnitude of risk on age at exposure (leukaemia, thyroid cancer and female breast cancer).
— The lifetime risks were inferred for both sexes and three different ages at exposure (1 year (infant), 10 years (child) and 20 years (adult)).
— Predictions of the cumulative risks for the 15 years following the accident were also made.
— Health risks for male emergency workers were inferred for three different ages (20 years, 40 years and 60 years).

The conclusion of the WHO health risk assessment for the rest of the world was that:

> "[N]o discernible increase in health risks from the Fukushima event is expected outside Japan. Outside the geographical areas most affected by radiation, even in locations within Fukushima prefecture, the predicted risks remain low and no observable (i.e., attributable) increases in cancer above natural variation in baseline rates are anticipated." [201]

The assessment estimated that, within the Fukushima region, the lifetime risk for some cancers may be elevated above baseline rates in certain age and sex groups that were in the areas most affected. In the highest dose locations, the WHO preliminary estimates of effective doses for the first year ranged from 12 to 25 mSv. Based on this, the estimated lifetime attributable risks (LARs) for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk, as methodological options were consciously chosen to avoid underestimation of risks.

With an understanding that the calculations were performed to avoid underestimation, the WHO report concluded that:

— For leukaemia, the LARs are predicted to increase by up to about 7% over baseline cancer rates in males exposed as infants.
— For breast cancer, the estimated LARs could increase by up to about 6% over baseline rates in females exposed as infants.
— For all solid cancers, the estimated LARs could increase by up to about 4% over baseline rates in females exposed as infants.

— For thyroid cancer, the estimated LARs could increase by up to about 70% over baseline rates in females exposed as infants.

The WHO report emphasizes that "due to the low baseline rates of thyroid cancer, even a large relative increase represents a small absolute increase in risk" [201]. It also recognizes that the assessments were based on preliminary estimates of radiation doses and that the calculated percentages "represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers" [201].

4.4.1.2. Assessment by UNSCEAR

As noted in Annex X, the issue of attributability of health effects to ionizing radiation is complex. In 2007, the United Nations General Assembly requested UNSCEAR "to clarify further the assessment of potential harm owing to chronic low-level exposures among large populations and also the attributability of health effects" [311].

UNSCEAR provided an answer to this request in its 2012 Report to the United Nations General Assembly [312]. It reached, inter alia, the following conclusion:

> "Increases in the incidence of health effects in populations cannot be attributed reliably to chronic exposure to radiation at levels that are typical of the global average background levels of radiation, among other reasons because of the uncertainties associated with the assessment of risks at low doses, the current absence of radiation-specific biomarkers for health effects and the intrinsic insufficient statistical power of epidemiological studies." [312]

UNSCEAR therefore decided to discourage the multiplication of very low doses by large numbers of individuals to estimate the number of radiation induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels. It also noted that theoretical calculations of hereditary effects were unsubstantiated, regardless of the dose incurred. It advised that "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure".

However, UNSCEAR underlined that public health bodies need to allocate resources appropriately, and that this may involve making projections of the risk of health effects for comparative purposes. "This method, though based upon reasonable but untestable assumptions, could be useful for such purposes provided that it were applied consistently, the uncertainties in the assessments were taken fully into account, and it were not inferred that the projected health effects were other than notional" [311].

In 2014, UNSCEAR published a report [5] in which it addressed the attribution of health effects to chronic low levels of radiation exposure monitored in the population affected by the Fukushima Daiichi accident. The key questions to be addressed are summarized as follows:

— To what degree a health effect that has been observed, either in an individual or as an increased incidence of health effects in a population, can be attributed to the chronic low levels of radiation exposure received by the population affected by the Fukushima Daiichi accident (and, conversely, to what degree could a potentially observed decrease in the incidence of health effects in that population be attributed to the radiation exposure)?
— Is it correct to infer radiation risks from the situation caused by the accident and apply commensurate radiation protection measures?
— Is it valid to project absolute numbers of health effects following the radiation exposure caused by the Fukushima Daiichi accident, particularly at levels at which an increased incidence in radiation

induced health effects have not been observed in any other population subjected to similar exposure conditions?

In summary, the conclusions of UNSCEAR concerning the first issue, related to the observation of health effects of the accident, were:

— "No radiation-related deaths or acute diseases have been observed among the workers and general public exposed to radiation from the accident" [5];
— "The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects are expected among exposed members of the public or their descendants" [5].

UNSCEAR also noted that:

> "The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported." [5].

With regard to the second and third of the questions above, UNSCEAR noted that its 2012 report [312] had advised that it is appropriate to make "projections of numbers for comparative purposes" [312] in the context of allocating public health resources, but specifically recommended against "multiplying very low doses by large numbers of individuals to estimate the numbers of radiation induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels" [312].

4.4.2. Post-accident health surveys in Japan

A number of health surveys were initiated in Japan following the Fukushima Daiichi accident. The FHMS focuses on the general population. The health of workers involved in remediation of the accident is also being closely monitored. Two key surveys are reviewed below.

4.4.2.1. Public health: Fukushima Health Management Survey

Recognizing the public anxiety concerning the accident at the Fukushima Daiichi NPP, Fukushima Prefecture established a health monitoring and support programme — the FHMS — about three months after the accident. The primary purposes of the survey are: "to assess residents' radiation dose, and to monitor residents' health conditions, which result in disease prevention, early detection and early medical treatment, thereby to maintain and promote their future health" [313].

The FHMS comprises a survey of basic health indicators and four more detailed, specialized surveys. Two million residents of Fukushima Prefecture have been targeted in the basic survey, with smaller numbers participating in the detailed surveys [202]. The estimations of internal exposures from radioactive material ingested or inhaled were not directly included in the survey but assessed separately using WBCs, as explained in Section 4.2. Some of the observations from the survey are described below. A discussion of the evidence for observable effects of radiation is given in Section 4.4.3.

The basic survey began with self-administered questionnaires mailed out to people who met residential or location criteria for being possibly connected with the consequences of the accident. Respondents were asked to record their movements following the accident in order to allow the results to be used in estimating radiation exposure from assessments of the variations in ambient dose equivalent in time and location. The overall response rate was about 27% (about 554 000 respondents,

including radiation workers), as of 31 December 2014. For the residents excluding radiation workers, the estimated external effective dose during the first four months of the accident was less than 2 mSv in 95% of individuals and less than 5 mSv in 99.8% of individuals surveyed. Similar figures were obtained for the subset of the population (about 74 000 respondents) in the Soso area: the estimated external effective dose over the first four months was less than 2 mSv in 95% of individuals and less than 5 mSv in 98.8% of individuals [214]. Doses estimated to have been received by workers and members of the public, based on all available sources of information, are presented in Section 4.2.

The four specialized surveys involved: ultrasonography thyroid screening of residents age 18 and under (target population: 370 000), termed the Thyroid Ultrasound Examination (TUE) Survey; comprehensive medical check-ups of evacuees (210 000); a mental health and lifestyle survey of the same evacuees; and a survey of pregnant women and nursing mothers (approximately 15 000 in each year).

Following an initial survey, the second screening of the TUE Survey revealed that, for the period until March 2015, over 99% of the results of about 299 233 respondents fell within a normal range [314]. For this group, no specific findings were identified during the screening; no suspicious nodules or small nodules with a diameter of less than 5 mm nor any small cysts with a diameter of less than 20 mm were found. These results were compared with ultrasonography screenings of thyroid nodules in three other prefectures in Japan [315], which revealed similar findings of 99% of individuals with results that fell within the same normal range. There were 2279 individuals in the TUE with results beyond the normal range who underwent further screenings. Of these, 112 were found to have malignant, or the suspicion of malignant, nodules and/or cysts, for which 99 individuals had a thyroid operation. Of these, 98 were malignant and one benign. Thyroid effects are explained in detail in Section 4.4.4 [314].

The comprehensive medical check-ups include tests for body mass index, glycated haemoglobin (HbA1c), liver function and blood pressure. Although it must be noted that, owing to evacuation, the population surveyed is not identical year after year, there was a marked increase in adverse test results for both men and women in 2011 and 2012. Notably, the percentages of men and women whose liver function test was over 51 units per litre in 2011 and 2012 are more than double the percentages of what they were before 2011 [316]. These results imply that the individuals have an increased risk of obesity related diseases, diabetes mellitus, liver diseases, and hypertension, among other things. Data for 1032 people examined in Iitate Village in 2011 and 2012 were compared with those of previous years, with results indicating rising obesity, hypertension and hyperlipidemia, and a small increase in diabetes [316].

In the mental health and lifestyle survey, questionnaires covered physiological and mental conditions, lifestyle changes, experiences of the earthquake and tsunami, and radiation related issues. A year after the accident, a significant proportion of residents of Fukushima Prefecture were observed to exhibit symptoms of post-traumatic stress disorder (PTSD) (about 20%) and general mental health issues (about 15%) [317]. General mental health issues in Fukushima Prefecture occurred at about twice the level of those in the other two prefectures severely affected by the earthquake and tsunami (about 7% in Iwate and Miyagi). Higher rates persisted two years after the accident, but to a lesser degree. Additionally, almost half of Fukushima Daiichi NPP workers were observed to have high scores for general mental health issues [317].

The survey of pregnant women and nursing mothers involved a questionnaire, sent out to all mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, which was returned by about 15 000 respondents. This survey is being updated every year to take account of new data, particularly on pregnancy and births. When answers on the questionnaire indicated that consultation was needed, doctors provided telephone consultations in some cases. In other cases, pregnant women and nursing mothers called or sent emails directly to midwives and

doctors at Fukushima Medical University. These telephone consultations covered health concerns about the effects of radiation, and general advice for the pregnant women and nursing mothers (including concerns about their children, issues of child rearing, life in evacuation centres and family matters). Between December 2011 and July 2012, 30% of the 1400 calls expressing the greatest concerns focused on the influence of radiation on health. Between October 2012 and May 2013, the greatest concern was health issues of pregnant woman or nursing mothers, representing about one third of over 1000 calls made in that period.

A study by Fujimori considered six geographical regions (Kenpoku, Kenchu, Kennan, Soso, Iwaki and Aizu), and the response rate for the survey was greatest in the regions most affected by the accident (Soso, Kenpoku and Kenchu) [318]. The results in 2011 and 2012 showed that the rates of premature birth and low birth weight were similar to the national averages, and the ratios of congenital anomalies and other abnormalities were also approximately similar to the general incidence rates [318]. By area, there were no significant differences in the rate of stillbirth or preterm delivery, but the incidence of low birth weight was significantly lower in Kenpoku and higher in Iwaki than in the other regions. The study concluded that "although it is possible to underestimate incidences when using a self-administrated questionnaire with variable response rate, we could conclude no significant adverse outcomes from the pregnancy and birth survey over the whole Fukushima prefecture after the disaster" [318].

Health consultations were also carried out when medical check-ups took place. Doctors and public health nurses gave advice on the prevention of primary and secondary diseases, such as hypertension, diabetes mellitus and cancer related to lifestyle changes. This was to provide support for deterioration of access to medical services due to the necessity of evacuation. Care for mental health issues was also provided for residents and their families, as well as consultation and explanations of the thyroid screening results.

4.4.2.2. Worker health: TEPCO emergency workers at the Fukushima Daiichi NPP

For the long term health care of emergency workers who were engaged at the Fukushima Daiichi NPP, various programmes, including regular health check-ups, are being conducted, depending on the effective doses to workers according to the guidelines of MHLW [292]. In addition, TEPCO independently provided ultrasound examinations of the thyroid for emergency workers whose thyroid equivalent dose (during emergency work in addition to ordinary radiation work) was more than 100 mSv in 2011. Taking into account the age of these workers, several symptoms can be expected to be detected for some workers by an ultrasound examination regardless of their radiation exposures. In order to examine the possible effect on the thyroid, an ultrasound examination with the same procedure has been conducted for a control group of the workers with lower exposure to the thyroid (100 mSv or less of thyroid equivalent dose). An interim report of this survey was available at the time of writing of this volume [319].

A total of 2064 workers were enrolled (672 in the more highly exposed group and 1437 in the control group). The majority of the participants were TEPCO employees, with 2.2% of participants being employed by subcontractors. All of the examinees were men with a mean age of 43 for the exposed group and 41.7 for the control group. The categories used to describe the results were the same as those for the FHMS TUE carried out in children. There were no significant differences between the groups with respect to the different categories.[46] The initial findings suggest no effect on the thyroid of exposure to radioiodine, which is consistent with the relatively low doses received by these adults (see Section 4.2.1), and the short time interval between exposure and examination.

[46] Smoking and alcohol consumption was not significantly different between exposed and control groups.

MHLW called an expert committee to discuss perspectives on a future epidemiological study for the emergency workers, and a report of the committee has been published [320]. It pointed out the importance of a long term prospective cohort study for the approximately 20 000 emergency workers who worked until 16 December 2011. The committee suggested the desired study design, including end points, dosimetry, follow-up methods, and so on. The decision to implement this large scale study was reached by the study group (in which the Radiation Effects Research Foundation played key role) in November 2014.

4.4.2.3. Worker health: Follow-up survey of other workers

In cooperation with experts in various fields from research institutes and universities in Japan, NIRS initiated a follow-up study for those workers involved in emergency and recovery operations after the Fukushima Daiichi accident. In the follow-up, results of regular and special health examinations will be collected periodically from each organization and stored in the secured database at NIRS. Based on the lessons learned from studies of recovery operation workers after the Chernobyl accident and other occupational studies, which have often shown mixed results, lifestyle factors, including smoking and other possible factors will be taken into account. The ongoing study will collect such data using a questionnaire at the beginning of the follow-up and subsequently every few years. Information on disease history for both cancer and other diseases is also being collected through the same questionnaire. Various sources, including national vital statistics, cancer registry data, and so on, will be used to ascertain the disease outcomes.

4.4.3. Evidence of observable health effects

Radiation induced health effects depend on the dose received and can be divided into tissue reactions (the severity of which increases with dose) and stochastic effects (likelihood of effect related to dose).

4.4.3.1. Tissue reactions

Tissue reactions (also known as deterministic effects) are those for which there is a threshold of dose below which they do not occur and for which the severity of the effect increases with increasing dose. The threshold is necessary, since a critical number of cells need to be damaged before an injury becomes clinically evident. Below the threshold, there may be sufficient redundancy, so that any cellular loss is inconsequential. Damaged cells may be removed and/or gradually replaced, maintaining normal tissue or organ function. Tissue reactions may often occur soon after exposure, particularly for rapidly dividing tissues, such as bone marrow, skin, the cells lining the gastrointestinal tract and mucous membranes. However, symptoms appear after a latency period. For some organs, tissue reactions may not become evident for months or even years. The thresholds vary for different organs and tissues of the body and are generally well above 100 mSv. One of the lowest thresholds adopted by the ICRP for protection purposes is 0.5 Gy, whether delivered over a short or protracted period, for induction of cataracts in the lens of the eye [262, 321, 322].

Based on the doses estimated to have been received by members of the public (Section 4.2.2), no tissue reactions are expected, and none has been observed to date. A small number of workers have received effective doses in excess of 100 mSv [194]. Most of this dose came from internal exposure — from radioactive material taken into the body — which would not have significantly exposed the lens of the eye.

Three workers received dose to the feet and lower leg, but the corresponding data have not yet been published. However, these workers were evaluated by NIRS: two were found to have received skin equivalent doses of less than 500 mSv, while the third wore boots and received almost no dose. The skin equivalent dose of the two most exposed workers were reported to be lower than the estimated

threshold for deterministic effects [262]. [47] None of these workers developed beta burns as confirmed by medical follow-up [323].

A 'prenatal (or antenatal) effect of exposure' is the term used to refer to effects of radiation on the embryo and fetus. At absorbed doses under 100 mGy, lethal effects of irradiation in the pre-implantation period of embryonic development are considered to be very infrequent, and there is an absorbed dose threshold of around 100 mGy for the induction of other effects [324–326]. Absorbed doses to the embryo and fetus that could be attributable to the accident were much lower than the threshold absorbed dose for the occurrence of these effects.

4.4.3.2. Stochastic effects

Stochastic radiation induced health effects are those for which the probability of their occurrence depends on dose. If such an effect occurs, its severity is independent of dose [256, 327]. The category of stochastic effects includes malignant diseases in exposed individuals and heritable effects in their offspring, although the latter effects have been observed only in animals and not in humans [312]. It is thought that stochastic effects are initiated by non-lethal transformations in somatic or germ cells, which may contribute, after a latency period, to malignant diseases or heritable effects, respectively. Some non-cancer health effects that may be connected with exposure to radiation are not sufficiently understood to determine whether they are stochastic responses [256].

The potential for radiation effects in children is an issue of special concern. International recommendations and standards for radiation protection take account of children in an exposed population. For radiation protection purposes, they postulate a potential nominal radiation risk for an entire population, i.e. a population including children that is about 30% higher than the postulated risk for an adult population (such nominal risks have been estimated on the basis of epidemiological studies of populations exposed to high radiation doses) [256, 328]. Following the lessons learned from the Chernobyl accident, the possibility of radiation induced thyroid cancer, particularly in children, has been a key consideration in the aftermath of the accident at the Fukushima Daiichi NPP. For this reason, effects on the thyroid are described in a separate section (Section 4.4.4).

As explained in the previous section, the dose received by an individual is the sum of doses from external and internal radiation. With respect to internal dose, there is an important interplay between the biological and physical half-life that affects the dose of radiation received by individual tissues in the body. While iodine is concentrated in the thyroid gland, caesium is neither actively taken up nor bound preferentially in any particular tissue in the body. Therefore although the two isotopes of caesium, ^{134}Cs and ^{137}Cs, have physical half-lives of around 2 and 30 years, respectively, caesium has a relatively shorter biological half-life of 70 days. It is likely that most of a single dose intake of ^{134}Cs and ^{137}Cs will be excreted from the body before emitting its radiation. Therefore, the dose received by the tissues from an intake of these two radioactive elements (iodine and caesium) will be markedly different, and for comparable intakes, the dose, and therefore the probability of radiation induced health effects, of ^{131}I is likely to be greater than that of ^{137}Cs.

In comparison with the general population, the workers at the Fukushima Daiichi NPP received higher whole body doses (see Section 4.2.1). A total of 174 received doses of greater than 100 mSv, with six receiving doses of above 250 mSv, including two workers with a whole body dose in excess of

[47] ICRP estimates for the exposure of the skin is that an early response, as early transient erythema, is seen a few hours after doses of >2000 mGy when the exposed area is relatively large. It also estimates that the approximate threshold doses are as follows: early transient erythema — 2000 mGy, main erythema reaction — 6000 mGy, temporary epilation — 3000 mGy, permanent epilation — 7000 mGy, dry desquamation — 14 000 mGy, moist desquamation — 18 000 mGy, secondary ulceration — 24 000 mGy, late erythema — 15 000 mGy, ischaemic dermal necrosis — 18 000 mGy, dermal atrophy (first phase) — 10 000 mGy, telangiectasia — 10 000 mGy and dermal necrosis (late phase) — >15 000 mGy [262].

600 mSv, the majority of which was due to internal radiation. The high contribution of the internal dose to the overall dose was due to inhalation of radioactive material [185]. The health of these workers is being closely monitored. However, given the level of doses received, the number of people involved and other factors, it is unlikely than any increase in cancer will be discernible (see Section 4.4.5).

Regarding effects other than cancer, two recent studies have suggested that there may be an increase in the risk for heart disease and stroke at moderate dose levels. Analysis of the participants in the lifespan study of the atomic bomb survivors showed an increased risk for both heart disease and stroke at doses over 500 mGy, but the authors stated that at lower doses it was difficult to be certain of any excess risk [329]. In a large study of nuclear workers exposed to radiation in the course of their normal work, an excess risk for circulatory disease was noted at doses over 350 mSv [330]. However, there are significant contradictory points in these studies and both suggest that there are insufficient data to draw conclusions for lower doses.

In addition, recent review papers have concluded that, despite evidence in animal models, there is no evidence for transgenerational effects in the human of exposure to radiation at any dose level [331, 332].

4.4.4. Studies of effects on the thyroid

Regarding thyroid cancer, children are more radiosensitive than adults. For a given intake of radioiodines, the dose to the thyroid for infants is eight or nine times larger than adults. A substantial environmental presence of ^{131}I can result in thyroid cancer in children. The normal incidence of some types of thyroid cancer in children is low, and the sensitivity of children's thyroid glands to radiation is high. Owing to this higher sensitivity, in the aftermath of the accident it was important to undertake screening follow-up in order to detect at an early stage any potential increase in the incidence of this type of cancer [333].

High doses of radiation can result in significant killing of cells in the thyroid that can reduce the function of the gland to such a level that hypothyroidism ensues. Hyperthyroidism can also occur, but again at high doses (exceeding 15 Gy). Effects at low and medium doses have been difficult to quantify, and the magnitude of the effect remains unclear [334]. As with the effects of radiation on thyroid cancer incidence, the effect is most pronounced in those who were exposed in childhood. Hypothyroidism can occur in adult patients treated with radiotherapy for head and neck cancer, but the radiation dose to the thyroid is much higher (of the order of 50 Gy) than that which has been recorded in the worker population at Fukushima Daiichi NPP. Where hypothyroidism does occur, it is usually transient.

Section 4.2 provides more detailed information on radiation doses received following the accident at the Fukushima Daiichi NPP. Some information of specific relevance to possible thyroid effects is reviewed here (see Annex IX).

4.4.4.1. Monitoring for thyroid health effects

The FHMS is introduced in Section 4.4.2. It was known that one of the major concerns for the exposed population was the possibility of long term effects of radiation on the thyroid. Consequently, the TUE Survey [202, 335] is an integral part of the FHMS and is directed at all inhabitants of Fukushima Prefecture who were aged between 0 and 18 years on 11 March 2011. Modern ultrasound equipment, such as that used in the TUE study, is able to detect thyroid carcinomas as small as a few millimetres in size, long before these may come to clinical attention (if ever, because some may remain asymptomatic during a whole lifetime). Thus, it is to be expected that more thyroid

abnormalities will be identified through this screening procedure than would occur through normal clinical procedures — this screening effect is well known.

An ultrasound examination of children will continue to be carried out biennially until the participants reach the age of 20 years, and every five years thereafter. The protocol of the TUE is carefully designed to establish a standardized examination procedure that is the most appropriate for the circumstances. The examinations are being conducted by Fukushima Medical University using modern, highly sensitive ultrasound equipment (10 MHz frequency probe for initial evaluation and 18 MHz frequency probe for confirmatory examination) [202, 335]. The first round of examinations started in October 2011 and was completed in March 2014. Based on current knowledge about the minimum latency of 4 to 5 years for radiation related thyroid cancer [246], cancers diagnosed at the initial TUE Survey, i.e. within three years of the Fukushima Daiichi accident, would not be expected to be radiation related; therefore, the initial survey will provide baseline data on the spectrum and frequency of thyroid abnormalities in children under the conditions of intense screening.

The adult thyroid is substantially less sensitive to the carcinogenic effects of ionizing radiation for the same received dose as that for children [336]. In addition, maximum dose estimates of external and internal thyroid exposure in Fukushima Prefecture residents are low (see Section 4.2.2), making the likelihood of developing thyroid cancer following adult exposures low. Thus, no special thyroid examination for those over 18 years at the time of the accidents is conducted or included as part of the Comprehensive Health Check [202, 337, 338] unless a patient has thyroid symptoms or concerns.

As of 31 March 2015, 299 543 children, or 81.5% of the TUE targeted population, have received an initial thyroid examination, and results are available for 299 233 children. The most common ultrasound findings are thyroid cysts, found in 143 268 (47.9%) children, followed by thyroid nodules found in 3968 (1.3%) children. It is important to note that 94.9% of cysts are ≤20 mm and 43.0% of nodules are ≤5.0 mm and would not have been detected without a sensitive screening tool. The majority of screened children (99.2%) had no thyroid abnormalities requiring additional testing, while 2279 (0.8%) had to be referred for confirmatory testing or required immediate attention [314]. The confirmatory testing includes advanced ultrasound examination, thyroid function testing, analysis of urinary iodine and fine needle aspiration biopsy (FNAB), where indicated. Functional thyroid tests and urinary iodine measurements are only performed in children suspected of having thyroid abnormalities. The results may not be applicable to the entire screened population.

A final diagnosis of papillary thyroid cancer (PTC) was confirmed in 95 children of 99 who underwent thyroid surgery. Of the four other cases, three were confirmed as poorly differentiated thyroid cancer and one is confirmed as a benign thyroid nodule. The mean age of individuals who presented with nodules that were suspicious for malignancy was 17.2 years (standard deviation: 2.7, range 8–22). These individuals were on average 14.8 years old (SD 2.6, range 6–18) at the time of the Fukushima Daiichi accident. The male to female ratio was 38 to 74 (1:1.95) and estimated median quantity of iodine in urine was 230 μg/day (the maximum among the 1917 other individuals surveyed was 35 700 μg/day). Because a number of patients are awaiting FNAB or surgery (N = 13), an accurate estimate of the baseline thyroid cancer prevalence is not yet possible.

To evaluate if there is an excess of thyroid cancer or other thyroid diseases following the Fukushima Daiichi accident, preliminary prevalence data for children in Fukushima Prefecture ideally need to be compared with the respective rates in Japanese children not affected by the accident but screened according to the same protocol and comparable in terms of age, sex and other risk factors. Comparison with rates derived from cancer registries in Japan or other countries should be avoided as misleading because the majority of cases reported to cancer registries are diagnosed by clinical methods and not by screening. Thus far, one relatively small study of approximately 4400 children from Aomori, Yamanashi, and Nagasaki prefectures is available for comparison with TUE findings [339]. The number of individuals with cancer or suspicion of cancer on FNAB, if there were any, was

not reported by Hayashida et al.[339]. Comparison of prevalence for several outcomes in two paediatric populations suggests that thyroid lesions, for example small thyroid cysts and nodules (≤5 mm), are common among children screened with sensitive ultrasound equipment. The limited size of the three prefecture study means that it provides an estimate of thyroid cancer rate for comparison with the Fukushima Prefecture findings only for common thyroid abnormalities such as nodules and cysts.

The results of the second screening examination (the first screening of the full scale survey) are available. As of 31 March 2015, 148 027 children of the TUE targeted population (about 385 000), have had received a TUE and test results are available for 121 997 children [340]. The most common ultrasound findings are thyroid cysts, found in 70 531 (57.8%) of the children, followed by thyroid nodules found in 1846 (1.5%) of children. It is important to note that 95.4% of cysts are ≤20 mm and 43.7% of nodules are ≤5.0 mm and would not have been detected without a sensitive screening tool. The majority of screened children (99.3%) had no thyroid abnormalities requiring additional testing, while 1043 (0.9%) had to be referred for confirmatory testing or required immediate attention.

A final diagnosis of PTC was confirmed in 5 children of 5 who underwent thyroid surgery. The mean age of individuals who presented with nodules that were suspicious for malignancy was 16.8 years (SD 3.5, range 10–22). These individuals were on average 13.1 years old (SD 3.5, range 6–18) at the time of the Fukushima Daiichi accident. The male to female ratio was 6 to 9 (1:1. 5) and estimated quantity of iodine in urine was 190 μg/d (the maximum among the 472 other individuals surveyed was 11 800 μg/d). Because the full scale TUE survey has not been completed and a number of patients are awaiting FNAB or surgery (N = 10), an accurate estimate of the baseline cancer prevalence is not yet possible [340].

The examinations use highly sensitive ultrasound sonography equipment for the screening of the thyroid gland, which has detected asymptomatic thyroid abnormalities (nodules, cysts and cancers) that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [341]. The latency time for radiation induced thyroid cancer is also longer that the four years since the accident. In many cases, thyroid cancers were found in children in the late teenage years and no case was found in the most vulnerable group of children who were at the age of 0–5 years as of 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the first screening conducted in 2011–2013 [342]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident.

4.4.4.2. Health monitoring of workers

Although the vast majority of workers at the Fukushima Daiichi NPP received thyroid equivalent doses below 100 mSv, 1709 individuals received doses above this level, with 12 workers receiving doses above 2 Sv and 2 doses in excess of 12 Sv (see Section 4.2.1). As noted earlier, the risk from thyroid cancer from exposure to radiation in adult life is very much lower than that from radiation exposure in childhood, and it is therefore unlikely that an increase in thyroid cancer in this population will be discernible. As described above, a survey of thyroid effects among the emergency workers of the Fukushima Daiichi NPP is ongoing to evaluate the possible association between thyroid doses and ultrasound examination results.

Since October 2011, MHLW, based on ministerial guidelines, has required TEPCO and employers to conduct cancer screening surveys including ultrasonic examination of the thyroid gland annually for emergency workers who were exposed to more than 100 mSv effective dose during emergency work. MHLW is responsible for conducting the tests for retired workers [292]. In 2013, MHLW sponsored a cross-section study on health effects of radiation exposure on thyroid glands. The research conducted

ultrasonic examination of thyroid glands for 627 emergency workers in the exposed group (exposed to more than 100 mSv thyroid equivalent dose) and the 1437 workers in the control group (exposed to not more than 100 mSv in thyroid equivalent dose) in early 2014. The results of the research can be used as a baseline result on ultrasonic examination of the thyroid gland for further epidemiological research [319].

4.4.5. Inference of future risk

No health effects among workers or members of the public that could be diagnosed by a physician and confirmed by pathology can be attributed to exposure to radiation arising from the Fukushima Daiichi accident (see Sections 4.4.2 and 4.4.3). In short, there are no discernible early health effects of radiation arising from the accident. However, it is important to consider whether there may be later (stochastic) health effects, in particular, the development of malignancies (cancer). Such effects appear after a delay that is different for different malignant diseases. For thyroid cancer, the latency period is estimated to be four years or more; for most solid cancers, it is typically longer [254]. So, even if an increase in the incidence of malignant diseases would be observable in principle in the future, it would be too early to see any evidence at the time of this analysis.

As explained in more detail in Annex X, for moderate and high doses of radiation, there is sufficient evidence from epidemiological studies to predict with a fair degree of confidence the future consequential increase in incidence of cancer in an exposed population. However, for low doses and very low doses (at the level generally reported following the Fukushima Daiichi accident), there is insufficient epidemiological evidence to demonstrate an increase in incidence of cancer in exposed populations. Observed effects cannot be unequivocally attributed to radiation, partly because other causes of the effect cannot be ruled out without the existence of an associated biomarker, and partly because the studies have insufficient statistical power to draw conclusions with confidence owing to the high natural incidence of cancer and associated uncertainties. Predictions based on the application of risk coefficients at such levels of dose are scientifically untestable with current knowledge.

Since the accident occurred, several hypothetical estimates of future incidence of cancer have been reported in the media, sometimes basing predictions on calculations of collective dose or its computational equivalent. Such predictions are inappropriate (see Annex X) and may lead to anxiety and emotional distress among exposed populations.

It is recognized, however, that estimates of possible incidence may serve a role in decision making. For example, such information is necessary in comparative analyses (e.g. selecting which is the preferred option from a range of possible preventative or remediation measures) and for resource allocation for health care purposes. Such an assessment may also help people to place the hypothetical risk of harm from radiation in context with other risks with which they are more familiar. This section therefore provides theoretical predictions of a statistical indicator of risk and projections of the hypothetical future incidence of various types of malignancies that could be associated with available estimates of radiation doses from the Fukushima Daiichi accident. These values are based on risk models that reflect the most widely held consensus of opinion in the scientific literature. It is necessary, however, to recognize that such estimates are notional and subject to uncertainties (see Section 4.4.1.2 and Annex X).

Some studies related to Chernobyl accident emergency workers that provide a useful comparison are referenced in Annex XI.

4.4.5.1. Risk models

One of the indicators used by epidemiologists in order to facilitate the theoretical inference of prospective radiation risks on a human population exposed to ionizing radiation is the so called

LARF. LARF is used to express the fraction of the total cancer incidence (both radiation associated and non-radiation associated) that is radiation induced for a population exposed to radiation. LARF is commonly expressed as a percentage. Risk models and approaches have been developed for calculation of LARF on the basis of experience and conclusions from epidemiological studies and taking account of medical and demographic features of the population of Japan. The mathematical basis for the selection of radiation risk models used in the following analyses is explained in Annex X.

Two mathematical models have been used to estimate the risks (expressed as LARF) and the nominal incidence of malignant diseases that might be inferred from the radiation doses reported for workers and members of the public (see Sections 4.2.1 and 4.2.2). These models are referred to as the ICRP model [256] and the WHO model, which is described in the WHO report on health effects from the Fukushima Daiichi accident [201]. This section presents summary information; more detailed information for each year and for different population groups is presented in Annex X.

4.4.5.2. Inferred risks for workers

At the time at which the risk calculations presented in this section were performed, information on worker doses was available for the period up to August 2013. More recent data have become available in the interim, and are presented in Section 4.2.1. The updated data include revised estimates of the doses received in the first year. However, these differences in dose are not considered to be sufficient to significantly affect the overall magnitude of the inferred risks or nominal estimates of the incidence of malignancies, or the relative magnitude of these values to the spontaneous (natural) incidence of health effects.

Table 4.4–1 presents the LARF for various forms of malignancy associated with the reported doses to workers at the Fukushima Daiichi NPP for the period March 2011–August 2014, derived using both risk models. It will be seen from this table that the inferred LARF is, in all cases, less than 1%, and that the values derived using the WHO model are higher. Tables 4.4–2 and 4.4–3 provide estimates of the nominal incidence of thyroid cancer cases associated with various ranges of radiation exposure, the inferred spontaneous incidence of thyroid cancer within each group of workers and the associated LARF, derived using the ICRP and WHO models, respectively. These tables indicate that the LARF for thyroid cancer varies significantly among the groups of workers, according to the thyroid dose received. The LARF for the whole worker population for which thyroid doses are available is of the order of 3% or less, depending on the risk model used (with the WHO model giving the higher estimates).

TABLE 4.4–1. LARF FOR FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED USING THE ICRP AND WHO MODELS.

(Summary follow-up period from March 2011 to August 2013)

	LARF (%) ICRP			LARF (%) WHO		
	Solid cancers	Leukaemia	All cancers	Solid cancers	Leukaemia	All cancers
TEPCO	0.13	1.37	0.15	0.26	0.95	0.27
Contractors	0.06	0.76	0.07	0.13	0.49	0.14
Total	0.07	0.85	0.08	0.15	0.56	0.16

TABLE 4.4–2. INFERRED NUMBER OF THYROID CANCER CASES AND LARF AMONG FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED WITH THE ICRP MODEL

Thyroid equivalent dose (mSv)	No. of workers	No. of radiation induced cases	No. of spontaneous cases	LARF (%)
>10 000	2	0.01	<0.01	65.05
2 000–10 000	10	0.02	0.02	42.67
1 000–2 000	63	0.02	0.13	15.69
500–1 000	188	0.04	0.40	8.51
200–500	790	0.07	1.68	4.16
100–200	656	0.03	1.39	1.83
<100	17 883	0.24	37.93	0.62
Total	19 592	0.42	41.56	1.00

TABLE 4.4–3. INFERRED NUMBER OF THYROID CANCER CASES AND LARF AMONG FUKUSHIMA DAIICHI NPP EMERGENCY WORKERS, CALCULATED WITH THE WHO MODEL

Thyroid equivalent dose (mSv)	No. of workers	No. of radiation induced cases	No of spontaneous cases	LARF (%)
> 10 000	2	0.03	<0.01	86.59
2 000–10 000	10	0.05	0.02	72.09
1 000–2 000	63	0.08	0.13	39.24
500–1 000	188	0.12	0.38	24.41
200–500	790	0.24	1.61	13.10
100–200	656	0.09	1.34	6.07
<100	17 883	0.79	36.53	2.11
Total	19 592	1.40	40.03	3.39

These tables suggest that, among the almost 20 000 workers for whom thyroid dose information is available, of the order of one radiation induced case of thyroid cancer may be predicted among the 40 or so that would be likely to occur spontaneously in this population. Thus, given these doses, it is unlikely that an increase in the incidence in cancer will be discernible among this group of workers.

These results are also shown in Figs 4.4–1 and 4.4–2.

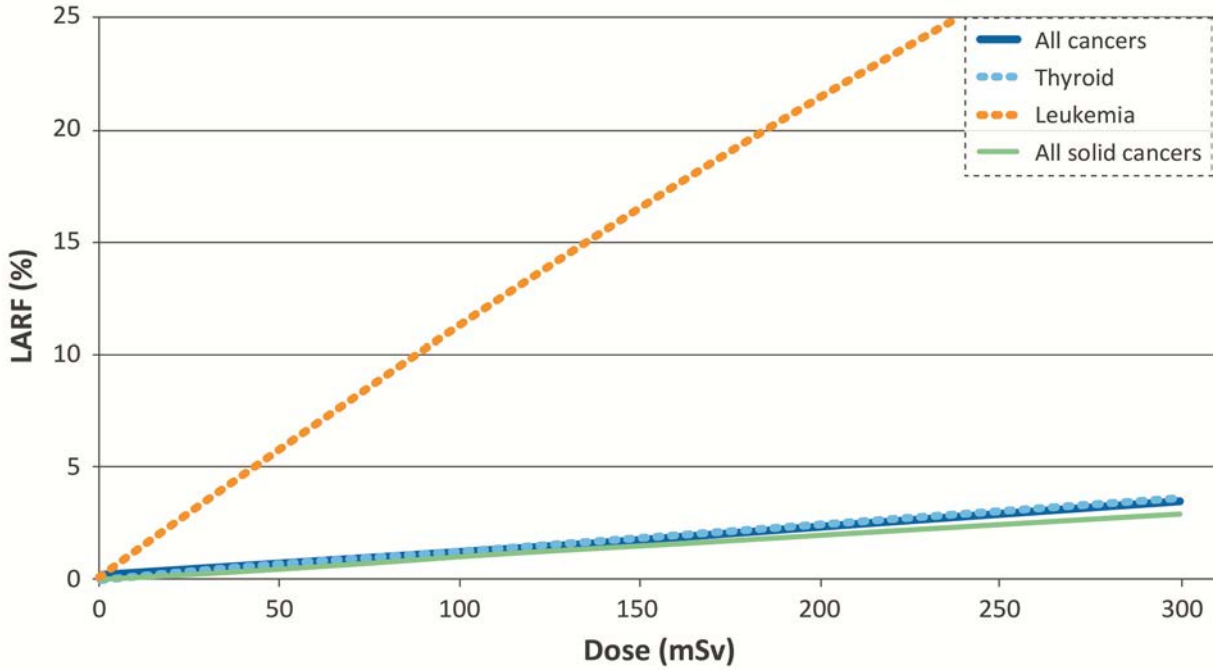


FIG. 4.4–1. Average age specific LARF (%) as a function of radiation dose, estimated with the ICRP model.

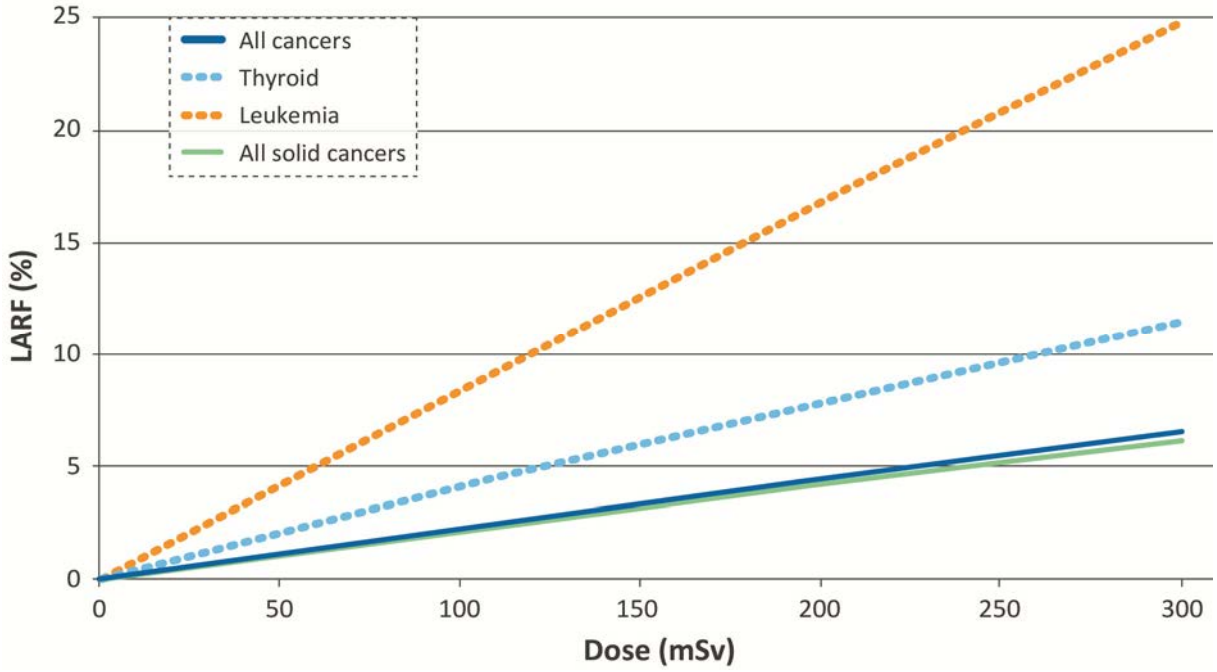


FIG. 4.4–2. Average age specific LARF (%) as a function of radiation dose, estimated with the WHO model.

4.4.5.3. Inferred risks for members of the public

LAR calculations have also been undertaken for the public at a range of locations and for various populations, including children in the areas where higher doses were received. These groups received lower doses than emergency workers, so the values of LARF are generally lower, at 1% or as low as 0.1%. The risk factors for thyroid cancer in young children are of the order of 1% for all of the areas for which thyroid dose information is available (see Annex X for more information). It is therefore

unlikely that an increase in the incidence in cancer, including thyroid cancer in children, will be discernible among members of the public as a result of releases from the Fukushima Daiichi accident.

4.4.5.4. Inference of potential risks from the Fukushima Daiichi accident

The value of the LARF was found to be less than 1%. This result may be placed in context by considering that data obtained from large scale epidemiological studies carried out following the Chernobyl accident have not been able to confirm inference of risk for LARF lower than 5% [343, 344]. The prospective theoretical risk inferred from the range of doses that appear to have been delivered during and following the Fukushima Daiichi accident are small, and it will not be possible to verify such a level of risk by the results of epidemiological studies.

In the low dose range, increases in cancer incidence are not discernible and hence increases in the incidence of cancer are not attributable to radiation at such doses.

4.4.6. Non-radiation effects: Mental health

There is evidence that the Fukushima Daiichi accident, and the subsequent radiation protection measures taken, have resulted in observable health effects that are not related to the action of radiation on tissues and cells in the human body. The presence of radiation is a component of the complex and stressful situation that arose following the accident. These health effects include psychological effects that reflect an apprehension about radiation exposure, and a lack of public understanding of the scientific data on health effects of low dose radiation. They also arise as an indirect consequence of measures such as evacuation that were taken to reduce radiation exposures. These have been highlighted in both of the UNSCEAR reports following the Chernobyl accident [246, 250], and the WHO [201] and UNSCEAR [5] reports following the accident at the Fukushima Daiichi NPP.

The Three Mile Island (TMI), Chernobyl and Fukushima Daiichi accidents produced anxiety and uncertainty about short and long term health consequences. In the previous accidents, these uncertainties were exacerbated by contradictory information from scientists and government and industry authorities; loss of faith in experts, related to protective actions taken to minimize potential radiation exposure; information of uncertain validity on both formal and informal media; and the rapid spread of rumours about birth defects, heart disease and, especially, cancer [345–347]. Studies of atomic bomb survivors and populations affected by the accidents at TMI and Chernobyl show strong associations between these uncertainties and observations of anxiety, depression and post-traumatic stress responses (PTSR), as well as medically unexplained physical symptoms [348–350]. These symptoms were found to be persistent and disabling in vulnerable subgroups impacted by the TMI and Chernobyl accidents, such as mothers of young children and cleanup workers. As a general example, Table 4.4–4 illustrates the cardinal symptoms of anxiety, depression and post-traumatic stress disorder (PTSD), which are the most common psychological conditions that occur after such accidents.

The small but growing number of surveys on the psychological aftermath following the Fukushima Daiichi accident has largely focused on the possibly vulnerable subgroups of the population (pregnant women and mothers of infants, rescue and cleanup workers and the evacuees). Some psychological consequences have already been detected in the affected population [202, 317, 351–359]. The largest survey of evacuees is the Mental Health and Lifestyle Survey conducted as part of Fukushima Medical University's Health Management Survey [202]. Information about other health effects can be seen in the study by Yabe et al. [317].

TABLE 4.4–4. EXAMPLES OF SYMPTOMS OF ANXIETY, DEPRESSION AND PTSD

Psychological condition	Examples of symptoms
Anxiety	Excessive worry
	Feeling fearful
	Feeling tense or keyed up
	Easily alarmed about health status
	Preoccupation with having or acquiring a serious illness
Depression	Persistent depressed mood
	Contemplation of suicide
	Significant change in weight or appetite
	Insomnia or hypersomnia
	Trouble in concentration
PTSD	Flashbacks, intrusive memories
	Nightmares
	Hypervigilance
	Easily startled
	Avoidance of trauma related thoughts

For the Mental Health and Lifestyle Survey, questionnaires first mailed in January 2012 contained standard symptom measures of trauma symptoms, PTSD and psychological distress (anxiety), as well as questions on concerns about radiation exposure and adversities resulting from the earthquake and tsunami. The adversities considered included loss of family or relatives, house damage, loss of employment, decrease in income, and evacuation destination (within or outside Fukushima Prefecture). Two methods were used for assessing the mental health status of adult evacuees[48]; the Kessler K6 scale[49] [360] and the post-traumatic stress disorder checklist (specific version, PCL-S)[50] [361]. An additional survey, using the CAGE questionnaire, was used to assess the level of alcoholism [362]. These surveys indicate that, over the period covered by this volume, mental health symptoms were higher than would be expected from surveys of the general population [352]. Preliminary results indicate that rates of probable PTSD, based on scoring above a standard cut-off point on the PTSD symptom questionnaire, are ~20% for women and ~17% for men. In contrast, the rate of PTSD in a general population sample of Japan reporting trauma exposure is less than 2% [352].

Yabe et al. [317] note that many evacuee households were separated and had to move several times. As a measure of general mental health, a factor, K6, was used in the survey. It was found that the percentage of adults who scored above the K6 cut-off for general mental health (14.6% in the fiscal year (FY) 2011 and 11.9% in FY 2012) was higher than usual, indicating mental health problems among the evacuees. In addition Yabe et al.[317] report that the percentage of adults scoring above the cut-off for PTSD using a checklist was 21.6% in FY 2011 and 18.3% in FY 2012.

[48] The target population was "the residents of evacuation zones including Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Namie Town, Katsurao Village, Minamisoma City, Tamura City, Yamakiya district of Kawamata Town, and Iitate Village" [317], which numbered in total 210, 189 in 2011 and 211,615 in 2012 [317].

[49] The Kessler scale was designed to be sensitive around the threshold for the clinically significant range of the distribution of non-specific distress in an effort to maximize the ability to discriminate cases of serious mental illness from non-cases. The text refers to the K6 Keller scale, which is one specific screening measure for psychological distress.

[50] The post traumatic stress disorder checklist is a 17 item self-report measure of post-traumatic stress disorder that assesses severity of PTSD symptoms.

The status of children's mental health was assessed using the Strength and Difficulties Questionnaire[51]. The proportion of children aged 4–6 years and of primary school age (6–12 years old) who scored above the cut-off (≥16) of the questionnaire were 24.4% in FY 2011 and 16.6% in FY 2012. These findings indicated psychological difficulties in children, with relative improvement year by year. Because of differences in measurement and metrics, it is not known how this level of distress compares with that found in children exposed to the earthquake and tsunami [353]. However, a study of depressive symptoms in a large sample of 6–15 year olds in Japan found a similar percentage scoring in the high distress range [363], suggesting that, as in the cases of the TMI and Chernobyl accidents, the affected children are highly resilient [364, 365].

Mothers and pregnant women [354]. Several studies and review papers have shown that, after the TMI and Chernobyl accidents, the psychological well-being of mothers of young children and pregnant women was poorer than that of other women and was adversely affected by radiation related fears [354]. Consistent with these findings, the Health Management Survey conducted a Pregnancy and Birth Survey that reported a rate of depression among mothers of young children and pregnant women of 14.6% [202]. A survey of mothers attending a check-up for children at 18 months of age in Fukushima City in 2012 indicated that 10% of these mothers were found to be depressed. Moreover, the rate of depression was two times higher among mothers residing in higher priority cleanup areas of Fukushima City than in those living in lower priority cleanup areas [355]. The rates in these two samples from Fukushima City are two to three times higher than expected for similarly aged women in Japan [356].

Following accidents involving the potential for significant radiation exposure, some pregnant women seek medical advice on whether or not their pregnancy should be terminated. A study by the Obstetrics and Gynaecology Department of the Fukushima Medical University reported that no such elective terminations were carried out in the aftermath of the accident [366, 367].

Workers [368]. A study was carried out comparing the mental health of workers at the two nearby nuclear power plants, Fukushima Daiichi and Fukushima Daini. Shigemura et al. found significantly more general psychological distress (GPD) and PTSR among workers at the Fukushima Daiichi NPP compared with the Fukushima Daini NPP workers in April–June 2011 [357, 358] (see Fig. 4.4–3). In both groups, there was a statistically significant association between the more severe distress and PTSR responses and experiencing perceived discrimination and slurs.

First responders. In a study of first responders (doctors, nurses, coordination staff) conducted in April 2011, 4.0% of the surveyed responders reported distress and 21.4% scored high on a depression symptom scale. However, the response rate was very low, and the prevalence estimates, though believed to be comparable with general population rates, have uncertain reliability. More importantly for the radiation related impact, the authors found that first responders who expressed concerns about radiation exposure were significantly more symptomatic on both measures than responders who were not concerned [359].

Evacuees living in shelters. In October–November 2012, a pilot study was conducted of evacuees living in shelters in two areas of Fukushima Prefecture [351]. The participation rate was low (13.4%). However, this was the first study related to the Fukushima Daiichi accident that involved face to face structured diagnostic interviews. The rates of diagnosable PTSD, depression and anxiety were found to be two to seven times higher than in the general population of Japan [369, 370].

[51] The Strengths and Difficulty Questionnaire is a brief child mental health questionnaire for children and adolescents aged 2–17 years, covering 25 attributes on symptoms related to mental health and behaviour divided between 5 scales: emotional symptoms, conduct problems, hyperactivity/inattention, peer relationship problems and prosocial behaviour.

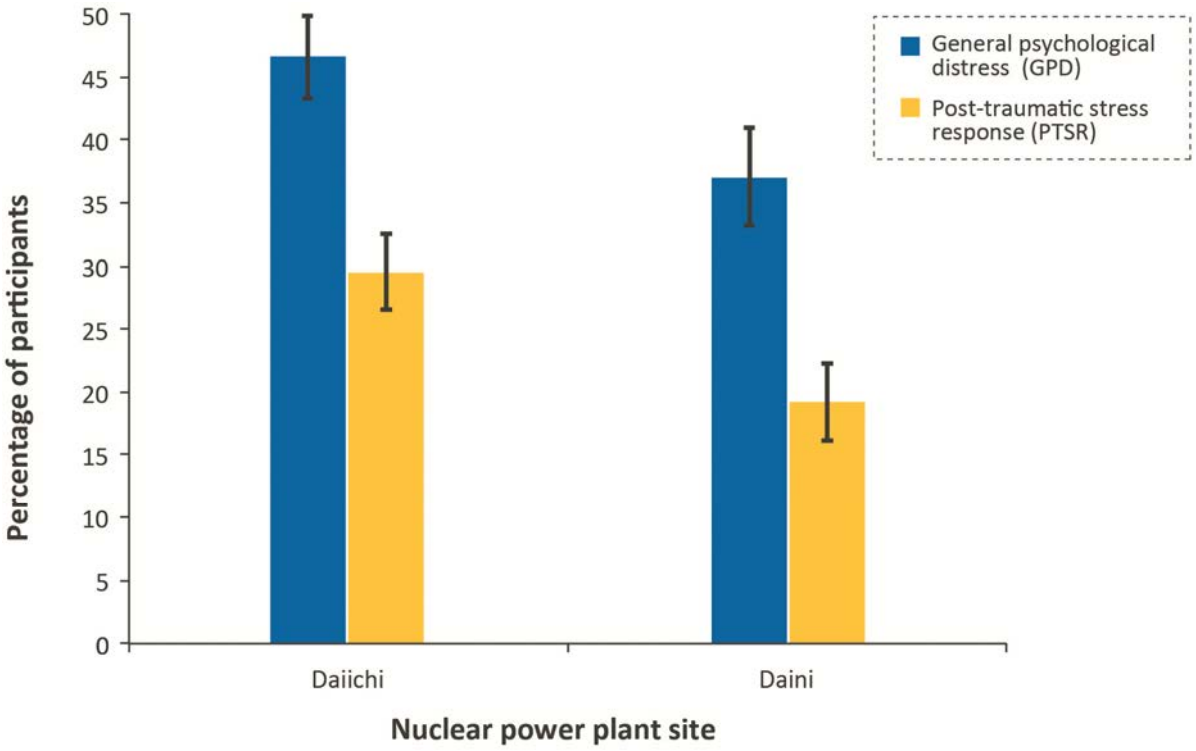


FIG. 4.4–3. Percentage of workers at the Fukushima Daiichi and Fukushima Daini NPPs reporting psychological distress, April 2011 [357].

Recent evidence suggests that concerns about radiation exposure similar to those that occurred after the TMI and Chernobyl accidents are widespread among Fukushima residents and evacuees. In the survey reported in Ref. [317] for residents and evacuees questioned in 2012, 3045 (9.5%) of residents reported that they felt an immediate effect of the accident was likely, for 19.5% a late effect was likely and 25.4% reported that a genetic effect was likely to occur as a result of exposure to releases from the Fukushima Daiichi NPP. This last finding is in spite of scientific evidence to the contrary. Two recent review studies of the data from the atomic bomb cohorts have shown that there is no transgenerational effect in people at any level of radiation dose [331, 332]. Thus, although the radiation doses received by the population are unlikely to result in discernible health effects, anxiety related to perceptions of exposure to radiation is very likely to lead to discernible psychological effects.

Communication and dissemination of accurate information received by the public at an early stage and during the development of the accident have helped to alleviate unwarranted psychological reactions [298].

4.4.7. Summary

The Fukushima Daiichi accident resulted in a large release of radioactive material to the environment, with the potential for exposing the local population to radiation. However, the affected population was largely protected against radiation exposure, and no one incurred a lethal dose of radiation or a dose sufficiently large to cause early health effects such as the tissue reactions often referred to as ‘deterministic effects’.

It should be noted, however, that there are health effects associated to radiation exposure that may be manifested after some latency time. These effects are commonly termed stochastic because of their probabilistic nature and are dominated by the induction of malignancies. The potential occurrence of

such effects cannot be disregarded at the time of writing owing to the latency periods for such effects. However, taking into account the low radiation doses incurred by members of the public in the regions affected by the accident, it is not expected that health effects will be discernible among the exposed members of the public or their descendants in the future.

The stochastic health effect with the greatest potential to be manifested after a nuclear accident is thyroid cancer among children. This is the result of the preferential absorption and irradiation of the thyroid gland following the intake of radioactive iodine by ingestion or inhalation. Previous experience shows that the dominant route for such intake is the ingestion of contaminated milk. In the case of the Fukushima Daiichi accident, this route was generally prevented by the implementation of controls on consumption, and the estimates of thyroid doses suggest that they were generally low. It seems, therefore, that there should not be any future increase in thyroid cancers that could be attributable to radiation exposure from the Fukushima Daiichi accident. Hereditable effects have also been mentioned to have such potential; however, a recent UNSCEAR report to the United Nations General Assembly states that "although demonstrated in animal studies, an increase in the incidence of hereditary effects in human populations cannot at present be attributed to radiation exposure" [371].

The health screening of workers and residents of Fukushima Prefecture has detected asymptomatic thyroid abnormalities — nodules, cysts and cancers — that would have gone undetected if asymptomatic children had been screened using standard equipment. Similar results were obtained when the same screening was carried out on children living far away from the areas affected by the accident [339, 341]. The latency time for radiation induced thyroid cancer is longer than the four years that have elapsed since the accident at the time of writing. In many cases, thyroid cancers were found in children in the late teenage years, but no cases were found in the most vulnerable group of children who were under five years of age on 11 March 2011. The proportion of suspicious or malignant cases was almost the same among regions in Fukushima Prefecture in the initial screening conducted in 2011–2013 [314]. These factors suggest that the thyroid abnormalities detected in the survey are unlikely to be associated with radiation exposure due to the accident. Following such a combined catastrophe of earthquake, tsunami and nuclear accident, psychological consequences among the affected population have been widely reported. Some of these effects can be associated to the fear and stigma caused by radiation exposure. While the majority of people impacted directly or indirectly by past accidents and disasters have proved resilient to the potential psychological effects from the situation, some vulnerable groups have been identified, including mothers and pregnant women, workers, and long term evacuees.

In the case of the Fukushima Daiichi accident, the inferred lifetime risk values are extremely low and well below the levels for which effects have been observed, and the hypothetical numbers of cancer cases calculated by using the risk models are a small fraction of the expected number of spontaneous cases. There is little likelihood of discerning an increase in cancer due to radiation from the accident at the Fukushima Daiichi NPP in the general population or among emergency workers in the future.

4.4.8. Observations and lessons

— **The risks of radiation exposure and the attribution of health effects to radiation need to be clearly presented to stakeholders, making it unambiguous that any increases in the occurrence of health effects in populations are not attributable to exposure to radiation, if levels of exposure are similar to the global average background levels of radiation.**
In the case of the Fukushima Daiichi accident, doses to members of the public were low and comparable with typical global average background doses. There is a need to clearly inform the public, particularly the people affected, that no discernible increased incidence of radiation related health effects is expected among exposed members of the public and their descendants as a result of the accident.

An understanding of radiation and its possible health effects is important for all those involved in an emergency, in particular for physicians, nurses, radiation technologists and medical first responders. This needs to be ensured through appropriate education and training of medical professionals in the topics of radioactivity, radiation and health effects associated with radiation exposure.

— **After a nuclear accident, health surveys are very important and useful, but should not be interpreted as epidemiological studies. The results of such health surveys are intended to provide information to support medical assistance to the affected population.**
The Fukushima Health Management Survey provides valuable health information for the local community, helping to ensure that any health effects are detected quickly, and that appropriate actions are taken to protect the health of the population. The overall results of health checks may provide important information, but they should not be misinterpreted as the results of an epidemiological assessment.

— **There is a need for radiological protection guidance to address the psychological consequences to members of the affected populations in the aftermath of radiological accidents. A Task Group of the ICRP has recommended that "strategies for mitigating the serious psychological consequences arising from radiological accidents be sought" [372].**
Psychological conditions have been reported as a consequence of the accident. This has been a repeated issue in the aftermath of accidents involving radiation exposure. In spite of its importance, these consequences have not been recognized in international recommendations and standards on radiological protection.

— **Factual information on radiation effects needs to be communicated in an understandable and timely manner to individuals in affected areas in order to enhance their understanding of protection strategies, alleviate their concerns and support their own protection initiatives.**
Arrangements at the national and local level need to be put in place to share information in an understandable manner with the public who may be affected by accidents with radiological consequences. The arrangements need to allow for person to person dialogue, so that individuals can seek clarifications and express their concerns. These arrangements will require the concerted efforts of the relevant authorities, experts and professionals in supporting and advising the affected individuals and communities. Sharing information is important when conveying decisions to protect these individuals, including the support of their own initiatives.

4.5. CONSEQUENCES FOR NON-HUMAN BIOTA

The releases of radionuclides to the environment as a result of the accident at the Fukushima Daiichi NPP not only raised concerns over the potential impact on humans but also over the possibility of any long term impacts on the living components of the environment.

Protection of the environment includes "the protection and conservation of: non-human species, both animal and plant, and their biodiversity; environmental goods and services". The term also includes "the production of food and feed; resources used in agriculture, forestry, fisheries and tourism; amenities used in spiritual, cultural and recreational activities; media, such as soil, water and air; and natural processes, such as carbon, nitrogen and water cycles" [220]. As explained in Section 4.3, environmental radiation protection objectives focus on populations. The ICRP has defined protection objectives as: to prevent or reduce the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities and ecosystems [256] (see Section 4.3.1).

Although residents within a 20 km radius of Fukushima Daiichi NPP were evacuated in order to reduce their radiation exposures, the exposure of non-human biota inhabiting these areas was unavoidable. Given the scale and complexity of the releases, the spatial and temporal variations in the

levels of deposited radionuclides, and the range of types of different terrestrial and aquatic biota affected, it has not been possible to obtain a fully comprehensive picture. Furthermore, the earthquake, the tsunami and the subsequent remedial work have given rise to physical and structural damage of the environment around the Fukushima Daiichi NPP, which also has consequences for the non-human biota.

The larger releases of radionuclides during the Chernobyl accident in 1986 led to the death of pine trees in the 'red forest' [373]. However, the release of radionuclides, and the corresponding doses to non-human biota occupying areas of high deposition in Japan, was much lower than in areas around Chernobyl. These facts indicate that severe detriments are not expected to have occurred and, in fact, acute effects were not observed immediately after the accident. Nevertheless, more subtle potential effects need to be investigated in the longer term.

4.5.1. Background to the assessment

4.5.1.1. The natural environment around the Fukushima Daiichi NPP

The location and characteristics of the environment around the Fukushima Daiichi NPP are described in Section 4.1.1. In the context of the present section, it should be noted that the terrestrial ecosystem structure is heterogeneous and contains many niches for wildlife. The Abukuma highlands contain a mixture of paddy fields, farmlands, secondary deciduous forest and evergreen coniferous trees, mainly cedar, where the biodiversity is high. Several coastal catchments extend from the coastal mountain range (at a distance of approximately 30 km from the coast) to the Pacific Ocean. The region is exposed to typhoons and spring snowmelt events, leading to severe soil erosion and subsequent export of sediment in rivers. There is a considerable range of birds and terrestrial mammals in the area[52], including the macaque monkey. The dominant natural species of trees include species of *Fagus*, *Carpinus*, *Zelkova*, *Aesculus*, *Pterocarpa*, *Acer* and *Abies*.

With regard to the marine environment, the local marine ecosystem is characterized by rich primary production, and the major primary producers are not only phytoplankton but also macro algae, especially brown algae. Such algae harbour rich fish and invertebrate fauna in the area [2].

4.5.1.2. The earthquake and the tsunami

The severe earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu, far in excess of that caused by radiation exposure. The earthquake induced topographic changes to the sea floor, and inundation following the tsunami resulted in the transfer of large volumes of marine sediments onshore. Elevated deposition of sediment affected the abundance of several benthic biota and may have a major impact on the biological functioning of the sediments for years to come [376]. The Biodiversity Center of Japan [377] has conducted an investigation on the impact of this event on the environment, excluding the radiation impact from the Fukushima Daiichi accident[53].

4.5.1.3. Environments affected

The releases of radionuclides, dispersion and deposition and the resulting activity concentrations in a range of environmental media have already been described in detail in Section 4.1.

---

[52] The Animal Distribution Atlas of Japan [374] and the Vegetation Map in Japan [375] describe the vegetation in Japan.

[53] Other reports of the effect of the tsunami on the ecosystems can be found in NAGAHATA, Y., How massive tsunami changed ecosystems (2012) [378]; NAKAJIMA, H. and KOARAI, M., Assessment of Tsunami Flood Situation from the Great East Japan Earthquake, Bulletin of the Geospatial Information Authority of Japan, Vol.59 December, 56–66 (2011) [379].

Terrestrial and freshwater environments

In the context of the terrestrial biota assessment in the initial phase, the MEXT soil survey described in Section 4.1 [380] is particularly useful. Samples for the first survey were collected between 6 June and 8 July 2011 from an area covering Fukushima, northern Ibaraki and southern Miyagi prefectures. The survey area comprised 2182 grid squares in total. A number of samples — normally five but ranging from one to seven depending on circumstances — were collected from each grid square. A consistent sample depth of 5 cm was used. All soil samples were analysed for gamma emitting radionuclides and the average deposition densities (Bq/m^2) were calculated. These measurements were used to construct accurate maps of activity concentrations in soil of each radionuclide measured.

Interception of ^{137}Cs, ^{134}Cs and ^{131}I by coniferous forest canopies were studied by Kato et al. (2012) [75] in Tochigi Prefecture, 150 km south-west of the Fukushima Daiichi NPP, with an estimated total deposition of ^{137}Cs in the area of less than 10 kBq. (See Annex III for more information.) Fresh water has been continuously monitored since the accident. Some aquatic species have also been measured. These data indicate that samples containing the highest activity concentrations were collected from rivers and lakes within Fukushima Prefecture. The information is presented in greater detail in Section 4.1.

Marine environment

Dispersed radionuclides in sea water may either be dissolved or adsorbed onto particulates that settle to bottom sediments, depending upon the chemical and physical characteristics of the radionuclides. A large fraction of radiocaesium is likely to remain in the water column and will follow the movement of the prevailing currents. When interaction with suspended material does occur, adsorption to clay is likely to be at least as important as adsorption (and presumably uptake) by plankton, which is often low [381]. Thereafter, transfer to bottom sediment can occur through processes such as the settling of particulate detrital products from plankton [382]. The highest activity concentrations of radionuclides were measured close to the Fukushima Daiichi NPP directly after the accident (in April 2011). The main radionuclides detected were ^{134}Cs, ^{137}Cs and, during the first few months, ^{131}I. The initially high levels of radiocaesium observed in proximity to the facility decreased significantly with time and space. According to UNSCEAR, the deposition of radiocaesium close to the coast was estimated to be around 10^4 Bq/m^2 and around 10^2–10^3 Bq/m^2 at a distance of 500 km [5]. However, the concentration of radionuclides in sea water was highly variable in both space and time, ranging from 1 to 50 kBq/L for ^{131}I and from 0.1 to 20 kBq/L for radiocaesium near the outlet in the coastal area within the first months following the accident. At greater distances, at locations in the open sea, the concentrations were much lower (>300 times). For the assessments in the initial phase, daily time series data of activity concentrations in sea water close to the Fukushima Daiichi NPP from TEPCO [118] and Vives-i-Batlle (2014) [383] were key sources of information.

Concentrations of radiocaesium in sediments from the surface of the seabed have been regularly measured in coastal areas. Close to the outlet of the Fukushima Daiichi NPP, the highest concentration of ^{137}Cs was detected in dry sediments (approximately100 kBq/kg dry mass) [5].

4.5.2. Dose assessment approaches, end points and benchmarks

To meet a growing demand for increased focus on the protection of the environment from ionizing radiation, several organizations have developed approaches to the assessment of radiation induced effects with the probability of causing long term consequences for non-human biota. These assessment methodologies tend to be based on simple assumptions. Uncertainties are thus usually taken into account by the use of conservative assumptions that tend to overestimate the radiological consequences [384].

The generally accepted approach has been to focus on the viability of biota populations and the integrity of ecosystems. Thus, it is assumed that, although individual biota may be harmed by radiation, it does not necessarily follow that this will have an impact on the survival of populations, nor on the structure and function of ecosystems.

The evaluation of potential impact is closely related to the assessments of the relevant biological end points. It is widely recognized that the most relevant biological end points in terms of potential environmental impact are those that could lead to changes in population size or structure and affect the ability of an organism to reproduce [385, 386].

Calculating radiation doses to biota is relatively simple, if certain simplifying assumptions are made. It is more difficult to relate the calculated doses to biological effects that can be attributed to the absorbed radiation. Naturally occurring radioactive material is ubiquitous in the environment, and in many cases, the natural background is the dominant source of exposure to any given organism [387].

The ICRP assessment approach has been adopted in this volume. This approach is based on a framework of an underlying set of twelve reference animals and plants (RAPs)[54] that relate exposure to dose, and dose to effect, for a limited number of biota that are typical of the major environments.

Numerical benchmarks have been developed that enable comparison with the estimated dose rates. The ICRP defined a set of reference values (Derived Consideration Reference Levels (DCRLs)) specific to each of the different RAPs, following a review of the effects of radiation on similar types of biota [260]. Each DCRL is a band of dose rates, spanning one order of magnitude, within which there is some chance of causing deleterious effects in individuals of a given RAP category arising from exposures to ionizing radiation according to the ICRP [260]. The relevant values and the list of reference animals and plants are given in Table 4.5–1.

TABLE 4.5–1. DERIVED CONSIDERATION REFERENCE LEVELS (DCRLs) FROM ICRP 108 (2008) [260]

DCRLs (mGy/d)	Reference animals and plants
0.1–1	Deer, rat, wild duck, pine tree
1–10	Frog, trout, flat fish, wild grass, brown seaweed
10–100	Bee, crab, earthworm

Other useful benchmarks have also been made available. In the scientific annexes to the 1996 and 2008 UNSCEAR reports [246, 255], published data on the exposures and effects on non-human biota

[54] RAPs are, by definition, points of reference, although other organisms could be identified similar to RAPs, relevant to each situation and geographical location. Reference data sets have been developed allowing exposures to be derived and placed in the context of dose effects information for RAPs [260]. For example, concentration ratios have been tabulated [260] by which whole body concentrations for the selected radionuclide concentrations in RAPs can be derived from corresponding radionuclide concentrations in ambient media. The explicit criterion for application of concentration ratios is that near steady state or equilibrium conditions exist between biotic and abiotic environmental compartments. However, this may not be valid for all types of radionuclides released to the environment and may have limited application for an emergency situation where ambient concentrations fluctuate rapidly with time. Once radionuclide activity concentrations in RAPs have been derived (or directly measured) and ambient media concentrations are known, dose rates can be calculated through the application of tabulated dose conversion factors [260].

have been evaluated[55]. The derived conclusions are that "chronic dose rates of less than 100 μGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities" and that "maximum dose rates of 400 μGy/h to a small proportion of the individuals in aquatic populations of biota would not have any detrimental effects at the population level" [246]. These values are in agreement with the values reported elsewhere [246, 388, 389].

Other values have been identified for guidance on the environmental impact assessments. The research projects ERICA[56] and PROTECT [390, 391], funded by the European Commission, defined a generic dose rate of 10 μGy/h, to be used as benchmarks for screening assessment purposes during chronic exposure conditions.

All these reported values are primarily related to chronic rather than acute exposures. These facts have to be taken into account when interpreting the results following the assessment of the radiological consequences for non-human biota in the areas around the Fukushima Daiichi NPP. Furthermore, care must be taken in deciding about the impact to populations of animals or plants as opposed to small groups of individuals as reflected in the DCRL compilation. Population modelling approaches demonstrate that the linkage from radiation effects in individuals to population impacts is very complex and may be dependent on factors other than radiation doses and the dose–response relationships such as life history traits [392].

4.5.3. The dose assessment of non-human biota in the vicinity of the Fukushima Daiichi NPP

The dose assessment undertaken for the purposes of this volume comprises two distinct components. The first part concerns the application of activity concentration of radionuclides in environmental media, i.e. water, sediment and soil (or deposition) to calculate doses to adult RAPs following the releases from the Fukushima Daiichi NPP. The use of such data reflects the absence, or sporadic coverage, of direct radionuclide activity concentrations measurements in plants and animals for this period and requires the application of transfer models in deriving the levels of radionuclides associated with wildlife. Nevertheless, it gives an indication of the likely dose rates, and thus the effects, of biota generally in these areas.

Dose rates to biota have thus been estimated for defined time periods following the releases from the Fukushima Daiichi NPP. The source of the input datasets for this part of the assessment is the same as those used by UNSCEAR in its 2013 report [5]; however, the methodology applied, in particular the methodology for modelling transfer in the environment, is different and specific to the application of RAPs.

The second part of the assessment is based on data pertaining to directly measured activity concentrations in biota (and their habitats) from the review presented in this volume (see Section 4.5.3.2). These data provide the most precise estimates of doses, because the approach avoids the use of transfer models with their concomitant uncertainties. Reference dosimetric models for

---

[55] UNSCEAR has repeatedly collated data on effects of radiation on non-human biota [246, 255] to provide, inter alia, a context for environmental impact assessments. Other compilations of data have also been made, of which the database FREDERICA, developed within the European Commission funded projects Framework for Assessment of Environmental Impact (FASSET), Environmental Risk from Ionizing Contaminants: Assessment and Management (ERICA) and Environmental Protection from Ionizing Contaminants in the Arctic (EPIC), is one of the more comprehensive. Data are structured as suggested by the ICRP.

[56] Several research projects have been supported by the EC during recent years, such as the FASSET, ERICA, Protection of the Environment from Ionizing Radiation in a Regulatory Context (PROTECT) and EPIC projects, which contributed to the ultimate goal of developing an integrated approach to assessing and managing the impact of radiation on the environment. In support of this aim, an assessment tool (ERICA) and a database on radiation effects in biota (FREDERICA) were developed. Work on the testing and intercomparison of the tools and methods developed in the aforementioned projects and elsewhere has continued at the IAEA through the EMRAS II and MODARIA programmes.

RAPs have been used in the exposure estimates for the second part of the assessment, whenever possible. In some cases, bespoke models were required where the biota differed considerably from those included in the list of RAPs. More details of the method used to calculate absorbed dose rates from activity concentration data are provided in Annex XII.

4.5.3.1. Assessment based on activity concentrations of radionuclides in environmental media

The assessment of the exposures resulting from the accident has been divided into three distinct periods in order to take into account the time dependence of the delivery of dose. The dose was estimated based on the time integrated activity concentrations in soil, fresh water and sea water (water and sediment) for the periods listed below:

— An early, acute period, during which exposures from short lived radionuclides, notably ^{131}I, occurred (30 days, mid-March–mid-April 2011);
— An intermediate period after 31–90 days (mid-May–mid-September 2011), when data on activity concentrations in the environment are available;
— Late period after 90 days (up to one year), when equilibrium is assumed, especially for radiocaesium (chronic exposures). [57]

These periods have been appropriately selected to address the time dependence of activity concentrations in the environment while removing an emphasis on ephemeral, very high values.

The radionuclides considered for the various assessments periods were:

— In the early and intermediate periods: ^{134}Cs, ^{137}Cs and ^{131}I;
— In the late period: ^{134}Cs, ^{137}Cs.

Other short lived radionuclides, particularly ^{132}I and ^{132}Te, may also have been important in the early acute period. However, the environmental measurements available for these radionuclides are too limited to allow a reliable estimate of dose rates.

Concentration ratios (CRs) can be used to derive activity concentrations in biota from activity concentrations in media. These values are strictly applicable in situations in which an equilibrium has been established between the levels of elements in different environmental media. These values are generally intended for application in assessing routine releases of radionuclides to the environment. However, the use of time integrated activity concentrations in media extends the applicability of this approach to situations where radionuclide concentrations are changing rapidly with time. Example calculations of CRs for biota in different environments are presented in Annex XII.

This approach has been used to calculate whole body concentrations of radionuclides in animals during the early and intermediate periods and in all biota types, including vegetation, during the late phase.

Terrestrial

The method of calculating the radionuclide content in vegetation at a specific time, accumulated via direct deposition from the air, is set out in Annex XII.

[57] Equilibrium is unlikely to have been established on a timescale of 90 days for some RAPs (notably the pine), leading to additional uncertainties.

A single deposition event on 15 March has been assumed to simplify the assessment[58]. Further information regarding the assumptions and parameters used in this assessment is presented in Annex XII.

Soil activity concentrations as a function of time (to allow derivation of external dose rates and application of CR values) are also required for exposure estimates. The method of calculating the component of deposited radioactivity which becomes associated with soil is set out in Annex XII.

The time integrated activity concentration in vegetation and soil is calculated for 0–30 day and 31–90 day periods. The radionuclide concentrations in soil at one year were determined for the late period exposure calculations.

Concentrations for terrestrial RAPs are derived from soil concentrations using CRs for terrestrial RAPs (Annex XII). Thereafter, doses for all biota are derived using the methodology described above.

The highest activity of ^{137}Cs at a location in Okuma Town was used to provide an indication of exposures to the most highly exposed individuals in animal and plant populations [5]. Corresponding ^{131}I levels were based on ^{131}I:^{134}Cs ratios [69] (see Annex XII).

Dose rates for terrestrial RAPs during the initial phases of the Fukushima Daiichi NPP releases are presented in Fig. 4.5–1. Maximum dose rates in the range of 0.8–0.9 mGy/h (approximately 20 mGy/d) were calculated for the (wild) grass and (pine) tree RAPs in the initial 0–30 day period post-accident. These dose rates decreased rapidly to be in the range of 10–20 μGy/h (0.25–0.5 mGy/d) within the first year of the assessment. Substantially lower dose rates were calculated for animals. Maximum dose rates were estimated in the initial 0–30 day period reflecting the contribution of ^{131}I to total exposures.

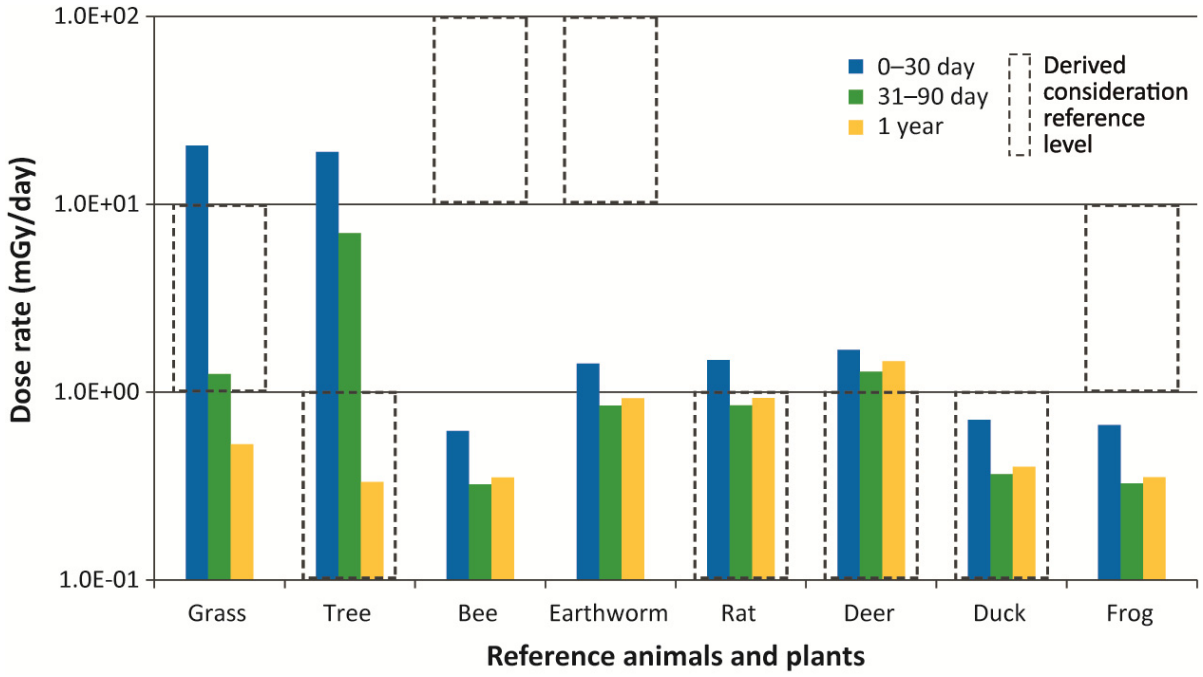


FIG. 4.5–1. Dose rates (mGy/d) for terrestrial RAPs versus time at Okuma Town.

[58] This corresponds to the date at which the greatest proportion of the atmospheric release occurred, while the wind direction and weather conditions led to deposition onto the terrestrial environment.

The deer RAP exhibited the highest estimated exposures of the animals considered in the assessment: maximum dose rates of 70 μGy/h (1.7 mGy/d) were estimated, but this value decreased to 60 μGy/h (1.4 mGy/d) in the first year. Accumulated dose rates for terrestrial RAPs are also presented in Fig. 4.5–1. The highest accumulated doses were derived for vegetation, reflecting the relatively high dose rates calculated for the (wild) grass and (pine) tree RAPs in the initial period. A significant fraction of the dose was accumulated over the 0–30 day period for all RAP categories.

Marine

Exposures of biota to radiation in the marine environment vary according to the organism's habitat. All biota will be internally exposed via the contaminated food web, and benthic biota are likely to receive a substantial additional external exposure from contamination associated with seabed sediments. External exposures of pelagic biota are likely to be low in comparison. The dispersal of radionuclides over large spatial areas with time will therefore moderate the exposures to pelagic marine fish and other marine species.

The time integrated activity concentrations in sea water and sediment have been derived for the periods: 0–30 days and 31–90 days.

The datasets for a point 30 m north of the discharge channel of Units 5 and 6 of Fukushima Daiichi NPP and the south channel, approximately 1.3 km south of the discharge channel from Units 3 and 4, were selected from UNSCEAR (2014) [5]. These constitute the sampling locations where activity concentrations were at a peak and correspond to those values presented in Section 4.1.2 of this volume.

Radionuclide concentrations in marine biota are obtained from the concentrations in the dissolved phase in sea water, multiplied by the appropriate concentration ratios as described in Annex XII.

Dose rates for marine RAPs during the initial phases of the Fukushima Daiichi NPP releases are presented in Fig. 4.5–2, along with accumulated doses for the periods of 0–30 days and 31–90 days. Maximum exposures were derived for the brown seaweed RAP, for which dose rates exceeded 70 mGy/d (3 mGy/h) in the initial 0–30 day period. This elevated dose rate reflected the relatively high bioaccumulation of radioiodine by macroalgae from sea water. However, dose rates decreased rapidly for this RAP group, with dose rates approaching 2.4×10^{-3} mGy/d (0.1 μGy/h) after one year of elapsed time. Dose rates for the flatfish and crab RAPs were in the range of 1.7–3.4 mGy/d (70–140 μGy/h) in the initial high exposure period and deceased to dose rates around 0.12–0.14 mGy/d (5–6 μGy/h) in the intermediate period. The elevated dose rates for these RAP groups in the late period compared with macroalgae reflects the importance of external exposure from radiocaesium in the seabed for flatfish and crab, Brown seaweed is assumed to be externally exposed to radionuclides present in the water column only.

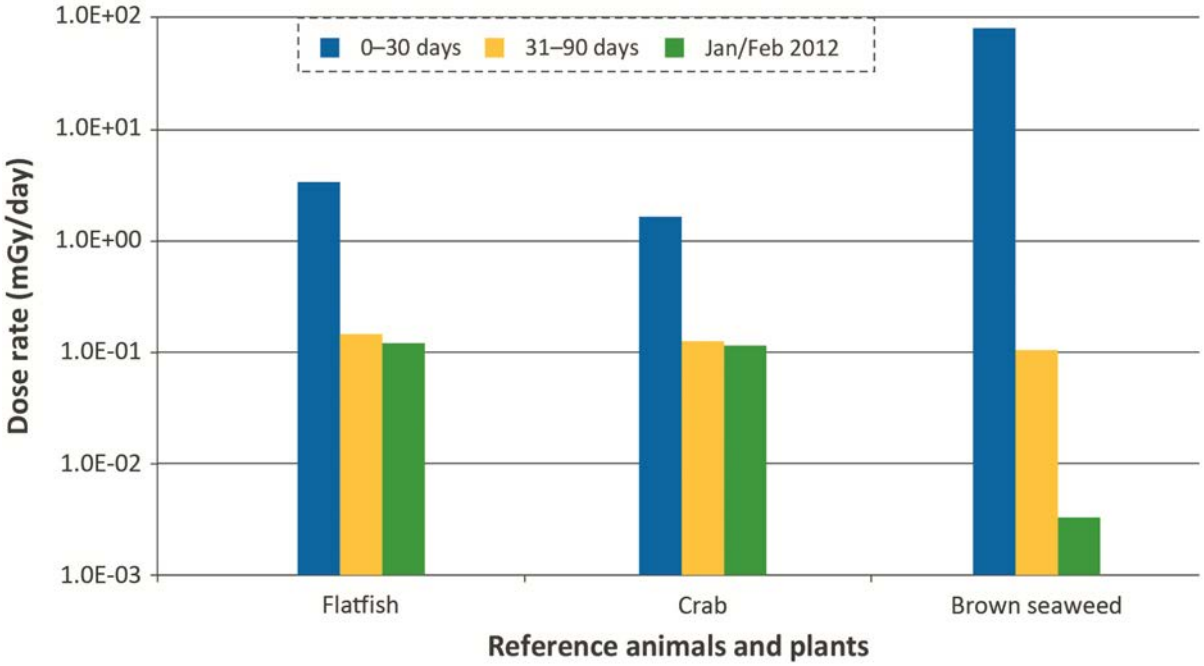


FIG. 4.5–2. Dose rate (mGy/d) for marine RAPs versus time at location 30 m north of discharge channel of Units 5 and 6 of the Fukushima Daiichi NPP.

4.5.3.2. Assessment based on directly measured activity concentrations in biota

Numerous papers have reported activity concentrations in biota that are said to arise from releases from the Fukushima Daiichi NPP. Data selected from information for radionuclide activity concentrations for biota presented in this volume have been used in conjunction with data on activity concentrations in the organism's habitat (i.e. in sea water, fresh water, sediments or soil) to provide a quantification of total exposures at the time of sampling. In practice, this was achieved by mapping each of the selected organism types onto an appropriate organism geometry and then using the corresponding dose conversion coefficients (DCCs) for internal and external exposures from ICRP Publication No. 108 [260] as described in Annex XII. In those cases where an appropriate geometry was not available, bespoke dose conversion coefficients were derived for what were effectively the representative organisms (RAPs)[59], using the ERICA tool [393, 394].

Concentrations of ^{134}Cs and ^{137}Cs in the muscle of Japanese monkeys (*Macaca fuscata*) inhabiting the forest area of Fukushima City were measured by Hayama [395]. Concentrations in muscle were in the range of 6000 to 25 000 Bq/kg for monkeys captured in areas with soil contamination levels in the range of 100 000 to 300 000 Bq/m^2. Levels decreased rapidly in May and June 2011 and reached an equilibrium value of around 1000 Bq/kg in monkeys captured during and after June, although there were substantial individual differences.

The concentration of radiocaesium in leaves of Japanese cedar, bamboo and *Clinopodium gracile* was measured by Tazoe et al. (2012) [396]. Samples of Japanese cedar leaves collected in April and June 2011, respectively, showed a much lower concentration of radiocaesium than leaves from the bamboo (approximately 450 kBq/kg), which might be due to the differences in overlapping branches (interception). Grass sampled from Namie Town showed a maximum activity concentration of approximately 350 kBq/kg of radiocaesium in April. Japanese mugwort showed very low

[59] The organism or group of organisms that are the actual ecological entity being assessed.

concentrations (<0.5 Bq/kg), despite relatively high concentrations of ^{137}Cs in the soil (6.3–27.1 kBq/kg).

Kuroda et al. (2013) [397] investigated the radiocaesium concentrations in the stemwood of three major Japanese tree species (oak, cedar and red pine trees) collected from five sites in Fukushima Prefecture. Half a year after the Fukushima Daiichi accident, radiocaesium was distributed in bark, sapwood and heartwood, indicating a very rapid translocation of radiocaesium into the wood. The concentration levels in the components of the tree depended on the radiocaesium deposition density. At all sites and for all species, radiocaesium activity concentrations were substantially greater in bark than they were in sapwood and heartwood.

The concentrations of earthworms in forests of Fukushima Prefecture were measured six months after the accident at three forest sites located at distances of 26 km–134 km from the site of the Fukushima Daiichi NPP [398]. Japan has a high diversity of terrestrial earthworms, especially those in the family *Megascolecidae*. Three plots were Japanese cedar plantations (*Cryptomeria japonica*), and one plot was a mixed forest of oak (*Quercus serrata*) and pine (*Pinus densiflora*). The deposition densities of radiocaesium ($^{134+137}$Cs) varied from 20 kBq/m^2 at a site located 134 km from the NPP to 1230 kBq/m^2 at a site located 26 km from the plant. The highest concentrations in earthworms were 61 ± 41 kBq/kg of ^{134}Cs; values of 70 ± 46 kBq/kg (dry weight) of ^{137}Cs were also found at this site. The lowest values — 1.26 ± 1.17 and 1.46 ± 1.17 kBq/kg (dry weight) for ^{134}Cs and ^{137}Cs, respectively — were obtained for soil invertebrates sampled at the distance of 134 km from the Fukushima Daiichi NPP. No substantial differences in $^{134+137}$Cs concentrations were identified for different species of earthworms on the same plots [398].

The concentrations of radiocaesium (^{134}Cs and ^{137}Cs) were measured in large web spiders, *Nephila clavata L. Koch* (*Nephilidae: Arachnida*), collected at three sites at different distances from the Fukushima Daiichi NPP about 1.5 years after the accident [399]. The radiocaesium concentrations in spiders were highest in a streamside secondary forest 33 km north-west of the Fukushima Daiichi NPP with a mean of 2.4 ± 1.2 kBq/kg (dry weight) for ^{134}Cs and 4.0 ± 1.8 kBq kg^{-1} (dry weight) for ^{137}Cs. At a hillside secondary forest 37 km north-west of the Fukushima Daiichi NPP, the mean concentrations of ^{134}Cs and ^{137}Cs were 0.83 ± 0.25 kBq/kg (dry weight) and 1.5 ± 0.5 kBq/kg (dry weight), respectively.

In a pine forest 62 km west of the Fukushima Daiichi NPP, very low radiocaesium concentrations were detected. The concentrations of ^{134}Cs and ^{137}Cs in spiders collected at each site tended to correlate with the measured external air dose rate at each site. Spiders are key components of food webs in forests and, consequently, the relatively high concentrations of measured radiocaesium in these species may indicate that the deposited radiocaesium from the accident had reached higher trophic levels of the food chains [399].

An overview of radiocaesium in freshwater fish in Fukushima Prefecture and eastern Japan was based on data published in Mizuno et al. in 2013 [400]. An isogram map shows the radiocaesium contamination of the Ayu (*Plecoglossus*) captured between May and September 2011 in each prefecture in eastern Japan. At about 100 km from the Fukushima Daiichi NPP, the average concentration was about 200 Bq/kg and decreased with larger distances. However, no information is given in the study about uncertainties or variability. Nor is any information provided on where the fish were caught. The data do, however, indicate that the levels of concentration in fish were relatively low.

With regard to the marine environment, activity concentrations in pelagic fish and plankton were measured in samples collected at 50 stations at the Japanese coast in June 2011 [401]. The amount of radiocaesium ranged from below the detection point to about 56 Bq/kg (dry weight). Silver-110m was occasionally detected in zooplankton, with concentrations up to 23.6 Bq/kg (dry weight). The authors

concluded that "radiation risks due to these radionuclides are below those generally considered harmful to marine animals and human consumers" [401]. The input datasets for the assessment are provided in Tables 4.5–2 and 4.5–3.

TABLE 4.5–2. INPUT DATA USED AND DOSE RATES DERIVED FOR THE ASSESSMENT BASED ON DIRECTLY MEASURED ACTIVITY CONCENTRATIONS IN TERRESTRIAL BIOTA

Species (RAP)	Activity concentration Bq/kg fresh weight biota (radionuclide)	Activity concentration Bq/kg dry weight or Bq/L (media)	Notes (date, location, methods)	Reference	Dose rate (mGy/d)
Japanese monkey, *Macaca fuscata*	2.5×10^4 (radiocaesium)	4.6×10^3 (soil)	April 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived using the methodology outlined by Ulanovsky et al. (2008) [394] and bodyweight data provided in article	Hayama et al. (2013) [395]	0.2
Japanese monkey, *Macaca fuscata*	1×10^3 (radiocaesium)	4.6×10^3 (soil)	July 2011; Fukushima City (>50 km NW of Fukushima Daiichi NPP); bespoke DCCs derived as above	Hayama et al. (2013) [395]	0.03
Japanese cedar, *Cryptomeria japonica* (Pine Tree)	3.3×10^3 (Cs-137) 2.8×10^3 (Cs-134)		August 2011; Kawauchi Village (37°20′15″N, 140°48′34″E) approximately 20 km W of Fukushima Daiichi NPP; whole tree activity concentrations, weighted according to model tree	Kuroda et al. (2013) [397]	0.1
Earthworm, *Amynthas sp.* (Earthworm)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	1.2×10^4 (Cs-137) 1.0×10^4 (Cs-134)	August 2011; Kawauchi Village (37°17′18 ″N, 140°47′47 ″E)	Hasegawa et al. (2013) [398]	0.4
Web spiders *Nephila clavata L. Koch* (Bee)	1.4×10^3 (Cs-137) 8.6×10^2 (Cs-134)	1.5×10^4 (Cs-137) 9.6×10^3 (Cs-134)	October 2012; streamside secondary forest dominated by broadleaved trees, about 33 km north-west of Fukushima Daiichi NPP; dry/fresh ratio = 0.36 for site. No soil data but appears to be in an area where soil deposition was approx. 1 MBq/m^2 from July 2011	Ayabe et al. (2014) [399]	0.1
Bamboo (Wild Grass)	2.0×10^5 (Cs-137) 2.0×10^5 (Cs-134) No data (I-131)	8.4×10^4 (Cs-137) 8.2×10^4 (Cs-134) 2.9×10^4 (I-131)	12 April 2011; Tetsuzan dam (37°34.5'N, 140°52.9'E), 21.8 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	2
Grass (Wild Grass)	1.9×10^5 (Cs-137) 1.6×10^5 (Cs-134)	9.0×10^3 (Cs-137) 9.0×10^3 (Cs-134)	13–14 April 2011; Namie Town (37°29′N, 141°00′E) approximately 20 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	1
Grass (Wild Grass)	5.9×10^3 (Cs-137) 6.0×10^3 (Cs-134)	8.5×10^3 (Cs-137) 8.5×10^3 (Cs-134)	June–July 2011; Keiko Park, Motomijya City (37°31′N, 140° 24′E), >50 km from Fukushima Daiichi NPP	Tazoe et al. (2012) [396]	0.1

TABLE 4.5–3. INPUT DATA USED FOR THE ASSESSMENT BASED ON DIRECTLY MEASURED ACTIVITY CONCENTRATIONS IN AQUATIC BIOTA

Species (RAP)	Activity concentration Bq/kg fresh weight biota (radionuclide)	Activity concentration Bq/kg dry weight or Bq/L (media)	Notes (date, location, methods)	Reference	Dose rate (mGy/d)
Ayu, *Plecoglossus altivelis altivelis* (Trout)	3.3×10^{3} (radiocaesium)	7.8×10^{3} (Cs-137) 6.9×10^{3} (Cs134)	Biota, Mano River between May and September 2011, sediment 29 May 2011; Mano River in Minamisoma City at Majima bridge approximately 40 km from Fukushima Daiichi NPP. The paper refers to quasi Cs-137, which appears to equate to radiocaesium (Cs-134 + Cs-137). A 1:1 ratio has been used. Water concentrations are not given, but a rough estimate of external exposures can be attained by assuming exposure to sediment. Maximum value reported for Ayu.	Mizuno and Kubo [400]	0.1
Zooplankton mixed Copepods (Zooplankton)	1.1×10^{1} (Cs-137) 8.2×10^{0} (Cs-134)	2.4×10^{-3} (Cs-137) 1.0×10^{-3} (Cs-134)	4–18 June 2011; at least 30 km offshore Fukushima Daiichi NPP; values given as dry weight, converted to fresh weight using factor from Hosseini et al. (2008) [402].	Buesseler et al. (2012) [401]	5×10^{-5}
Fish – S. gracile (Flatfish)	2.8×10^{0} (Cs-137) 2.7×10^{0} (Cs-134)	3.9×10^{0} (Cs-137) 3.8×10^{0} (Cs-134)	4–18 June 2011; at least 30 km offshore from Fukushima Daiichi NPP; S. gracile appears to be a deep water species: note surface water activities used (likely to be conservative).	Buesseler et al. (2012) [401]	1×10^{-4}

Dose rates for terrestrial plants and animals for which direct activity concentration measurements in biota were available (Table 4.5–2) are presented in Fig. 4.5–3 for two periods corresponding to 0–90 days post-accident and the 'chronic exposure' (later than 90 days, i.e. equilibrium conditions) period following this. Maximum dose rates of approximately 1 to 2 mGy/d (50 to 90 μGy/h) were calculated for bamboo and grass in the 0–90 day period at sites located at around 20 km from the Fukushima Daiichi NPP. Although dose rates for grass appear to have decreased relatively sharply with time, falling to approximately 0.1 mGy/d (approximately 5 μGy/h) after the 90 day period, this might equally be explained by sampling location — the latter exposure estimate pertaining to a site exceeding a distance of 50 km from the Fukushima Daiichi NPP. For Japanese monkeys (*Macaca fuscata*) inhabiting the forest area of Fukushima City, absorbed dose rates of approximately 0.2 mGy/d (8 μGy/h) in the initial period (April 2011) can be derived. These values decrease to

approximately 0.03 mGy/d (1 μGy/h) in the late period (post-July 2011). By the summer of 2011, and at a distance of approximately 20 km west of the Fukushima Daiichi NPP, dose rates for earthworms and cedar trees were approximately 0.4 mGy/d (15 μGy/h) and 0.1 mGy/d (5 μGy/h) respectively. Finally, dose rates for web spiders for a sampling site about 33 km north-west of Fukushima Daiichi NPP, were of the order of 0.1 mGy/d (5 μGy/h) in October 2012.

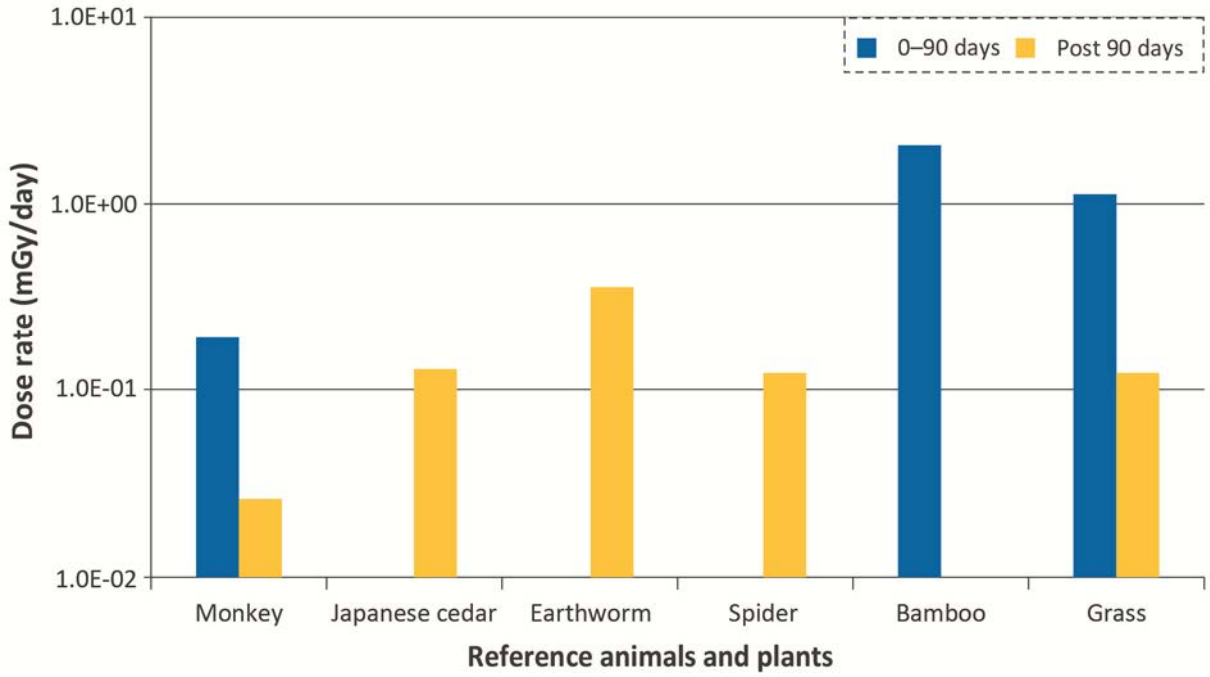


FIG. 4.5–3. Dose rates for terrestrial plants and animals for which direct activity concentration measurements in biota were available.

The dose rate for marine plants and animals for which direct activity concentration measurements in biota were available (Table 4.5–3) are presented in Fig. 4.5–4 for the period post-90 days following releases from the Fukushima Daiichi NPP. Bearing in mind that the marine samples were collected at least 30 km off the shore of the Fukushima Daiichi NPP, dose rates for marine fish and zooplankton fell substantially below 2.4×10^{-4} mGy/d (0.01 μGy/h). In contrast, dose rate for freshwater fish sampled at around 40 km from the Fukushima Daiichi NPP may have exceeded 0.1 mGy/d (4 μGy/h) in the chronic exposure phase.

Any assessment of the effects on non-human biota is inevitably subject to a high degree of uncertainty. In this particular assessment, it was difficult to account for short lived radionuclides in the initial post-accident period. Overall uncertainties associated with the types of models applied in this assessment, particularly those involving a biological transfer component (and as required in a large part of the most contaminated areas), are normally large — as typified by the observation that estimations using different models often differ from one another by more than an order of magnitude [403]. In contrast, where dose rates were estimated using directly measured concentrations of radionuclides in biota, uncertainties are much lower.

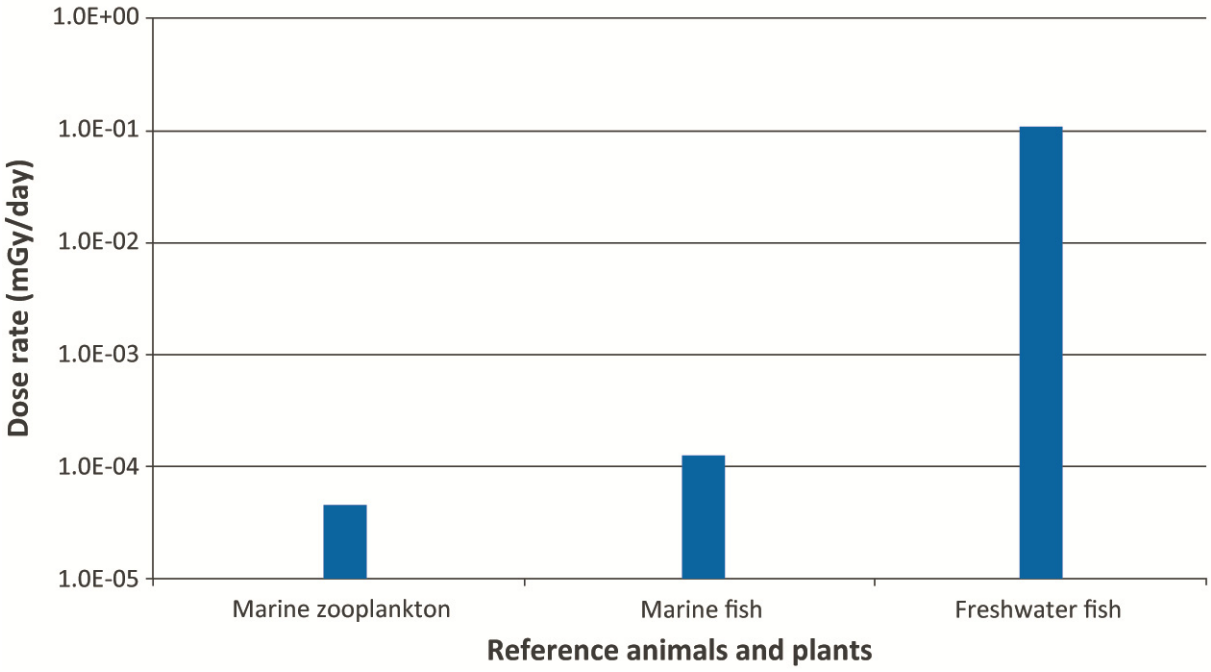


FIG. 4.5–4. Dose rates for freshwater and marine animals for which direct activity concentration measurements in biota were available (summer 2011).

The approach outlined does not account for inhomogeneity in radionuclide concentrations within biota, which may lead to elevated exposures for different tissues compared with the whole organism. In the case of acute doses, it is important to have a good estimation of the dose to the most radiosensitive tissues and organs of an organism — such as the apical meristem of trees. Although attempts have been made to simulate the dynamics of radionuclide retention and loss in vegetation, the approach presented above is largely based on an assumption of equilibrium between radionuclides in biota and their surrounding media. In the case of acute contamination situations, doses to radiosensitive organs of biota species, such as apical meristem of trees, are much higher compared with doses to the whole body, because they are the first forest compartments to be exposed to contamination and because of their tendency to intercept radionuclides from passing plumes. To take into consideration these effects, the FORESTLAND dynamic model [404, 405] was utilized for the same deposition data inputs as outlined in Annex XII. Although the FORESTLAND model was not developed specifically for the areas affected, it was well validated based on data from different areas and has a proven ability to provide reliable assessments [406]. The doses to the top of crowns calculated based on this approach are in a range of 200–400 mGy for the first 30 days after the deposition and in a range of 250–500 mGy for 90 days after the deposition. These values are similar to those given in Fig. 4.5–1 for the (pine) tree RAP.

Thyroid doses from inhalation of ^{131}I by mammals may be an important component of exposure in the early periods following the accident. This route of exposure is not modelled explicitly, nor does the methodology account for specific organ doses (as only whole body activity concentrations have been derived). Even if it were possible to derive ^{131}I thyroid concentrations and concomitant doses in the thyroid of wild mammals, the available dose rate benchmarks are based primarily on whole body exposures.

The experience gained after the accident at the Chernobyl accident clearly indicated that the radiation damage to grazing agricultural animals was caused by exposure of the thyroid from radioiodine

accumulation. An impaired thyroid function in cattle was related to the dose received by the thyroid[60] [407], and the estimated thyroid doses at which no effects were observed were found to be about 20 Gy [373].

4.5.4. The radiological consequences for non-human biota

4.5.4.1. General considerations

In any exposure situation, spatial and temporal deposition patterns set the initial conditions for radiation induced effects in all living biota, but on an individual level. The response of an individual organism to initially induced damage is, in turn, dependent not only upon the physical parameters of the dose delivered but also upon the intrinsic radiosensitivity of the organism, relevant to the end point studied. Thus, understanding the dose and dose rate dependence of the response to radiation is the key aspect of interest for risk estimations in relation to radiation exposures.

Acute exposures to ionizing radiation are delivered within a limited time period, usually within minutes or hours, in contrast to chronic exposure, which may last for weeks, months or years. Concurrently, the effects and effect levels are commonly different between these exposure regimes, which may have implications for the long term consequences. There is a wide range of acute doses required to cause death in individual non-human biota. Lethal doses ($LD_{50/30}$) range from 2 to 10^4 Gy in the report by UNSCEAR (2011) [246], depending on factors such as the exposure conditions and the life stages of the biota, with early life stages generally considered to be more sensitive to acute radiation doses.

When doses that lead to death in an individual are delivered over a long period, the dose rate is much less than for fatal acute exposures [246]. Lowering the dose rates allows the recovery of tissues or organs and increases the tolerance to higher total doses. Similarly, partial body irradiation may increase the tolerance, since critical parts of vital organs may be unexposed.

There is, furthermore, a dilemma in that as the ecological relevance of a system increases, so does the complexity of the system, and, correspondingly, the difficulty in assessing or measuring the response(s) to a stressor. For this reason, toxicological investigations most often focus on simpler systems, or on tissue and individual effects. Attempts must then be made to extrapolate individual effects data to populations and the higher levels of organization. While most scientific data available to date on radiation dose–effect relationships concern individual animal and plant biota [255, 408, 409], these data lack information on special system level effects, as already stressed in radiological protection [410].

Direct effects on the variation of species and ecosystems that are induced by radiation are rare but could be observed in large controlled field studies where external irradiation was performed with gamma radiation sources at high and very high dose rates [411, 412]. For example, high dose rates have resulted in a reversible depletion of radiosensitive plants [413]. As for radiation accidents like the one at Chernobyl, ecological impact stems from the first acute period of exposure, when the releases of activity are the highest. At a later stage, indirect effects may become more pronounced but might not be explicitly related to radiation [414].

[60] A reduction of 69% in function with a thyroid dose of 50 Gy, and an 82% reduction in animals that received a dose of 280 Gy [407].

4.5.4.2. *Observations from post-Chernobyl accident studies on the impact on ecosystems and populations*

The time course of radiation impact on ecosystems following nuclear accidents has been described in relation to the Chernobyl and Kyshtym accidents [373]. Initially, the dose rates decreased rapidly due to the decay of short lived radionuclides (e.g. ^{131}I). Later, migration of the deposited radionuclides vertically and laterally in soil (e.g. ^{137}Cs) led to heterogeneous exposures and, in a longer time perspective, low exposures to the biota prevailed over comparatively long periods of time [414].

The area around the Chernobyl NPP has a temperate climate and flourishing flora and fauna. The complex time dependence of the released radionuclide composition and variable meteorological conditions over ten days of active emission caused an extremely inhomogeneous deposition pattern and a wide scatter of dose burden to the biota. The acute dose rates in the first 20 days following the start of the accident came mainly from short lived radionuclides which were deposited onto plant and ground surfaces. In the zone immediately surrounding the Chernobyl NPP, the deposition was more than 3.7×10^{13} Bq/km^{-2}, which caused numerous acute adverse effects in the biota. The pine forest was severely damaged up to 7 km from the reactor, and lethal doses to the pine needles amounted to 20–100 Gy (acute dose). The initial dose rate in the 'red forest' was 5 mGy/h (120 mGy/d). Leaf gigantism was observed in deciduous trees, while no visual effects on herbaceous plants were evident in 1986 in the 10 km evacuation zone. In addition, vertebrate animals also received high thyroid doses as a result of internal exposure from radioiodine during this early period.

Approximately 80% of the total radiation dose accumulated by animals and plants was received in the first three months following the accident, with 95% due to beta radiation. During the summer and autumn of 1986, the dose rate at the soil surface declined to less than 10% of the initial values as short lived radionuclides decayed, although damaging doses were still accumulated. A third, continuing phase of radiation exposure was characterized by chronic dose rates at levels less than 1% of the initial values, derived mainly from ^{137}Cs. The contribution to the total dose rate from gamma and beta radiation was comparable owing to the migration of much of the ^{137}Cs into the soil. Studies following the Chernobyl accident indicated that the coniferous plants and coniferous forest (ecosystem) are radiosensitive populations in the environment [373].

It has to be noted that the populations of biota around the Chernobyl NPP have recovered substantially during the years following the accident. But the nature and scale of the recovery has been confounded by drastic changes in human activity, including termination of agricultural and industrial activities and the accompanying environmental pollution in the most affected area. As a result, the populations of many plants and animals have expanded.

4.5.4.3. *The radiological consequences for non-human biota in proximity to the Fukushima Daiichi NPP*

Around the Fukushima Daiichi NPP, the releases of radionuclides and thus the doses to non-human biota were highest during the first weeks and months following the initial releases. For large accidental releases of radioactive material in general, it is during this period that the potential for acute damage in tissues and organs may arise. If the dose is high enough, death can occur due to failure of important organ systems.

The estimated doses to the terrestrial RAPs during the first weeks after the accident were highest for plants. The accumulated dose is approximately 0.6 Gy for the first 30 day period for both the (pine) tree and (wild) grass RAPs. From data collated for forest affected by deposition after the Chernobyl accident, UNSCEAR [246] reported that minor damage characterized by disturbances in growth, reproduction and morphology of conifers could be observed at doses from 0.5 to 1.2 Gy. More serious, sublethal damage, including destruction of meristems and partial death of conifers, was not

observed until doses were in the range of 10–20 Gy. Herbaceous plants, including grasses, are considered to be more radioresistant, and after the Chernobyl accident, sterility of seeds was not observed at doses below 5 Gy [246]. From the assessed doses, it is possible to infer that any direct lethal effects in even relatively sensitive plants such as conifers would not have occurred. Comparison with the DCRLs shows that the calculated dose rates exceed the DCRL band for pine, grass and mammals during the first 90 days after the accident.

For the terrestrial deer RAP, the estimated dose rate of 1.7 mGy/d for the period of 0–30 days falls just within the range (1–10 mGy/d) where there is a potential for reduced reproductive success, owing to increased male sterility [260]. However, comparison with the $LD_{50/30}$ data for the deer RAP indicates that the calculated accumulated doses were orders of magnitude below levels at which lethal effects would be observed. In other words, the estimated total dose during the acute phase was such that no major acute radiation induced effects would have been expected at the calculated exposure levels. Similarly, limited impacts may be inferred from the second part of the assessment, in which experimental data on radionuclide activity concentrations measured directly in plants and animals have been used. To illustrate this, for grass, the calculated dose rate of 2 mGy/d in the 0–30 day period fell within the ICRP's DCRL band but below a dose rate where reduced reproductive capacity in these types of plants has been recorded [260]. Although not directly comparable, because ICRP's tabulated dose rates pertain to chronic exposure regimes, the comparison nevertheless suggests that exposures are unlikely to affect population viability. Similarly, dose rates for Japanese monkey at 0.2 mGy/d in the early phase fell in a DCRL band, considered for the related deer and rat RAPs, to constitute a very low probability of effects. In contrast, dose rates for earthworms (0.4 mGy/d) fell substantially below the corresponding DCRL (10–100 mGy/d) where effects are considered unlikely[61].

The marine biota category, brown seaweed received the highest exposures among the RAPs considered, with dose rates exceeding 70 mGy/d in the initial period of 0–30 days. The highest accumulated doses were observed for brown seaweed at 2.4 Gy, and thus within the same order of magnitude as the acute threshold value proposed at the ecosystem level for the marine environment of 4.84 Gy [415], also reported by UNSCEAR [246].

Dose rates in the range of 10–100 mGy/d have the potential to cause effects on reproduction and growth rate in (individual) macroalgae [260]. Nonetheless, these elevated exposures were limited in space — the values used in the assessment relate to a position 30 m from the main release area — and in time. The spatially limited and transient nature of the highly elevated exposure indicates that releases from the Fukushima Daiichi NPP were unlikely to have caused any substantial harm to regional populations of brown seaweed.

Dose rates for offshore marine biota in the late phase were extremely low, and the maximum dose rate for freshwater fish of 0.1 mGy/d fell substantially below the appropriately comparable DCRL band for trout (1–10 mGy/d). Nevertheless, short lived radionuclides, including ^{131}I, were generally not included in the assessment, based on measured activity concentrations in plants and animals; actual doses in the early phase may have been somewhat higher than those calculated. It is possible that dose rates may have exceeded corresponding DCRL bands in some cases, but they are unlikely to have been at a level that would cause detriment to populations of wild plants and animals.

Although the methods used for the assessments are simple, they are robust and encompass the main exposure pathways relevant for assessing exposures to wild plants and animals. Nonetheless, the

[61] It should be noted that the DCRLs have been defined in terms of bands of dose rates spanning one order of magnitude relevant to each RAP. In planned exposure situations, the ICRP advises that the lower boundary of the relevant DCRL band be used as the appropriate reference point for protection of different types of biota, while in emergency situations the upper boundary of the DCRL band is more appropriate as a reference [259].

treatment of heterogeneous distributions of some radionuclides, such as radioiodine, is subject to considerable uncertainty. The possibility that some individual biota received rather high local doses, for example to the thyroid[62], cannot be excluded, although a response at the population level would be unlikely given the short duration of elevated radioiodine levels in time and space.

Interactions between species and other constituents in the environment affected by radiation may have indirect implications for ecosystem function but are difficult to disentangle from effects on individuals.

It is possible to conclude that, although dose rates exceeded some reference values included in ICRP and UNSCEAR publications in the early phases of the accident, no impact on populations and the ecosystems (both terrestrial and marine environments) is expected. Furthermore, long term effects are not expected, given that the estimated short term doses were generally well below levels at which highly detrimental acute effects might be expected, and dose rates declined relatively rapidly after the accident.

4.5.5. Review of relevant studies on modelling of doses and field observations of effects in proximity to the Fukushima Daiichi NPP

4.5.5.1. Observations from assessment of the Fukushima Daiichi NPP by UNSCEAR

UNSCEAR examined the impact of the Fukushima Daiichi accident on non-human biota within the first year or so [5]. The main conclusion of the evaluation was that, although the existing benchmarks may have been exceeded in the terrestrial ecosystems for limited periods after the accident, population effects of major significance were unlikely. Furthermore, estimated doses to marine biota (in the intermediate phase) did not indicate the potential for effects on populations of these biota.

The investigation was, as far as practicable, based on measured radionuclide concentrations in biota and their habitat, but in many cases, transfer models starting from an input as media concentrations were applied. The ERICA methodology [393] was widely applied. Koriyama City was selected in its entirety as a representative area for the terrestrial assessment, covering relatively low to high contamination levels in locations where direct measurements of activity concentrations in biota were available. During June 2011, high percentile dose rates in a range between 1.2 and 2.2 μGy/h for terrestrial mammals and birds were estimated for Koriyama City at 50–100 km west of the Fukushima Daiichi NPP. Dose rates were also calculated by UNSCEAR using the mean deposition levels for Okuma Town and default transfer parameters. The dose rates estimated for mid-June 2011 were 71 μGy/h for deer/herbivorous mammals and 26 μGy/h for grass.

For the marine ecosystem, dose rates in the period 10 May 2011 to 12 August 2012, for coastal locations where biological samples were available, ranged from 0.10 to 0.25 μGy/h, i.e. much less than for terrestrial biota. UNSCEAR concluded that, for the late phase (months to years) after the accident, effects in individuals of certain species, especially mammals (terrestrial), may exist in areas of highest deposition. Predicted exposures derived by UNSCEAR for both marine and freshwater biota during the late phase were well below thresholds above which effects could be deemed likely. UNSCEAR thus concluded that "the possibility of direct effects of radiation exposure on non-human biota was geographically constrained and that, in areas outside of that considered by this assessment, the potential for such effects on biota may be deemed insignificant" [5].

Dose rates and accumulated doses in the intermediate phase of the accident (first months after the accident) were much higher than doses calculated for the later phases; terrestrial dose rates (including

[62] See, e.g., Refs [416, 417].

the short lived isotopes ^{132}Te and ^{132}I) may have been as high as 1 mGy/h in the terrestrial environment and exceeded 20 mGy/h for macrolagae in the marine environment. Accumulated doses over the intermediate phase were estimated to have fallen short of levels found to cause observable effects in non-human biota, as reported in reviews such as those concerning exposures in the aftermath of the Chernobyl accident. Estimated doses to marine biota during the intermediate phase did not indicate the potential for effects on populations of these biota, although effects on individual macroalgae (e.g. impacts on growth and reproduction) close to the discharge area may have occurred.

Table 4.5–4 provides a comparison of the maximum dose rates and accumulated doses for RAPs estimated in this assessment with those estimated by UNSCEAR [5]. There are some discrepancies between these dose rates that might be explained by considering what the maximum dose rates actually represent. Whereas the maximum (initial period) dose rates for this assessment are actually integrated values over the specified 30 day period, the values from UNSCEAR (2014) [5] represent dose rates for particular instantaneous moments in time within the 30 day period.

TABLE 4.5–4. MAXIMUM DOSE RATES AND ACCUMULATED DOSES FOR REFERENCE ANIMALS AND PLANTS IN THE INITIAL PERIOD FROM THIS ASSESSMENT AND UNSCEAR (2014) [5]

Reference animals and plants	Maximum dose rate — mGy/day (accumulated dose: mGy) in 0–30 day period: IAEA assessment	Maximum dose rate — mGy/day (accumulated dose: mGy) in 0–30 day period: UNSCEAR (2014) [9]
Wild grass	21 (600)	135 (500)[a]
Pine tree	19 (600)	34 (400)[a]
Earthworm	1.4	7
Bee	0.6	4
Rat	1.5	8
Deer	1.7 (50)	9 (200)[a]
Duck	0.7	4
Trout	N/A	N/A
Frog	0.7	4
Brown seaweed	80 (2400)	480 (6800)
Crab	1.6 (50)	3 (80)[b]
Flatfish	3.4 (100)	3.4 (120)[c]

[a]Using FASTer model (Avila et al., 2004).
[b]Using D-DAT model (Vives-i-Batlle, 2014) and accumulated dose for 90 days.
[c]Not assessed for this period.

4.5.5.2. Assessments based on other published model calculations and field observations

A number of studies of radiation induced effects following the accident at the Fukushima Daiichi NPP had been published by the end of 2014.

Soon after the accident, radiation doses to forest and marine biota during the first 30 days were assessed [418]. The methods were based on the application of equilibrium transfer models from measured radionuclide activity concentrations in soil and sea water. Maximum dose rates were estimated to be 210 mGy/d for marine birds, 2600 mGy/d for benthic biota and 4600 mGy/d for macroalgae. However, neither the applied assessment methods nore the selected deposition pattern is applicable to the non-equilibrium conditions existing at the time.

Radiation dose rates to fish, molluscs and algae were assessed for the first three months following the accident using dynamic methods [419]. The average dose rates, for example, to pelagic fish in the coastal zone, were estimated to be 0.9–1.2 mGy/d from March to May 2011. The estimated dose rates for fish and molluscs were below 10 mGy/d. Activity concentrations measured in tuna fish captured off the Californian coast in August 2011 [387] were used to reconstruct internal doses. The doses resulting from the Fukushima Daiichi accident were found to be more than two orders of magnitude lower than the lowest commonly applied screening benchmark of 10 μGy/h.

Some other studies of dose rates and of observed radiation induced effects following the accident have been published (e.g. [418, 420–422], from which it is difficult to draw firm conclusions for a variety of reasons, which include the dosimetry applied or the lack of reliable controls. There are difficulties involved in collecting radio-ecological information in accidental situations [246]. However, it is important to take account of potentially significant temporal variations in dose rates, especially in the early phase, and to ensure that radiological input data are sufficiently representative of the spatial coverage required to estimate effects at the population level [418]. Furthermore, it is necessary to confirm single observations of suspected impacts by using transparent and reliable statistical treatment of data; otherwise it is impossible to draw conclusions about dose–response relationships based on observations.

4.5.6. Summary

The assessment of the potential radiological impact of the accident on non-human biota comprises two distinct components: an estimation of dose rates based on activity concentrations of radionuclides in environmental media, i.e. water, sediment and soil (or deposition); and data pertaining to directly measured activity concentrations in biota (and their habitat) published in the literature.

For the first assessment, the ICRP approach of reference organisms was adopted. Three distinct time periods were considered: an early acute period with larger releases of particularly short lived radionuclides; an intermediate period up to 90 days after the accident; and a late period of chronic exposures. The estimated dose rates were then compared with the ICRP DCRLs and other relevant benchmarks. The second type of assessment also drew upon the ICRP approach using DCRLs and other relevant dose–response data to put the dose rates derived for specified non-human biota into perspective.

The estimated doses were highest for plants during the first weeks after the accidents but remained below levels at which acute effects would be anticipated. The DCRLs were exceeded for some terrestrial RAPs (such as pine, grass, deer and rat) in the early phases, which could imply a potential for harm (defined as a detriment to sensitive end points in this case) in some of the most exposed individuals. However, no impact on populations or the ecosystems would be expected. DCRLs were also exceeded for marine Brown seaweed, but the spatially limited and transient nature of the highly elevated exposures suggests that the releases from the Fukushima Daiichi accident were unlikely to have caused any substantial harm to regional populations of this biota group. Long term effects are not expected given that the estimated short term doses were generally well below levels where acute effects might be expected and dose rates in the environment declined relatively rapidly after the accident.

No observations of direct radiation induced effects in plants and animals have yet been reported, based on analyses undertaken using appropriate dosimetry and experimental designs. The long term consequences of the releases on the environment are considered to be insignificant, although the elapsed time since the accident is relatively short for making a decisive judgement.

4.5.7. Observations and lessons

— **During any emergency phase, the focus has to be on protecting people. Doses to the biota cannot be controlled and could be potentially significant on an individual basis. Knowledge of the impacts of radiation exposure on non-human biota needs to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems. Following a large release of radionuclides to the environment, an integrated perspective needs to be adopted to ensure sustainability of agriculture, forestry, fishery and tourism and of the use of natural resources.**
It may be difficult to substantially reduce doses to non-human biota because of the impracticability of introducing countermeasures. Impact assessments for plants and animals in the aftermath of accidents such as that at the Fukushima Daiichi NPP require consideration of numerous potential stressors — radiation exposure being one of many. Consideration also needs to be given to the potential for the buildup and accumulation of long lived radionuclides in the environment and how this might affect plants and animals over multiple generations.

APPENDIX I
MAPS OF LEVELS OF RADIOACTIVITY AND RADIONUCLIDES IN THE ENVIRONMENT

A range of environmental monitoring was undertaken during and following the Fukushima Daiichi accident, notably measurements of ambient dose equivalent rates for external exposures, activity concentrations in air and deposited on the ground, and levels of radionuclides in the terrestrial and marine environments, including activity concentrations in food and drinking water.

A Comprehensive Radiation Monitoring Plan was developed that included a comprehensive assessment of the distribution of radionuclides deposited on the ground and the migration of radionuclides through different media [423]. In addition to the large amount of government led environmental monitoring activities, many volunteer and other organizations gathered information to help understanding of the radiological situation in the environment in the area surrounding the Fukushima Daiichi NPP. An overview of information available for various types of measurements and materials is presented in Annex III.

This appendix provides a sample of measured data on the geographical distribution of radioactivity and key radionuclides in the environment, in the form of a series of maps.

I.1. AMBIENT DOSE EQUIVALENT RATE

The first aerial monitoring of ambient dose equivalent that provided a map of levels in the environment was performed by the US Department of Energy/National Nuclear Security Administration (US DOE/NNSA) from 17 to 19 March (see Annex III, Fig. III–2) [424].

Joint aerial surveys were carried out by MEXT and US DOE/NNSA of the area within 80 km of the NPP between 6 and 29 April and 18 and 26 May 2011. Since then, a number of repeat surveys of this area have been undertaken by MEXT. Additional surveys of the evacuation areas and of wider areas have also been performed. The aerial surveys performed for the period until March 2015 are summarized in Table I.1. The web site of the NRA of Japan contains information on all of the aerial surveys done to date [425].

TABLE I.1. AERIAL SURVEYS[a]

Survey name	Survey date	Decay date[b]	Issuing date	Area surveyed	References
The situation in Japan[c]	17–19 Mar. 2011			<30 km	Lyons and Colton (2012) [424]
First aerial monitoring survey[d]	6–29 Apr. 2011	29 Apr. 2011	6 May 2011	≤80 km	[57]
Second aerial monitoring survey[d]	18–26 May 2011	26 May 2011	16 Jun. 2011	≤100 km, plus parts of Ibaraki and Toshigi	[58]
Third aerial monitoring survey	31 May–2 Jul. 2011	2 Jul. 2011	8 Jul. 2011	≤80 km	[59]
Fourth aerial monitoring survey	22 Oct.–5 Nov. 2011	5 Nov. 2011	16 Dec. 2011	≤80 km	[60]

TABLE I.1. AERIAL SURVEYS[a] (cont.)

Survey name	Survey date	Decay date[b]	Issuing date	Area surveyed	References
Fourth aerial monitoring survey	22 Oct.–5 Nov. 2011	5 Nov. 2011	16 Dec. 2011	≤80 km	[60]
Aerial monitoring survey in the restricted areas and deliberate evacuation areas	6–10 Feb. 2012	10 Feb. 2012	24 Feb. 2012	Restricted and deliberate evacuation areas	[61]
Fifth aerial monitoring survey	22–28 Jun. 2012	28 Jun. 2012	28 Sep. 2012	≤80 km	[62]
Aerial monitoring survey beyond 80 km of the Fukushima Daiichi NPP	2 Apr.–7 May 2012	28 Jun. 2012	28 Sep. 2012	>80 km with dose rates ≥0.2 μSv/h (western Fukushima, Ibaraki, Gunma, Tochigi, Miyagi, southern Iwate, northern Chiba, and eastern Yamagata prefecture)	[62]
Sixth aerial monitoring survey	31 Oct.–16 Nov. 2012	16 Nov. 2012	1 Mar. 2013	≤80 km	[63]
Aerial monitoring survey beyond 80 km of the Fukushima Daiichi NPP	31 Oct.–28 Dec. 2012	28 Dec. 2012	1 Mar. 2013	>80 km with dose rates ≥0.2 μSv/h (western part of Fukushima, Ibaraki, southern part of Iwate, northern part of Chiba, Gunma, Tochigi, Miyagi, and the eastern part of Yamanashi)	[63]
Aerial monitoring in the evacuation-directed zones	4–11 Mar. 2013	11 Mar. 2013	13 May 2013	Areas under evacuation orders	[64]
Seventh aerial monitoring survey	27 Aug.–28 Sep. 2013	28 Sep. 2013	25 Dec. 2013	≤80 km	[65]
Eighth aerial monitoring survey	3 Sep.–19 Nov. 2013	19 Nov. 2013	7 Mar. 2014	>80 km; Fukushima and its neighbouring prefectures	[67]
Ninth aerial monitoring survey	1 Sep.–7 Nov. 2014	7 Nov. 2014	13 Feb. 2015	≤80 km	[68]

[a] Referred to as 'airborne surveys' in the referenced sources.
[b] The later date is used as the reference date for calculating physical decay.
[c] Carried out by US DOE.
[d] Carried out by MEXT and US DOE.

In these measurements, the non-terrestrial background (cosmic and aircraft) is removed on the basis of measurements over water (lake, not ocean). The terrestrial background is not removed, but is

insignificant in the 80 km region (initial survey only). In later surveys, background subtraction had to be taken into account.

Maps of dose rates measured by aerial surveys are presented in Fig. 4.1–6.

Deposition densities of ^{134}Cs, ^{137}Cs and ^{131}I were also derived from these aerial measurements (see Section 4.1.2.2).

I.2. SOIL MEASUREMENTS

The MEXT Comprehensive Radiation Monitoring Plan included initiatives to assess the activity concentrations of radionuclides in soil using consistent sampling and analytical procedures. Samples for the first survey — Research on Distribution of Radioactive Substances Discharged by the Accident at TEPCO's Fukushima Daiichi NPP [380, 426] — were collected between 6 June and 8 July 2011 from an area covering Fukushima Prefecture, northern Ibaraki Prefecture and southern Miyagi Prefecture. Based on the results of aerial monitoring and other environmental monitoring, the area within 80 km of the Fukushima Daiichi NPP was divided into 2 km × 2 km grid squares. The area between 80 and 100 km and the areas in neighbouring prefectures were divided into 10 km × 10 km grid squares. The study area comprised in total 2182 grid squares. A number of samples — normally five but ranging from one to seven depending on circumstances — were collected from each grid square. A consistent sample depth of 5 cm was used.

All soil samples were analysed for gamma emitting radionuclides (such as ^{134}Cs, ^{137}Cs, ^{131}I, ^{129m}Te and ^{110m}Ag). An average deposition density (Bq/m^2) was calculated by dividing the sum of the results of measurements of each individual sample — including a zero value for those below the limit of detection — by the number of analyses performed. If all sample measurements were below the limit of detection, no value was reported. A subset of samples were also analysed for isotopes of strontium (^{89}Sr and ^{90}Sr) and plutonium (^{238}Pu, ^{239,240}Pu). This was due to the more time consuming procedures required for analysis of these radionuclides: priority was given to samples from grid squares where levels of radiocaesium had already been found to be highest. Ambient dose equivalent rates were also measured at a height of 1 m above the ground surface at one location in each grid square.

These measurements were used to construct maps of activity concentrations in soil of each radionuclide measured. This information, together with in situ measurements of ambient dose equivalent rates, was used in the UNSCEAR assessment to assess radiation doses to the public living in different locations [5].

The deposition density of ^{134}Cs is shown in Fig. I.1; the corresponding map for ^{137}Cs is Fig. 4.1–12. Maps of ^{137}Cs and ^{134}Cs deposition densities were also derived from aerial monitoring surveys and are shown in Figs 4.1–13 and 4.1–14.

As sampling for this survey was performed some three to four months after accidental releases from the Fukushima Daiichi NPP, the levels of ^{131}I had generally decayed to levels which were not detectable by gamma spectrometry. In fact, deposition densities could be reported for less than 20% of the grid squares described above owing to the number of measurement results below the limit of detection.

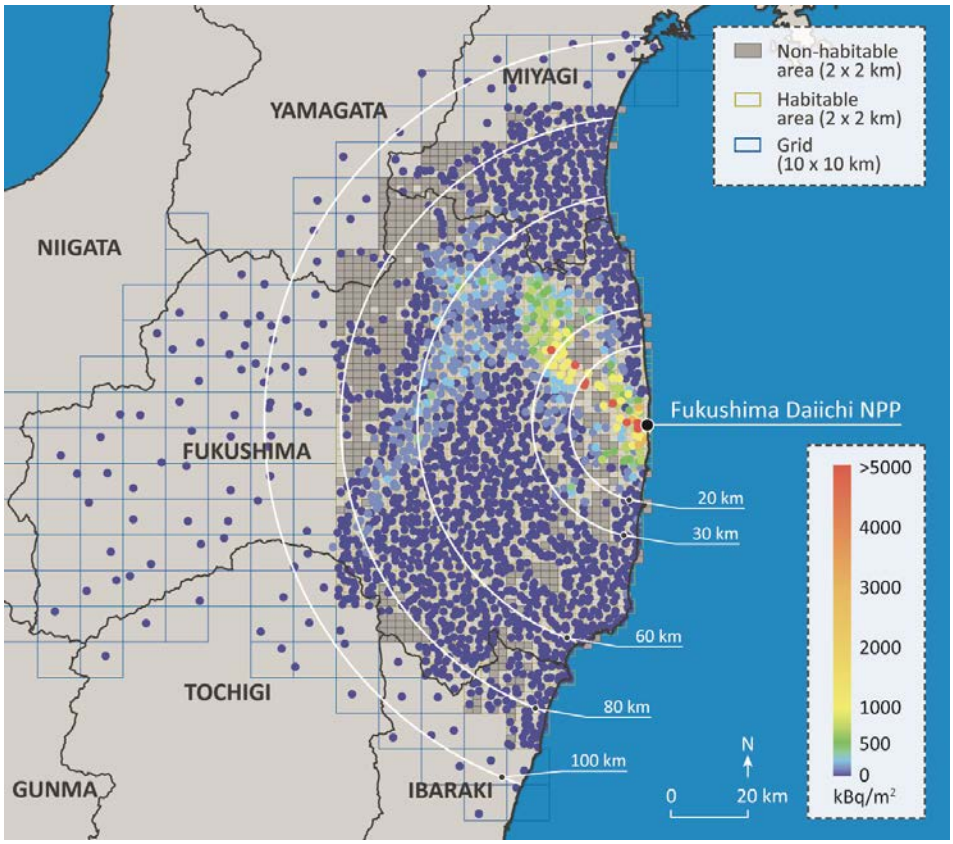


FIG. I.1. Map of deposition density of ^{134}Cs (kBq/m^2) based on the results of soil measurements.

To resolve this, values of ^{131}I were estimated from measurements of ^{129}I. A pilot study was first undertaken to measure ^{129}I using accelerator mass spectrometry (AMS) in a total of 82 samples from grid squares from which it had been possible to measure ^{131}I by gamma spectrometry [427]. These results were used to calculate a conversion factor between activity concentrations of ^{129}I and those of ^{131}I. The parallel measurement of ^{131}I by gamma spectrometry and ^{129}I by AMS carried out for 82 soil samples produced a good correlation (R^2 = 0.84), which gave confidence in the reliability of this method. The isotopic ratio of ^{129}I to ^{131}I, decay corrected to 11 March 2011, was around 21. This value is comparable with the ratio of around 16 obtained for rain water [70, 71] and 22.3 ± 6.3 for soil samples, and with the estimated ratio from the operational history of the reactor (18–21) [71].

In order to derive values of ^{131}I for 388 grid squares from which no value could be detected by gamma spectrometry, one sample from each was analysed for ^{129}I by AMS. Activity concentrations of ^{131}I for these samples were estimated by applying measured ^{129}I to ^{131}I conversion factor to the results. Iodine-127 (stable iodine) was also measured in the samples by inductively coupled plasma mass spectrometry in order to facilitate the subtraction of the contribution of ^{129}I from fallout from atomic weapons tests. A correction factor was also calculated (from ^{137}Cs) to account for the fact that only one sample from each location was analysed (due to time constraints). The resulting map of ^{131}I distribution, including both the original gamma spectrometry measurements and those derived from ^{129}I, is shown in Fig. 4.1–15.

A map of ^{131}I deposition density has also been estimated from the results of the first aerial survey, also shown in Fig. 4.1–15. In contrast to the earlier maps of ^{134}Cs and ^{137}Cs, which were derived from aerial surveys by applying constant conversion coefficients, the activity concentrations for the ^{131}I map were derived by fitting iodine photo peaks in the measured gamma spectra.

Maps of the deposition densities of ^{129m}Te and ^{110m}Ag are shown in Figs I.2 and I.3, respectively.

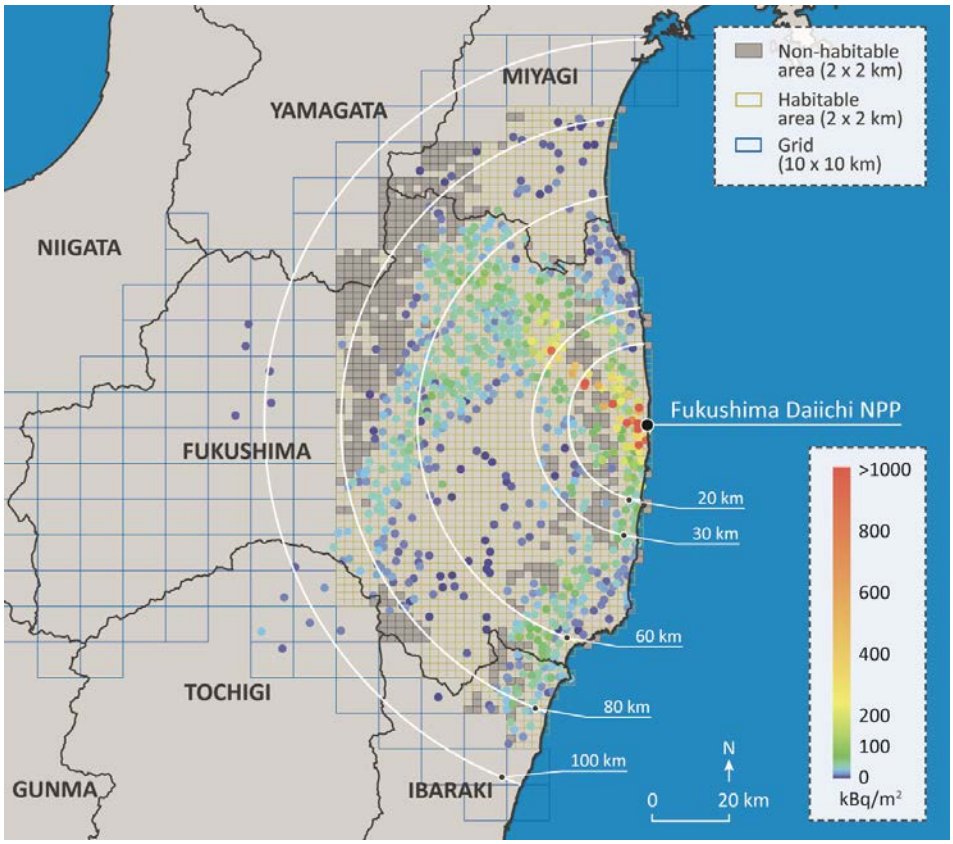


FIG. I.2. Deposition density of ^{129m}Te (kBq/m^2) based on the results of soil measurements.

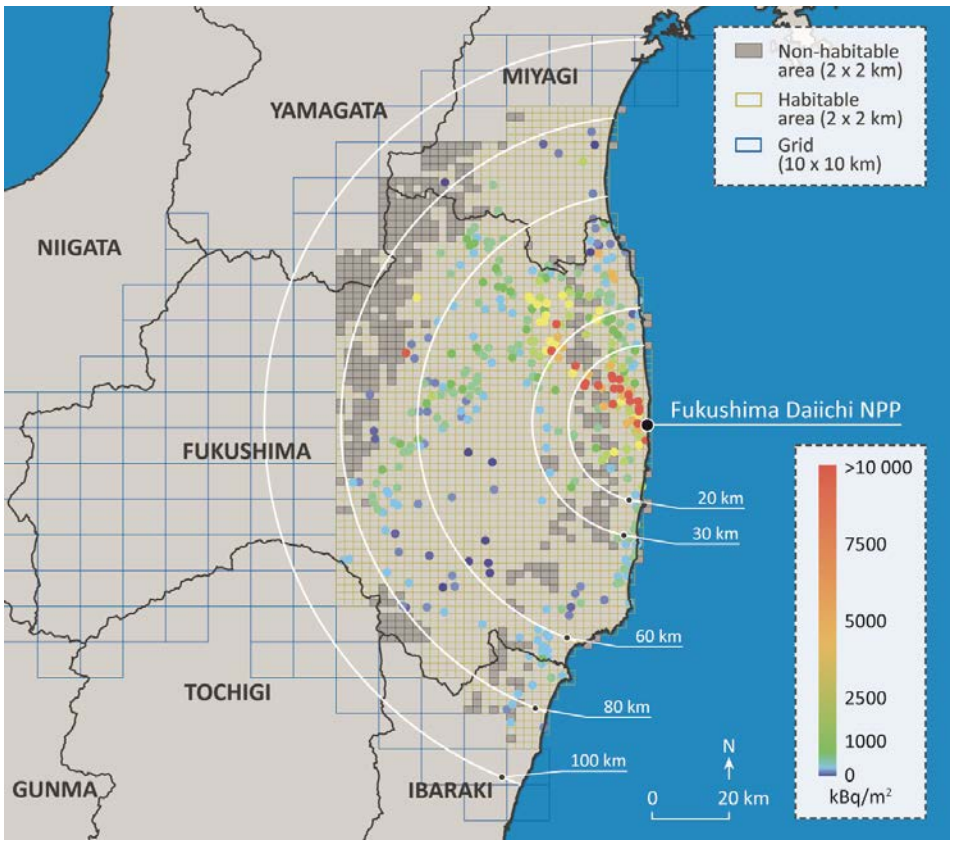
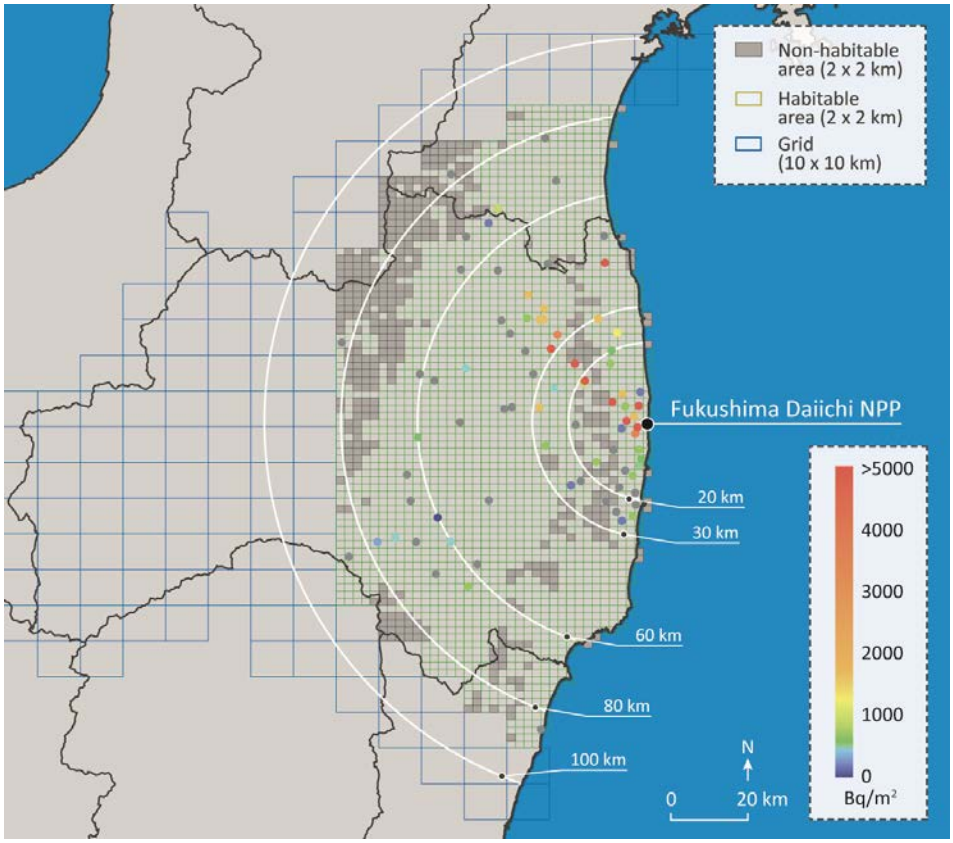
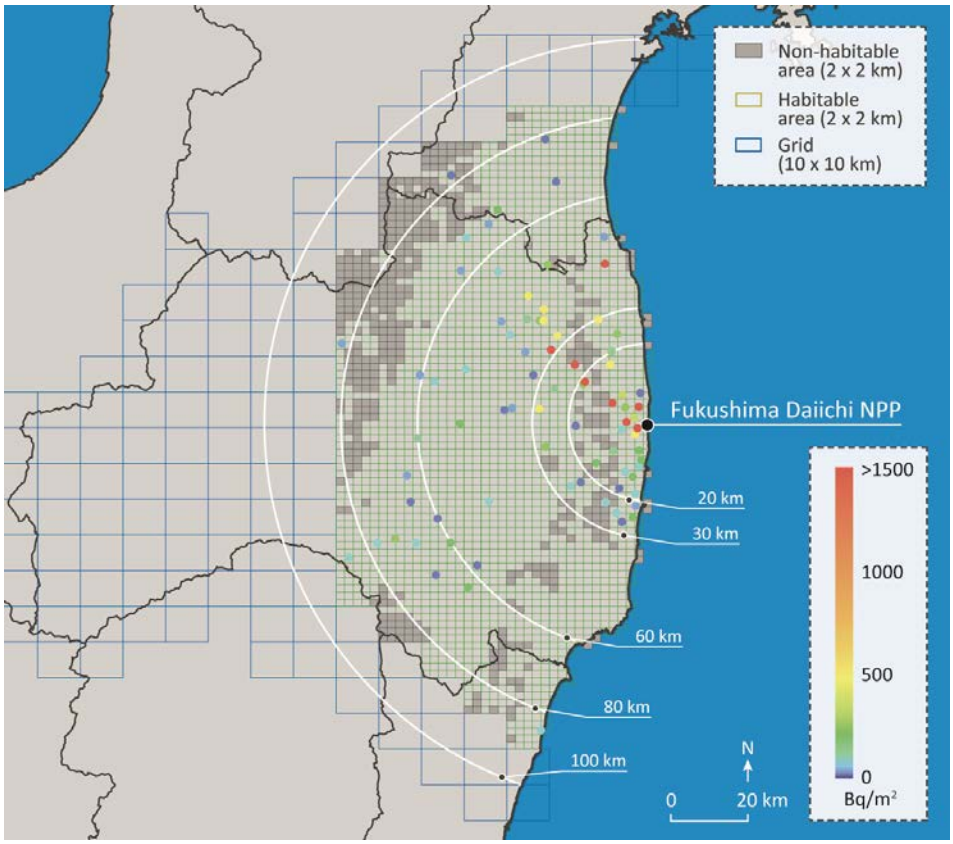


FIG. I.3. Deposition density of ^{110m}Ag (kBq/m^2) based on the results of soil measurements.

A map of deposition densities of ^{89}Sr and ^{90}Sr is shown in Fig. I.4. As previously noted, the levels of the strontium isotopes measured were three to four orders of magnitude lower than those of radiocaesium, reflecting the small amounts released owing to the low volatility of this element. Similar results were found by Steinhauser et al. [428], who measured activity concentrations of beta emitting ^{90}Sr and β/γ emitting ^{134}Cs and ^{137}Cs in soil and vegetation samples from several areas known to have been subjected to relatively high levels of deposition. The ^{90}Sr concentrations in the samples did not exceed 1000 Bq/kg and were up to four orders of magnitude lower than the respective levels of ^{137}Cs.



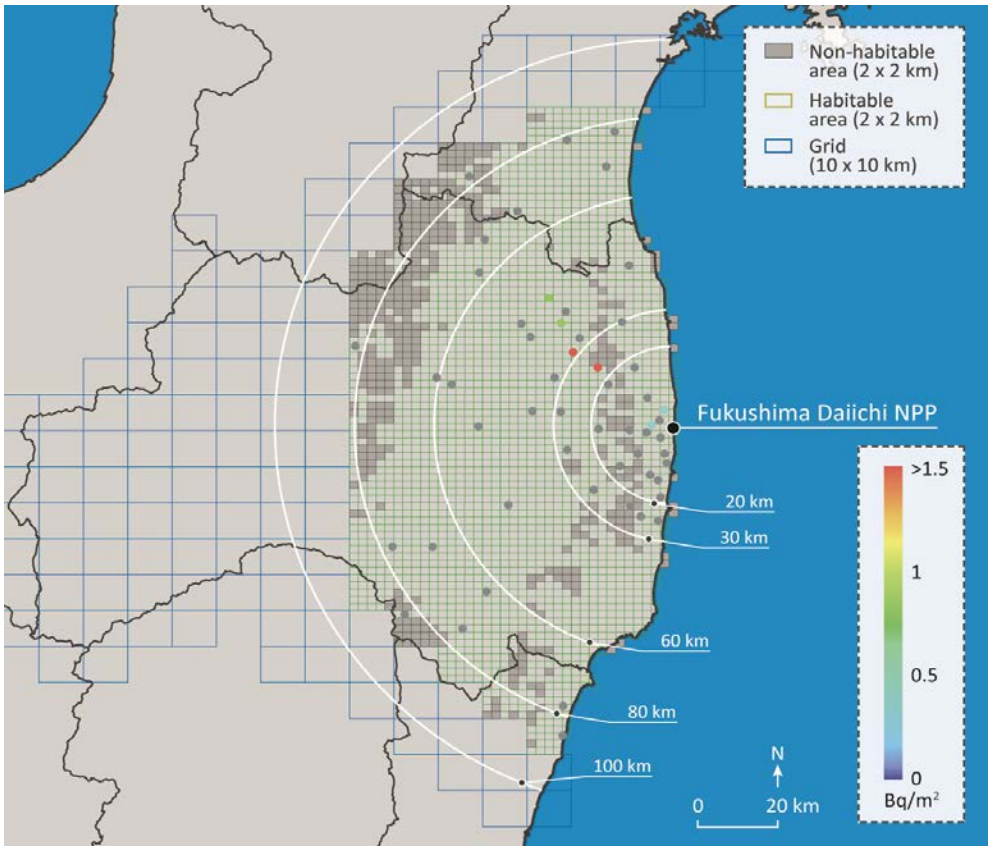
(a)



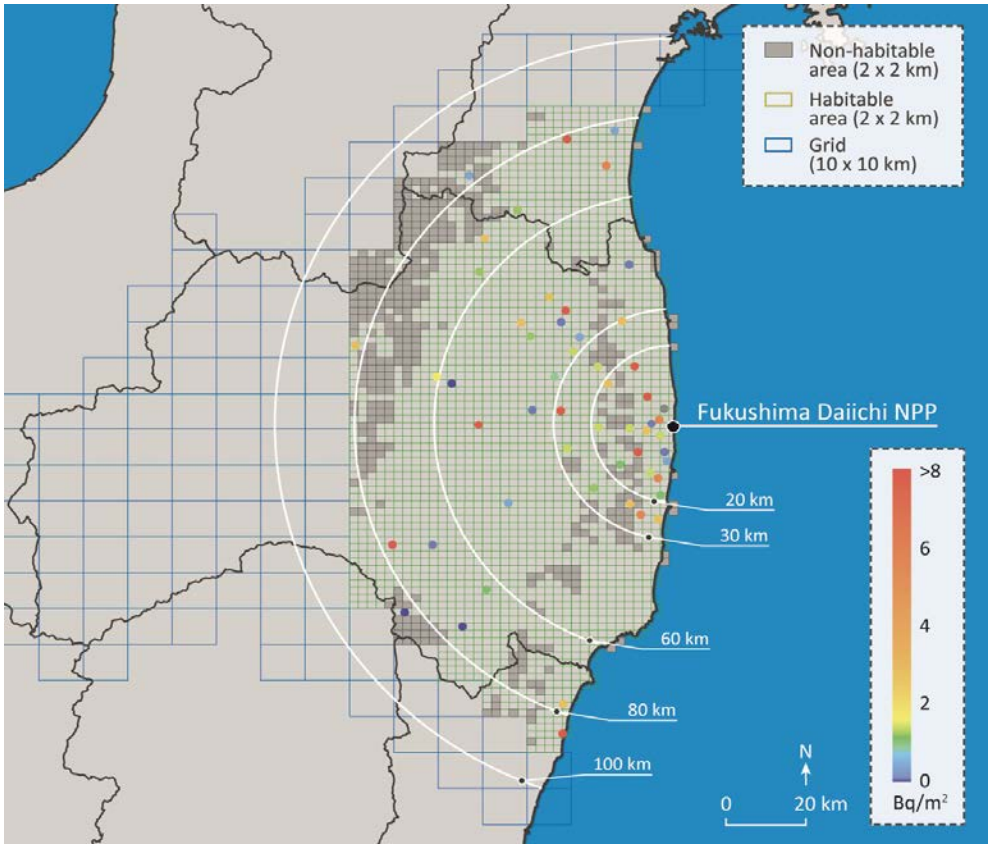
(b)

FIG. I.4. Deposition density of (a) ^{89}Sr and (b) ^{90}Sr (Bq/m^2) based on the results of soil measurements.

Plutonium isotopes (^{238}Pu and $^{239,240}Pu$) were measured in a number of samples relatively far from the Fukushima Daiichi NPP in Fukushima Prefecture, as shown in Fig. I.5. Isotopic ratios distinct from those of global fallout ($^{240}Pu/^{239}Pu$ atom ratio ~ 0.32 and $^{238}Pu/^{239+240}Pu$ activity ratio of 1.1–2.9) were found and subsequently shown to have been characteristic of the fuel from Unit 3 of the Fukushima Daiichi NPP [18, 429]. The activity concentrations measured were very low, close to or often below the level of detection. There has been no convincing evidence of the type of hot particles (fuel fragments) which were seen following the Chernobyl accident [73].



(a)



(b)

FIG. I.5. Deposition density of (a) ^{238}Pu and (b) $^{239+240}$Pu (Bq/m^2) based on the results of soil measurements.

APPENDIX II
STATISTICAL ANALYSIS OF INDIVIDUAL DOSE DATA

II.1. INTRODUCTION

The basic statistical methodology applied was to fit an appropriate theoretical statistical function to the distribution of the measurements (i.e. *N* versus the parameter measured), with the objective of assessing the extent of agreement or deviation from that function. The theoretical distribution assumed was the log-normal probability density function and the log-normal cumulative probability distribution (see Box 4.1–1 and Box 4.2–1).

As indicated below, due to the scarcity and inhomogeneity of data available, some additional analysis was necessary to determine whether the log-normal distribution was applicable. This included an analysis of the effect of different assumptions regarding the distribution of data within reported intervals (or bins). Cumulative probability distributions were developed for the purpose of determining the extent to which the available data fitted the log-normal function and to form the basis of analysing log-normal statistics, as appropriate. Normalized idealized probability density functions were also constructed for comparison purposes. A comparison of the results of these approaches will be the subject of a future publication. A summary of the analysis is presented in this appendix.

The log-normal mathematical function can generally be used to approximate positive–variant data of many types, including those related to radiation measurement [430–433]. For positive–variant data such as the number of people who were exposed to a certain dose, an asymmetric distribution can be expected. The log-normal distribution offers the simplest mathematical means of describing such distributions and is most commonly found in practice [434].

The cumulative probability distribution can be estimated simply by fitting a straight line to a plot of such data on normal probability scale versus log scale axes. A simple plot such as this will quickly show whether a log-normal function is an adequate representation of the data. If this is the case, descriptive statistics such as the geometric mean and geometric standard deviation can be derived.

This statistical procedure can also be used to check and validate datasets and to identify systematic deviations from the expected log-normal distribution pattern. Following the Chernobyl accident in 1986, this method was used successfully to assess the distribution of doses to the public [435]. Values greater than the fitted log-normal, especially in the higher dose tail, were investigated further because such deviations indicated a higher probability of occurrence than one would have expected from a log-normal distribution, and were generally due to enhanced external doses from ‘hot spots’ or additional ingestion doses due to non-adherence to restrictions on the consumption of certain foods.

The main goal of the analysis described in this appendix is to determine whether each dataset of measurements following the Fukushima Daiichi accident could be described by a log-normal distribution, as was generally the case for similar datasets compiled after the Chernobyl accident [435]. In order to enhance the precision of the analysis, an additional stage of investigating the fit of the log-normal probability density functions (PDFs) was used, in addition to the cumulative probability distribution. The main advantage of this process is that, if the log-normal function proves to be a reasonable fit for the distribution of data, log-normal statistics may then be used to describe the distribution of parameters, such as activity concentrations and doses.

In the case of the accident at the Fukushima Daiichi NPP, the analysis of certain datasets of measured radiation doses was complicated by two factors:

(1) Some measurements were aggregated as the number of cases *N* per measurement interval (or bin). For example, in the case of measurements of radiation exposures the datasets comprised the number of people who received a dose within specific intervals, the width of which depended on the type of dose measured and on the measurement techniques and instrumentation employed.
(2) For many datasets, the majority of measurements were either around or below the limit of detection.

Therefore, for these datasets, the application of more sophisticated methods of analysis was required. In order to thoroughly test for log-normality, the distribution of the probability over the width of the measurement interval was considered and the probability density function was used in addition to the cumulative distribution to determine whether the log-normal distribution was a suitable fit for the dataset and, thus, whether log-normal statistics could be applied. The details of this methodology are provided in the next subsection. The datasets analysed in this way include:

— Occupational doses received by TEPCO employees and contractors (internal, external and thyroid exposures);
— Thyroid doses of 1080 children resident in three municipalities in Fukushima Prefecture at the time of the accident;
— Estimates of external doses received by residents of Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP;
— External exposures of residents of a number municipalities in Fukushima Prefecture assessed by personal dosimeters.

II.2. OVERVIEW OF THE METHODOLOGY

It was assumed that the measurements in each dataset could be described by a log-normal function and an analysis of the maximum likelihood was performed.

For a given dose D, logarithmic mean μ and standard deviation σ, the log-normal probability is given by:

$$P(D) = \frac{1}{(2\pi)^{1/2} D\sigma} \exp\left[- \frac{(\ln D - \mu)^2}{2\sigma^2} \right]$$

The data collected for a series of doses D_i are obtained with a total probability of:

$$P_{tot} = \prod_i P(D_i)$$

The objective of the analysis was to identify the optimal theoretical log-normal distribution, described by μ and σ, which gives rise to the maximum value of P_{tot}, corresponding to the best agreement with the measured values and their uncertainties.

For the data collected within intervals (bins) with a width of $\Delta = 2\delta$, the expected number of cases $N(D_i)$ within an arbitrary bin centred on D_i must thus be proportional to:

$$N(D_i) = \int_{D_i - \delta}^{D_i + \delta} \frac{1}{(2\pi)^{1/2} D\sigma} \exp\left[- \frac{(\ln D - \mu)^2}{2\sigma^2} \right] dD = \int_{zd}^{zg} \frac{1}{(2\pi)^{1/2}} \exp(-0.5 z^2) dz$$

where

$$zd = \frac{\ln(D_i - \delta) - \mu}{\sigma}$$

and

$$zg = \frac{\ln(D_i + \delta) - \mu}{\sigma}$$

$N(D_i)$ should be scaled by a normalization factor A in order to fit the measured data. Therefore:

$$i^{\text{th}} \text{ measured value} = AN(D_i)$$

Using the classical maximum likelihood methodology, the value of the misfit function (χ^2) is calculated: each term in this function is weighted by an inverse of appropriate variance of the measured data point. In fact, the fitting of a theoretical function to the data requires assignment of the combined statistical uncertainty of the values plotted on both the vertical and horizontal axes. In this case the variances used are:

$$\sigma_i^2 = N_i + \left[A \frac{dN(D_i)}{dD_i} \sigma_{D_i} \right]^2$$

where the second term describes the impact of the uncertainty of the measured dose. Because the probability of a dose within a bin with the width $\Delta = 2\delta$ is assumed to be uniform, the variance of the dose is:

$$\sigma_D^2 = \frac{1}{12}\Delta^2 = \frac{1}{3}\delta^2$$

The normalization factor, A, was calculated according to classical minimization of χ^2.

It is possible that by ignoring the fact that data has been binned, and by simply fitting the probability distribution function (PDF) using a single appropriate value of the dose, the maximum of the PDF may be significantly overestimated. Such maxima are likely to be artefacts resulting from the limitations of the analysis and are unlikely to have physical meaning. When the binning is required but has not been considered in the analysis, substantial differences between the parameters obtained from fitting the PDF and cumulative distribution may arise.

Care also needs to be taken in interpreting values obtained around the detection limit because it is not always clear if the value *N* given at, say, 1 mSv, reflects the number of persons who received the doses between 0.5 and 1.5 mSv, or between 0 and 1.0 mSv. These issues are considered below with specific reference to the available data on doses to workers and the population following the Fukushima Daiichi accident.

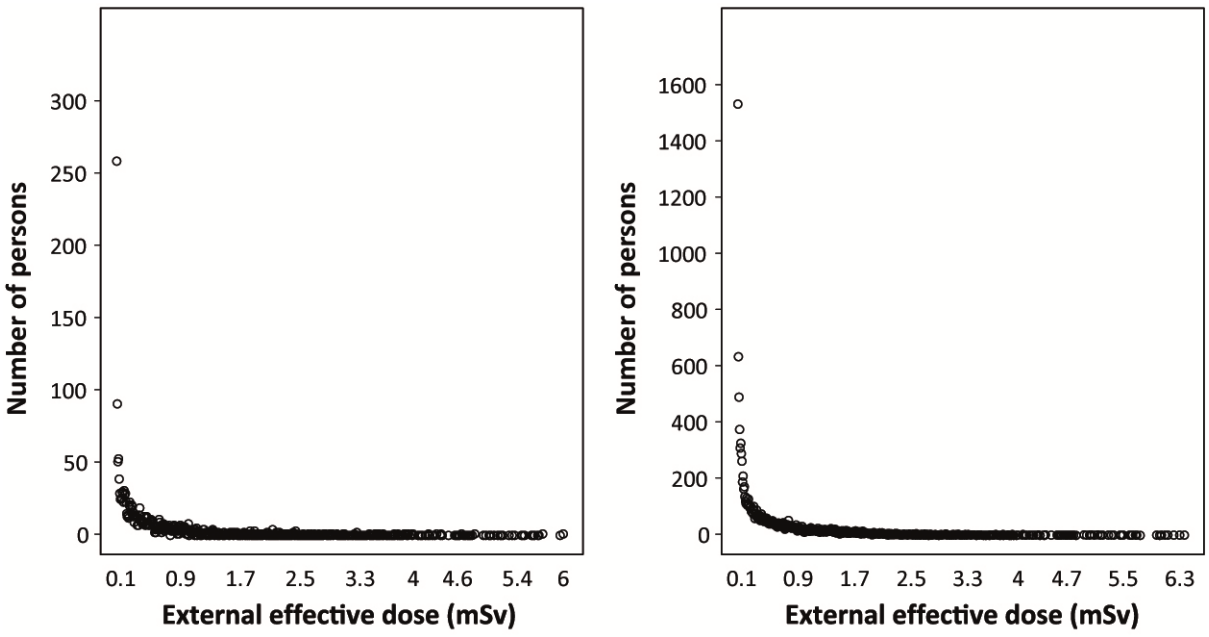
Probability plots were generated according to the same methodology used to analyse data measured following the Chernobyl accident [435].

As indicated elsewhere (see Box 4.2–1), owing to the scarcity and inhomogeneity of data, both the normalized bins of the available data and the resulting normalized probability density had to be ‘idealized’ into what was considered the most likely normalized distribution of bins and the corresponding probability density functions. These are represented in the figures on the left in the series of figures below. Conversely, the cumulative probability functions were constructed using the

data directly and they are not based on the idealized probability distributions. These functions are shown on the right in the series of figures below. There is not, therefore, a direct correspondence between these two representations of the distributions; the curves on the left represent the most probable normalized distribution of bins and corresponding probability density function, and those on the right are the cumulative distribution functions derived directly from the available data.

II.3. OCCUPATIONAL EXPOSURE DATASETS

As an illustration of the characteristics of the data available on doses to worker doses, the frequency distribution of the external dose to TEPCO workers and contractors in 2012 is presented in Fig. II.1.



(a) (b)

FIG. II.1. Frequency distribution of the reported external effective doses to (a) TEPCO employees and (b) contractors for the FY 2012.

The frequency distribution displayed in Fig. II.1 indicates that there are some deviations from a log-normal distribution. Inspection of the data shows two features which make detailed analysis difficult:

(1) Very high number of cases *N* associated with the first dose band,
(2) Very long tail with levels of *N* close to 1.

It is not immediately obvious how the reported doses should be interpreted. The first point indicates that the first dose interval (or bin) includes non-detected cases (i.e. where measurement values were below the levels of detection). In the following analysis it was assumed that:

— The first point is the cumulative number of persons who received the dose up to the lowest value.
— The next points represent the number of people within the dose interval (or bin). For example, the original numbers *N* for doses 20, 30, 40, etc., are treated as values obtained in bins 20±5, 30±5, 40±5, etc.

As explained earlier, such features of the data are not as problematic for the analysis which uses the cumulative distributions as this function is not as sensitive to the considerable variations in *N*. Furthermore, the assumptions related to binning do not significantly affect the fitted parameters.

Some of the data provided by TEPCO feature very small increments in the doses reported and, in addition, show larger scatter than might be expected. In such cases, the original data were aggregated into wider bins resulting in a smoother behaviour of the *N(D)* function.

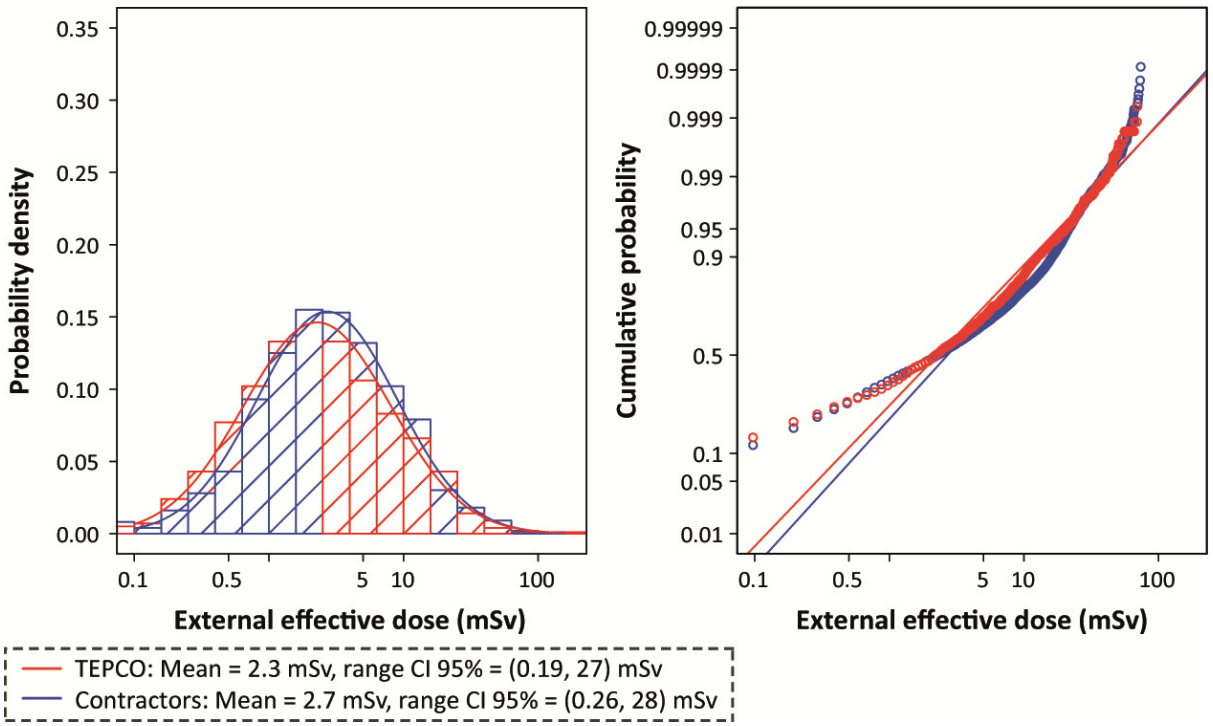
II.3.1. External exposures

For TEPCO employees in FY 2011 after binning the original data into 10 mSv intervals, the following statistics were obtained for the cumulative probability distribution and probability density function given in Table II.1.

TABLE II.1. COMPARISON OF THE ESTIMATED CUMULATIVE PROBABILITY DISTRIBUTION OF DOSES TO TEPCO WORKERS AND CONTRACTORS IN 2011 USING DIFFERENT LOG-NORMAL STATISTICAL METHODS

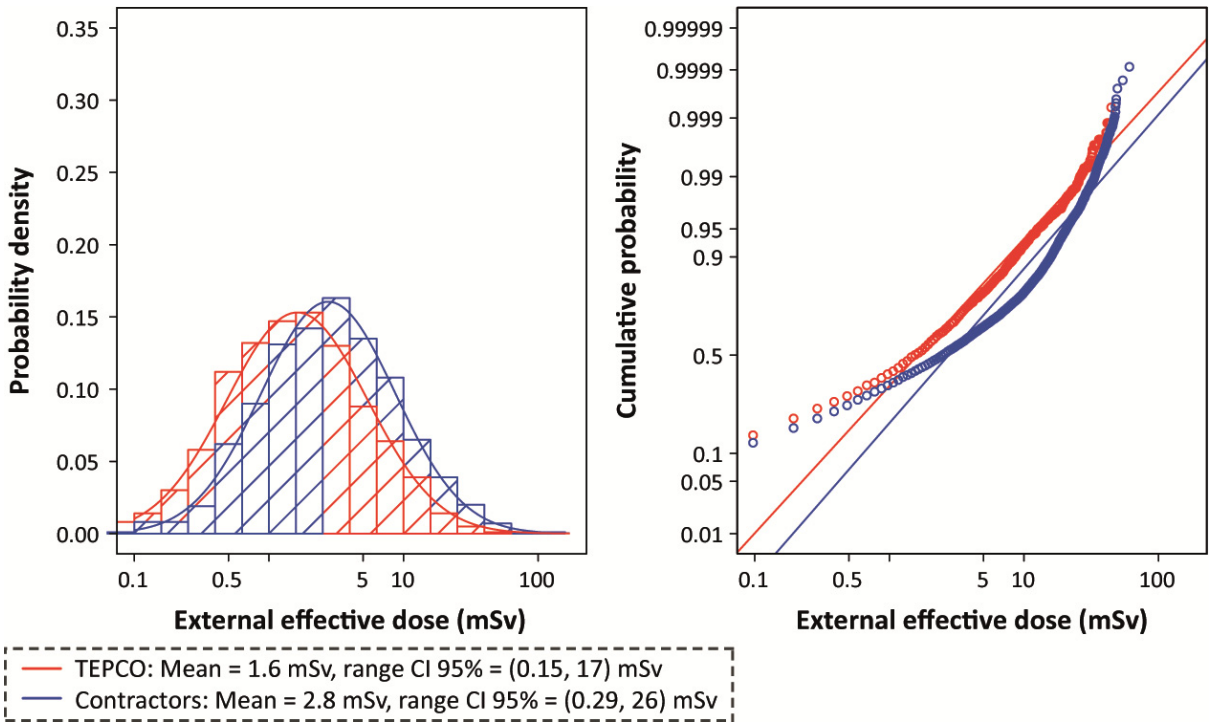
Statistic	Estimated doses to TEPCO workers (mSv)		Estimated doses to contractors (mSv)	
	Cumulative density function	Probability density function	Cumulative density function	Probability density function
Mean	16.8	10.6	7.1	7.8
67% confidence interval	5.9–48	3.42–33	2.8–18	3.6–17
95% confidence interval	2.1–134	1.11–101	1.1–45	1.7–36
χ^2	0.09	5.32	0.04	—

The results for the year 2011 are presented in Section 4.2.1 and the associated distributions are given in Figs 4.2–5 to 4.3–7. These data are consistent with those presented in Section 4.2.1 that were prepared according to the methodology used to analyse data following the Chernobyl accident. The results of the analysis for FY 2012, FY 2013 and FY 2014 are summarized in Table II.2. The data available for subsequent years are presented in Figs II.2–II.4. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.



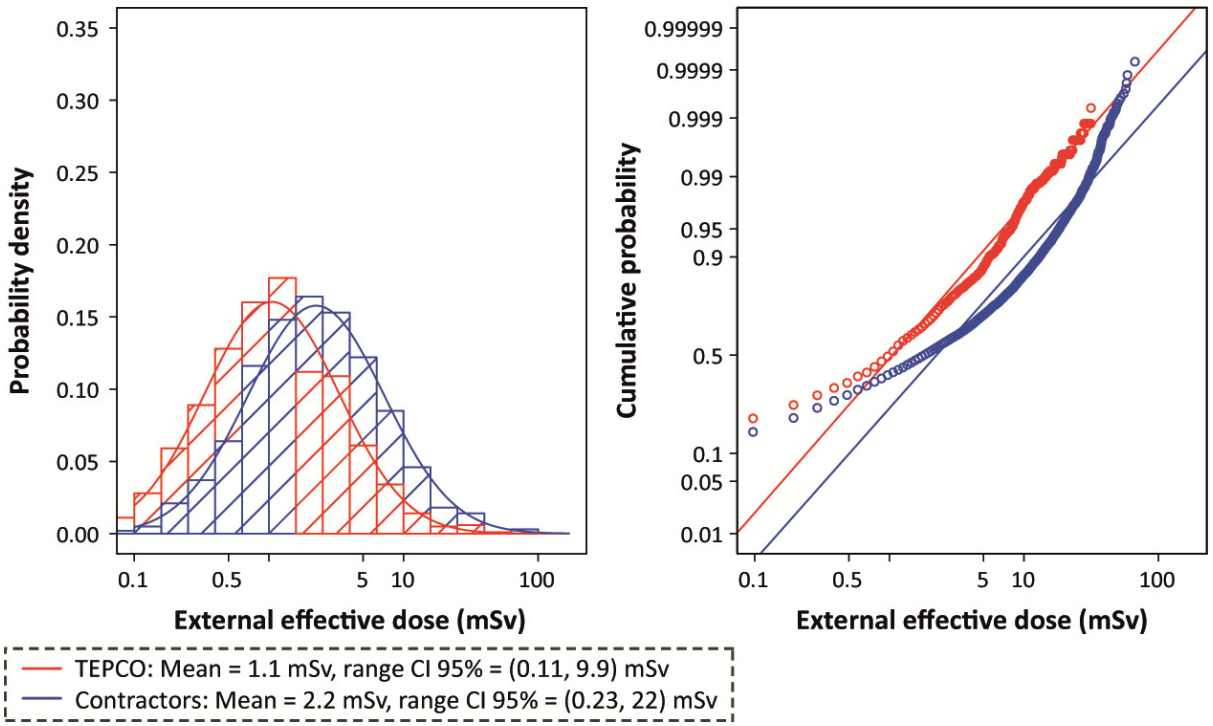
(a) (b)

FIG. II.2. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2012.



(a) (b)

FIG. II.3. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2013.



(a) (b)

FIG. II.4. (a) Normalized idealized probability density function and (b) cumulative probability distribution for the reported external effective doses to TEPCO employees and contractors for FY 2014.

TABLE II.2. SUMMARY OF THE ANALYSIS OF EXTERNAL DOSES RECEIVED BY TEPCO EMPLOYEES AND CONTRACTORS AT THE FUKUSHIMA DAIICHI NPP IN FY 2012 TO FY 2014

Year: best fit for cumulative distribution	Mean dose (mSv) CI 95%	
	Workers	Contractors
2012	2.3 (0.19, 27)	2.7 (0.26, 28)
2013	1.6 (0.15, 17)	2.8 (0.29, 26)
2014	1.1 (0.11, 9.9)	2.2 (0.23, 22)

Table II.2 demonstrates that the reported mean external effective doses received by TEPCO employees decreased progressively from around 2 mSv in 2012 to around 1 mSv in 2014. There is a similar order of reduction in the 95th percentile over this period, from 27 mSv to approximately 10 mSv. For contractors, the decrease in dose was less marked, and indeed the mean values for 2012 and 2013 are essentially the same. The 95th percentile values are also similar. There is, however, an indication of a reduction in 2014 to a mean value of around 2 mSv and in the 95th percentiles from 28 mSv in 2012 to 22 mSv in 2014. The probability density functions and the cumulative probability distributions (Figs II.2–II.4) also clearly illustrate a divergence in the distribution of doses received by TEPCO workers and contractors; in 2012 the distributions for the two groups are almost identical, while for 2014 two distinct distributions can be seen.

II.3.2. Internal exposures

The distribution of reported internal effective doses received by workers in 2011 is presented in Section 4.2.1 (Fig. 4.2–7). These data were also analysed by binning the values into dose intervals of widths 5 mSv and 0.5 mSv. The results obtained are shown in Table II.3.

TABLE II.3. COMPARISON OF STATISTICS FOR DIFFERENT LOG-NORMAL FITTING TECHNIQUES AND APPROACHES TO ALLOW FOR DATA AGGREGATION WITHIN DOSE INTERVALS (BINNING) FOR INTERNAL DOSES TO WORKERS (FY 2011)

Statistic		Estimated doses assuming dose interval of 5 mSv (mSv)		Estimated doses assuming dose interval of 0.5 mSv (mSv)	
		Cumulative density function	Probability density function	Cumulative density function	Probability density function
Mean		2.59	2.44	0.12	0.07
67% interval	confidence	0.59–11	0.55–10.8	0.01–2.1	0.0–3.3
95% interval	confidence	0.14–49	0.12–47.9	0.0–36	0.0–58
χ^2		0.11	2.68	0.31	2.56

The data estimated assuming a dose interval of 5 mSv are consistent with those presented in Section 4.2.1. These data illustrate the effect of assumptions regarding the dose intervals (or bins) and suggest that the fit of cumulative distribution data is good while the PDF is rather poor.

II.3.3. Doses to the thyroid

In the case of thyroid doses, the data tend towards an exponential decrease as a function of dose rather than a log-normal distribution. The extent of the deviation of these data from a log-normal distribution is illustrated in Fig. II.5, which presents the frequency distribution of the original measurement data and that based on log-normal fitting. While a reasonable agreement can be obtained with the cumulative log-normal distribution, a direct comparison of the PDF shows that such agreement cannot be considered to support an assumption of log-normality.

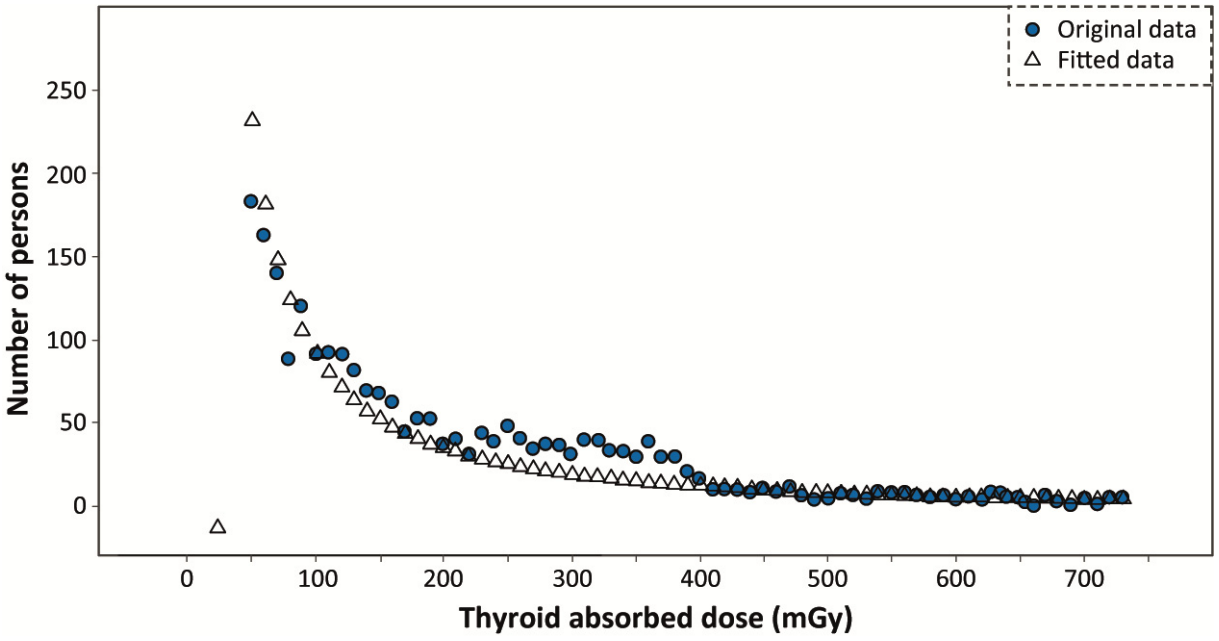


FIG. II.5. Frequency distribution of thyroid equivalent doses received by contractors at Fukushima Daiichi NPP in FY 2011 (March 2011–March 2012).

A normalized idealized probability density function and cumulative probability distribution of reported thyroid equivalent doses received by TEPCO workers and contractors in 2011 is presented in Fig. 4.2–8.

II.3.4. Summary of occupational exposure analysis

With the exception of thyroid dose measurements, the results derived are adequately described by a log-normal distribution, although there are some deviations from it. The differences in the parameters associated with the fit of the distributions are not significantly different between the application of the PDF and cumulative distribution approaches. These analyses provide a coherent set of statistical parameters.

II.4. THYROID DOSES RECEIVED BY CHILDREN RESIDENT IN THREE MUNICIPALITIES OF FUKUSHIMA PREFECTURE

A survey of thyroid exposure was conducted as screening to determine the need for further medical attention. A net screening level of 0.2 μSv/h was defined for this purpose. A statistical analysis of measured thyroid doses of 1080 children from three municipalities in Fukushima Prefecture cannot conclusively support or dismiss the assumption of a log-normal probability density function (PDF) to express the distribution of doses to the thyroid among the population of Fukushima Prefecture. Further analysis of the information and data from this survey is presented in Annex VII.

II.5. APPLICATION OF THE METHODOLOGY TO EXTERNAL DOSES TO RESIDENTS

The external effective doses received by residents of various municipalities in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP (11 March–11 July 2011) have been estimated by means of environmental dose rate measurements and responses to questionnaires on locations during that period. More information is presented in Section 4.2.2. The number of people receiving doses within bins of width 1 mSv has been reported for people from different municipalities and from specific regions of Fukushima Prefecture. The information for

individual municipalities within and outside a 20 km radius of Fukushima Daiichi NPP is presented and explored in Section 4.2.2.2 and Fig. 4.3–13 and is not presented in more detail here. However, the frequency distribution of estimated external effective doses for people in Iitate Village provides an example of the difficulties and the value of evaluating the fit of reported data to a log-normal distribution (see Fig. II.6).

The following features are seen in Fig. II.6:

— The original data exhibit a double peak structure (one peak at about 1 mSv and the second at around 5 mSv), which is not compatible with the assumption of a log-normal distribution.
— Different parameters are obtained from fits using PDF and cumulative distributions.

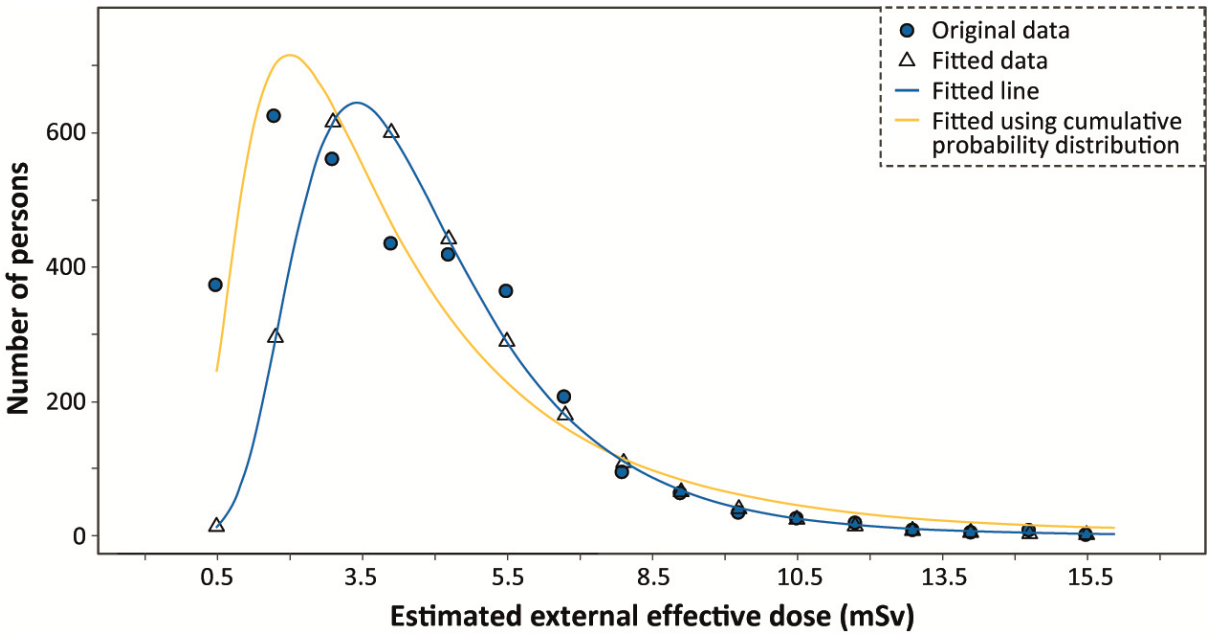


FIG. II.6. Estimated external effective doses received by residents of Iitate Village in the first four months following the accident at the Fukushima Daiichi NPP.

From this, it is apparent that the fitting of two different functions may result in a different evaluation of the weights denoted to individual points to the overall distribution. However, the deviation of the distribution from the log-normal is also valuable information from a radiation protection point of view. This distribution, with a double peak structure, may be indicative of the exposure of different groups of the population to different radiological conditions, for example, due to different patterns of evacuation and levels of radionuclides in the environment.

Figure II.6 also demonstrates that the lowest doses are underestimated by the fitting procedure when the PDF is used. This is due to treating the lowest bin in the same way as those for higher doses — by averaging over the dose interval — whereas it actually represents the cumulative values obtained between 0 and 1.0 mSv.

The distributions of estimated external effective doses received by residents of various regions in Fukushima Prefecture in the first four months following the accident are presented in Figs II.7–II.12, beginning with Soso, the region in which Iitate Village is located. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.

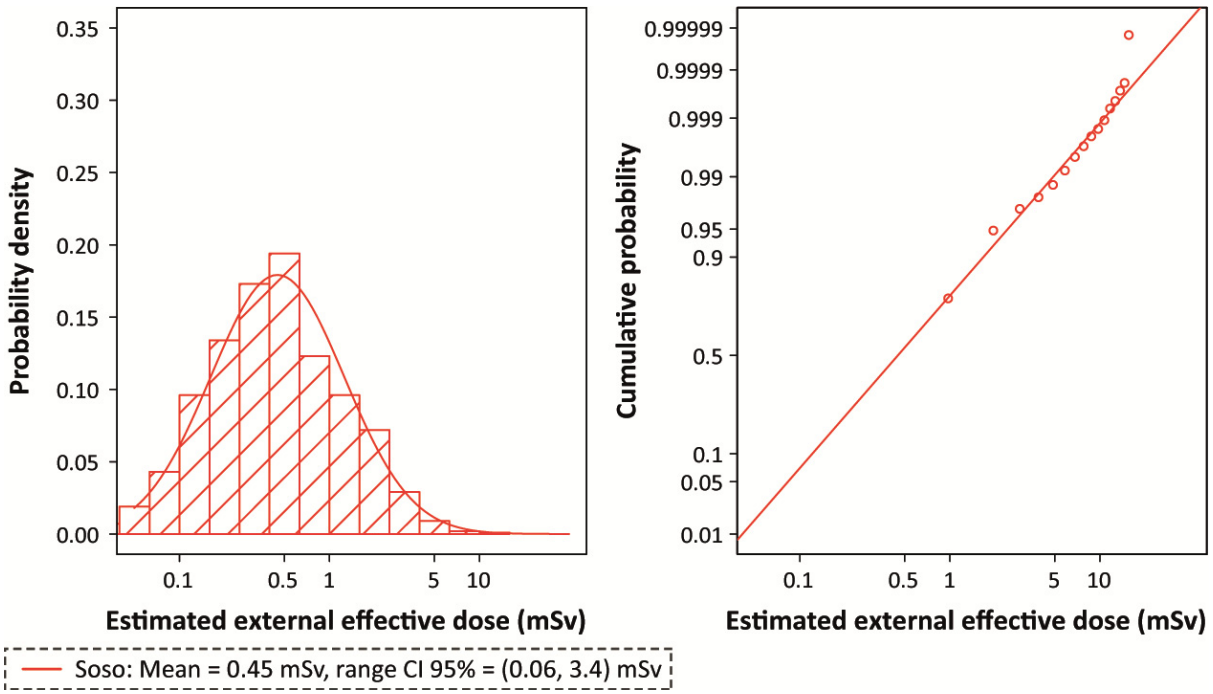


FIG. II.7. Estimated external effective doses received by residents of the Soso region in the first four months following the accident at the Fukushima Daiichi NPP.

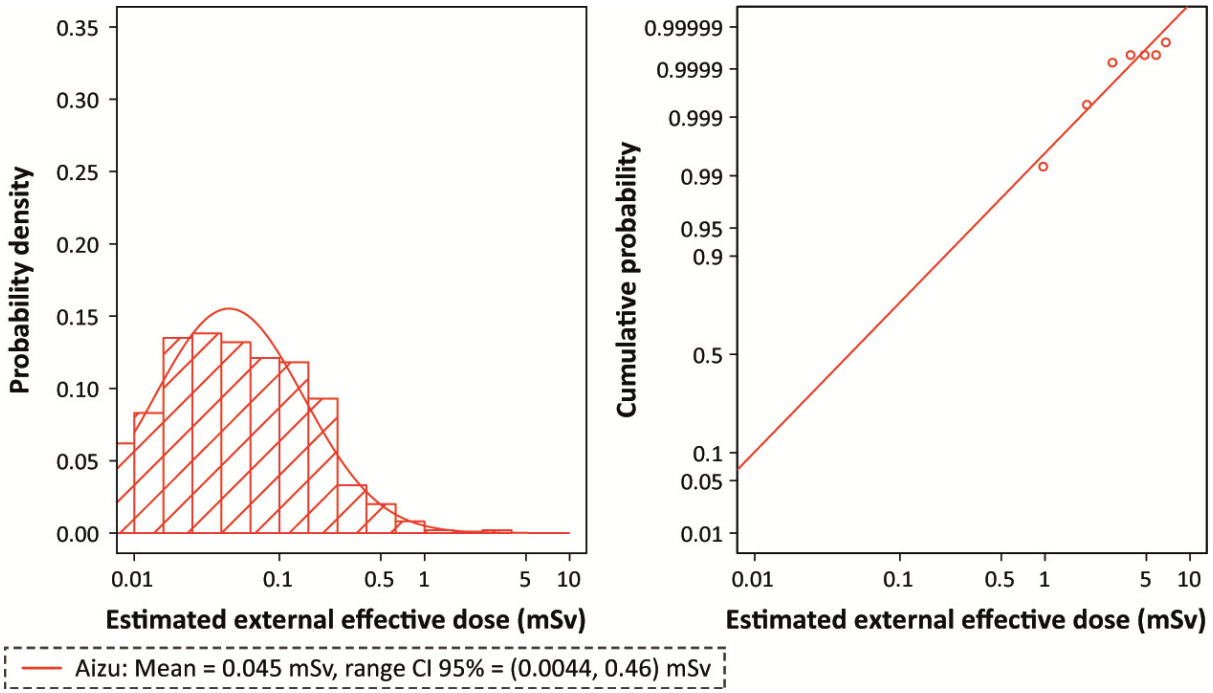


FIG. II.8. Estimated external effective doses received by residents of the Aizu region in the first four months following the accident at the Fukushima Daiichi NPP.

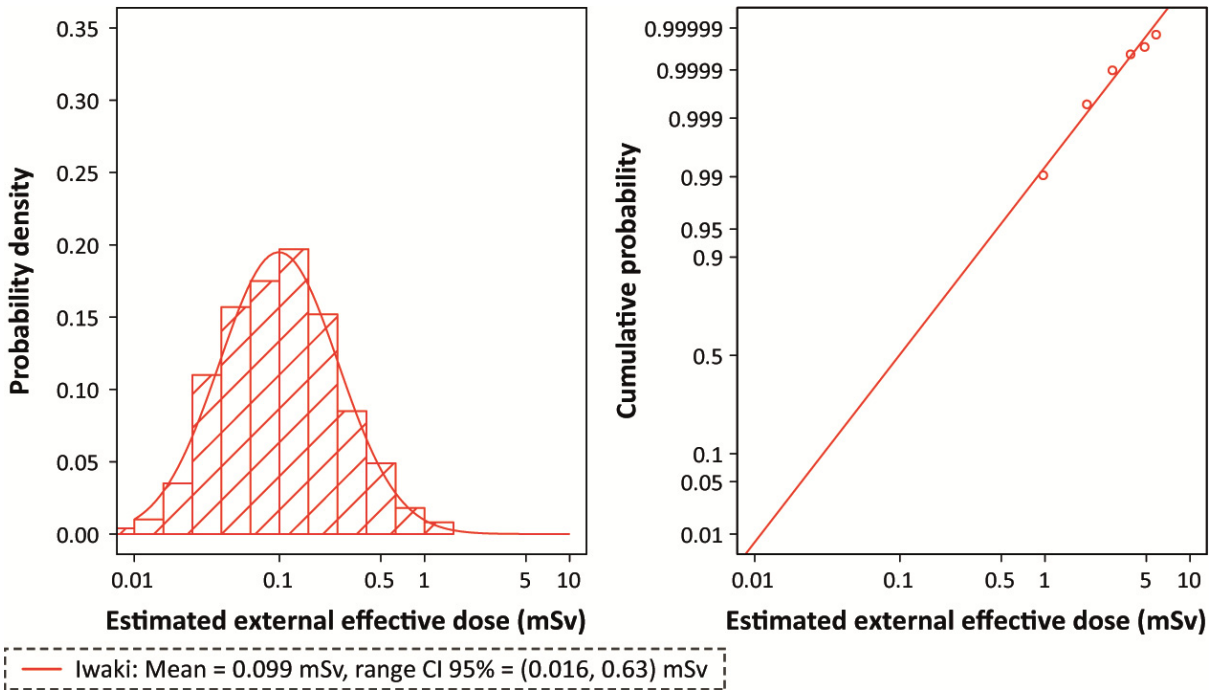


FIG. II.9. Estimated external effective doses received by residents of the Iwaki region in the first four months following the accident at the Fukushima Daiichi NPP.

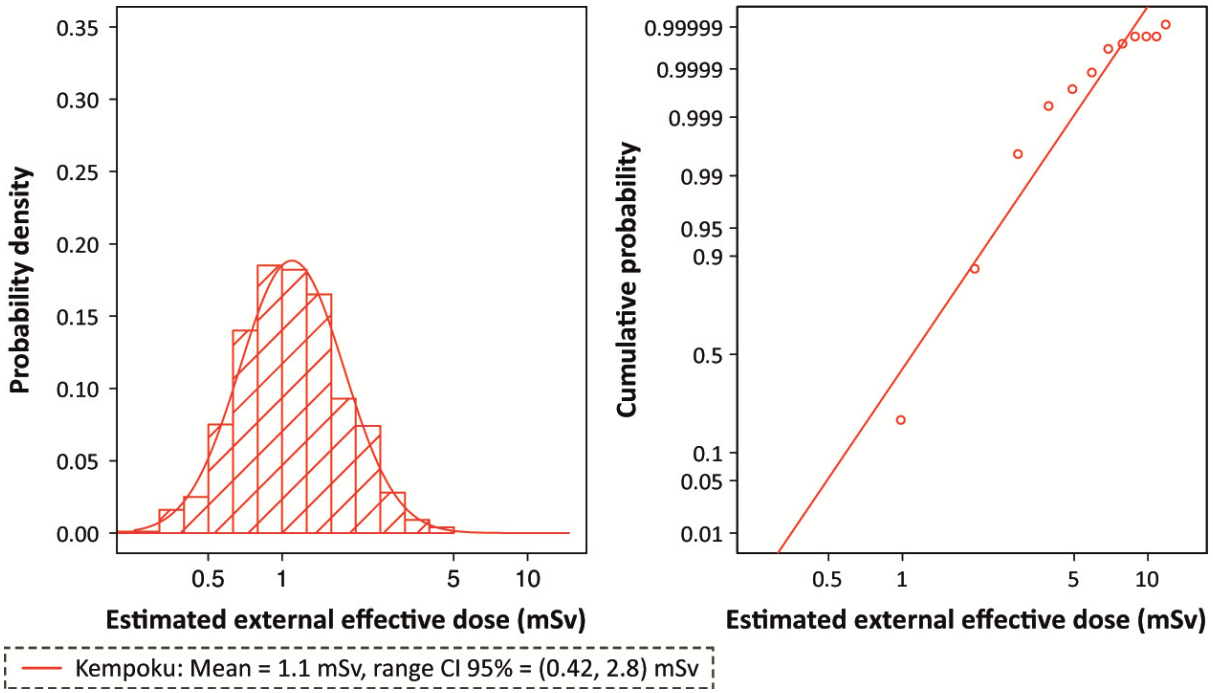


FIG. II.10. Estimated external effective doses received by residents of the Kempoku region in the first four months following the accident at the Fukushima Daiichi NPP.

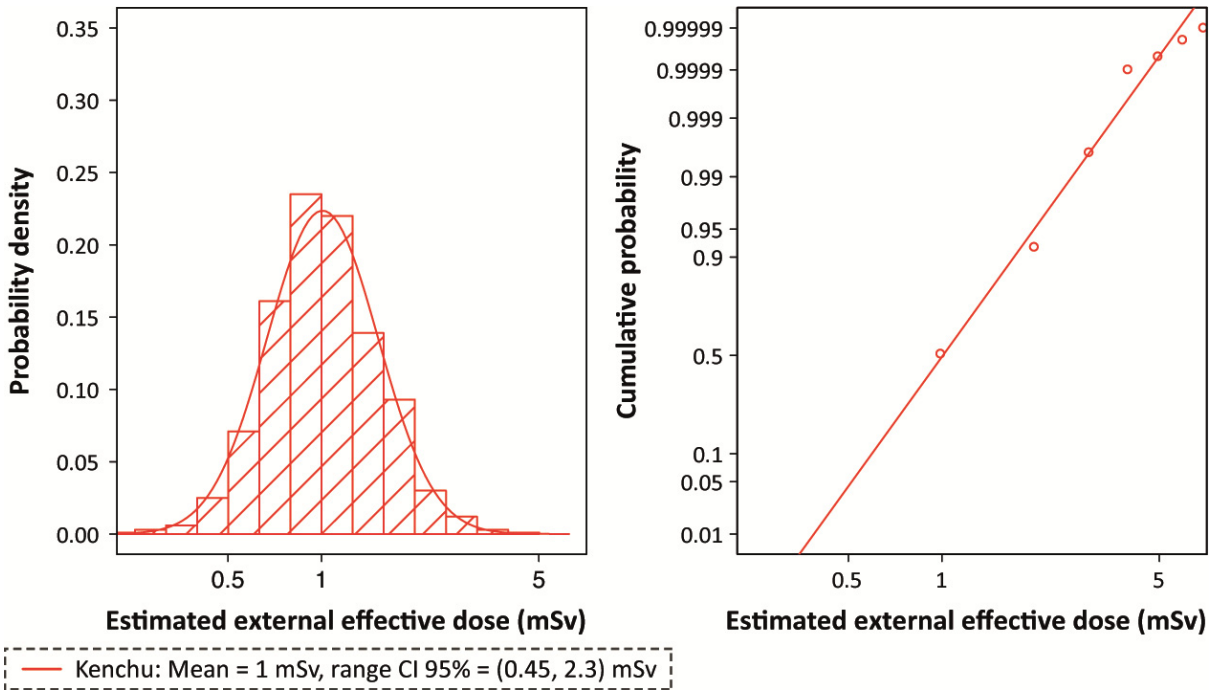


FIG. II.11. Estimated external effective doses received by residents of the Kenchu region in the first four months following the accident at the Fukushima Daiichi NPP.

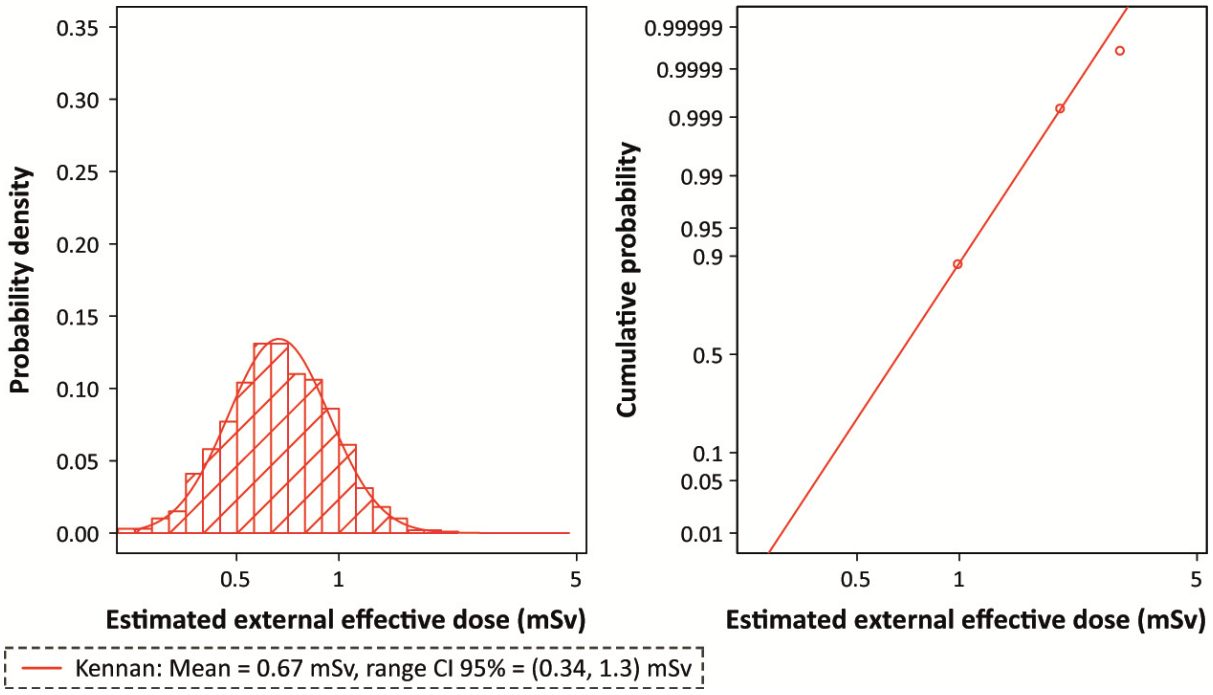


FIG. II.12. Estimated external effective doses received by residents of the Kennan region in the first four months following the accident at the Fukushima Daiichi NPP.

The mean external effective doses in the first four months following the accident, in all the regions in the figures, were estimated to be of the order of 1 mSv or below and the 95th percentiles were of the order of 3 mSv or below. This pattern of dose is also illustrated by the data presented for different age groups in Figs II.13–II.15. These figures demonstrate that there is no significant difference between the distribution of external effective doses for the different age groups for which information is

available. In these figures the normalized idealized probability density function is presented on the left and the cumulative probability distribution on the right.

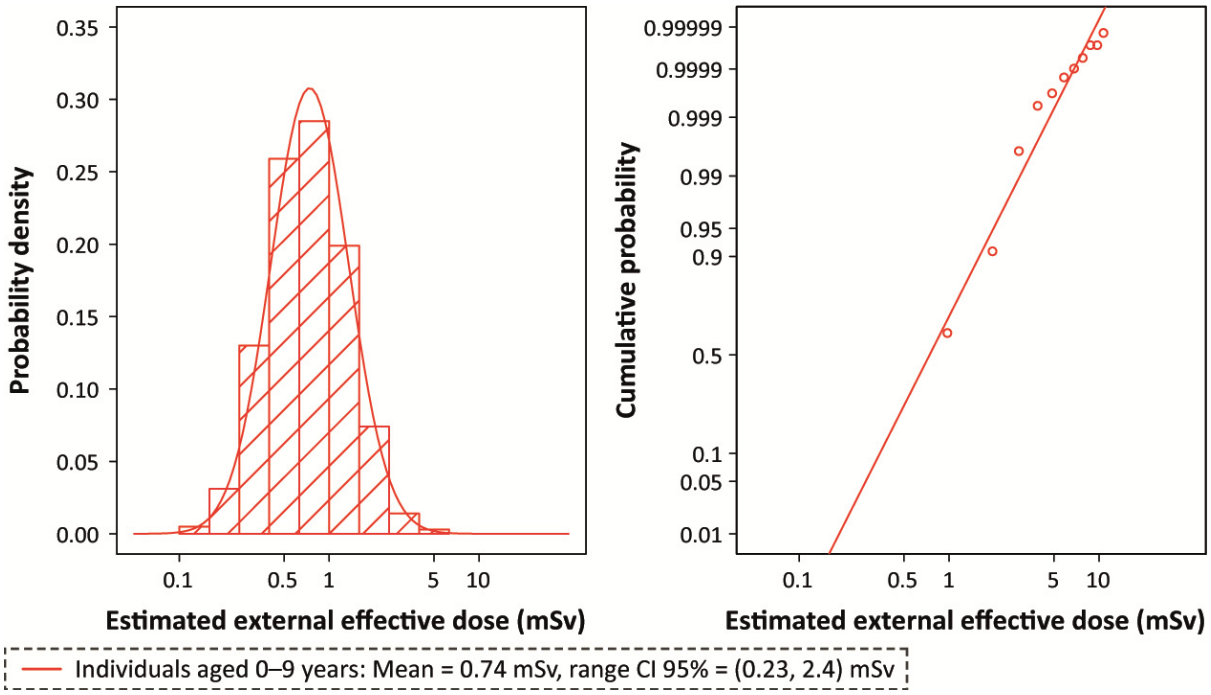


FIG. II.13. Estimated external effective doses received by children (aged 0–9 years) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

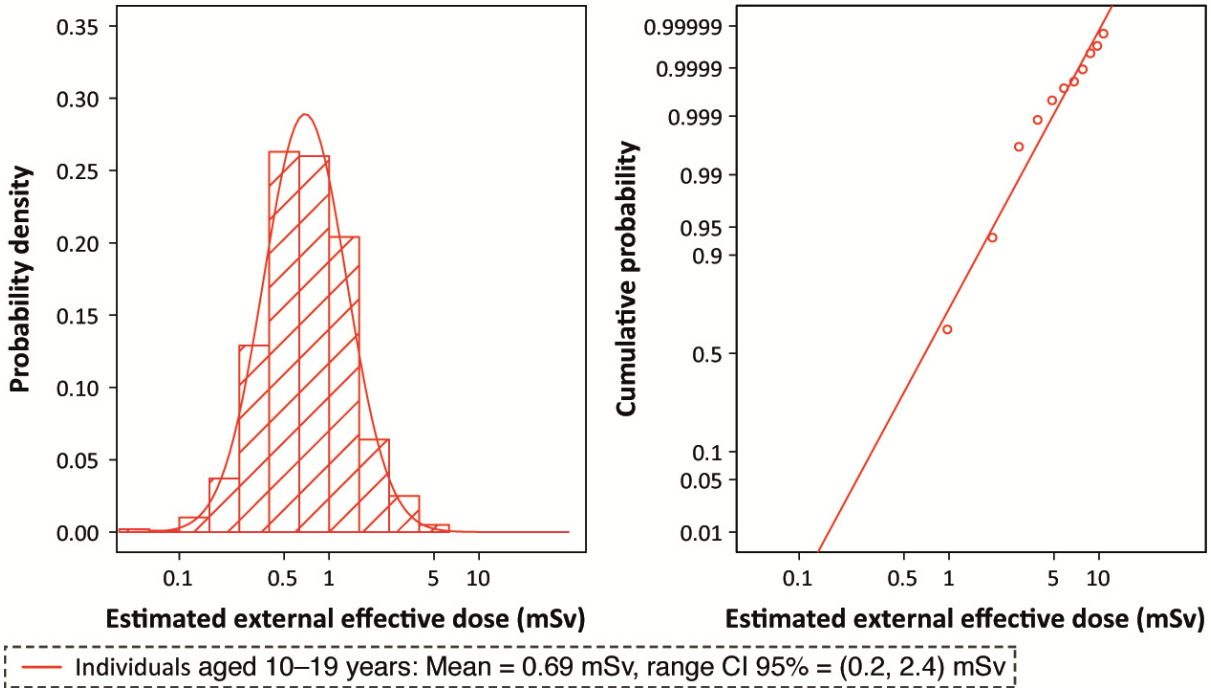


FIG. II.14. Estimated external effective doses received by young people (aged 10–19 years) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

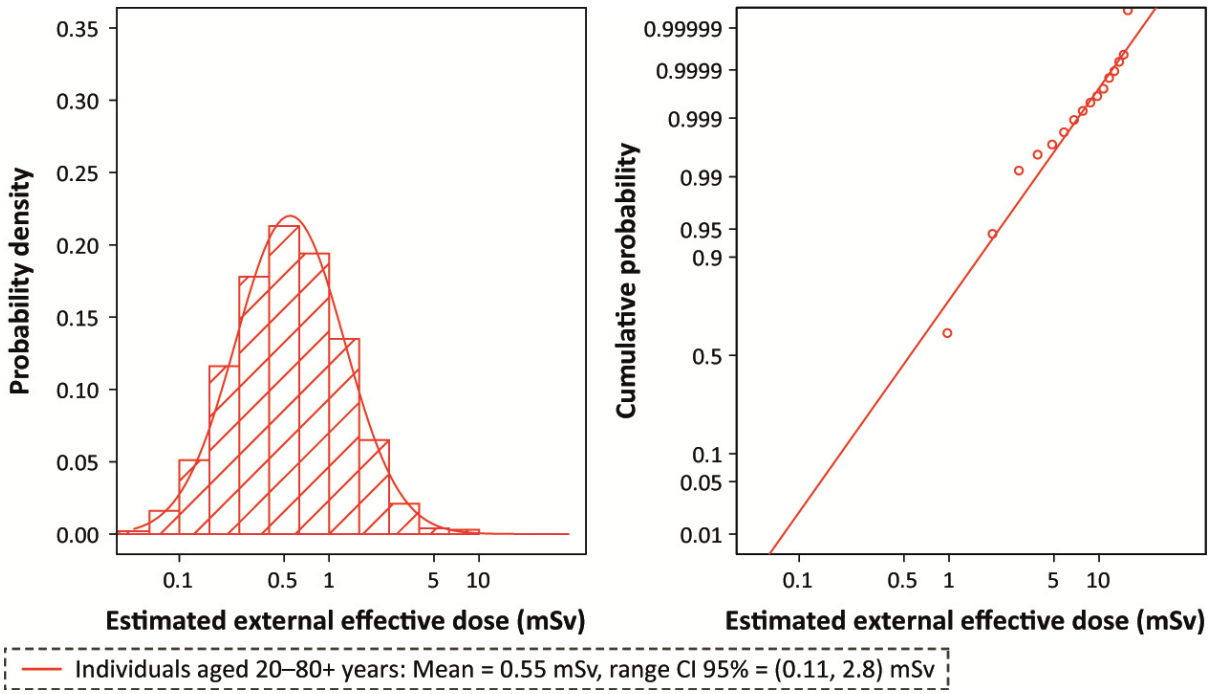


FIG. II.15. Estimated external effective doses received by adults (aged 20 years or older) in Fukushima Prefecture in the first four months following the accident at the Fukushima Daiichi NPP.

II.6. PERSONAL EXTERNAL DOSIMETRY DATA PROVIDED BY FUKUSHIMA PREFECTURE

Fukushima Prefecture made a range of datasets publicly available through its web site, including the results of personal dosimetry and WBC measurements undertaken in Fukushima Prefecture during and since 2011. These data are summarized in Table II.4 [226].

TABLE II.4. SUMMARY OF PERSONAL DOSIMETRY DATA PROVIDED BY FUKUSHIMA PREFECTURE [226]

Place	Date	Number of samples	Comments
Date City	Sep. 2011–Feb. 2012	8 982	Cumulative log-normal distribution function and probability density function presented in Section 4.2.2
	Jul. 2012 – Jun. 2013	36 721	Cumulative log-normal distribution function and probability density function for different occupational groups presented in this appendix
			Comparison of external doses estimated by different methods presented in Section 4.2.2.-
Fukushima City	Sep.–Oct. 2011 Oct.–Nov. 2011	5 750 and 5 580	Cumulative log-normal distribution function presented in Section 4.2.2 and probability density function presented in this appendix
	1 Nov. 2012–31 Jan. 2013	15 945 (< 15 years)	Cumulative log-normal distribution function and probability distribution presented in this appendix
Tamura City	30 Aug.–30 Sep. 2011	4 401	Cumulative log-normal distribution function and probability density function presented in this appendix
	30 Sep.–10 Jan. 2012	4 570	Cumulative log-normal distribution function and probability density function presented in this appendix
	11 Jun.–11 Sep. 2012	4 318	Cumulative log-normal distribution function and probability density function presented in this appendix
	11 Sep.–11 Dec. 2013	3 634	Cumulative log-normal distribution function and probability density function presented in this appendix
Iwaki City	1 Nov. 2011–31 Jan. 2012	30 910 (< 15 years)	Cumulative log-normal plot presented in Section 4.2.2. Additional information probability distribution information for different groups of schoolchildren presented in this appendix

The log-normal distribution is generally a good representation of these data, although there are some deviations, as represented by the normalized idealized probability density functions and cumulative distribution functions for each city for which data are available in the sections below.

II.6.1. Distribution of personal dosimetry data for Date City

The main survey periods for which data are available for Date City are summarized in Table II.5. The cumulative probability distribution and the idealized normalized probability density function appropriate for exposures in 2011 are presented in Section 4.2.2. The data from subsequent surveys also allow the doses estimated using different methods to be compared, as explored further in Section 4.2.2.

During the period July 2012–June 2013, over 35 000 workers in Date City took part in a survey of external doses. Information on their occupation was also recorded, so that the results of this survey can be used to investigate the effect of different occupations on the external doses received. The distribution of the doses received by different occupational groups from external exposure are presented in Fig. II.16.

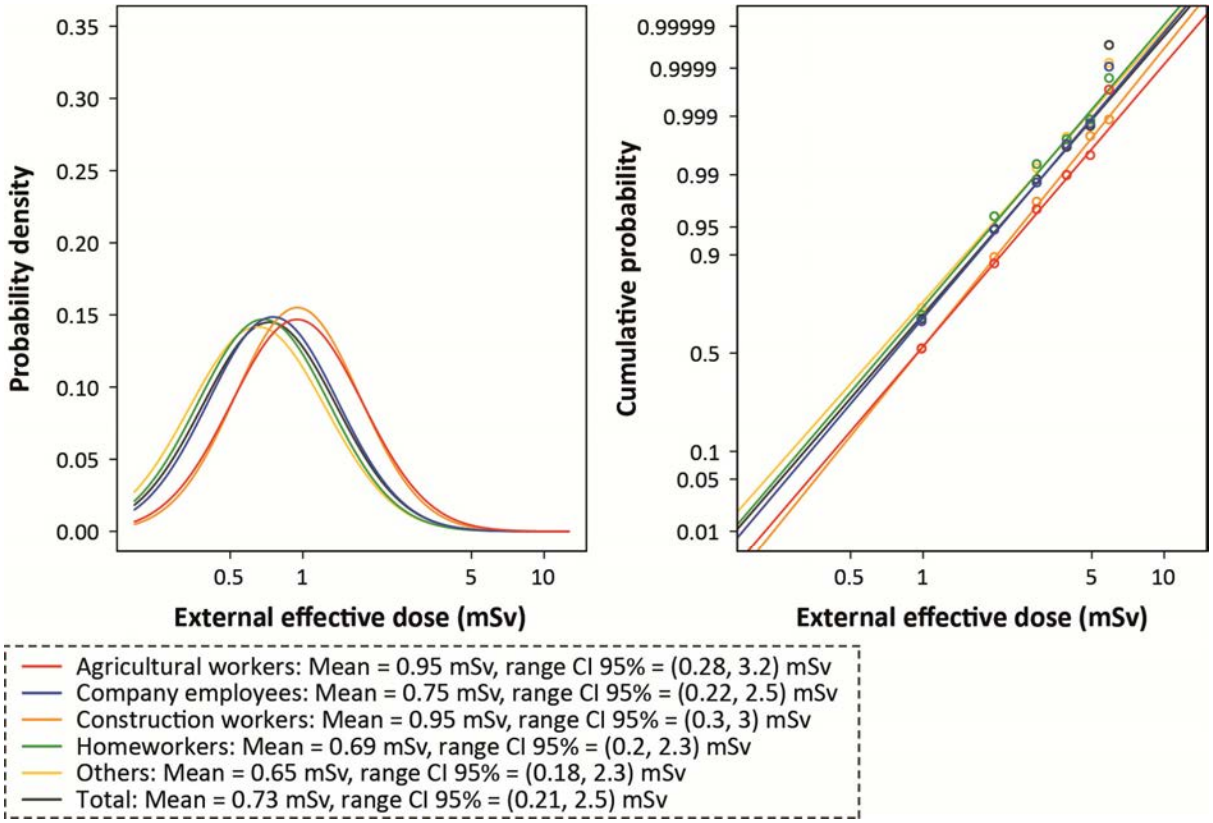
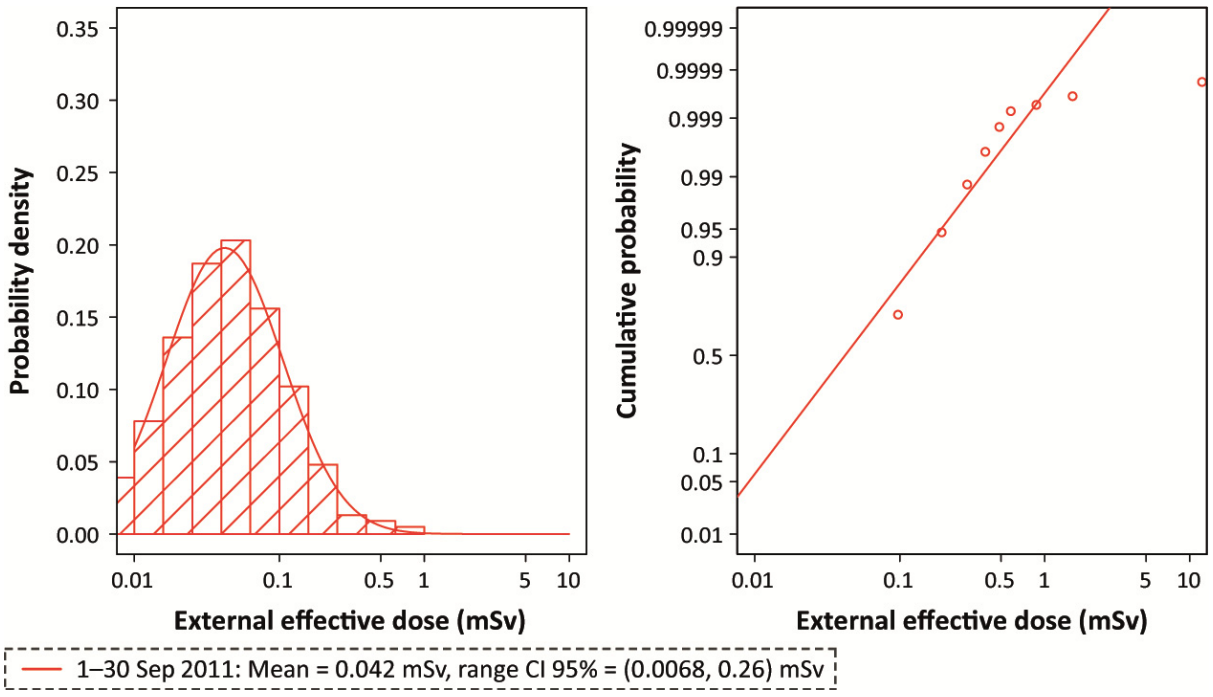


FIG. II.16. (left) Normalized idealized probability density function of external effective doses to different occupational groups in Date City; (right) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period July 2012–June 2013.

Figure II.16 demonstrates that the distribution of doses to agricultural and construction workers are shifted towards higher doses in comparison to other workers, as a consequence of the greater time spent outdoors. Indoor workers and other groups of the population receive lower doses due to the shielding effect of buildings from radioactive material deposited on the ground.

II.6.2. Distribution of personal dosimetry data for Fukushima City

Information on the estimated external effective doses received by the population of Fukushima City is available for three measurement periods, beginning in September 2011. The normalized idealized probability density function and the cumulative probability distribution for the doses estimated for each period are presented in Figs II.17–II.19 [226].

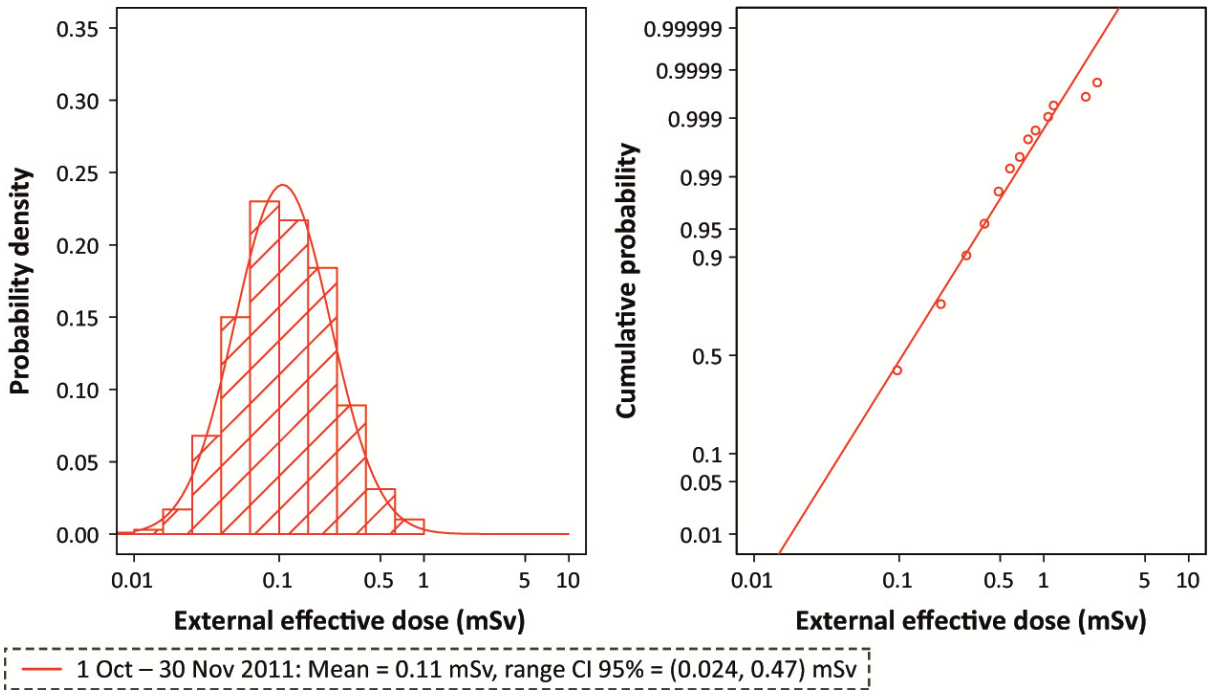


(a) (b)

FIG. II.17. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1–30 September 2011.

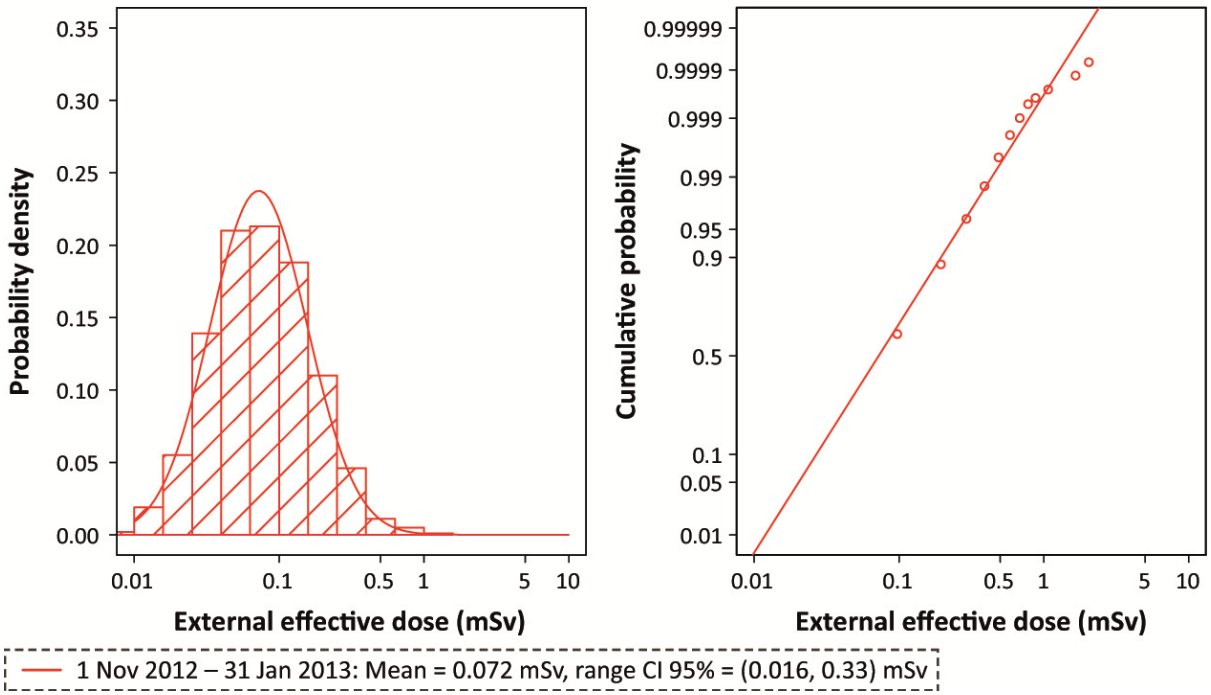
These figures demonstrate that there is some deviation from the log-normal distribution towards the upper tail, associated with higher doses. These results indicate that a mean dose of around 0.04 mSv was received by residents of Fukushima City in September 2011 and that the 95% confidence interval is around 0.01–0.3 mSv. One outlying result exceeds 10 mSv, while others are around 1 mSv or below.

Figures II.18 and II.19 indicate that the cumulative probability distribution is closer to a straight line corresponding to the log-normal distribution, indicating that this distribution is a better fit for the personal dosimetry data measured in the later periods of measurement in the city (1 October–30 November 2011 and 1 November 2012–31 January 2013). The mean values and 95% confidence values for these periods are presented, together with those of those of the month of September 2011, in Table II–5.



(a) (b)

FIG. II.18. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1 October–30 November 2011.



(a) (b)

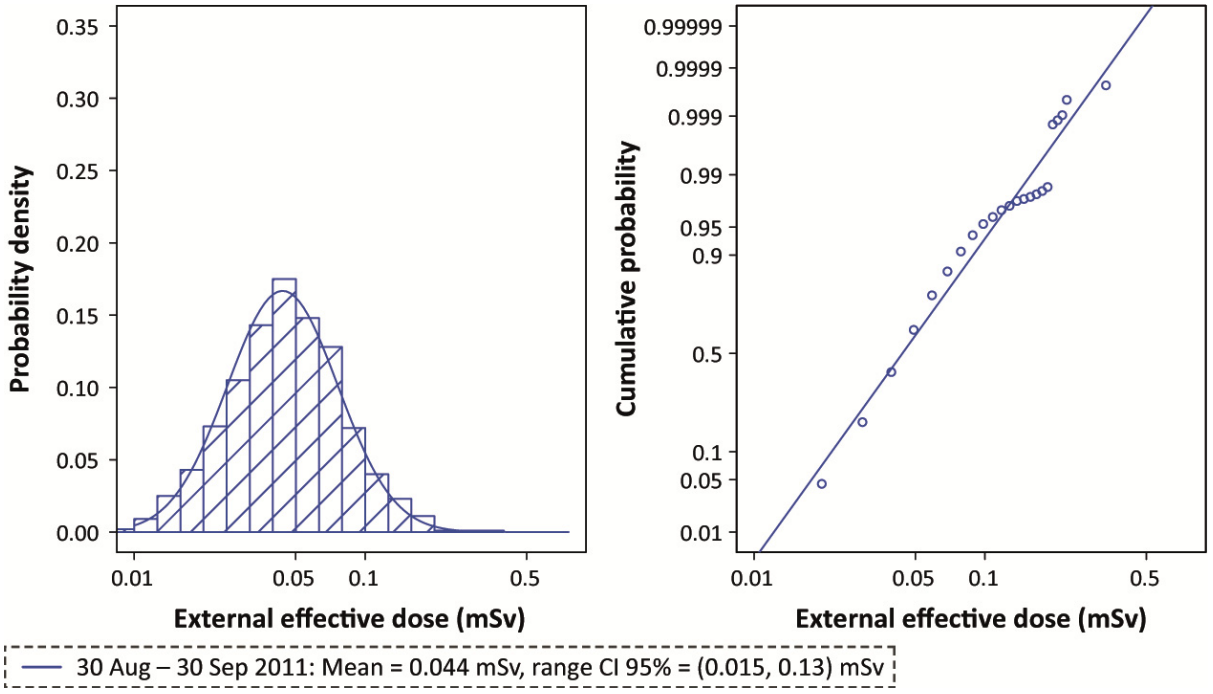
FIG. II.19. (a) Normalized idealized probability density function of external effective doses to residents of Fukushima City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements in Fukushima City for the period 1 November 2012–31 January 2013.

TABLE II.5. EXTERNAL DOSES MEASURED BY PERSONAL DOSIMETRY IN FUKUSHIMA CITY DURING THE SPECIFIED PERIODS (mSv) [226]

	1 September–30 September 2011	1 October–3 November 2011	1 November 2012–31 January 2013
Mean	0.04	0.11	0.07
95% confidence interval	0.07–0.26	0.02–0.47	0.02–0.33

II.6.3. Distribution of personal dosimetry data for Tamura City

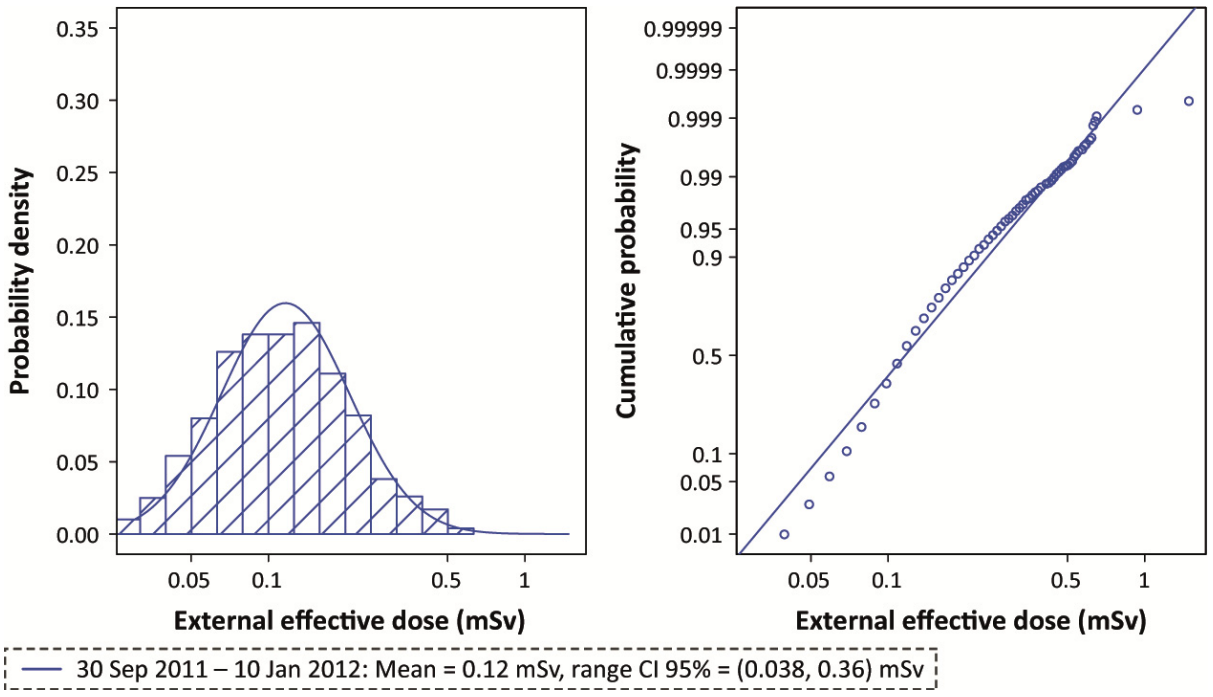
The external effective doses received by the population of Tamura City were available for four measurement periods beginning at the end of August 2011 and extending until mid-September 2012. The normalized idealized probability density function and the cumulative probability distribution for the doses estimated for each period are presented in Figs II.20–II.23 [207].



(a) (b)

FIG. II.20. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 30 August–30 September 2011.

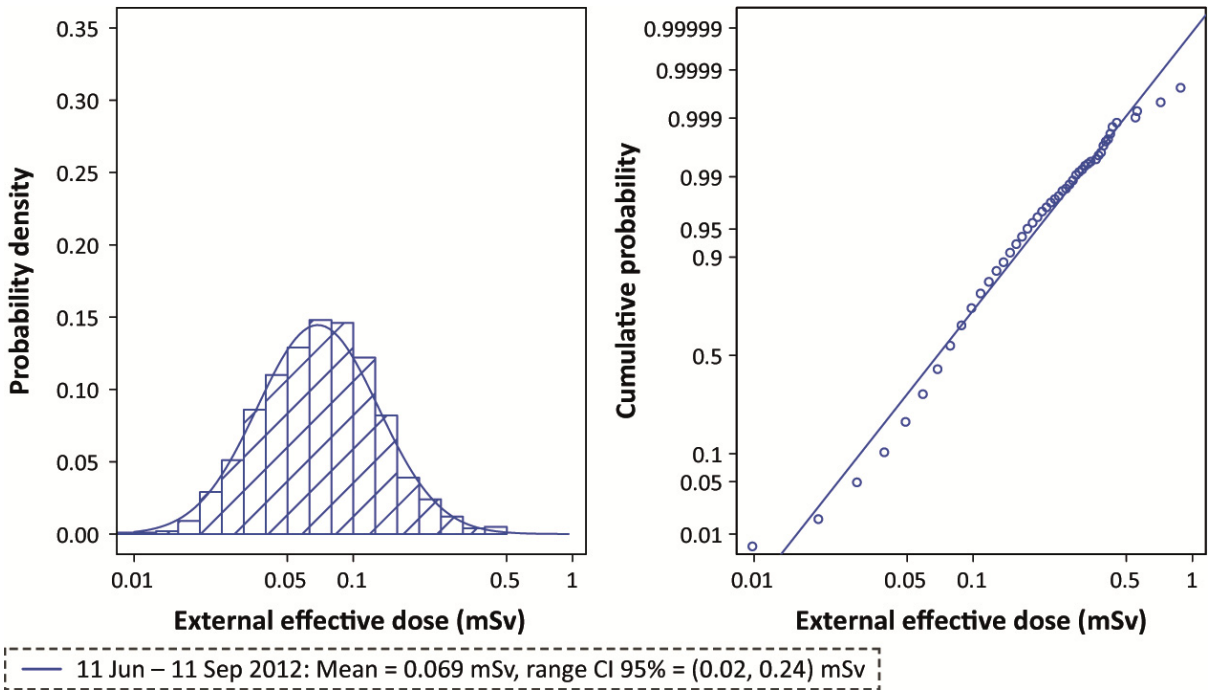
Deviations from the log-normal are illustrated in the cumulative probability function and in the probability density function for the same dataset.



(a) (b)

FIG. II.21. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 30 September 2011–10 January 2012.

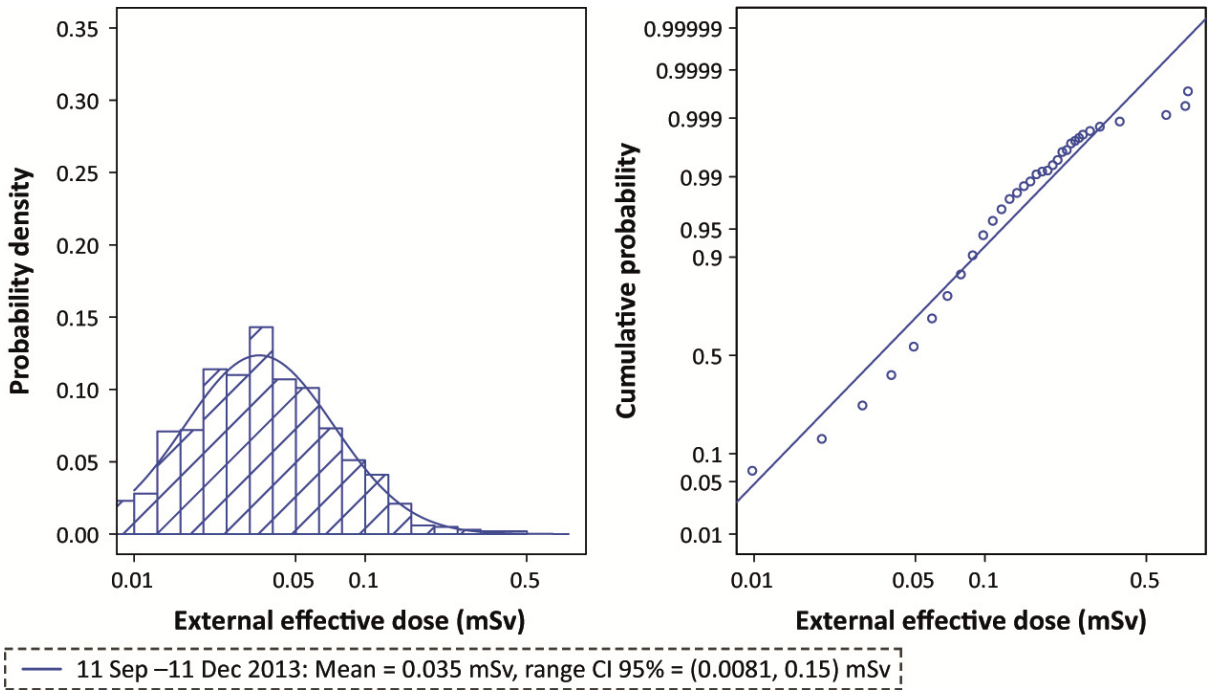
The data for the later measurement period in 2011 (Fig. II.21) appear to fit the log-normal distribution, although there are some deviations. The personal dosimetry data for the subsequent period (11 June 2012–11 September 2012) also demonstrate a reasonable fit to the log-normal. These data also show a reduction in mean dose, consistent with radioactive and environmental decay processes (and possibly remediation measures).



(a) (b)

FIG. II.22. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 11 June–11 September 2012.

The final dataset for Tamura City suggests some deviation from the log-normal distribution such that the confidence intervals should be treated with some caution (Fig. II.23). However, the mean values indicate a continued decrease due to decay mechanisms and possibly remediation. The statistics associated with external doses measured in Tamura City in different periods are summarized in Table II.6.



(a) (b)

FIG. II.23. (a) Normalized idealized probability density function of external effective doses to residents of Tamura City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 11 September – 11 December 2013.

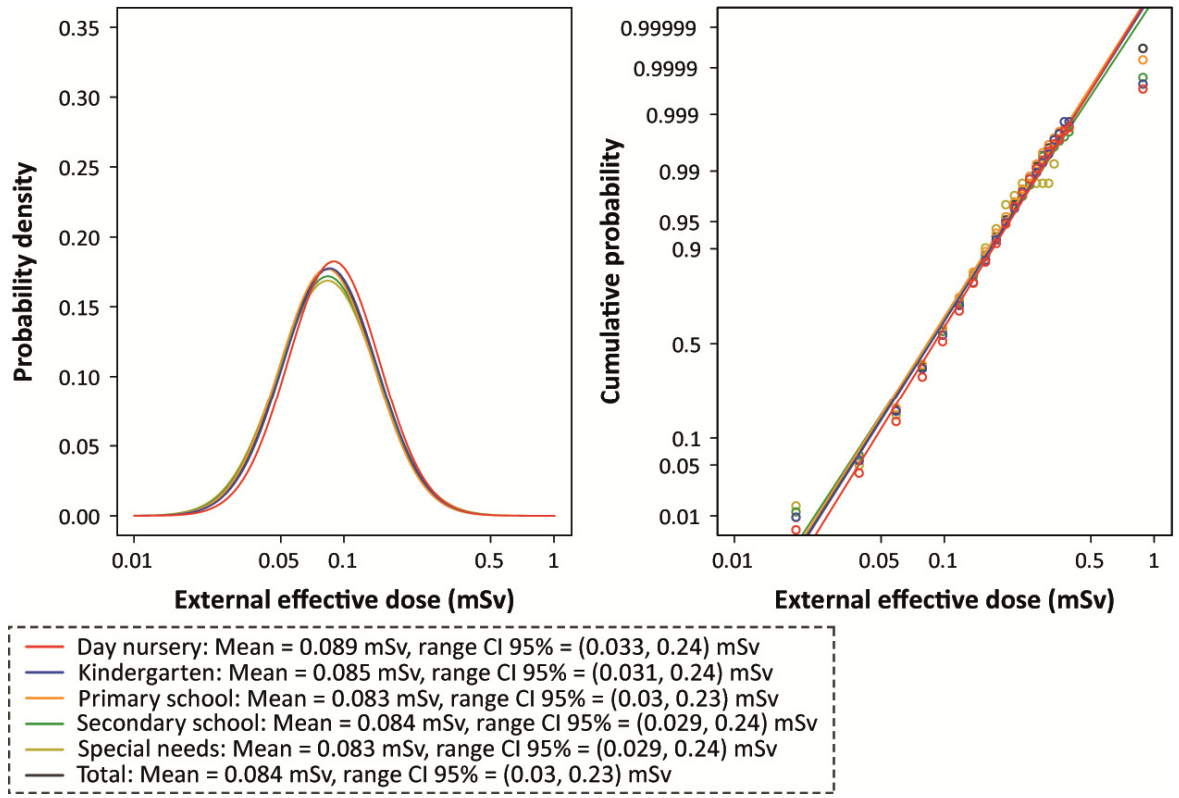
TABLE II.6. EXTERNAL DOSES MEASURED BY PERSONAL DOSIMETRY IN TAMURA CITY DURING THE SPECIFIED PERIODS (mSv) [207]

	30 Aug–30 Sep. 2011	30 Sep. 2011–10 Jan. 2012	11 Jun.–11 Sep. 2012	11 Sep.–11 Dec. 2013
Mean	0.044	0.12	0.069	0.035
95% confidence interval	0.015–0.13	0.038–0.36	0.002–0.24	0.008–0.15
χ^2	4.4	—	—	5.4

Note: The values of χ^2 are presented where the values indicate deviations from a log-normal distribution (illustrated by the high maximum values in the PDFs above).

II.6.4. Distribution of personal dosimetry data in Iwaki City

Approximately 30 000 school children in Iwaki City took part in a survey in which they wore personal dosimeters during the period 1 November 2011–31 January 2012. The results of these measurements have been made available [217, 218] and allow the distribution of external effective doses received by school children of different ages to be determined, as illustrated in Fig. II.24. The distribution of the effective doses is effectively the same for each of the age groups of schoolchildren, with a mean of around 0.4 mSv and a 95th percentile value of approximately 1.5 mSv or slightly less.



(a) (b)

FIG. II.24. (a) Normalized idealized probability density function of external effective doses to children of various school ages in Iwaki City; (b) log-normal cumulative probability distribution, based on personal dosimetry measurements for the period 1 November 2011–31 January 2012.

II.7. INTERNAL EXPOSURES TO RESIDENTS OF MUNICIPALITIES IN FUKUSHIMA PREFECTURE MEASURED BY WHOLE BODY COUNTERS

The dataset of measurements of internal exposures of residents of Namie Town derived from WBCs (Namie 2012, 2013 for ^{134}Cs and ^{137}Cs) [226] does not allow an analysis of the probability distributions. The levels of incorporated radiocaesium are low relative to the relative detection levels of the WBCs so that almost all data points are within the first dose interval. Further analysis of the remaining results would lead to ambiguous results.

II.8. SUMMARY

A general feature of all of the datasets for which a statistical analysis has been attempted is that the levels of effective doses were, in general, extremely low. In most cases the measurement results are either below or broadly comparable with the limit of detection of the radioanalytical technique employed. The subsequent large dynamic range between the first and higher dose intervals restricts the effectiveness of this type of analysis. In the case of the Chernobyl accident, the levels of dose received by workers and the public were generally higher relative to the limits of detection.

REFERENCES

[1] TERADA, H., KATATA, G., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident, Part II: Verification of the source term and analysis of regional-scale atmospheric dispersion, J. Environ. Radioact. **112** (2012) 141–154.

[2] UNITED NATIONS ENVIRONMENT PROGRAMME, Regional and National Reports on Marine and Coastal Biodiversity Data and Information in the Northwest Pacific Region, UNEP, Nairobi (2007).

[3] COMMITTEE FOR COMPILING OF "FLORA IN FUKUSHIMA PREFECTURE", Flora in Fukushima Prefecture, Tokyo (1987) (in Japanese).

[4] ENVIRONMENTAL AGENCY OF JAPAN, Report of 3rd Basic Investigation on Conservation of Natural Environment: Amphibians and Reptiles, Environmental Agency, Tokyo (1988) (in Japanese).

[5] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Vol. I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[6] GAUNTT, R.O., et al., MELCOR Computer Code Manuals Version 1.8.6, Sandia National Laboratories, Albuquerque, NM (2005).

[7] CHATELARD, P., REINKE, N., Overview of the Integral Code ASTEC V2.0 16 April 2013, Institut de Radioprotection et de Sûreté Nucléaire and Gesellschaft für Anlagen- und Reaktorsicherheit, Fontenay-aux-Roses and Cologne (2009).

[8] ELECTRIC POWER RESEARCH INSTITUTE, MAAP4 Applications Guidance: Desktop Reference for Using MAAP4 Software, EPRI, Palo Alto, CA (2010).

[9] ESLINGER, P.W., et al., Source term estimation of radioxenon released from the Fukushima Dai-ichi nuclear reactors using measured air concentrations and atmospheric transport modeling, J. Environ. Radioact. **127** (2014) 127–132.

[10] SEHGAL, B.R., Nuclear Safety in Light Water Reactors Severe Accident Phenomenology, Elsevier, Amsterdam and Boston (2012).

[11] JACQUEMAIN, D., et al., Les Accidents de Fusion du Coeur des Réacteurs Nucléaires de Puissance État des Connaissances, IRSN, Les Ulis (2013).

[12] BOWYER, T.W., et al., Elevated radioxenon detected remotely following the Fukushima nuclear accident, J. Environ. Radioact. **102** 7 (2011) 681–687.

[13] THAKUR, P., BALLARD, S., NELSON, R., An overview of Fukushima radionuclides measured in the northern hemisphere, Sci. Total Environ. **458–460** (2013) 577–613.

[14] SHOZUGAWA, K., NOGAWA, N., MATSUO, M., Deposition of fission and activation products after the Fukushima Dai-ichi nuclear power plant accident, Environ. Pollut. **163** (2012) 243–247.

[15] SAEGUSA, J., KIKUTA, Y., AKINO, H., Observation of gamma-rays from fallout collected at Ibaraki, Japan, during the Fukushima nuclear accident, Appl. Radiat. Isot. **77** (2013) 56–60.

[16] YOSHIDA, N., TAKAHASHI, Y., Land-surface contamination by radionuclides from the Fukushima Daiichi nuclear power plant accident, Elements **8** 3 (2012) 201–206.

[17] HAYNES, W.M., CRC Handbook of Chemistry and Physics: A Ready Reference Book of Chemical and Physical Data, CRC, Boca Raton, FL (2012).

[18] ZHENG, J., et al., Isotopic evidence of plutonium release into the environment from the Fukushima DNPP accident, Sci. Rep. **2** (2012).

[19] HOSHI, H., HIRANO, M., "Severe accident analyses of Fukushima-Daiichi Units 1 to 3", paper presented at the side event of the 56th IAEA General Conference, Vienna, 2012.

[20] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Additional Report of the Japanese Government to the IAEA: The Accident at TEPCO's Fukushima Nuclear Power Stations, Second Report (2011), http://www.meti.go.jp/english/earthquake/nuclear/iaea/iaea_110911.html

[21] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Regarding the Evaluation of the Conditions on Reactor Cores of Unit 1, 2 and 3 Related to the Accident at Fukushima Dai-ichi Nuclear Power Station, Tokyo Electric Power Co., Inc. (2011), http://www.nsr.go.jp/archive/nisa/english/press/2011/06/en20110615-5.pdf

[22] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Fukushima, One Year Later. Initial Analyses of the Accident and its Consequences, IRSN, Fontenay-aux-Roses (2012).
[23] MATHIEU, A., KORSAKISSOK, I., QUELO, D., Atmospheric dispersion and deposition of radionuclides from the Fukushima Daiichi nuclear power plant accident, Elements **8** 3 (2012) 195–200.
[24] MATHIEU, A., et al., État de la modélisation pour simuler l'accident nucléaire de la centrale Fukushima Daiichi, Pollut. Atmos. **2013** (2013) 217.
[25] RUBINSHTEIN, K.G., et al., Software package of atmospheric radionuclide distribution models and its use for assessing the radiation conditions after the Fukushima Dai-ichi nuclear power plant accident, Russ. Meteorol. Hydrol. **37** 9 (2012) 586–597.
[26] ARUTYUNYAN, R.V., et al., Estimation of radionuclide emission during the March 15, 2011 accident at the Fukushima-1 NPP (Japan), At. Energy **112** 3 (2012) 188–193.
[27] DOLGANOV, K.S., et al., Real-time calculation of the accident at the Fukushima-1 NPP (Japan) using the Sokrat Code, At. Energy **114** 3 (2013) 161–168.
[28] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, Report of the UN Chernobyl Forum Expert Group "Environment", Radiological Assessment Reports Series No. 8, IAEA, Vienna (2006).
[29] NUCLEAR REGULATORY AUTHORITY, Readings of Air Dose in the 20 km Zone of Fukushima Dai-ichi NPP (2015),
http://radioactivity.nsr.go.jp/en/list/239/list-1.html
[30] YASUNARI, T.J., Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident, PNAS **108** 49 (2011) 19530–19534.
[31] KAJINO, M., MADMS: Modal aerosol dynamics model for multiple modes and fractal shapes in the free-molecular and near-continuum regimes, J. Aerosol Sci. **42** 4 (2011) 224–248.
[32] KONDO, H., et al., Activities of the disaster medical assistance team (DMAT) in response to the TEPCO Fukushima nuclear power plant accident, J. Natl. Inst. Public Health **60** 6 (2011) 502–509.
[33] TAKEMURA, T., et al., A numerical simulation of global transport of atmospheric particles emitted from the Fukushima Daiichi nuclear power plant, SOLA **7** (2011) 101–104.
[34] KATO, M., SHINODA, T., TSUBOKI, K., AIKI, H., "Advection diffusion simulation using CReSS", paper presented at the 2011 Autumn Meeting of the Meteorological Society of Japan, Nagoya, 2011.
[35] SCIENCE COUNCIL OF JAPAN, A Review of the Model Comparison of Transportation and Deposition of Radioactive Materials Released to the Environment as a Result of the Tokyo Electric Power Company's Fukushima Daiichi Nuclear Power Plant Accident (2014),
http://www.jpgu.org/scj/report/20140902scj_report_e.pdf
[36] NAGAI, H., CHINO, M., TERADA, H., KATATA, G., "Atmospheric Dispersion Simulations of Radioactive Materials Discharged from the Fukushima Daiichi Nuclear Power Plant Due to Accident: Consideration of Deposition Process", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp. 2012) (Kurihara, O., Akahane, K., Fukuda, S., Miyahara, N., Yonai, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 137–138.
[37] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND ECONOMY, Results of Airborne Monitoring Survey by MEXT in Iwate, Shizuoka, Nagano, Yamanashi, Gifu, and Toyama Prefectures, and Revision of the Past Airborne Monitoring Results by Refrecting the Influences of Natural Radionuclides (2011),
http://radioactivity.nsr.go.jp/en/contents/4000/3177/24/1270_111114.pdf
[38] WORLD METEOROLOGICAL ORGANIZATION, Meeting of the WMO Task Team on Meteorological Analyses for the Fukushima Daiichi Nuclear Power Plant Accident, Geneva, 30 November–2 December 2011, Final Rep., WMO, Geneva (2011).
[39] INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE, Accident de la Centrale de Fukushima Daiichi: Modélisation de la Dispersion des Rejets Radioactifs dans l'Atmosphère à l'Échelle Mondiale (2011),
http://www.irsn.fr/FR/popup/Pages/irsn-meteo-france_30mars.aspx
[40] TOKYO ELECTRIC POWER COMPANY, Fukushima Nuclear Accidents Investigation Report (Attachment) (2012),
http://www.tepco.co.jp/en/press/corp-com/release/betu12_e/images/120620e0106.pdf

[41] KATATA, G., OTA, M., TERADA, H., CHINO, M., NAGAI, H., Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi nuclear power plant accident. Part I: Source term estimation and local-scale atmospheric dispersion in early phase of the accident, J. Environ. Radioact. **109** (2012) 103–113.
[42] OHKURA, T., et al., Emergency Monitoring of Environmental Radiation and Atmospheric Radionuclides at Nuclear Science Research Institute, JAEA following the Accident of Fukushima Daiichi Nuclear Power Plant, Japan Atomic Energy Agency, Tokaimura (2012).
[43] BUESSELER, K., AOYAMA, M., "Fukushima results", Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp. Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).
[44] NUCLEAR REGULATION AUTHORITY, Radiation Monitoring Information: Monitoring Information of Environmental Radioactivity Level, NRA (2015) (in Japanese), http://radioactivity.nsr.go.jp/ja/list/191/list-1.html
[45] TOKYO ELECTRIC POWER COMPANY, Monitoring by Sampling. Results of Radioactive Analysis around Fukushima Daiichi Nuclear Power Station, http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/index-e.html
[46] FURUTA, S., et al., Results of the Environmental Radiation Monitoring following the Accident at the Fukushima Daiichi Nuclear Power Plant: Interim Report (Ambient Radiation Dose Rate, Radioactivity Concentration in the Air and Radioactivity Concentration in the Fallout), Japan Atomic Energy Agency, Tokaimura (2011) (in Japanese).
[47] HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION, Results of Environmental Radiation Measurements 17 December 2013, KEK, Ibaraki (2013) (in Japanese).
[48] CENTRE FOR THE PROMOTION OF DISARMAMENT AND NON-PROLIFERATION, Detection of Radionuclides at the CTBT Radionuclides Observatory Station at Takasaki (2012) (in Japanese), http://www.cpdnp.jp/pdf/120420Takasaki_report_Apr15.pdf
[49] CENTRE FOR THE PROMOTION OF DISARMAMENT AND NON-PROLIFERATION, Observation of Particular Radionuclides at the CTBT Takasaki Radionuclides Observatory (2013) (in Japanese), http://www.cpdnp.jp/pdf/130110Takasaki_report_Dec31.pdf
[50] JAPAN CHEMICAL ANALYSIS CENTER, Analysis on Ambient Dose Rate and Concentration of Noble Gases at Chemical Analysis Center (2011) (in Japanese), http://donjon.rulez.jp/refeqsum/bunsekicenternodo.pdf
[51] AMANO, H., et al., Radiation measurements in the Chiba metropolitan area and radiological aspects of fallout from the Fukushima Dai-ichi nuclear power plants accident, J. Environ. Radioact. **111** (2012) 42–52.
[52] OHTA, T., et al., Prediction of groundwater contamination with ^{137}Cs and ^{131}I from the Fukushima nuclear accident in the Kanto district, J. Environ. Radioact. **111** (2012) 38–41.
[53] METEROLOGICAL RESEARCH INSTITUTE OF JAPAN, A 50-Year History of Artificial Radionuclides in the Environment: Fallout Containing Strontium-90, Caesium-137 and Plutonium (2007) (in Japanese), http://www.mri-jma.go.jp/Dep/ap/ap4lab/recent/ge_report/2007Artifi_Radio_report/Chapter5.htm
[54] METEOROLOGICAL RESEARCH INSTITUTE, Artificial Radionuclides in the Environment 2013 (2013) (in Japanese), http://www.mri-jma.go.jp/Dep/ap/ap4lab/recent/ge_report/2013Artifi_Radio_report/2013Artifi_Radio_report.pdf
[55] HIROSE, K., Temporal variation of monthly ^{137}Cs deposition observed in Japan: Effects of the Fukushima Daiichi nuclear power plant accident, Appl. Radiat. Isot. **81** (2013) 325–329.
[56] KANEYASU, N., OHASHI, H., SUZUKI, F., OKUDA, T., IKEMORI, F., Sulfate aerosol as a potential transport medium of radiocesium from the Fukushima nuclear accident, Environ. Sci. Technol. **46** 11 (2012) 5720–5726.
[57] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, US DEPARTMENT OF ENERGY, Results of Airborne Monitoring by the Ministry of Education, Culture, Sports, Science and Technologyand the US Department of Energy (2011), http://radioactivity.nsr.go.jp/en/contents/4000/3180/24/1304797_0506.pdf

[58] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, UNITED STATES DEPARTMENT OF ENERGY, Results of the 2nd Airborne Monitoring by the Ministry of Education, Culture, Sports, Science and Technology and the US Department of Energy (2011), http://radioactivity.nsr.go.jp/en/contents/4000/3165/24/1304797_0616e.pdf
[59] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the Third Airborne Monitoring Survey by MEXT (2011), http://radioactivity.nsr.go.jp/en/contents/5000/4182/24/1304797_0708e.pdf
[60] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the Fourth Airborne Monitoring Survey by MEXT (2011), http://radioactivity.nsr.go.jp/en/contents/4000/3179/24/1270_1216.pdf
[61] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of Airborne Monitoring in Restricted Areas and Deliberate Evacuation Areas (2012), http://radioactivity.nsr.go.jp/en/contents/5000/4709/24/203_0224_e.pdf
[62] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the (i) Fifth Airborne Monitoring Survey and (ii) Airborne Monitoring Survey Outside 80 km from the Fukushima Dai-ichi NPP (2012), http://radioactivity.nsr.go.jp/en/contents/6000/5790/24/203_0928_14e.pdf
[63] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, (i) Results of the Sixth Airborne Monitoring and (ii) Airborne Monitoring out of the 80 km Zone of Fukushima Dai-ichi NPP (2013), http://radioactivity.nsr.go.jp/en/contents/7000/6099/24/203_e_0301_18.pdf
[64] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the Airborne Monitoring in the Evacuation-directed Zones (2013), http://radioactivity.nsr.go.jp/en/contents/7000/6936/24/270_0513.pdf
[65] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Monitoring Air Dose Rates from a Series of Aircraft Surveys 30 Months after the Fukushima Daiichi NPS Accident (2013), https://www.nsr.go.jp/data/000067233.pdf
[66] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Ambient Dose Rates by Airborne Monitoring Survey 30 Month after the TEPCO Fukushima Daiichi NPP Accident Results (2013) (in Japanese), http://www.nsr.go.jp/data/000047766.pdf
[67] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the Eighth Airborne Monitoring Survey (2013) (in Japanese), http://radioactivity.nsr.go.jp/ja/contents/9000/8909/24/362_20140307.pdf
[68] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Results of the Ninth Airborne Monitoring Survey (2013) (in Japanese), http://radioactivity.nsr.go.jp/ja/contents/11000/10349/24/150213_9th_air.pdf
[69] TORII, T., SUGITA, T., OKADA, C.E., REED, M.S. BLUMENTHAL, D.J., Enhanced analysis methods to derive the spatial distribution of ^{131}I deposition on the ground by airborne surveys at an early stage after the Fukushima Daiichi nuclear power plant accident, Health Phys **105** 2 (2013) 192–200.
[70] XU, S., et al., Iodine isotopes in precipitation: Temporal responses to ^{129}I emissions from the Fukushima nuclear accident, Environ. Sci. Technol. **47** 19 (2013) 10851–10859.
[71] MIYAKE, Y., et al., Isotopic ratio of radioactive iodine (^{129}I/^{131}I) released from Fukushima Daiichi NPP accident, Geochem. J. **46** 4 (2012) 327–333.
[72] IMANAKA, T., Early radiation survey of Iitate Village, which was heavily contaminated by the Fukushima Daiichi accident, conducted on 28 and 29 March 2011, Health Phys. **102** 6 (2012) 680–686.
[73] KASHPAROV, V.A., Hot particles at Chernobyl, Environ. Sci. Pollut. Res. **1** (2003) 21–30.
[74] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERY, Current Situation and Countermeasures to Radioactive Caesium in Beef Meat and Rice Straw (2013) (in Japanese), http://www.anan-zaidan.or.jp/lecture/4.harada.pdf
[75] KATO, H., ONDA, Y., TERAMAGE, M., Depth distribution of ^{137}Cs, ^{134}Cs, and ^{131}I in soil profile after Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact. **111** (2012) 59–64.
[76] TANAKA, K., et al., Vertical profiles of iodine-131 and cesium-137 in soils in Fukushima Prefecture related to the Fukushima Daiichi nuclear power station accident, Geochem. J. **46** 1 (2012) 73–76.

[77] TERAMAGE, M.T., Vertical distribution of radiocesium in coniferous forest soil after the Fukushima nuclear power plant accident, J. Environ. Radioact. **137** (2014) 37–45.
[78] OHASHI, S., OKADA, N., TANAKA, A., NAKAI, W., TAKANO, S., Radial and vertical distributions of radiocesium in tree stems of *Pinus densiflora* and *Quercus serrata* 1.5 y after the Fukushima nuclear disaster, J. Environ. Radioact. **134** (2014) 54–60.
[79] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND ECONOMY, Results of Airborne Monitoring Survey by MEXT in Aichi, Aomori, Ishikawa, and Fukui Prefectures (2011), http://radioactivity.nsr.go.jp/en/contents/4000/3176/24/1270_1125.pdf
[80] KAWAMURA, H., et al., Preliminary numerical experiments on oceanic dispersion of ^{131}I and ^{137}Cs discharged into the ocean because of the Fukushima Daiichi nuclear power plant disaster, J. Nucl. Sci. Technol. **48** 11 (2011) 1349–1356.
[81] STOHL, A., et al., Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition, Atmos. Chem. Phys. **12** 5 (2012) 2313–2343.
[82] KOBAYASHI, T., NAGAI, H., CHINO, M., KAWAMURA, H., Source term estimation of atmospheric release due to the Fukushima Dai-ichi nuclear power plant accident by atmospheric and oceanic dispersion simulations, J. Nucl. Sci. Technol. **50** 3 (2013) 255–264.
[83] WINIAREK, V., et al., Estimation of the caesium-137 source term from the Fukushima Daiichi nuclear power plant using a consistent joint assimilation of air concentration and deposition observations, Atmos. Environ. **82** (2014) 268–279.
[84] TSUMUNE, D., TSUBONO, T., AOYAMA, M., HIROSE, K., Distribution of oceanic ^{137}Cs from the Fukushima Dai-ichi nuclear power plant simulated numerically by a regional ocean model, J. Environ. Radioact. **111** (2012) 100–108.
[85] ESTOURNEL, C., et al., Assessment of the amount of cesium-137 released into the Pacific ocean after the Fukushima accident and analysis of its dispersion in Japanese coastal waters, J. Geophys. Res. **117** (2012) C11014.
[86] BAILLY DU BOIS, P., et al., Estimation of marine source-term following Fukushima Dai-ichi accident, J. Environ. Radioact. **114** (2012) 2–9.
[87] MIYAZAWA, Y., et al., Inverse estimation of source parameters of oceanic radioactivity dispersion models associated with the Fukushima accident, Biogeosciences **10** 4 (2013) 2349–2363.
[88] JAPAN ATOMIC ENERGY AGENCY, Workshop on the Reconstruction of Environmental Release of Radionuclides and Dispersion Processes after the Fukushima Daiichi Nuclear Power Plant Accident (2012) (in Japanese), http://nsec.jaea.go.jp/ers/environment/envs/FukushimaWS/
[89] YAMAGATA, H., "Updated status of Fukushima Daiichi nuclear power station", paper presented at the side event at the 57th IAEA General Conference, Vienna, 2013.
[90] TOKYO ELECTRIC POWER COMPANY, Detection of Radioactive Materials from the Seawater around the Discharge Canal of Fukushima Daiichi Nuclear Power Station (2011), http://www.tepco.co.jp/en/press/corp-com/release/11032201-e.html
[91] NUCLEAR AND INDUSTRIAL SAFETY AGENCY, Leakage of Highly Contaminated Water from the Unit 2 Reactor in the Fukushima Daiich NPP (2011) (in Japanese), http://www.meti.go.jp/press/2011/04/20110425002/20110425002-2.pdf
[92] TOKYO ELECTRIC POWER COMPANY, Effects of the Release of Water Containing Radioactivity Exceeding the Limit for Discharge (2011) (in Japanese), http://www.tepco.co.jp/cc/press/betu11_j/images/110521f.pdf
[93] YASUDA, I., Hydrographic structure and variability in the Kuroshio-Oyashio transition area, J. Oceanogr. **59** 4 (2003) 389–402.
[94] YASUDA, I., OKUDA, K., SHIMIZU, Y., Distribution and modification of North Pacific intermediate water in the Kuroshio-Oyashio interfrontal zone, J. Phys. Oceanogr. **26** 4 (1996) 448–465.
[95] KUMAMOTO, Y., AOYAMA, M., HAMAJIMA, Y., MURATA, A., KAWANO, T., Impact of Fukushima-derived radiocesium in the western north Pacific ocean about ten months after the Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact. **140** (2015) 114–122.
[96] POVINEC, P.P., et al., Dispersion of Fukushima radionuclides in the global atmosphere and the ocean, Appl. Radiat. Isot. **81** (2013) 383–392.

[97] BROECKER, W.S., The Great Ocean Conveyor: Discovering the Trigger for Abrupt Climate Change, Princeton University Press, Princeton (2010).
[98] KAERIYAMA, H., et al., Southwest intrusion of ^{134}Cs and ^{137}Cs Derived from the Fukushima Dai-ichi nuclear power plant accident in the Western North Pacific, Environ. Sci. Technol. **48** 6 (2014) 3120–3127.
[99] NATIONAL OCEANOGRAPHY CENTRE, Measuring Currents (2015), http://noc.ac.uk/research-at-sea/exploration-at-sea/surface-above/measuring-currents
[100] EVRARD, O., et al., Evolution of radioactive dose rates in fresh sediment deposits along coastal rivers draining Fukushima contamination plume, Sci. Rep. **3** (2013).
[101] TOKYO ELECTRIC POWER COMPANY, Updated worker doses, official communication (2015).
[102] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Exposure Dose of Workers at the Fukushima Daiichi Nuclear Power Station, Attachment: Distribution of Thyroid Equivalent Doses (2015), http://www.tepco.co.jp/en/press/corp-com/release/2015/1248073_6844.html
[103] HONDA, M.C., AONO, T., AOYAMA, M., Dispersion of artificial caesium-134 and -137 in the Western North Pacific one month after the Fukushima accident, Geochem. J. **46** 6 (2012) e1–9.
[104] MASUMOTO, Y., "Ocean models: How far/fast does Fukushima contamination travel?", Exploring the Impacts of the Fukushima Dai-ichi Nuclear Power Plants on the Ocean (Proc. Fukushima Ocean Impacts Symp.Tokyo, 2012), Woods Hole Oceanographic Institution, Woods Hole, MA (2012).
[105] MASUMOTO, Y., et al., Oceanic dispersion simulations of ^{137}Cs released from the Fukushima Daiichi nuclear power plant, Elements **8** 3 (2012) 207–212.
[106] RYPINA, I.I., et al., Short-term dispersal of Fukushima-derived radionuclides off Japan: Modeling efforts and model-data intercomparison, Biogeosciences **10** 1 (2013) 4973–4990.
[107] AOYAMA, M., HIROSE, K., IGARASHI, Y., Re-construction and updating our understanding on the global weapons tests ^{137}Cs fallout, J. Environ. Monitor. **8** 4 (2006) 431–438.
[108] KUMAMOTO, Y., MURATA, A., KAWANO, T., AOYAMA, M., Fukushima-derived radiocesium in the Northwestern Pacific ocean in February 2012, Appl. Radiat. Isot. **81** (2013) 335–339.
[109] INOMATA, Y., et al., Distribution of radionuclides in surface seawater obtained by an aerial radiological survey, J. Nucl. Sci. Technol. **51** 9 (2014) 1059–1063.
[110] UNITED STATES DEPARTMENT OF ENERGY, DOE Response to the Radiological Release from the Fukushima Dai-ichi Nuclear Power Plant (2011), http://enformable.com/2011/10/june-30th-2011-doe-response-to-the-radiological-release-from-the-fukushima-dai-ichi-nuclear-power-plant/
[111] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission) (2013), https://www.iaea.org/sites/default/files/final_report120214.pdf
[112] NUCLEAR REGULATION AUTHORITY, Readings of Sea Area Monitoring (2014), http://radioactivity.nsr.go.jp/en/list/205/list-1.html
[113] OIKAWA, S., TAKATA, H., WATABE, T., MISONOO, J., KUSAKABE, M., Distribution of the Fukushima-derived radionuclides in seawater in the Pacific off the coast of Miyagi, Fukushima, and Ibaraki Prefectures, Japan, Biogeosciences **10** 7 (2013) 5031–5047.
[114] AOYAMA, M., MURATA, A., NISHINO, S., Global nutrients data synthesis based on reference material of nutrients of seawater, Geophys. Res. Abstr. **15** (2013).
[115] AOYAMA, M., UEMATSU, M., TSUMUNE, D., HAMAJIMA, Y., Surface pathway of radioactive plume of TEPCO Fukushima NPP1 released ^{134}Cs and ^{137}Cs, Biogeosciences **10** 1 (2013) 265–283.
[116] AOYAMA, M., TSUMUNE, D., UEMATSU, M., KONDO, F., HAMAJIMA, Y., Temporal variation of ^{134}Cs and ^{137}Cs activities in surface water at stations along the coastline near the Fukushima Dai-ichi nuclear power plant accident site, Japan, Geochem. J. **46** 4 (2012) 321–325.
[117] NUCLEAR REGULATION AUTHORITY, Change of the Radioactivity Concentration of the Seawater in Sea Area Close to Fukushima Daiichi NPS / Coastal Sea Area (2015), http://radioactivity.nsr.go.jp/en/contents/8000/7742/24/engan.pdf
[118] BUESSELER, K., AOYAMA, M., FUKASAWA, M., Impacts of the Fukushima nuclear power plants on marine radioactivity, Environ. Sci. Technol. **45** 23 (2011) 9931–9935.

[119] NUCLEAR REGULATION AUTHORITY, Implementation Guides on Sea Area Monitoring in FY2013 (2013), http://radioactivity.nsr.go.jp/en/contents/8000/7147/24/274_s_20130401.pdf
[120] OTOSAKA, S., KATO, Y., Radiocesium derived from the Fukushima Daiichi nuclear power plant accident in seabed sediments: Initial deposition and inventories, Environ. Sci.: Processes Impact **16** 5 (2014) 978–990.
[121] NUCLEAR REGULATION AUTHORITY, Environmental Radioactivity and Radiation in Japan, http://www.kankyo-hoshano.go.jp/en/index.html
[122] JAPAN ATOMIC ENERGY AGENCY, Simulation of Radioactivity Concentrations in the Pacific Ocean (2011), http://www.jaea.go.jp/english/jishin/kaisetsu04.pdf
[123] OTOSAKA, S., KOBAYASHI, T., Sedimentation and remobilization of radiocesium in the coastal area of Ibaraki, 70 km south of the Fukushima Dai-ichi nuclear power plant, Environ. Monit. Assess. **185** 7 (2013) 5419–5433.
[124] KUSAKABE, M., OIKAWA, S., TAKATA, H., MISONOO, J., Spatiotemporal distributions of Fukushima-derived radionuclides in nearby marine surface sediments, Biogeosciences **10** 7 (2013) 5019–5030.
[125] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Report of Comprehensive Monitoring Program for Radioactivity in the Marine Environments, MEXT, Tokyo (2012) (in Japanese).
[126] BU, W.T., et al., Vertical distributions of plutonium isotopes in marine sediment cores off the Fukushima coast after the Fukushima Dai-ichi nuclear power plant accident, Biogeosciences **10** 4 (2013) 2497–2511.
[127] NUCLEAR REGULATION AUTHORITY, Sea Area Monitoring (Weekly Report) (2015), http://radioactivity.nsr.go.jp/en/list/295/list-1.html
[128] TOKYO ELECTRIC POWER COMPANY, Situation of Storage and Treatment of Accumulated Water Including Highly Concentrated Radioactive Materials at Fukushima Daiichi Nuclear Power Station (127th Release) (2013), http://www.tepco.co.jp/en/press/corp-com/release/betu13_e/images/131127e0101.pdf
[129] FISHERIES AGENCY, Results of the Monitoring on Radioactivity Level in Fisheries Products (2015), http://www.jfa.maff.go.jp/e/inspection/index.html
[130] BUESSELER, K., Fukushima and ocean radioactivity, Oceanography **27** 1 (2014) 92–105.
[131] AONO, T., et al., "Observation of radionuclides in marine biota off the coast of Fukushima Prefecture after TEPCO's Fukushima Daiichi nuclear power station accident", Radiation Monitoring and Dose Estimation of the Fukushima Nuclear Accident (TAKAHASHI, S., Ed.), Springer, Tokyo (2014) 115–123.
[132] SOHTOME, T., et al., Radiological impact of TEPCO's Fukushima Dai-ichi nuclear power plant accident on invertebrates in the coastal benthic food web, J. Environ. Radioact. **138** (2014) 106–115.
[133] WADA, T., et al., Effects of the nuclear disaster on marine products in Fukushima, J. Environ. Radioact. **124** (2013) 246–254.
[134] KASAMATSU, F., ISHIKAWA, Y., Natural variation of radionuclide ^{137}Cs concentration in marine organisms with special reference to the effect of food habits and trophic level, Mar. Ecol. Prog. Ser. **160** 1–3 (1997) 109.
[135] TOKYO ELECTRIC POWER COMPANY, Counter Measures to Migration of Fish in the Port of Fukushima Daiichi NPP (2011) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/handouts/2013/images/handouts_130712_02-j.pdf
[136] TOKYO ELECTRIC POWER COMPANY, Status of the Fukushima Daiichi Nuclear Power Station With Focus on Countermeasures for Contaminated Water (2014), http://www.tepco.co.jp/en/decommision/planaction/images/140127_01.pdf
[137] FISHERIES AGENCY OF JAPAN, MINISTRY OF AGRICULTURE, FORESTRY AND FISHERY, Report on the Monitoring of Radionuclides in Fishery Products (March 2011–March 2014) (2014), http://www.mofa.go.jp/files/000040303.pdf
[138] MADIGAN, D.J., BAUMANN, Z., FISHER, N.S., Pacific bluefin tuna transport Fukushima-derived radionuclides from Japan to California, Proc. Natl. Acad. Sci. **109** 24 (2012) 9483–9486.

[139] TOKYO ELECTRIC POWER COMPANY, Countermeasures for Water Leakage: The Groundwater Bypass System (2013), http://www.tepco.co.jp/en/nu/fukushima-np/water/13062501-e.html
[140] TOKYO ELECTRIC POWER COMPANY, Nuclide Analysis Results of Radioactive Materials in Accumulated Water in Turbine Building Basement at Fukushima Daiichi NPS (2013), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2013/images/tb_water_130731-e.pdf
[141] TOKYO ELECTRIC POWER COMPANY, Approach to the Ocean-side Trench Investigation at the Fukushima Daiichi Nuclear Power Station (2013), http://www.tepco.co.jp/en/nu/fukushima-np/handouts/2013/images/handouts_130726_12-e.pdf
[142] TOKYO ELECTRIC POWER COMPANY, Analysis Results of Accumulated Water at Unit 2 Seaside Trench in Fukushima Daiichi Nuclear Power Station (2013), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2013/images/trench02_13072801-e.pdf
[143] TOKYO ELECTRIC POWER COMPANY, Expansion Plan of Storage Tanks for Contaminated Water (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/handouts/2014/images/handouts_140418_13-j.pdf
[144] TOKYO ELECTRIC POWER COMPANY, Countermeasures for Water Leakage: Contaminated Water Leakage from the Tank in the H4 Area (2013), http://www.tepco.co.jp/en/nu/fukushima-np/water/13082101-e.html
[145] TOKYO ELECTRIC POWER COMPANY, Sampling Results Regarding the Water Leak at a Tank in the H4 Area in Fukushima Daiichi Nuclear Power Station (2013), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2013/images/south_discharge_130912-2-e.pdf
[146] TOKYO ELECTRIC POWER COMPANY, Fukushima Daiichi NPS Prompt Report 2014. Immediately Release: TEPCO Workers Discover and Halt Water Overflow from Tank; No Impact Expected on Seawater (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1234394_5892.html
[147] MINISTRY OF THE ENVIRONMENT, Preliminary Results of Ground Water Monitoring for Radioactive Substances in Tohoku and Kanto Blocks (2014) (in Japanese), https://www.env.go.jp/air/rmcm/result/attach/h26_s_tohoku-kanto.pdf
[148] TOKYO ELECTRIC POWER COMPANY, Sampling Results Regarding the Influence on the Water Leak at a Tank in the H4 Area in Fukushima Daiichi Nuclear Power Station (Around the H4 Area) (2014), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2014/images/around_h4_14040101-e.pdf
[149] IKEUCHI, Y., Temporal Variations in Radioactivity Concentrations in River Water, Riverbeds and Suspended Sediments (2014) (in Japanese), http://fukushima.jaea.go.jp/initiatives/cat01/pdf05/02-04.pdf
[150] JAPAN CHEMICAL ANALYSIS CENTRE, Radioactivity Survey Data in Japan, Environmental and Dietary Materials, JCAC, Chiba (2011).
[151] MINISTRY OF THE ENVIRONMENT, FY2011 Radioactive Material Monitoring Surveys of the Water Environment (2012), http://www.env.go.jp/en/water/rmms/result_pw-fy2011.html
[152] NAGAO, S., et al., Export of ^{134}Cs and ^{137}Cs in the Fukushima River Systems at Heavy Rains by Typhoon Roke in September 2011, Biogeosciences **10** 10 (2013) 6215–6223.
[153] KANDA, J., "Long-term sources: To what extent are marine sediments, coastal groundwater, and rivers a source of ongoing contamination?", paper presented at Fukushima Ocean Impacts Symposium, Tokyo, 2012.
[154] YAMASHIKI, Y., et al., "Estimation of radioactive contaminant load from Abukuma river", paper presented at the Fukushima Ocean Impacts Symposium, Tokyo, 2012.
[155] CHARTIN, C., et al., Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume, Anthropocene **1** (2013) 23–34.
[156] UNITED NATIONS, FAO/IAEA Food Database, UNSCEAR 2013 Report, Attachment C-8 of Annex A:, Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[157] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Results of Inspections on Radioactivity Levels in Raw Milk (2015), http://www.maff.go.jp/e/seisan/milk_inspection/rawmilk.html
[158] MINISTRY OF HEALTH, LABOUR AND WELFARE, New Standard Limits for Radionuclides in Foods (2012) (in Japanese), http://www.mhlw.go.jp/shinsai_jouhou/dl/leaflet_120329.pdf
[159] ISHIDA, K., "Contamination of wild animals: Effects on wildlife in high radioactivity areas of the agricultural and forest landscape", Agricultural Implications of the Fukushima Nuclear Accident (NAKANISHI, T.M., TANOI, K., Eds), Springer, Tokyo (2013) 119–129.
[160] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Revision of the "Concepts of Inspection Planning and the Establishment and Cancellation of Items and Areas to Which Restriction of Distribution and/or Consumption of Foods Concerned Applies" (2013), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-130319_2.pdf
[161] FISHERIES AGENCY, Results of the Inspection on Radioactivity Materials in Fisheries Products (2012), www.jfa.maff.go.jp/e/inspection/other/201103-201203e1.xls
[162] FISHERIES AGENCY, Results of the Inspection on Radioactivity Materials in Fisheries Products (2013), www.jfa.maff.go.jp/e/inspection/other/eigo250329_1.xls
[163] FISHERIES AGENCY, Results of the Inspection on Radioactivity Materials in Fisheries Products (2014), www.jfa.maff.go.jp/e/inspection/other/eigo260331_1.xls
[164] FISHERIES AGENCY, Results of the Inspection on Radioactivity Materials in Fisheries Products (2015), www.jfa.maff.go.jp/e/inspection/other/e150330.xls
[165] TOKYO ELECTRIC POWER COMPANY, Nuclide Analysis Results of Fish and Shellfish (the Ocean Area within 20 km Radius of Fukushima Daiichi NPS) (2013), http://www.tepco.co.jp/en/nu/fukushima-np/f1/smp/2013/images/fish_130315-e.pdf
[166] TOKYO ELECTRIC POWER COMPANY, Nuclide Analysis Results of Fish and Shellfish (the Ocean Area within 20km Radius of Fukushima Daiichi NPS) (2012), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_120928_01-e.pdf
[167] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Survey Results of Radioactive Materials in Tap Water, MHLW, Tokyo (2011).
[168] HAMADA, N., OGINO, H., Food safety regulations: What we learned from the Fukushima nuclear accident, J. Environ. Radioact. **111** (2012) 83–99.
[169] NUCLEAR REGULATION AUTHORITY, Reading of Radioactivity Level in Drinking Water by Prefecture (2014), http://radioactivity.nsr.go.jp/en/list/193/list-1.html
[170] MINISTRY OF THE ENVIRONMENT, Results of the Measurement of Concentration of Radioactive Substances in Groundwater-Quality Monitoring in Fukushima (2nd Report) (2011), http://radioactivity.nsr.go.jp/en/contents/5000/4264/24/5020_070714.pdf
[171] JAPAN ATOMIC ENERGY AGENCY, Measurement Results of Radioactivity Concentrations in the Drinking Water by Water Suppliers/Local Governments Conducted by the Nuclear Regulation Authority and Ten Prefectures near Fukushima Prefecture (Miyagi, Yamagata, Niigata, Ibaraki, Tochigi, Gumma, Saitama, Tokyo, Kanagawa and Chiba Prefecture) (2014), http://emdb.jaea.go.jp/emdb/en/portals/30200000005/
[172] MOMOSHIMA, N., SUGIHARA, S., ICHIKAWA, R., YOKOYAMA, H., Atmospheric radionuclides transported to Fukuoka, Japan remote from the Fukushima Dai-ichi nuclear power complex following the nuclear accident, J. Environ. Radioact. **111** (2012) 28–32.
[173] WORLD HEALTH ORGANIZATION, Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, WHO, Geneva (2012).
[174] DRAXLER, R.R., HESS, G.D. , An overview of the HYSPLIT_4 modelling system for trajectories, dispersion, and deposition, Aust. Meteor. Mag. **47** (1998) 295–308.
[175] KIM, C.K., et al., Radiological impact in Korea following the Fukushima nuclear accident, J. Environ. Radioact. **111** (2012) 70–82.

[176] HUH, C.A., HSU, S.C., LIN, C.Y., Fukushima-derived fission nuclides monitored around Taiwan: Free tropospheric versus boundary layer transport, Earth Planet. Sci. Lett. **319–320** (2012) 9–14.
[177] Ministerial Ordinance on Exemption of the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku-Pacific Ocean Earthquake in 2011, Ordinance of the Ministry of Health Labour and Welfare No. 23 of 2011 (Japan)
[178] MINISTRY OF HEALTH, LABOUR AND WELFARE, Overview of the Outline of the Draft Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku — Pacific Ocean Earthquake in 2011 (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111121_a03.pdf
[179] YASUI, S., 250 mSv: Temporary increase in the emergency exposure dose limit in response to the TEPCO Fukushima Daiichi NPP accident and its decision making process, J. Occup. Environ. Hyg. **12** 4 (2014) D35–D42.
[180] Local Public Service Act, Act No. 261 of 1950, as last amended on 13 June, 2014 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/S25/S25HO261.html
[181] AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY, Recommendations for Limiting Exposure to Ionizing Radiation (1995) (Guidance note NOHSC:3022(1995)) and National Standard for Limiting Occupational Exposure to Ionizing Radiation (NOHSC:1013(1995)), ARPNSA, Canberra (2002).
[182] UNITED STATES PACIFIC COMMAND, USPACOM Message, DTG:161643Z Mar 2011, Subject: CDRUSPACOM Guidance on Radiation Force Health Protection Requirements for US Forces Supporting Operation Tomodachi (DTRA-TR-12-001 (R1) and DTRA-TR-12-004) (2011).
[183] MINISTRY OF HEALTH, LABOUR AND WELFARE, Future Actions Based on Experiences Such as Exposure Dose Control at the TEPCO Fukushima Daiichi Nuclear Power Plant (2012), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_120810_a01.pdf
[184] MINISTRY OF HEALTH, LABOUR AND WELFARE, Response and Action Taken by the MHLW of Japan on Radiation Protection for Workers Involved in the TEPCO Fukushima Daiichi NPP Accident, MHLW, Tokyo (2013).
[185] YASUI, S., Lessons learned: Radiological protection for emergency workers at the TEPCO Fukushima Daiichi APP (Part 2), J. Occup. Environ. Hyg. **10** 12 (2011) D163–D171.
[186] TOKYO ELECTRIC POWER COMPANY, Method of Internal Dose Estimations for Workers at Fukushima Daiichi Nuclear Power Station (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu13_e/images/130705e0103.pdf
[187] SUTO, Y., et al., Biodosimetry of restoration workers for the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi nuclear power station accident, Health Phys. **105** 4 (2013) 366–373.
[188] MINISTRY OF HEALTH, LABOUR AND WELFARE, Cautions Issued for Wearing "Respiratory Protective Equipment" Used by Workers Engaged in Restoration Operations at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111014.html
[189] TOKYO ELECTRIC POWER COMPANY, Accumulated Exposure Dose Distribution by Fiscal Year, Period: March 11, 2011–December 31, 2014 (2015), http://www.tepco.co.jp/en/press/corp-com/release/betu15_e/images/150130e0304.pdf
[190] KURIHARA, O., et al., Measurements of ^{131}I in the thyroids of employees involved in the Fukushima Daiichi nuclear power station accident, J. Nucl. Sci. Technol. **50** 2 (2013) 122–129.
[191] KURIHARA, O., et al., "Direct measurements of employees involved in the Fukushima Daiichi nuclear power station accident for internal dose estimates: JAEA's experiences", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.) (KURIHARA, O., KAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 13–26.
[192] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, Publication 60, Pergamon Press, Oxford and New York (1991).
[193] MINISTRY OF HEALTH, LABOUR AND WELFARE, Re-evaluation Results of Committed Doses for Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_130705_a02.pdf

[194] YASUI, S., Governmental re-evaluation of the committed effective dose received by emergency workers at the TEPCO Fukushima Daiichi NPP accident, J. Occupat. Environ. Hyg. **12** 5 (2015) D60–D70.
[195] TOKYO ELECTRIC POWER COMPANY, Reevaluation of Internal Exposure Doses of TEPCO Workers During Emergency Work at Fukushima Daiichi Nuclear Power Station (2014), http://www.tepco.co.jp/en/press/corp-com/release/betu14_e/images/140325e0201.pdf
[196] MINISTRY OF HEALTH, LABOUR AND WELFARE, Results of the Additional Re-evaluation of Committed Effective Doses of Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2014) (in Japanese), http://www.mhlw.go.jp/stf/houdou/0000041525.html
[197] FIRE AND DISASTER MANAGEMENT AGENCY, Radiation Exposure of Firefighters who Worked in the Fukushima Daiichi Nuclear Power Plant from 18 March 2011 to 25 March 2011, official communication (2014).
[198] Ordinance on Prevention of Ionizing Radiation Hazards, Ordinance of the Ministry of Labour No. 41 of September 30, 1972, as last amended by Ordinance No. 172 of July 16, 2001 (Japan) (in Japanese), http://law.e-gov.go.jp/htmldata/S47/S47F04101000041.html
[199] NATIONAL POLICE AGENCY, Policemen On-site and Off-site, official communication (2014).
[200] DEFENSE THREAT REDUCTION AGENCY, Radiation Dose Assessments for Shore-based Individuals in Operation Tomodachi, DTRA-TR-12-001, DTRA, Fort Belvoir, VA (2012).
[201] WORLD HEALTH ORGANIZATION, Health Risk Assessment from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami, Based on a Preliminary Dose Estimation, WHO, Geneva (2013).
[202] YASUMURA, S., et al., Study protocol for the Fukushima Health Management Survey, J. Epidemiol. **22** 5 (2012) 375–383.
[203] AKAHANE, K., et al., NIRS external dose estimation system for Fukushima residents after the Fukushima Dai-ichi NPP accident, Sci. Rep. **3** (2013) 1670.
[204] NAGATAKI, S., TAKAMURA, N., KAMIYA, K., AKASHI, M., Measurements of individual radiation doses in residents living around the Fukushima nuclear power plant, Radiat. Res. **180** 5 (2013) 439–447.
[205] DATE CITY, Results of Measurements with Glass Badges (2012) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/7608.pdf
[206] NIHONMATSU CITY, Results of Survey on Exposed Dose Among Residents (2012) (in Japanese), http://www.city.nihonmatsu.lg.jp/uploaded/attachment/10014.pdf
[207] TAMURA CITY, Results of Radiation and Radioactivity Monitoring in Tamura City (2012) (in Japanese), http://www.city.tamura.lg.jp/uploaded/attachment/2118.pdf
[208] KORIYAMA CITY, Summary of the Measurement with Personal Dosimeters (2012) (in Japanese), http://www.city.koriyama.fukushima.jp/063000/koho/documents/kouhou201205.pdf
[209] FUKUSHIMA PREFECTURE, Results of Measurements Made Using Personal Dosimeters in 22 Municipalities Omitting Names of Cities, Towns and Villages (2012) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/6485.pdf
[210] FUKUSHIMA MEDICAL UNIVERSITY, "Basic survey (radiation dose estimates)" (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015) (2015), http://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey.pdf
[211] INTERNATIONAL ATOMIC ENERGY AGENCY, Planning for Off-site Response to Radiation Accidents in Nuclear Facilities, IAEA-TECDOC-225, IAEA, Vienna (1979).
[212] FUKUSHIMA MEDICAL UNIVERSITY, "Response rates to the basic survey by district. Data as of 30 June 2014" (Proc. 16th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2014), http://www.fmu.ac.jp/radiationhealth/results/media/16-1_Basic_Survey_Appendix.pdf
[213] ISHIKAWA, T., "The basic survey: Estimation of external doses to residents in Fukushima Prefecture", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/6_S2_Ishikawa.pdf

[214] FUKUSHIMA MEDICAL UNIVERSITY, "Response rates to the basic survey by district. Data as of 31 December 2014" (Proc. 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey Fukushima, 2015), https://www.fmu.ac.jp/radiationhealth/results/media/18-1_Basic_Survey_Appendix.pdf
[215] NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The Official Report of the Fukushima Nuclear Accident Independent Investigation Commission, National Diet of Japan, Tokyo (2012).
[216] DATE CITY, Results of Dosimetry with Personal Dosimeter (2012) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/7629.pdf
[217] IWAKI CITY, Results of Personal Dose Measurement with Cumulative Dosimeters: An Outline (2014) (in Japanese), http://www.city.iwaki.fukushima.jp/bukyoku/hokenfukushibu/13359/013763.html
[218] GOVERNMENT OF JAPAN, Monitoring Data Provided by the Permanent Mission of Japan to the IAEA, official communication (2014).
[219] DATE CITY, Newsletter on Recovery and Revival in Date City No. 8: Analyses on Measurement of Annual Dose from External Exposure (2013) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/10035.pdf
[220] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).
[221] GOLIKOV, V., et al., Evaluation of conversion coefficients from measurable to risk quantities for external exposure over contaminated soil by use of physical human phantoms, Radiat. Environ. Biophys **46** 4 (2007) 375–382.
[222] NUCLEAR REGULATION AUTHORITY, WBC data requested by WG4 experts, official communication (2014).
[223] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCE, "Estimation of internal exposure at NIRS", paper presented at the 3rd meeting of the Oversight Committee of the Fukushima Prefecture Health Management Survey, Fukushima, 2011 (in Japanese),
[224] MOMOSE, T., et al., "Whole-body counting of Fukushima residents after the TEPCO Fukushima Daiichi nuclear power station accident", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.) (KURIHARA, O., KAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 67–82.
[225] TAKAHASHI, S., (Ed.), Radiation Monitoring and Dose Estimation of the Fukushima Nuclear Accident, Springer, Tokyo (2014).
[226] FUKUSHIMA PREFECTURE, Results of Whole Body Counter Measurements (2015) (in Japanese), https://www.pref.fukushima.lg.jp/sec/21045b/wbc-kensa-kekka.html
[227] HAYANO, R.S., et al., Internal radiocesium contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP accident as measured by extensive whole-body-counter surveys, Proc. Jpn. Acad. **89** 4 (2013) 157–163.
[228] TSUBOKURA, M., GILMOUR, S., TAKAHASHI, K., OIKAWA, T., KANAZAWA, Y., Internal radiation exposure after the Fukushima nuclear power plant disaster, JAMA **308** 7 (2012) 669.
[229] MATSUDA, N., et al., Assessment of internal exposure doses in Fukushima by a whole body counter within one month after the nuclear power plant accident, Radiat. Res. **179** 6 (2013) 663–668.
[230] MORITA, N., et al., Spatiotemporal characteristics of internal radiation exposure in evacuees and first responders after the radiological accident in Fukushima, Radiat. Res. **180** 3 (2013) 299–306.
[231] DATE CITY, Results of Internal Exposure Measurement with Whole Body Counters (WBC) (2012) (in Japanese), http://www.city.date.fukushima.jp/uploaded/attachment/7628.pdf
[232] MOTOMIYA CITY, Never Forget 11 March 2011: A Record in Motomiya City (2014) (in Japanese), http://www.city.motomiya.lg.jp/data/kouhoushi/shinsaikiroku-all.pdf

[233] KIM, E., et al., "Screening survey on thyroid exposure for children after the Fukushima Daiichi Nuclear power station accident", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.) (KURIHARA, O., AKAHANE, K., FUKUDA, S., MIYAHARA, N., YONAI, S., Eds), National Institute of Radiological Sciences, Chiba (2012) 59–66.
[234] KURIHARA, O., et al., "Reconstruction of early internal dose in the TEPCO Fukushima NPS accident - thyroid dose", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 2nd NIRS Symp.), National Institute of Radiological Sciences, Tokyo (2013) 141–162.
[235] TOKONAMI, S., et al., Thyroid doses for evacuees from the Fukushima nuclear accident, Sci. Rep. **2** 507 (2012) 1–4.
[236] SHINKAREV, S., et al., "Thyroid measurements of the Russian citizens living in Japan following the Fukushima accident", Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 2nd NIRS Symp. Tokyo, 2013) (abstract).
[237] KAMADA, N., SAITO, O., ENDO, S., KIMURA, A., SHIZUMA, K., Radiation doses among residents living 37 km northwest of the Fukushima Dai-ichi nuclear power plant, J. Environ. Radioact. **110** (2012) 84–89.
[238] HIRAKAWA, et al., Surveys of food distribution just after the nuclear accident and challenges, J. Jpn. Soc. Safety Eng. **53** 3 (2014) 167–172.
[239] MITSUBISHI RESEARCH INSTITUTE, INC., Dose Assessment Study of the Internal Exposure Due to Food Just after the Nuclear Accident, MRI, Tokyo (2014) (in Japanese),
[240] FUKUSHIMA PREFECTURE, Results of Radioactivity Monitoring in Daily Food in Fukushima Prefecture (2013) (in Japanese),
http://www.pref.fukushima.lg.jp/sec_file/monitoring/etc/nitijyousyoku2013-0718.pdf
[241] MINISTRY OF HEALTH, LABOUR AND WELFARE, Survey of Dietary Intake of Radionuclides (September to October 2012) (Annual Radiation Dose from Radionuclides in Foods) (2013),
http://www.mhlw.go.jp/english/topics/2011eq/dl/index_food_policies_20131011_2.pdf
[242] NUCLEAR SAFETY COMMISSION, Thyroid Dose Screening Among Children (2012) (in Japanese),
https://www.nsr.go.jp/archive/nsc/info/20120913_2.pdf
[243] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996). (This publication is superseded by GSR Part 3 (2014)).
[244] GAVRILIN, Y., et al., Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus — Part I: ^{131}I, short-lived radioiodines (^{132}I, ^{133}I, ^{135}I), and short-lived radiotelluriums (^{131M}Te and ^{132}Te), Health Phys **86** 6 (2004) 565–585.
[245] SHINKAREV, S.M., et al., Credibility of Chernobyl thyroid doses exceeding 10 Gy based on in-vivo measurements of ^{131}I in Belarus, Health Phys. **94** 2 (2008) 180–187.
[246] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. II, Scientific Annexes C, D and E, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2011).
[247] SHINKAREV, S.M., et al., Estimation of the contribution of short-lived radioiodines to the thyroid dose for the public in case of inhalation intake following the Fukushima accident, Radiat. Prot. Dosim. **164** 1–2 (2015) 51–56.
[248] NISHIHARA, K., IWAMOTO, H., SUYAMA, K., Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant, Japan Atomic Energy Agency, Tokaimura (2012) (in Japanese).
[249] NATIONAL INSTITUTE OF RADIOLOGICAL SCIENCES, Reconstruction of Early Internal Dose in the TEPCO Fukushima Daiichi Nuclear Power Station Accident (Proc. 1st NIRS Symp.), NIRS, Chiba (2012).
[250] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2008 Report, Vol. I, Annexes A and B, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2010).

[251] EUROPEAN ATOMIC ENERGY COMMUNITY, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, INTERNATIONAL MARITIME ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Fundamental Safety Principles, IAEA Safety Standards Series No. SF-1, IAEA, Vienna (2006).
[252] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION, Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-R-2, IAEA, Vienna (2002).
[253] UNITED NATIONS, Hereditary Effects of Radiation (Report to the General Assembly), UNSCEAR 2001 Report, Scientific Annex: Hereditary Effects of Radiation, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2001).
[254] UNITED NATIONS, Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2006 Report, Volume I, Scientific Annexes A and B, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2009).
[255] UNITED NATIONS, Sources and Effects of Ionizing Radiation (Report to the General Assembly), UNSCEAR 1996 Report, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (1996).
[256] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Elsevier, Oxford (2007).
[257] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (Interim Edition), IAEA Safety Standards Series No. GSR Part 3 (Interim), IAEA, Vienna (2011). (This publication is superseded by GSR Part 3 (2014)).
[258] UNITED NATIONS, Report of the United Nations Conference on Environment and Development. ANNEX I: Rio Declaration on Environment and Development, UN, Rio de Janeiro (1992).
[259] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Environment under Different Exposure Situations, Publication 124, Pergamon Press, Oxford and New York (2014).
[260] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Environmental Protection: The Concept and Use of Reference Animals and Plants, Publication 108, Elsevier, Oxford (2008).
[261] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Statement on Tissue Reactions (2011), http://www.icrp.org/docs/ICRP%20Statement%20on%20Tissue%20Reactions.pdf
[262] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP Statement on Tissue Reactions/Early and Late Effects of Radiation in Normal Tissues and Organs: Threshold Doses for Tissue Reactions in a Radiation Protection Context, Publication 118, Elsevier, Oxford (2012).
[263] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Principles for Intervention for Protection of the Public in a Radiological Emergency, Publication 63, Pergamon Press, Oxford and New York (1993).
[264] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection of the Public in Situations of Prolonged Radiation Exposure, Publication 82, Pergamon Press, Oxford and New York (1999).
[265] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protecting People Against Radiation Exposure in the Event of a Radiological Attack, Publication 96, Elsevier, Oxford (2005).
[266] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency, Publication 111, Elsevier, Oxford (2009).
[267] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Cost-benefit Analysis in the Optimization of Radiation Protection, Publication 37, Pergamon Press, Oxford and New York (1983).
[268] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Optimization and Decision-Making in Radiological Protection, Publication 55, Pergamon Press, Oxford and New York (1990).

[269] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The Optimisation of Radiological Protection — Broadening the Process, Publication 101b, Elsevier, Oxford (2006).
[270] The Statute of the International Atomic Energy Agency, as last amended up to 28 December, 1989, IAEA, Vienna (1989).
[271] The Agency's Health and Safety Measures, INFCIRC/18, IAEA, Vienna (1960).
[272] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS OFFICE FOR THE COORDINATION OF HUMANITARIAN AFFAIRS, WORLD HEALTH ORGANIZATION,Arrangements for Preparedness for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GS-G-2.1, IAEA, Vienna (2007).
[273] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency, IAEA Safety Standards Series No. GSG-2, IAEA, Vienna (2011).
[274] INTERNATIONAL LABOUR ORGANIZATION, Convention Concerning the Protection of Workers Against Ionising Radiations, No. 115, ILO, Geneva (1960).
[275] Convention on Early Notification of a Nuclear Accident INFCIRC/335, IAEA, Vienna (1986).
[276] Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency, INFCIRC/336, IAEA, Vienna (1986).
[277] Convention on Nuclear Safety, INFCIRC/449, IAEA, Vienna (1994).
[278] Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, INFCIRC/546, IAEA, Vienna (1997).
[279] Atomic Energy Basic Act, Act No. 186 of 1955, as last amended by Act No. 155 of 2004 (Japan),
[280] The Law Concerning Prevention from Radiation Hazards due to Radioisotopes, etc., Law No. 167 of 1957, as last amended by Law No. 96 of 31 July, 2002 (Japan).
[281] Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, Act No. 166 of 1957, as last amended by Act No. 84 of 2007 (Japan),
http://www.nsr.go.jp/archive/nisa/english/resources/legislativeframework/files/ReactorRegulation.pdf
[282] Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156 of 1999, as last amended by Act No. 118 of 2006 (Japan),
http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf
[283] Industrial Safety and Health Act, Act No. 57 of 1972, as last amended by Law No. 25 of 31 May, 2006 (Japan),
http://www.ilo.org/wcmsp5/groups/public/---ed_protect/---protrav/---ilo_aids/documents/legaldocument/wcms_117327.pdf
[284] Installation of Commercial Power Reactors, Ordinance of the Ministry of International Trade and Industry of December 28, 1978, as latest amended on December 10, 2014 (Japan).
[285] Notification of Dose Limits etc., According to the Installation of Commercial Power Reactors, of March 21, 2001, as last amended on November 22, 2005 (Japan).
[286] National Personnel Authority Rules 10-5 (Prevention of Radiation Injuries in Staff), as of 1963 (Japan) (in Japanese),
http://law.e-gov.go.jp/htmldata/S38/S38F04510005.html
[287] RADIATION COUNCIL, Incorporation of Recommendations of ICRP (Pub. 60) into the National Legal Framework (1998) (in Japanese),
http://www.nsr.go.jp/archive/mext/b_menu/shingi/housha/sonota/81009.htm
[288] MINISTRY OF HEALTH, LABOUR AND WELFARE, Results of Supervision/Instructions to Employers of Decontamination Works (January–June 2013) and Request to the Employers (2013),
http://www.mhlw.go.jp/english/topics/2011eq/workers/ri/pr/pr_130724.html
[289] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations, Publication 109, Pergamon Press, Oxford and New York (2009).

[290] MINISTRY OF HEALTH, LABOUR AND WELFARE, Publication and Enforcement of "the Ministerial Ordinance for Abolishment of Exemption in the Ordinance on Prevention of Ionizing Radiation Hazards in Response to the Situation Resulting from the Tohoku–Pacific Ocean Earthquake in 2011" (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/pr_111216.html
[291] MINISTRY OF HEALTH, LABOUR AND WELFARE, Re: Guidance about the Radiation Exposure Dose During Later Radiation Works Other than Emergency Works for the Workers Who Had Been Engaged in Emergency Works (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/rp/ri_0428_01.html
[292] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Maintaining and Improving Health of Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/pr_111011_a01.pdf
[293] CODEX ALIMENTARIUS COMMISSION, Codex General Standard for Contaminants and Toxins in Food and Feed, Codex Standard 193-1995 as last amended 2013, Codex Alimentarius Commission, http://www.fao.org/fileadmin/user_upload/agns/pdf/CXS_193e.pdf
[294] CODEX ALIMENTARIUS COMMISSION, Report of the Twenty-third Session of the Codex Committee on Food Additives and Contaminats, FAO and WHO, The Hague (1991).
[295] INTERNATIONAL ATOMIC ENERGY AGENCY, Intervention Criteria in a Nuclear or Radiation Emergency, Safety Series No. 109, IAEA, Vienna (1994). (This publication is superseded by GSG-2 (2011)).
[296] WORLD HEALTH ORGANIZATION, Guidelines for Drinking-water Quality, 4th edn, WHO, Geneva (2011).
[297] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Concepts of Exclusion, Exemption and Clearance, IAEA Safety Standards Series No. RS-G-1.7, IAEA, Vienna (2004).
[298] GONZÁLEZ, A.J., AKASHI, M., BOICE, J.D., Jr., CHINO, M., HOMMA, T., ISHIGURE, N., KAI, M., KUSUMI, S., LEE, J.-K., MENZEL, H.-G., NIWA, O., SAKAI, K., WEISS, W., YAMASHITA, S., YONEKURA, Y., Radiological protection issues arising during and after the Fukushima nuclear reactor accident, J. Radiol. Prot. **33** 3 (2013) 497–571.
[299] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).
[300] HEDEMANN-JENSEN, P., McEWAN, A.C., Is ICRP guidance on the use of reference levels consistent? J. Radiol. Prot. **31** 4 (2011) 431–444.
[301] KAI, M., Some lessons on radiological protection learnt from the accident at the Fukushima Dai-ichi nuclear power plant, J. Radiol. Prot. **32** 1 (2012) N101–105.
[302] SAKAI, K., Reference levels in the context of Fukushima — Lessons learned and a challenge for the radiation protection system, Ann. ICRP **41** (3-4) (2012) 282–285.
[303] TANIGAWA, K., HOSOI, Y., HIROHASHI, N., IWASAKI, Y., KAMIYA, K., Loss of life after evacuation: Lessons learned from the Fukushima accident, Lancet **379** 9819 (2012) 889–891.
[304] MINAMISOMA CITY, Nuclear Damages Dispute Resolution for ADR Center Settlement Case (2014) (in Japanese), http://www.city.minamisoma.lg.jp/index.cfm/10,15968,88,html
[305] Compensation Gap Spread, Fukushima Minpo (6 February 2014) (in Japanese).
[306] NUCLEAR EMERGENCY RESPONSE HEADQUARTER, Basic Strategy and Issues in Revision of the Warning Area and Evacuation Order Area (2011) (in Japanese), http://www.kantei.go.jp/jp/singi/genshiryoku/dai23/23_06_gensai.pdf
[307] NUCLEAR SAFETY COMMISSION, Regulatory Guide: Emergency Preparedness for Nuclear Facilities, NSC, Tokyo (1980).
[308] CONSUMER AFFAIRS AGENCY, Result of the 5th Consumer Perception Survey on Radioactivity in Food (2015) (in Japanese), http://www.caa.go.jp/safety/pdf/150310kouhyou_1.pdf
[309] Constitution of the World Health Organization of 1948, as last amended 2005, WHO, Geneva, http://www.who.int/governance/eb/who_constitution_en.pdf
[310] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3

[311] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation, UNSCEAR 2012 Report, Scientific Annex A (Advanced copy): Attributing Health Effects to Ionizing Radiation Exposure and Inferring Risks, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2015).
[312] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/67/46, UN, New York (2012).
[313] FUKUSHIMA PREFECTURE, Terms of Reference of the Committee for the Fukushima Health Management Survey (2011) (in Japanese), http://www.pref.fukushima.lg.jp/uploaded/attachment/65128.pdf
[314] FUKUSHIMA PREFECTURE, Interim Report of Thyroid Ultrasound Examination (Preliminary Baseline Screening) (Proc. 19th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey) (2015), http://www.fmu.ac.jp/radiationhealth/results/media/19-2_Thyroid_Ultrasound_Examination_I-S.pdf
[315] TANIGUCHI, N., et al., Ultrasonographic thyroid nodular findings in Japanese children, J. Med. Ultrasonics **40** 3 (2013) 219–224.
[316] OHTSURU, A., Information Provided during the Consultancy Meeting to Discuss Issues Related to Radiological Consequences in Connection to the Preparation of the Chapter 4 (Radiological Consequences) and Chapter 5 (Post Accident Recovery) of the IAEA Report on the Fukushima Daiichi Accident, Tokyo, official communication (2013).
[317] YABE, H., et al., Psychological distress after the Great East Japan Earthquake and Fukushima Daiichi nuclear power plant accident: Results of a Mental Health and Lifestyle Survey Through the Fukushima Health Management Survey in FY2011 and FY2012, Fukushima J. Med. Sci. **60** 1 (2014) 57–67.
[318] FUJIMORI, K., et al., Pregnancy and birth survey after the Great East Japan Earthquake and Fukushima Daiichi nuclear power plant accident in Fukushima Prefecture, Fukushima J. Med. Sci. **60** 1 (2014) 75–81.
[319] SOBUE, T., Summary Research Report: Research on Thyroid Gland Examinations, etc. of Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2014), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/ort/pr_140805_a2.pdf
[320] MINISTRY OF HEALTH, LABOUR AND WELFARE, Report of the Expert Meeting on Epidemiological Studies Targeting Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2014), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/Report_20140604.pdf
[321] BOUFFLER, S., AINSBURY, E., GILVIN, P., HARRISON, J., Radiation-induced cataracts: The Health Protection Agency's response to the ICRP statement on tissue reactions and recommendation on the dose limit for the eye lens, J. Radiol. Prot. **32** 4 (2012) 479–488.
[322] THORNE, M.C., Regulating exposure of the lens of the eye to ionising radiations, J. Radiol. Prot. **32** 2 (2012) 147–154.
[323] TOKYO ELECTRIC POWER COMPANY, Result of the Investigation on Exposure to Radiation of Workers from Cooperative Companies at Unit 3 in Fukushima Daiichi Nuclear Power Station (2011), http://www.tepco.co.jp/en/press/corp-com/release/11032503-e.html
[324] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Pregnancy and Medical Radiation, Publication 84, Pergamon Press, Oxford and New York (2000).
[325] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Doses to the Embryo and Foetus from Intakes of Radionuclides by the Mother, Publication 88, Pergamon Press, Oxford and New York (2001).
[326] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Biological Effects after Prenatal Irradiation (Embryo and Foetus), Publication 90, Pergamon Press, Oxford and New York (2003).
[327] BOICE, J.D., Jr., Radiation epidemiology: A perspective on Fukushima, J. Radiol. Prot. **32** 1 (2012) N33–40.
[328] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Low-dose Extrapolation of Radiation-related Cancer Risk, Publication 99, Elsevier, Oxford (2005).
[329] SHIMIZU, Y., et al., Radiation exposure and circulatory disease risk: Hiroshima and Nagasaki atomic bomb survivor data, 1950–2003, Br. Med. J. **340** (2010) b5349.

[330] MCGEOGHEGAN, D., BINKS, K., GILLIES, M., JONES, S., WHALEY, S., The non-cancer mortality experience of male workers at British nuclear fuels plc, 1946–2005, Int. J. Epidemiol. **37** 3 (2008) 506–518.
[331] LITTLE, M.P., GOODHEAD, D.T., BRIDGES, B.A., BOUFFLER, S.D., Evidence relevant to untargeted and transgenerational effects in the offspring of irradiated parents, Mutat. Res. **753** 1 (2013) 50–67.
[332] NAKAMURA, N., SUYAMA, A., NODA, A., KODAMA, Y., Radiation effects on human heredity, Annu. Rev. Genet. **47** (2013) 33–50.
[333] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/63/46, UN, New York (2008).
[334] RON, E., BRENNER, A., Non-malignant thyroid diseases after a wide range of radiation exposures, Radiat. Res. **174** 6 (2010) 877–888.
[335] YAMASHITA, S., Tenth Warren K. Sinclair keynote address — The Fukushima nuclear power plant accident and comprehensive health risk management, Health Phys **106** 2 (2014) 166–180.
[336] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Vol. II, Scientific Annex B: Effects of Radiation Exposure of Children, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2013).
[337] AKIBA, S., MIZUNO, S., The third analysis of cancer mortality among Japanese nuclear workers, 1991–2002: Estimation of excess relative risk per radiation dose, J. Radiol. Prot. **32** 1 (2012) 73–83.
[338] Nagataki, S., Thyroid consequences of the Fukushima nuclear reactor accident, Eur. Thyroid J. **1** 3 (2012) 148–158.
[339] HAYASHIDA, N., et al., Thyroid ultrasound findings in children from three Japanese prefectures: Aomori, Yamanashi and Nagasaki, PLoS ONE **8** 12 (2013) e83220.
[340] FUKUSHIMA PREFECTURE, "Thyroid ultrasound examination (full-scale thyroid screening program)" (Proc. 19th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey) (2015), http://www.fmu.ac.jp/radiationhealth/results/media/19-2_Thyroid_Ultrasound_Examination_F-S.pdf
[341] HAYASHIDA, N., et al., Thyroid ultrasound findings in a follow-up survey of children from three Japanese Prefectures: Aomori, Yamanashi, and Nagasaki, Sci. Rep. **5** (2015).
[342] FUKUSHIMA PREFECTURE, FUKUSHIMA MEDICAL UNIVERSITY, Proceedings of the 18th Prefectural Oversight Committee Meeting for Fukushima Health Management Survey (2015), http://www.fmu.ac.jp/radiationhealth/results/20150212_Thyroid_Ultrasound_Examination.html
[343] IVANOV, V.K., Lessons from Chernobyl and prognosis for Fukushima: Radiological consequences, J. Radiol. Prot. **32** 1 (2012) N55.
[344] IVANOV, V.K., et al., Radiation-epidemiological studies of thyroid cancer incidence in Russia after the Chernobyl accident (estimation of radiation risks, 1991–2008 follow-up period), Radiat. Prot. Dosimetr. **151** 3 (2012) 489–499.
[345] CWIKEL J.G., HAVENAAR, J. M., BROMET E.J. (Eds), "Understanding psychological and societal response to toxic hazards. The psychological response of individuals, groups, authorities and media", Toxic Turmoil: Psychological and Societal Consequences of Ecological Disasters , Kluwer, New York (2002) 39–65.
[346] PRINCE-EMBURY, S., ROONEY, J.F., Psychological adaptation among residents following restart of Three Mile Island, J. Trauma. Stress **8** 1 (1995) 47–59.
[347] RAHU, M., Health effects of the Chernobyl accident: Fears, rumours and the truth, Eur. J. Cancer **39** 3 (2003) 295–299.
[348] BAUM, A., GATCHEL, R.J., SCHAEFFER, M.A., Emotional, behavioral, and physiological effects of chronic stress at Three Mile Island, J. Consult. Clin. Psychol. **51** 4 (1983) 565–572.
[349] ADAMS, R.E., GUEY, L.T., GLUZMAN, S.F., BROMET, E.J., Psychological well-being and risk perceptions of mothers in Kyiv, Ukraine, 19 years after the Chornobyl disaster, Int. J. Soc. Psychiatry **57** 6 (2011) 637–645.
[350] YAMADA, M., IZUMI, S., Psychiatric sequelae in atomic bomb survivors in Hiroshima and Nagasaki two decades after the explosions, Soc. Psychiatry Psychiatr. Epidemiol. **37** 9 (2002) 409–415.
[351] KAWAKAMI, N., Mental Health of Residents Living in Shelters, Japanese Association of Epidemiology, Tokyo (2014).

[352] KAWAKAMI, N., TSUCHIYA, M., UMEDA, M., KOENEN, K.C., KESSLER, R. C., Trauma and post traumatic stress disorder in Japan: Results from the World Mental Health Japan Survey, J. Psychiatr. Res. **53** (2014) 157–165.
[353] IWADARE, Y., et al., Post traumatic symptoms in elementary and junior high school children after the 2011 Japan earthquake and tsunami: Symptom severity and recovery vary by age and sex, J. Pediatrics **164** 4 (2014) 917–921.e911.
[354] BROMET, E.J., Emotional consequences of nuclear power plant disasters, Health Phys. **106** 2 (2014) 206–210.
[355] GOTO, A., et al., Maternal confidence of Fukushima mothers before and after the nuclear power plant disaster in Northeast Japan: analyses of municipal health records, J. Commun. Healthcare **7** 2 (2014) 106–116.
[356] BROMET, E.J., et al., Cross-national epidemiology of DSM-IV major depressive episode, BMC Med. **9** 1 (2011) 90.
[357] SHIGEMURA, J., TANIGAWA, T., SAITO, I., NOMURA, S., Psychological distress in workers at the Fukushima nuclear power plants, JAMA **308** 7 (2012) 667–669.
[358] SHIGEMURA, J., et al., Associations between disaster exposures, peritraumatic distress, and posttraumatic stress responses in Fukushima nuclear plant workers following the 2011 nuclear accident: the Fukushima NEWS project study, PLoS One **9** 2 (2014) e87516.
[359] MATSUOKA, Y., et al., Concern over radiation exposure and psychological distress among rescue workers following the Great East Japan Earthquake, BMC Public Health **12** (2012) 249.
[360] KESSLER, R.C., et al., Screening for serious mental illness in the general population, Arch. Gen. Psychiat. **60** 2 (2003) 184–189.
[361] BLANCHARD, E.B., JONES-ALEXANDER, J., BUCKLEY, T.C., FORNERIS, C.A., Psychometric properties of the PTSD checklist (PCL), Behav. Res. Ther. **34** 8 (1996) 669–673.
[362] EWING, J.A., Detecting alcoholism: The CAGE questionnaire, JAMA **252** 14 (1984) 1905–1907.
[363] DENDA, K., KAKO, Y., KITAGAWA, N., KOYAMA, T., Assessment of depressive symptoms in Japanese school children and adolescents using the Birleson depression self-rating scale, Int. J. Psychiatry Med. **36** 2 (2006) 231–241.
[364] BROMET, E., CONNELL, M., HOUGH, L., Mental health of children near the Three Mile Island Reactor, J. Prev. Psychiatry **2** (1984) 275–301.
[365] BROMET, E.J., et al., Children's well-being 11 years after the Chornobyl catastrophe, Arch. Gen. Psychiatry **57** 6 (2000) 563–571.
[366] NOMURA, Y., "Pregnancy and birth survey (by the Radiation Medical Science Center for the Fukushima Health Management Survey)", paper presented at 3rd Int. Expert Symp. on Beyond Radiation and Health Risk: Toward Resilience and Recovery, Fukushima, 2014, http://www.fmu.ac.jp/radiationhealth/symposium201409/media/10_S2_Nomura_FINAL(0909).pdf
[367] NOMURA, Y., FUJIMORI, K., Survey of pregnant women in Fukushima Prefecture and future issues, Fukushima J. Med. Sci. **60** 2 (2014) 213.
[368] RAHU, K., et al., Chernobyl cleanup workers from Estonia: Follow-up for cancer incidence and mortality, J. Radiol. Prot. **33** 2 (2013) 395–411.
[369] KAWAKAMI, N., SHIMIZU, H., HARATANI, T., IWATA, N., KITAMURA, T., Lifetime and 6-month prevalence of DSM-III-R psychiatric disorders in an urban community in Japan, Psychiatry Res. **121** 3 (2004) 293–301.
[370] KAWAKAMI, N., et al., Twelve-month prevalence, severity, and treatment of common mental disorders in communities in Japan: Preliminary finding from the World Mental Health Japan Survey 2002–2003, Psychiatry Clin. Neurosci. **59** 4 (2005) 441–452.
[371] UNITED NATIONS, Report of the United Nations Scientific Committee on the Effects of Atomic Radiation, A/68/46, UN, New York (2013).
[372] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Report of ICRP Task Group 84 on Initial Lessons Learned from the Nuclear Power Plant Accident in Japan vis-à-vis the ICRP System of Radiological Protection, ICRP, Ottawa (2012).
[373] GERAS'KIN, S. A., FESENKO, S. V., ALEXAKHIN, R. M., Effects of non-human species irradiation after the Chernobyl NPP accident, Environ. Int. **34** 6 (2008) 880–897.
[374] BIODIVERSITY CENTER OF JAPAN, The Animal Distribution Atlas of Japan (2015) (in Japanese), http://www.biodic.go.jp/kiso/atlas

[375] BIODIVERSITY CENTER OF JAPAN, Vegetation Map in Japan (2015) (in Japanese), http://www.vegetation.biodic.go.jp
[376] OGURI, K., et al., Hadal disturbance in the Japan Trench induced by the 2011 Tohoku–Oki earthquake, Sci. Rep. **3** (2013).
[377] BIODIVERSITY CENTER OF JAPAN, Official web site about the effect of the earthquake and the tsunami (in Japanese), http://www.shiokaze.biodic.go.jp
[378] NAGAHATA, Y., How Huge Tsunami Changes the Ecosystems? Kodansha, Tokyo (2012) (in Japanese).
[379] NAKAJIMA, H., KOARAI, M., Assessment of tsunami flood situation from the Great East Japan Earthquake, Bull. Geosp. Inf. Auth. Jpn **59** (2011) 55–66.
[380] EMERGENCY OPERATION CENTER, MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, AGRICULTURE, FORESTRY AND FISHERIES RESEARCH COUNCIL, MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Summarized Version of the "Results of the Research on Distribution of Radioactive Substances Discharged by the Accident at TEPCO's Fukushima Dai-ichi NPP" (2011), http://radioactivity.nsr.go.jp/en/contents/1000/294/24/PressR04%200802s.pdf
[381] HELDAL, H.E., STUPAKOFF, I., FISHER, N.S., Bioaccumulation of ^{137}Cs and ^{57}Co by five marine phytoplankton species, J. Environ. Radioact. **57** 3 (2001) 231–236.
[382] THORNTON, B., et al., Distribution of local ^{137}Cs anomalies on the seafloor near the Fukushima Dai-ichi nuclear power plant, Mar. Pollut. Bull. **74** 1 (2013) 344–350.
[383] VIVES I BATLLE, J., et al., The impact of the Fukushima nuclear accident on marine biota: Retrospective assessment of the first year and perspectives, Sci. Total Environ. **487** (2014) 143–153.
[384] OUGHTON, D., "Ethical aspects of protection of the environment from ionising radiation", paper presented at EC Article 31 Scientific Seminar, Luxembourg, 2012.
[385] PENTREATH, R.J., Feasibility of Disposal of High-level Radioactive Waste into the Seabed, OECD/NEA, Paris (1988).
[386] PENTREATH, R.J., A system for radiological protection of the environment: Some initial thoughts and ideas, J. Radiol. Prot. **19** 2 (1999) 117–128.
[387] FISHER, N.S., et al., Evaluation of radiation doses and associated risk from the Fukushima nuclear accident to marine biota and human consumers of seafood, PNAS **110** 26 (2013) 10670–10675.
[388] ROSE, G., Epidemiology and environmental risks, Soz. Praventivmed. **37** 2 (1992) 41–44.
[389] INTERNATIONAL ATOMIC ENERGY AGENCY, Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards, Technical Reports Series No. 332, IAEA, Vienna (1992).
[390] GARNIER-LAPLACE, J., et al., Issues and practices in the use of effects data from FREDERICA in the ERICA integrated approach, J. Environ. Radioact. **99** 9 (2008) 1474–1483.
[391] ANDERSSON, P., et al., Protection of the environment from ionising radiation in a regulatory context (protect): Proposed numerical benchmark values, J. Environ. Radioact. **100** 12 (2009) 1100–1108.
[392] ALONZO, F., et al., Modelling the propagation of effects of chronic exposure to ionising radiation from individuals to populations, J. Environ. Radioact. **99** 9 (2008) 1464–1473.
[393] BROWN, J.E., et al., The ERICA tool, J. Environ. Radioact. **99** 9 (2008) 1371–1383.
[394] ULANOVSKY, A., PRÖHL, G., GOMEZ-ROS, J.M., Methods for calculating dose conversion coefficients for terrestrial and aquatic biota, J. Environ. Radioact. **99** 9 (2008) 1440–1448.
[395] HAYAMA, S., et al., Concentration of radiocesium in the wild Japanese monkey (*Macaca fuscata*) over the first 15 months after the Fukushima Daiichi nuclear disaster, PLoS One **8** 7 (2013) e68530.
[396] TAZOE, H., et al., Radioactive pollution from Fukushima Daiichi nuclear power plant in the terrestrial environment, Radiat. Prot. Dosim. **152** 1–3 (2012) 198–203.
[397] KURODA, K., KAGAWA, A., TONOSAKI, M., Radiocesium concentrations in the bark, sapwood and heartwood of three tree species collected at Fukushima forests half a year after the Fukushima Dai-ichi nuclear accident, J. Environ. Radioact. **122** (2013) 37–42.
[398] HASEGAWA, M., et al., Radiocesium concentrations in epigeic earthworms at various distances from the Fukushima nuclear power plant 6 months after the 2011 accident, J. Environ. Radioact. **126** (2013) 8–13.

[399] AYABE, Y., KANASASHI, T., HIJII, N., TAKENAKA, C., Radiocesium contamination of the web spider *Nephila Clavata* (Nephilidae: Arachnida) 1.5 years after the Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact. **127** (2014) 105–110.
[400] MIZUNO, T., KUBO, H., Overview of active cesium contamination of freshwater fish in Fukushima and Eastern Japan, Sci. Rep. **3** (2013).
[401] BUESSELER, K.O., et al., Fukushima-Derived Radionuclides in the Ocean and Biota off Japan, PNAS **109** 16 (2012) 5984–5988.
[402] HOSSEINI, A., THORRING, H., BROWN, J.E., SAXEN, R., ILUS, E., Transfer of radionuclides in aquatic ecosystems — Default concentration ratios for aquatic biota in the ERICA tool, J. Environ. Radioact. **99** 9 (2008) 1408–1429.
[403] LINKOV, I., BURMISTROV, D., Model uncertainty and choices made by modelers: Lessons learned from the International Atomic Energy Agency model intercomparisons, Risk Anal. **23** 6 (2003) 1297–1308.
[404] AVILA, R., et al., "Conceptual overview of forestland — a model to interpret and predict temporal and spatial patterns of radioactively contaminated forest landscapes", Contaminated Forests (LINKOV, I., SCHELL, W.R., Eds), Springer, Amsterdam (1999) 173–183.
[405] FESENKO, S., SPIRIDONOV, S., AVILA, R., "Modelling of ^{137}Cs behaviour in forest game food chains", Contaminated Forests (LINKOV, I., SCHELL, W.R., Eds), Springer, Amsterdam (1999) 239–247.
[406] INTERNATIONAL ATOMIC ENERGY AGENCY, Modelling the Migration and Accumulation of Radionuclides in Forest Ecosystems, IAEA-BIOMASS-1, IAEA, Vienna (2002).
[407] ASTASHEVA, N.P., "Influence of radiation released during the Chernobyl NPP accident on clinical and physiological status of agricultural animals", Problems of Agricultural Radiology, UIAR, Kiev (1991) 176–180 (in Russian).
[408] COPPLESTONE, D., HINGSTON, J., REAL, A., The development and purpose of the FREDERICA radiation effects database, J. Environ. Radioact. **99** 9 (2008) 1456–1463.
[409] REAL, A., SUNDELL-BERGMAN, S., KNOWLES, J.F., WOODHEAD, D.S., ZINGER, I., Effects of ionising radiation exposure on plants, fish and mammals: Relevant data for environmental radiation protection, J. Radiol. Prot. **24** 4a (2004) A123–137.
[410] BRÈCHIGNAC, F., DOI, M., Challenging the current strategy of radiological protection of the environment: Arguments for an ecosystem approach, J. Environ. Radioact. **100** 12 (2009) 1125–1134.
[411] WOODWELL, G.M., Design of the Brookhaven experiment on the effects of ionzing radiation on a terrestrial ecosystem, Radiat. Bot. **3** 2 (1963) 125–133.
[412] MACDONALD, C.R., The Effects of Radiation Exposure on Wild Life: Report to the Commercial Chemicals Evaluation Branch, Environment Canada, Northern Environmental Consulting and Analysis, Pinawa (1998).
[413] SPARROW, A.H., HOWARD, A., COWIE, F.G., SCHWEMMER, S.S., NAUMAN, A.F., Chromosomes and cellular radiosensitivity, IV. A new radiotaxon represented by the ferns, Int. J. Radiat. Biol. Relat. Stud. Phys. Chem. Med. **27** 4 (1975) 343–354.
[414] ALEXAKHIN, R.M., "Remediation of areas contaminated after radiation accidents", Radioactivity in the Environment (VOIGT, G., FESENKO, S., Eds), Elsevier, Oxford (2009) 177–222.
[415] GARNIER-LAPLACE, J., et al., First derivation of predicted-no-effect values for freshwater and terrestrial ecosystems exposed to radioactive substances, Environ. Sci. Technol. **40** 20 (2006) 6498–6505.
[416] MILLER, J.K., SWANSON, E.W., Performance and iodine metabolism of dairy cattle with iodine^{131} irradiation injury, J. Dairy Sci. **50** 1 (1966) 90–95.
[417] GARNER, R.J., SANSOM, B.F., JONES, H.G., WEST, L.C., Fission products and the dairy cow, J. Comp. Path. Therap. **71** (1961) 71–84.
[418] GARNIER-LAPLACE, J., BEAUGELIN-SEILLER, K., HINTON, T.G., Fukushima wildlife dose reconstruction signals ecological consequences, Environ. Sci. Technol. **45** 12 (2011) 5077–5078.
[419] KRYSHEV, I.I., KRYSHEV, A.I., SAZYKINA, T.G., Dynamics of radiation exposure to marine biota in the area of the Fukushima NPP in March–May 2011, J. Environ. Radioact. **114** (2012) 157–161.
[420] HIYAMA, A., et al., The biological impacts of the Fukushima nuclear accident on the pale grass blue butterfly, Sci. Rep. **2** (2012).
[421] MØLLER, A.P., NISHIUMI, I., SUZUKI, H., UEDA, K., MOUSSEAU, T.A., Differences in effects of radiation on abundance of animals in Fukushima and Chernobyl, Ecol. Indic. **24** (2013) 75–81.

[422] AKIMOTO, S., Morphological abnormalities in gall-forming aphids in a radiation-contaminated area near Fukushima Daiichi: Selective impact of fallout? Ecol. Evol. **4** 4 (2014) 355–369.
[423] NUCLEAR REGULATION AUTHORITY, Comprehensive Radiation Monitoring Plan (2015), http://radioactivity.nsr.go.jp/en/list/274/list-1.html
[424] LYONS, C., COLTON, D., Aerial measuring system in Japan, Health Phys **102** 5 (2012) 509–515.
[425] NUCLEAR REGULATION AUTHORITY, Airborne Monitoring Survey Results (2013), http://radioactivity.nsr.go.jp/en/list/307/list-1.html
[426] SAITO, K., et al., Detailed Deposition density maps constructed by large-scale soil sampling for gamma-ray emitting radioactive nuclides from the Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact. **139** (2015) 308–319.
[427] MURAMATSU, Y., MATSUZAKI, H., TOYAMA, C., OHNO, T., Analysis of ^{129}I in the soils of Fukushima Prefecture: Preliminary reconstruction of ^{131}I deposition related to the accident at Fukushima Daiichi nuclear power plant (FDNPP), J. Environ. Radioact. **139** (2015) 344–350.
[428] STEINHAUSER, G., SCHAUER, V., SHOZUGAWA, K., Concentration of strontium-90 at selected hot spots in Japan, PLoS ONE **8** 3 (2013) e57760.
[429] YAMAMOTO, M., An early survey of the radioactive contamination of soil due to the Fukushima Dai-ichi nuclear power plant accident, with emphasis on plutonium analysis, Geochem. J. **46** 4 (2012) 341–353.
[430] AITCHISON, J., BROWN, J.A.C., The Lognormal Distribution, with Special Reference to its Uses in Economics, Cambridge University Press, London (1963).–
[431] DANIELS, W.M., HIGGINS, N.A., Environmental Distribution and the Practical Utilisation of Detection Limited Environmental Measurement Data, National Radiological Protection Board, Chilton, Didcot (2002).
[432] FINNEY, D.J., Probit Analysis: A Statistical Treatment of the Sigmoid Response Curve, Cambridge University Press, London (1952).
[433] GILBERT, R.O., Statistical Methods for Environmental Pollution Monitoring, Van Nostrand Reinhold Company, New York (1987).
[434] LIMPERT, E., STAHEL, W.A., ABBT, M., Log-normal distributions across the sciences: Keys and clues, BioSciences **51** 5 (2001) 341–352.
[435] INTERNATIONAL ATOMIC ENERGY AGENCY, The International Chernobyl Project: Technical Report, IAEA, Vienna (1991).

CONTENTS OF CD-ROM

The following annexes to Technical Volume 4 are included on the attached CD-ROM:

Annex I: Characteristics and measurement of radioactivity and radiation levels

Annex II: Local and regional meteorological conditions in East Japan during 11–23 March 2011

Annex III: Levels of radioactivity in the terrestrial environment

Annex IV: Radioactivity in the marine environment arising from releases following the Fukushima Daiichi accident

Annex V: UNSCEAR assessment of the dose to the public

Annex VI: Information on measurement studies investigated in the production of Technical Volume 4

Annex VII: Analysis of thyroid measurements of children conducted in Fukushima Prefecture, 26-30 March 2011

Annex VIII: Conventions recommendations, safety standards, laws, and regulations

Annex IX: Introduction to radiation effects on the thyroid

Annex X: Radiation and health effects and inferring radiation risks from the Fukushima Daiichi accident

Annex XI: Risk assessments for workers and the population following the Chernobyl accident

Annex XII: Calculations used in the assessment of doses to non-human biota

ABBREVIATIONS

AGL	height above ground level
AMS	accelerator mass spectrometry
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
BSS	Basic Safety Standards
CED	committed effective dose
CI	confidence interval
CNS	Convention on Nuclear Safety
CPS	counts per second
CRIEPI	Centre of the Central Research Institute of the Electric Power Industry
CR	concentration ratio
CTBTO	Comprehensive Nuclear Test-Ban-Treaty Organization
DCA	dicentric chromosome array
DCCs	dose conversion coefficients
DCRL	Derived Consideration Reference Level
DOE	United States Department of Energy
EPD	electronic personal dosimeter
EPIC	Environmental Protection from Ionizing Contaminants in the Arctic
ERIC	Environmental Risk from Ionizing Contaminants: Assessment and Management
FAO	Food and Agriculture Organization of the United Nations
FASSET	Framework for Assessment of Environmental Impact
FDMA	Fire and Disaster Management Agency
FHMS	Fukushima Health Management Survey
FNAB	fine needle aspiration biopsy
FY	fiscal year
GDAS	Global Data Assimilation System
GEOMAR	Research Center for Marine Geosciences
GLs	guidance levels
GPD	general psychological distress
Gy	gray
HPGe	High Purity Germanium
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
ICRP	International Commission on Radiological Protection
ILO	International Labour Organization
IMMSP	Institute of Mathematical Machines and Systems Problems
IRSN	Institut de radioprotection et de sûreté nucléaire (Institute for Radiological Protection and Nuclear Safety)
JAEA	Japan Atomic Energy Agency
JCOPET	Tide-resolving regional nested subsystem of Japan Coastal Ocean Predictability Experiment
JKEO	Japan Agency for Marine–Earth Science and Technology Kuroshio Extension Observatory
KEO	Kuroshio Extension Observatory
KIOST	Korea Institute of Ocean Science and Technology
KNOT	Kyodo North Pacific Ocean Time-series
Kobe U	Kobe University
LARF	lifetime attributable risk fraction
LARs	lifetime attributable risks
LD	lethal dose
MAFF	Ministry of Agriculture, Forestry and Fisheries
MCR	main control room
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology

MHLW	Ministry of Health, Labour and Welfare
MSSG	Multi-Scale Simulator for the GeoEnvironment
NIES	National Institute for Environmental Studies
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant
NRA	Nuclear Regulation Authority
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OP	Onahama Port
PADs	personal alarm dosimeters
PAHO	Pan American Health Organization
PDF	probability density function
PPE	personal protective equipment
PROTECT	Protection of the Environment from Ionizing Radiation in a Regulatory Context
PTC	papillary thyroid cancer
PTSD	post-traumatic stress disorder
PTSR	post-traumatic stress response
RAPs	reference animals and plants
SDF	Self-Defense Forces
SPEEDI	System for Prediction of Environmental Emergency Dose Information
TEPCO	Tokyo Electric Power Company
TMI	Three Mile Island
TUE	Thyroid Ultrasound Examination
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
US DOE/NNSA	US Department of Energy/National Nuclear Security Administration
USPACOM	United States Pacific Command
UTC	Universal Time Coordinated
WBC	whole-body counter
WHO	World Health Organization
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization

CONTRIBUTORS TO DRAFTING AND REVIEW

WORKING GROUP 4 (WG4): RADIOLOGICAL CONSEQUENCES

Co-Chairs

González, A.
Nuclear Regulatory Authority
Argentina

Chhem, R. (until August 2014)
Department of Nuclear Sciences and Applications
IAEA

Meghzifene, A. (September 2014 onwards)
Department of Nuclear Sciences and Applications
IAEA

Pinak, M.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Müskens, P. (until August 2013)
Department of Nuclear Safety and Security
IAEA

Bevington, L. (September 2013 onwards)
Department of Nuclear Safety and Security
IAEA

Members

Akashi, M.
National Institute of Radiological Sciences
Japan

Betancourt, A.
Agencia de Energía Nuclear y Tecnologías de Avanzada
Cuba

Blumenthal, D.
National Nuclear Security Administration
Department of Energy
USA

Bromet, E.J.
State University of New York at Stony Brook
USA

Brown, J.
Norwegian Radiation Protection Authority
Norway

Coleman, C.N.
National Cancer Institute
USA

Demidchik, Y.
Belarusian Academy of Science and
Belarusian Medical Academy of Post-Graduate Education
Belarus

Dobrzyński, L.
National Centre for Nuclear Research
Poland

Gallego, E.
Universidad Politécnica de Madrid
Spain

Haquin, G.
Soreq Nuclear Research Center
Israel

Jones, C.G.
Permanent Mission of the United States of America to the IAEA in Vienna and
Nuclear Regulatory Commission
USA

Lee, J.K.
Hanyang University
Republic of Korea

Magnusson, S.
Icelandic Radiation Safety Authority
Iceland

Mason, C.
BHP Billiton
Australia

McEwan, A.C.
Senior Consultant
New Zealand

McGinnity, P.A.
Environmental Protection Agency
Ireland

Ng, K.H.
University of Malaya
Malaysia

Niwa, O.
Kyoto University and
Fukushima Medical University
Japan

Pentreath, R.J.
University of Reading
United Kingdom

Perrin, M.L.
Nuclear Safety Authority
France

Rochedo, E.
Coordination of Nuclear Installations
Brazil

Shinkarev, S.
Federal Medical Biological Agency
Russian Federation

Sundell-Bergman, S.
Swedish University of Agricultural Sciences Uppsala
Sweden

Thomas, G.
Imperial College London
United Kingdom

Valentin, J.
Jack Valentin Radiological Protection
Sweden

Invited experts and contacts points

Brenner, A.
National Cancer Institute
USA

Chino, M.
Japan Atomic Energy Agency
Japan

Fukui, T.
Nuclear Regulation Authority
Japan

Ivanov, V.
National Radiation and Epidemiological Registry
Russian Federation

Makihira, A.
Tokyo Electric Power Co., Inc.
Japan

Nagataki, S.
Nagasaki University
Japan

Ohtsuru, A.
Fukushima Medical University
Japan

IAEA Secretariat staff supporting WG4

Harms, A.V.
McGinnity, P.A.
Nies, H.
Osvath, I.
Sakai, K.
Yonehara, H.

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group (INSAG)

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Mohammad Jais, A.
International Nuclear Safety Group

Niu, S.
International Labour Organization

Sharma, S.K. †
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

† Deceased.

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13-December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

5–9 May 2014
6th meeting of WG 4, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Consultants services (CS) meetings

24–26 March 2014
CS on Radioactivity in the Environment, Monaco

20–21 May 2014
CS on Radiation and Log-Normal Distributions, Vienna

23–27 June 2014
CS on Radiation and Log-Normal Distributions, Vienna

Bilateral meetings in Japan

25–27 November 2013
CS to Discuss Issues Related to Radiological Consequences in Connection with the Preparation of Chapter 4 (Radiological Consequences) and Chapter 5 (Post-accident Recovery)

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

15-1816



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)

The Fukushima Daiichi Accident

Technical Volume 5/5
Post-accident Recovery

IAEA
International Atomic Energy Agency

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 5
POST-ACCIDENT RECOVERY

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWAZILAND
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

THE FUKUSHIMA DAIICHI ACCIDENT

TECHNICAL VOLUME 5
POST-ACCIDENT RECOVERY

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Fax: +43 1 2600 29302
Tel.: +43 1 2600 22417
Email: sales.publications@iaea.org
http://www.iaea.org/books

©IAEA, 2015

Printed by the IAEA in Austria
August 2015
STI/PUB/1710

IAEA Library Cataloguing in Publication Data

The Fukushima Daiichi accident — Vienna : International Atomic Energy Agency, 2015.

v. ; 30 cm.
STI/PUB/1710
ISBN 978–92–0–107015–9 (set)
Includes bibliographical references.

1. Nuclear reactor accidents — Analysis. 2. Nuclear power plants — Accidents — Analysis. 3. Nuclear reactor accidents — Japan — Fukushima-ken. 4. Radioactive pollution — Health aspects — Japan — Fukushima-ken. 5. Radioactive waste management. 6. Emergency management. I. International Atomic Energy Agency.

IAEAL 15–00988

EDITORIAL NOTE

This publication has been prepared from contributions submitted by many international experts to the five Working Groups for the preparation of the technical volumes. The content does not necessarily reflect the views of IAEA Member States, or the organizations nominating experts.

Great care has been taken to maintain the accuracy of information contained in this publication. Neither the IAEA, nor its Member States, however, assume any responsibility for consequences that may arise from its use, nor are any warranties made of any kind in connection with this publication.

This publication is not intended to address issues of responsibility, legal or otherwise, for acts or omissions on the part of any person or entity.

Extracts from this publication may be freely used elsewhere, provided that acknowledgement of the source is made. If any attribution in this publication indicates that the information (including photographs and graphics) is from a source or site external to the IAEA, permission for reuse must be sought from the originating source.

The use of particular designations of countries or territories does not imply any judgement by the IAEA as to the legal status of such countries or territories, or of the delimitation of their boundaries, or of their authorities and institutions.

The mentioning of names of specific companies or products, whether or not indicated as registered, does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA assumes no responsibility for the accuracy or continued existence of URLs for external or third party Internet web sites referred to in this publication and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

ACKNOWLEDGEMENTS

Financial assistance was provided by Canada, Japan, the Russian Federation, the United Kingdom and the United States of America.

In-kind contributions were received from Argentina, Australia, Belarus, Brazil, Canada, China, Cuba, the Czech Republic, Finland, France, Germany, Ghana, Iceland, India, Indonesia, Israel, Italy, Japan, the Republic of Korea, Malaysia, Mexico, Morocco, the Netherlands, New Zealand, Norway, Pakistan, the Philippines, Poland, the Russian Federation, Slovakia, South Africa, Spain, Sweden, Switzerland, the Syrian Arab Republic, Turkey, Ukraine, the United Arab Emirates, the United Kingdom, the United Republic of Tanzania and the United States of America. In-kind contributions were also received from the European Commission, the Food and Agriculture Organization of the United Nations, the International Commission on Radiological Protection, the International Labour Organization, the International Nuclear Safety Group, the OECD Nuclear Energy Agency, the United Nations Scientific Committee on the Effects of Atomic Radiation, the World Association of Nuclear Operators and the World Meteorological Organization.

The Government of Japan provided invaluable support by making available a considerable amount of information, arranging for Japanese experts to support the work on the report and ensuring logistical assistance for bilateral meetings in Japan.

The United Nations Scientific Committee on the Effects of Atomic Radiation supported the IAEA by sharing the relevant database of references from its 2013 report and allowing information and figures from this report to be reproduced.

The IAEA thanks the large number of experts who were involved in this report. It is the result of the dedicated efforts of many people. All participants listed at the end of this technical volume made valuable contributions, but a particularly heavy load was borne by the Co-Chairs and coordinators of the working groups. The efforts of many expert reviewers, including members of the International Technical Advisory Group, are also gratefully acknowledged.

THE REPORT ON THE FUKUSHIMA DAIICHI ACCIDENT

At the IAEA General Conference in September 2012, the Director General announced that the IAEA would prepare a report on the Fukushima Daiichi accident. He later stated that this report would be "an authoritative, factual and balanced assessment, addressing the causes and consequences of the accident, as well as lessons learned".[1]

The report is the result of an extensive international collaborative effort involving five working groups with about 180 experts from 42 Member States (with and without nuclear power programmes) and several international bodies. This ensured a broad representation of experience and knowledge. An International Technical Advisory Group provided advice on technical and scientific issues. A Core Group, comprising IAEA senior level management, was established to give direction and to facilitate the coordination and review. Additional internal and external review mechanisms were also instituted. The organizational structure for the preparation of this publication is illustrated in Fig. 1.

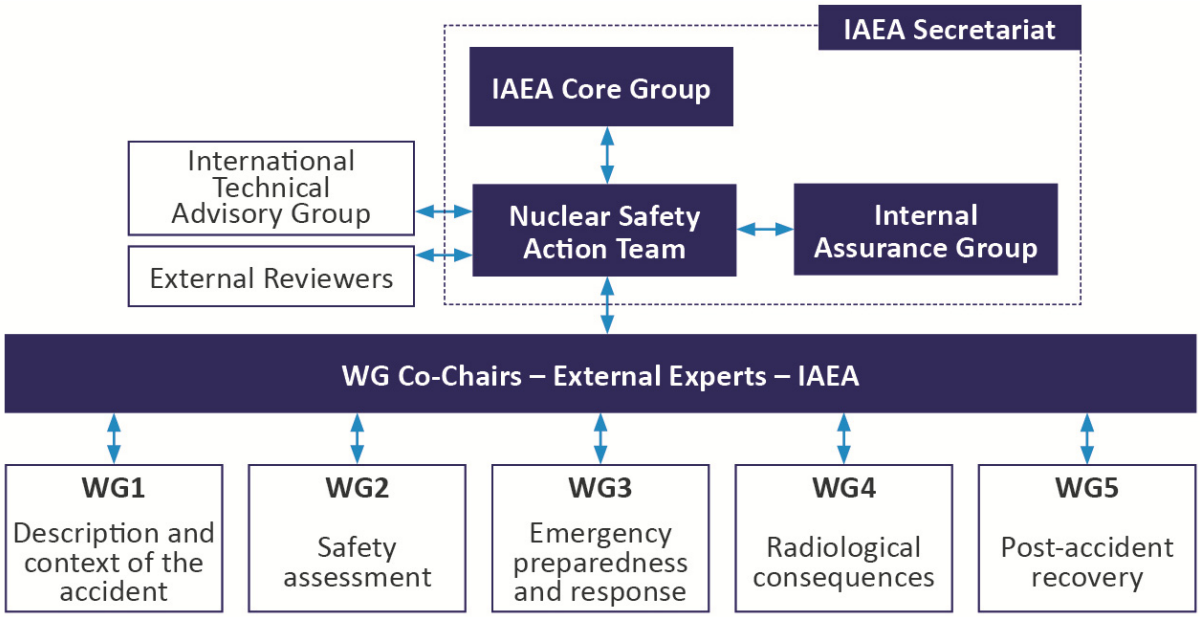


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

The Report by the Director General consists of an Executive Summary and a Summary Report. It draws on five detailed technical volumes prepared by international experts and on the contributions of the many experts and international bodies involved.

The five technical volumes are for a technical audience that includes the relevant authorities in IAEA Member States, international organizations, nuclear regulatory bodies, nuclear power plant operating organizations, designers of nuclear facilities and other experts in matters relating to nuclear power.

---

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Introductory Statement to Board of Governors (2013), https://www.iaea.org/newscenter/statements/introductory-statement-board-governors-3.

The relationship between the content of the Report by the Director General and the content of the technical volumes is illustrated in Fig. 2.

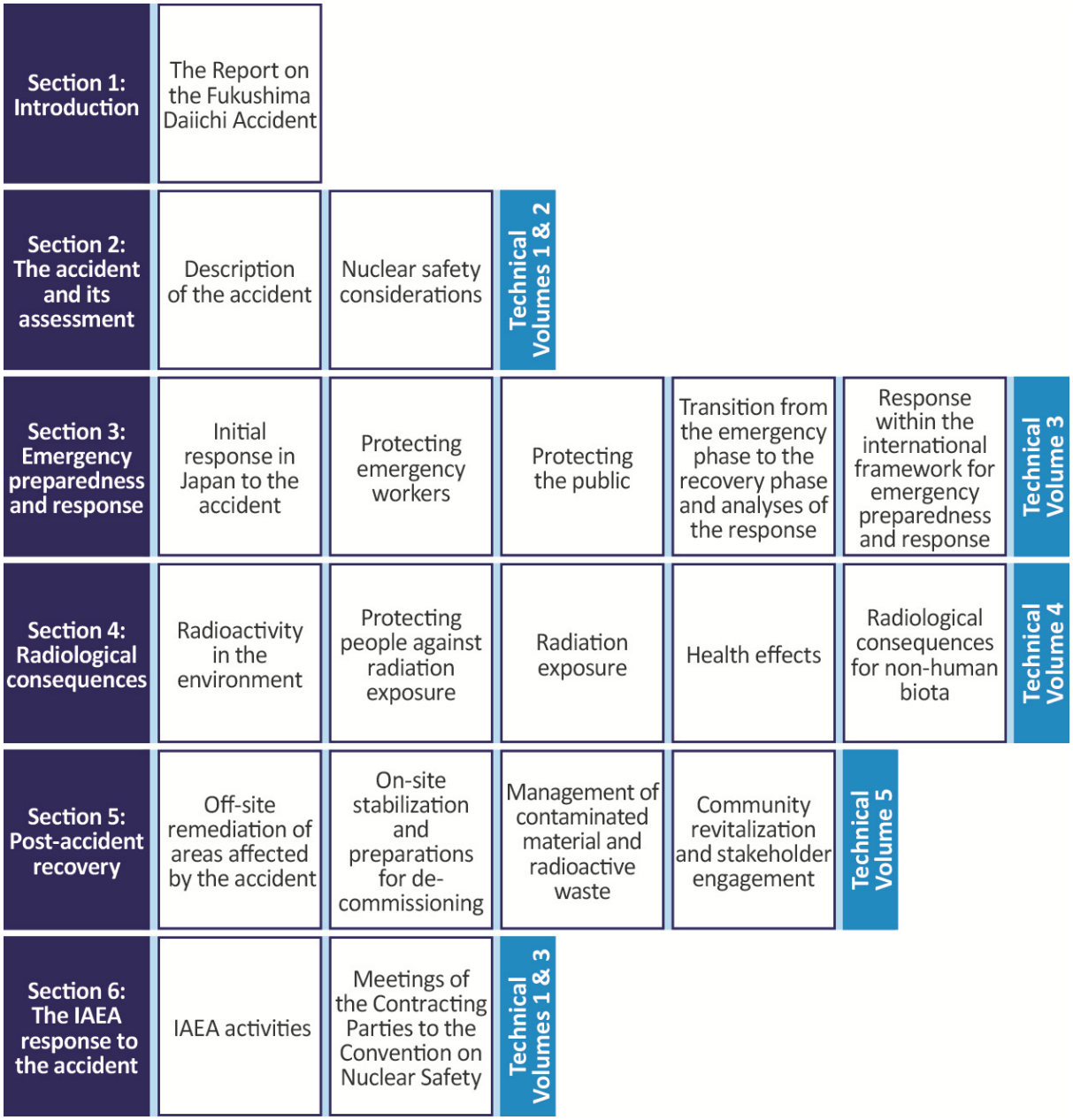


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

POST-ACCIDENT RECOVERY 1

5. INTRODUCTION 1

5.1. BACKGROUND TO POST-ACCIDENT RECOVERY 2
5.1.1. Goals of recovery 2
5.1.2. Basis for recovery 3
5.2. REMEDIATION 5
5.2.1. Introduction 5
5.2.2. Remediation and exposure pathways 6
5.2.3. Planning for remediation in Japan after the Fukushima Daiichi accident 9
5.2.4. The remediation strategy and objectives adopted in Japan 15
5.2.5. Procedures for implementation of remediation 23
5.2.6. Remediation in the Intensive Contamination Survey Area 32
5.2.7. Remediation in the Special Decontamination Areas 36
5.2.8. Implementation of action levels in foods and other materials 45
5.2.9. Summary 52
5.2.10. Observations and lessons 56
5.3. ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING 57
5.3.1. Introduction 57
5.3.2. Management and regulation of on-site activities 58
5.3.3. The mid- and long term roadmap towards decommissioning 60
5.3.4. Preparations for decommissioning 64
5.3.5. Achieving readiness for decommissioning 89
5.3.6. Summary 91
5.3.7. Observations and lessons 93
5.4. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE 94
5.4.1. Introduction 94
5.4.2. Legal framework and responsibilities 95
5.4.3. Off-site management of waste and contaminated material 102
5.4.4. On-site management of waste and contaminated material 118
5.4.6 Summary 133
5.4.7 Observations and lessons 134
5.5. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT 134
5.5.1. Introduction 134
5.5.2. The legal framework 135
5.5.3. The affected population and infrastructure 137
5.5.4. Recovery and revitalization strategies 147
5.5.5. Stakeholder engagement and communication 153
5.5.6. Media reporting and consequences 162
5.5.7. Addressing the question of what is safe 162
5.5.8 Summary 164
5.5.9 Observations and lessons 165

APPENDIX I: Pilot demonstration projects for remediation in Japan 167

REFERENCES 179
ABBREVIATIONS 198
CONTRIBUTORS TO DRAFTING AND REVIEW 200
INTERNATIONAL TECHNICAL ADVISORY GROUP 203
MEETINGS 204

POST-ACCIDENT RECOVERY

5. INTRODUCTION

This volume deals with the recovery stage of the accident at the Fukushima Daiichi nuclear power plant (NPP). It provides a description and analysis of the initial recovery actions, and also looks ahead based on the current plans for recovery activities.

One of the main objectives of this volume is to provide a comprehensive description of on-site and off-site recovery efforts following the emergency phase of the Fukushima Daiichi accident. Until now, this information has been widely dispersed. Another major objective is to formulate lessons learned on the basis of these efforts. This volume presents:

- What is now known about the recovery from the Fukushima Daiichi accident, including the status and effectiveness of remedial and management actions;
- Lessons and observations arising from the experience of undertaking recovery actions following the accident that are useful for the international community to enhance nuclear safety worldwide.

The scope of the volume covers the recovery activities and their timing. In the period immediately following the accident, priority was given to the stabilization of conditions at the plant and ensuring the safety of the public. Protective actions included the evacuation of residents from selected areas and the implementation of food restrictions, as described in more detail in Technical Volume 3. As time progressed, and the conditions at the NPP improved and were stabilized, greater emphasis was placed on off-site recovery from the accident, including the remediation of the environment, infrastructure and the affected communities.

In the context of this volume, recovery means the achievement of an acceptable level from which society can again fully function. Recovery entails:

- The remediation of contaminated areas;
- The stabilization of the damaged reactors, and preparations for their eventual decommissioning;
- The effective and safe management of the resulting contaminated material and radioactive waste, leading to their ultimate disposal;
- The reestablishment of infrastructure and the revitalization of communities.

The timeline for the progression of the accident is important in defining the scope of this volume:

- **Phase 1 (the emergency phase):** From March 2011 to December 2011 (consistent with achievement of a 'cold shutdown state'[1], officially brought the accident phase of events at the Fukushima Daiichi NPP to a close).[2] This period is covered in Technical Volumes 1–3.
- **Phase 2 (the transitional phase):** This phase covers an indeterminate period of time, with regard to off-site remediation, during which some aspects of the transition began (some as early as 1 April 2011) and continued until the end of March 2012.
- **Phase 3 (the existing exposure situation):** This period is considered to have begun in December 2011 for on-site stabilization and decommissioning and in April 2012 for off-site remediation.

[1] On 16 December 2011, the Government–TEPCO Integrated Response Office announced that the conditions for a cold shutdown state had been achieved in Units 1–3. The term cold shutdown state was defined by the Government of Japan at the time specifically for the Fukushima Daiichi NPP.

[2] According to the criteria set by the Government of Japan at the time.

This volume deals with the transitional phase and the existing exposure situation. Thus, the periods that are covered for both off-site remediation and on-site stabilization and decommissioning are:

— December 2011 to December 2014[3]: Analyses of actions taken by Japan;
— After December 2014: Analyses of the future actions planned by Japan.

There is a period of overlap with Technical Volume 3, which covers the emergency activities. The present volume deals with recovery activities, including those that occurred during the emergency phase.

The actions being undertaken or planned to achieve defined recovery goals are discussed in detail in the following sections:

— Section 5.2: Remediation;
— Section 5.3: On-site stabilization and preparation for decommissioning;
— Section 5.4: Management of contaminated material and waste;
— Section 5.5: Community revitalization and stakeholder engagement.

These sections include observations and lessons related to recovery activities based on international best practices, including the IAEA safety standards and other relevant experience. Many of these lessons are applicable whenever recovery from an accident or other events that disperse radioactive contamination to the environment takes place.

This volume includes an appendix that provides an overview of the pilot demonstration projects for remediation undertaken in Japan. It is also supported by four annexes (included on the CD-ROM attached to this volume):

— Annex I provides an overview of reference levels for remediation and of the development of a comprehensive framework for post-accident recovery.
— Annex II includes information on international best practices for assessing recovery operations.
— Annex III provides an outline of the guidelines on the scope of nuclear damage.
— Annex IV includes a comparative analysis of remediation strategies and experience after the Fukushima Daiichi accident and the Chernobyl accident.

5.1. BACKGROUND TO POST-ACCIDENT RECOVERY

This section provides an overview of the goals for both on-site and off-site recovery following the Fukushima Daiichi accident. It also describes the basis for recovery, including key aspects of the framework for post-accident recovery developed in Japan following the accident, and the nature of international best practice. The section is supported by Annexes I and II, which explore these aspects in more detail.

5.1.1. Goals of recovery

The goals for on-site recovery for the Fukushima Daiichi NPP are, broadly: for each of the damaged reactors to attain a state of stability, with no risk of additional environmental contamination; and for plans and processes for managing the on-site waste and for the eventual decommissioning of the NPP to be established.

[3] In some cases, information on ongoing projects was available for the period up to and including May 2015. This information was included in this volume, where appropriate.

The goal of off-site recovery for people affected by the accident is to reduce radiation doses from the environment that have resulted from the accident and to re-establish an acceptable basis for a fully functioning society in the affected areas. The goal of a return to a condition of normality cannot mean a return to the same situation that existed prior to the accident. It is to be expected that, even after remediation, some constraints on people's ways of life may remain in some specific areas. However, the expectation of recovery is that many aspects of a new normality will be at least equivalent to the pre-accident quality of life, and that, wherever possible, enhancements of lifestyle experiences and values can be achieved.

What is meant specifically by 'normality' is not easily defined, nor will the definition be universally agreed upon. Indicators of a revitalized infrastructure and community will vary between the evacuated and the non-evacuated populations and include factors such as a place to call home, a sense of safety, established community structures, availability of employment, provision of health care and aged care facilities, educational and leisure facilities, stability and the certainty of governing structures, economic well-being, opportunities for farming and local food production, and the involvement of stakeholders in decision making.

A major goal of the post-accident recovery programme is for people in the affected areas to again feel safe living there. It is important to find an answer to the question, 'is it safe?' The difficulty with all attempts to provide objective definitions of what is safe is that they fail to acknowledge and address the additional subjective elements of the question. Within the context of post-accident recovery, the questions confronting the community are:

- What are safe reference levels[4] for off-site remediation?
- What actions should be undertaken at the NPP site to render it safe, including actions to manage the water used to cool fuel within the damaged reactors? What are the safe strategies for storing and disposing of the contaminated accident waste?
- What is the path forward for safe management of the contaminated water stored on-site?

The manner in which the objective and subjective perceptions of safety within the affected communities influence the determination of the relevant recovery criteria, and the importance for stakeholder consultation of being able to answer what is safe, are discussed in detail in Section 5.5.

5.1.2. Basis for recovery

A recovery plan is the collection of management structures and strategies that implement the actions that will achieve the required reduction in radiation exposure, in order to meet recovery criteria. The determination of criteria for post-accident recovery and the planning of the programme and strategies for recovery are closely linked. The conditions in the aftermath of any accident are unlikely to be ideal for developing a comprehensive framework for accident recovery. In particular, there are difficulties in involving stakeholders in determining the recovery criteria and strategies amidst the disruption associated with the immediate aftermath of the accident.

[4] A reference level in "an emergency exposure situation or an existing exposure situation [is] the level of dose, risk or activity concentration above which it is not appropriate to plan to allow exposures to occur and below which the optimization of protection and safety is implemented" [1].

The issues that are vital for recovery, and for which criteria are required, fall broadly into three categories:

(1) Remediation[5] (cleanup) reference levels and derived action levels;
(2) Reactor stabilization and decommissioning plans and actions;
(3) Waste management strategies and disposal options.

For example, in developing a remediation programme, it is necessary to define the level of radiation exposure that is acceptable, as well as a remediation strategy to achieve the required reduction in radiation exposure.

Reference levels are established by the government, the regulatory body or another relevant authority and are used for optimization of protection and safety in existing exposure situations. The reference level is the target for the overall remediation strategy. Individual actions taken in achieving this target are guided by derived remediation action levels [1, 3].

It is important not to set the reference levels too high, which could jeopardize the required safety objective, or too low, which could result in a less than optimal use of limited resources. Guidance on the concept and use of reference levels, and on setting appropriate values, is available from international standards and best practice [1, 4].

The application of reference levels for remediation and the associated development of a framework for post-accident recovery is described in more detail in Annex I. This includes information about the evolution of strategies for recovery adopted following the Fukushima Daiichi accident.

5.1.2.1. International best practice

The general radiation protection principles that underpin the criteria for post-accident recovery are found in international standards and best practice. An overview of the relevant sources of international best practice relevant to post-accident recovery is presented in Annex II, together with the principles that guide the setting of the criteria. In essence, international best practice is derived from relevant IAEA safety standards, past experience and peer analysis. Other sources of international best practice include expert reports by organizations such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the OECD Nuclear Energy Agency (NEA) (The OECD is the Organisation for Economic Co-operation and Development).

This volume includes objective assessments of the recovery programme within the context of international best practice. The summary statements and observations and lessons at the end of each major subsection of this volume present key points that can be taken forward to improve preparedness for post-accident recovery worldwide.

5.1.2.2. Planning and preparedness in Japan for post-accident recovery

Preparedness for post-accident recovery is distinct from emergency preparedness planning. In Japan, prior to the Fukushima Daiichi accident, emergency preparedness was addressed in the Act on Special Measures Concerning Nuclear Emergency Preparedness (hereafter referred to as the Nuclear Emergency Act) [5]. This Act, passed in 1999, prescribes the declaration of a nuclear emergency situation, the establishment of a Nuclear Emergency Response Headquarters (NERHQ) and the implementation of protective actions.

---

[5] The IAEA Safety Glossary defines remediation as “any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans” [2]. It further specifies that “complete removal of the contamination is not implied”.

The basic plan for emergency preparedness called for in the Nuclear Emergency Act establishes the basis for nuclear emergency response in Japan. It defines measures to prevent the occurrence and/or progression of a nuclear accident and to restore the situation in the affected area to its previous condition, to the extent possible, after a nuclear emergency. The Act includes planning for control and termination of an emergency situation, but there was no planning in this Act (or in any other legislation) for post-accident recovery following the termination of the emergency.

Because of the lack of pre-accident planning for post-accident recovery, the Japanese authorities were required, in the immediate aftermath of the Fukushima Daiichi accident, to establish radiation protection criteria, a legislative basis, regulations and planning documents to guide the programme of recovery. As indicated above, the aftermath of an accident is not an ideal time to develop such a comprehensive framework for accident recovery. In particular, it is difficult to involve stakeholders in determining the recovery criteria and strategies at such a time.

5.1.2.3. Planning of stabilization measures and preparation for decommissioning

Prior to the accident, planning for the eventual decommissioning of the Fukushima Daiichi NPP was addressed under the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors (hereafter referred to as Reactor Regulation Act) [6] as established in 1957. Last amended in 2007, this Act also regulated the management of waste at the Fukushima Daiichi NPP following normal decommissioning. The accident at the Fukushima Daiichi NPP, however, has already and will, in the future, produce much larger and more varied kinds of waste than would be anticipated to arise from normal operations.

5.1.2.4. Preparedness for post-accident waste management

Stabilization of a damaged NPP and on-site decontamination and remediation efforts in the surrounding areas result in large quantities of contaminated material and radioactive waste. The management of such material — with its varying physical, chemical and radiological properties — is complex and requires significant efforts.

At the time of the accident, the existing legislation, the Waste Management and Public Cleansing Law [7], enacted in 1970, did not apply to waste that was contaminated with radioactive material (Article 2, Clause 1 of the Act), and there was no other law that regulated the disposal of disaster waste and radioactive contaminated material.

The existing near surface waste disposal facility for radioactive waste from normal operation of NPPs is not available for disposal of radioactive contaminated materials. Similarly, before the accident, there were no plans in place for the management of the large volumes of water contaminated in the process of cooling the fuel in the damaged reactors.

5.2. REMEDIATION

5.2.1. Introduction

The accident at the Fukushima Daiichi NPP resulted in the release of radionuclides to the environment and deposition onto the land and sea. The key radionuclides giving rise to radiation doses in the longer term are radiocaesium isotopes (^{134}Cs and ^{137}Cs), which are present in both the terrestrial and aquatic environments. Because ^{134}Cs decays with a half-life of approximately two years (and ^{137}Cs decays more slowly with a half-life of approximately 30 years), the doses received by people will decline naturally without intervention. The need for remediation therefore depends on the evolution of the doses with time.

The extent and duration of the contamination and the projected additional doses[6] that would be received by people in a specific region need to be assessed as part of the development of a policy and remediation strategy to ensure that people can safely live in the affected areas. This policy and remediation strategy, and the implementation of large scale remediation measures that are efficient, achievable and sustainable, are essential to ensure that the protection of the public is optimized and that radiation doses meet adopted criteria. This overall approach is intended to ensure radiological safety while minimizing negative social, economic and environmental impacts [8].

This section describes the remediation policy and strategy, and their application in Japan after the Fukushima Daiichi accident. It also summarizes the experience of remediation in the areas affected by the accident.

This section concentrates specifically on the period after the emergency phase, and after the associated protective actions considered in Technical Volume 3 had been implemented. Here, remediation is considered as part of the post-accident recovery phase and as relevant to the existing exposure situation [1, 9, 10].

The establishment of a comprehensive framework for remediation following the accident is described. The objectives of remediation, addressing both radiological and non-radiological criteria and national policies, are also outlined. The major exposure pathways are described together with the site characterization that is essential to identify the specific needs for remediation. The manner in which remediation criteria have been applied is also described. The development and testing of remedial actions to identify those most suitable to reduce exposures or dose rates in residential areas, for, agricultural land, forests and selected water bodies are summarized in Appendix I. Based on the testing, the measures implemented and the progress achieved by December 2014 (or until May 2015, where such information was available at the time of writing) are summarized. The remediation approaches in Japan are compared with those that were applied after the Chernobyl accident in Annex IV. The section concludes with a summary and key observations and lessons identified as a consequence of the accident.

The impact of the earthquake and tsunami of 11 March 2011 and the subsequent accident and evacuation of the population for an extended period have meant that normal social and economic activities in the affected areas have ceased and infrastructure has deteriorated in the affected areas. Therefore, the return of people to a normal life and livelihood requires not only remediation to reduce radiation exposure, but also the revitalization of infrastructure. In developing the remediation strategy in Japan, the importance of revitalizing the contaminated areas, by ensuring the development of economic activity and suitable livelihoods, has been emphasized and is discussed in more detail in Section 5.5.

5.2.2. Remediation and exposure pathways

As described in more detail in Technical Volume 4, there are two categories of exposure pathways:

- Internal exposure pathways, where the source of exposure is incorporated into the body, typically by inhalation or ingestion;
- External exposure pathways, where the source of exposure remains outside the body.

Possible internal exposure pathways in a longer term post-accident situation are primarily the ingestion of radionuclides in food and beverages. Inhalation of resuspended radionuclides from soils or sediments is also possible, especially for agricultural or remediation workers.

[6] Additional dose is a measure of dose that excludes the contribution from natural background radiation.

Possible external exposure pathways of most relevance to the long term post-accident situation are exposure from the radionuclides deposited on the ground, on paved residential surfaces (asphalt, concrete, etc.), on building surfaces (walls, roofs and floors), on vegetation (including trees) or on sediments (on the shores of rivers, lakes or the sea).

Currently, the dominant pathway of public exposure is external irradiation from radiocaesium deposited on the ground, paved surfaces, building roofs and walls, trees and other surfaces. The ambient dose rates resulting from the radionuclides in the environment are influenced both by the deposition density of deposited radionuclides on the surfaces and by natural factors, such as the initial attenuation of radiation in soil, the presence of snow cover and the geometrical arrangements of buildings, vegetated and paved areas. External dose rates decline due to physical decay, weathering from surfaces and vertical migration down soil and sediment profiles. The rate at which the latter two processes occur varies for different types of contaminated surfaces and soils.

5.2.2.1. Remediation and internal exposure pathways

In contrast to the situation following the Chernobyl accident, where both external and internal pathways contributed significantly to the total dose, following the Fukushima Daiichi accident, external dose was substantially more important (See Appendix I for more information). Therefore, remediation activities have focused on intensive decontamination of residential areas. Control of internal doses was focused on restrictions and monitoring of food and feed, as well as the remediation of farmland.

As indicated above, the dominant internal exposure pathway in the long term post-accident period is ingestion of foods; inhalation of resuspended material is unlikely to contribute significantly to dose in most circumstances. Radionuclides in soils, sediments and water can transfer through human food chains and lead to internal doses to humans.

Internal doses have been largely prevented by the widespread restrictions on the sale and distribution of contaminated food, supported by a comprehensive monitoring of food items. Agricultural products were intensively inspected, and food items containing contamination above permissible levels were automatically removed from the food market. These procedures are described in more detail in Section 5.2.8. Other reasons that might explain the estimated low internal doses of inhabitants of areas affected by the accident may include:

- The use of agricultural soils with contamination levels above those which could lead to radiocaesium activity concentrations in rice that exceeded permissible levels was prohibited for rice production in 2011.
- The rates of transfer of radiocaesium from soil to crops and animals are generally low. Most of the soil in the accident affected areas (such as gray lowland soil, andosols, brown forest soils and brown lowland soil) is of relatively high fertility and of loamy texture. These soils are characterized by low radiocaesium mobility, with transfer ratios that are about ten times lower than many of the soil types in the areas most affected by the Chernobyl accident.
- The fraction of food products produced locally is not large; the food basket of the population living in the affected areas is composed of many products that come from unaffected areas.
- The use of feed for livestock was controlled to ensure that radiocaesium activity concentrations in food products of animal origin are below the action level, although there were instances in 2011 in which higher levels resulted from the use of contaminated feed (as discussed in Technical Volume 3). In general, dairy cows in the contaminated areas in Japan are housed and do not normally graze on pasture (which is often more contaminated than stored fodder).

5.2.2.2. Remediation and external exposure pathways

External doses received by different population groups depend not only on radionuclide deposition density and the ambient dose rate over flat areas, but also on social and demographic factors. Therefore, data on the fraction of time spent outdoors, the dwelling type (wall material, number of floors, etc.) and the type of production or educational building have been collated to estimate external doses in Japan [11]. The characteristics of the external exposure pathways associated with different areas are introduced below.

Residential areas

The residents of cities and towns located in the areas affected by the accident are exposed to gamma radiation, both indoors and outdoors. Radionuclides deposited on the ground contribute most to the external exposure indoors. However, the contribution of radionuclides deposited on the roof can be substantial, particularly for the top floor of the building. The contribution to external dose of both external and internal walls is usually minor, as is that of other indoor contamination. A substantial fraction of gamma radiation is attenuated by building structures. The ambient dose rate in residential areas is, therefore, much lower than that over large areas of undisturbed contaminated soil.

In Japan, many people (including most people in Fukushima and neighbouring prefectures) spend most of their time indoors, either in residential wooden or plastered houses or buildings associated with industry/work or education [12, 13]. Due to the shielding effect of the building material, the indoor ambient dose rate, as compared to that in open fields, constitutes 40% in wooden houses with one to three floors, 20% in plastered houses with one to three floors and 10% in concrete buildings [11, 14, 15].

In contrast to undisturbed soil, radiocaesium is gradually removed to sewage facilities from most human-made surfaces (asphalt, concrete, tile, etc.) by weathering and human activities, such as traffic. Radionuclides detached from surfaces can also concentrate in various traps (cracks, slots, etc.), forming hot spots, for example, under roof gutters. Hot spots are usually identified by monitoring before remediation activities start and are decontaminated as the first priority. In Japan, the radiocaesium activity on the surface was highest for sites below rainwater gutters or where rainwater collects, followed by gardens, roofs and concrete floors. There were slight differences in these trends depending on the composition and other characteristics of the surfaces [16, 17].

Radiocaesium deposited in parks, on lawns and other areas of unpaved land may contribute to public exposure as well. Such public facilities are generally decontaminated, or dug up, as a priority, especially if they are utilized by children; this was done in Japan as one of the first remediation actions taken in 2011.

Farmland

Radionuclides deposited on farmland can contribute to external exposure of agricultural workers. The ambient dose rate is highest over large undisturbed areas. In this case, gamma radiation comes from a large surrounding area (with a radius up to several tens of metres) especially when there is little lateral migration of radionuclides on flat terrain.

Forests

Radionuclide deposition in forests can result in external exposure of the general public. People visiting forests for recreational purposes are exposed to external gamma radiation from radionuclides deposited on the ground and litter, and contained in bark, branches and the foliage. When contaminated firewood is burnt, the activity concentrations of radiocaesium in the resulting ash are

one to two orders of magnitude higher than in wood. As the ambient dose rate over ash disposal areas can be substantially elevated, the use of firewood affected by radioactive material is restricted. High radiocaesium concentrations have occurred in some ash in Japan after the burning of bark, which then had to be treated as a contaminated material. To avoid the accumulation of highly contaminated ash, large amounts of unprocessed bark are currently being stored. To facilitate treatment of bark, the government is subsidizing the costs of treating damaged products, transportation of bark and temporary storage.

5.2.3. Planning for remediation in Japan after the Fukushima Daiichi accident

Given that external dose from radionuclides deposited on the ground and other surfaces is the main pathway of exposure, the remediation strategy developed in Japan is focused on decontamination[7] activities to reduce the levels of radiocaesium, thereby reducing the potential for such exposures. Internal doses continue to be controlled by restrictions on food, as well as through remediation activities on agricultural land (see Section 5.2.8).

5.2.3.1. Characterization and measurement for remediation planning

Decisions on the need for remediation depend, among other things, on the measured dose rates, activity concentrations on the ground and in other materials, including foods.

Initial decisions on the need for remediation in the existing exposure situation were based on the available information generated in the first year after the accident, including the data on aerial measurements [18]. To support the aerial measurements, various supplementary methods, such as car-borne monitoring, hand-carried monitoring and fixed point monitoring with portable survey meters were applied.

An extensive ground monitoring programme was conducted under the direction of Ministry of Education, Culture, Sports, Science and Technology (MEXT) and with the cooperation of Japan Atomic Energy Agency (JAEA), various universities and research institutes. Extensive surveys giving ambient dose equivalent rates and deposition densities of the gamma emitting radionuclides (^{110m}Ag, ^{129m}Te, ^{131}I, ^{134}Cs and ^{137}Cs) on soil were conducted in June–July 2011 [19, 20], and large scale airborne surveys were performed during the autumn of 2011 (see Fig. 5.2–1). The latter provided the primary input data for the estimation of external exposure at district level in Fukushima Prefecture and the prefectures of Miyagi, Tochigi, Gunma, Ibaraki, Iwate and Chiba [13] used in the planning and implementation of remediation. The estimated area with an annual additional dose greater than 5 mSv was 436 km^2, comprising 51 km^2 of residential areas, 13 km^2 of trunk roads, 349 km^2 of farmland and 23 km^2 of other types of land (forest areas, which comprised 1343 km^2, were not included in this category). If the more heterogeneously contaminated regions with an annual effective dose in the range of 1–5 mSv are also included, the estimated area increases to 642 km^2 (excluding forest).

[7] IAEA Safety Glossary [2] defines decontamination as "the complete or partial removal of [radioactive] contamination by a deliberate physical, chemical or biological process.…This definition is intended to include a wide range of processes for removing contamination from people, equipment and buildings, but to exclude the removal of radionuclides from within the human body or the removal of radionuclides by natural weathering or migration processes, which are not considered to be decontamination." The majority of remediation measures used in Japan involve decontamination. However, in some Japanese documents, the term decontamination includes some remedial actions that do not involve removal of contamination and are focused on the modification of the exposure pathways to humans. Here, the term remediation is used, which covers both decontamination and other measures aimed at reducing doses to individuals.

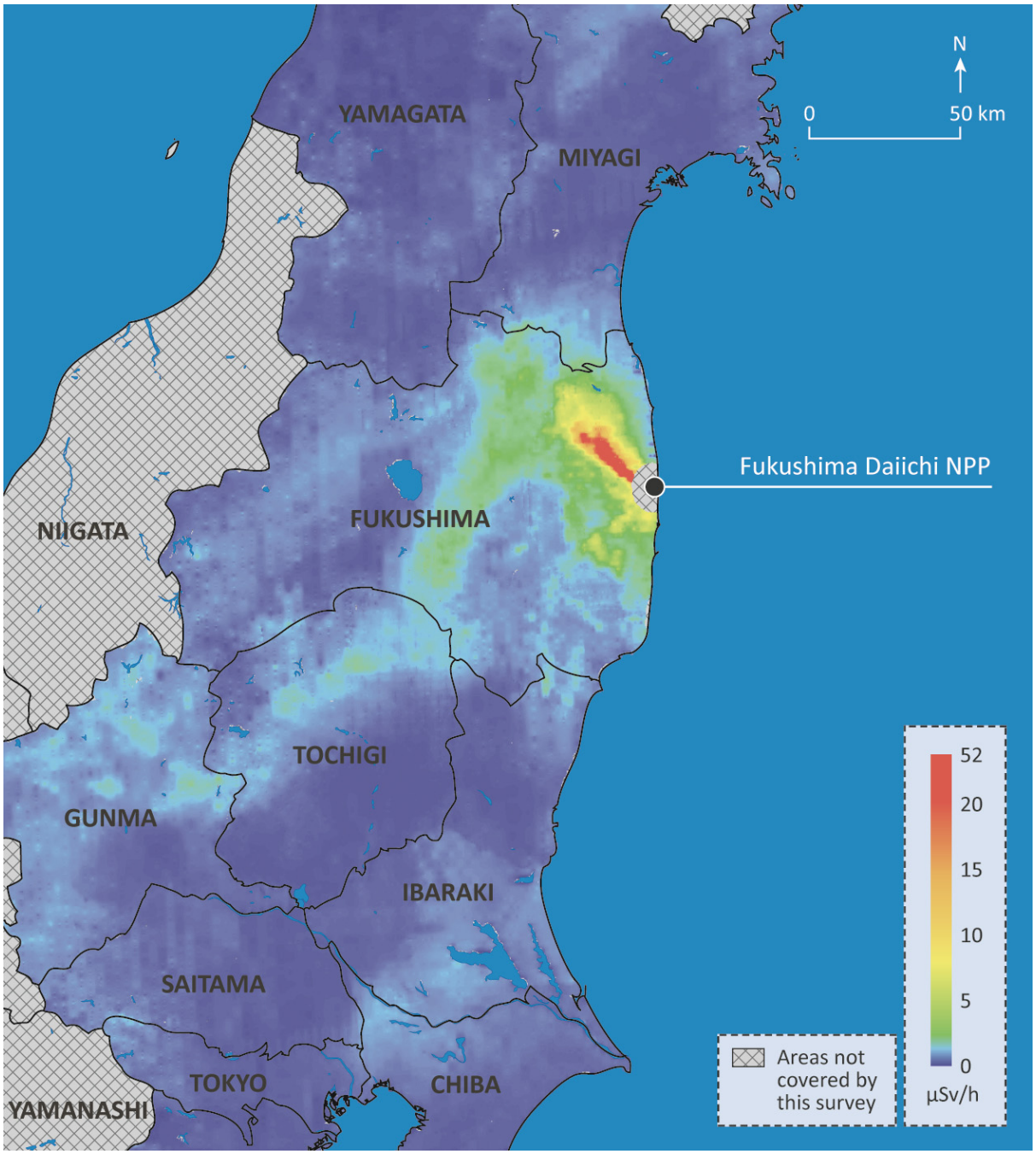


FIG. 5.2–1. Ambient dose rates 1 m above the ground surface (in μSv/h) estimated from an airborne monitoring survey (as of 18 September 2011) [21].

Methods to predict the effectiveness of decontamination were developed and implemented in the highly contaminated areas in the early stages after the accident. In areas identified as requiring remediation, designated according to estimated effective dose, more detailed characterization was carried out, improving the quantity and quality of data with respect to spatial and temporal variation to allow decisions to be made about suitable remediation strategies and plans [19].

Measurements of ambient dose rates have been conducted at different times throughout each year since the Fukushima Daiichi accident using a variety of different techniques [19]. In situ measurements over flat fields have been conducted since December 2011 using a portable germanium detector. Car-borne measurements of the dose rate are carried out using sodium iodide and caesium

iodide detector systems that send data to a central server using a mobile phone network. Survey meters have been distributed to local governments. The range of dose rate and environmental measurements available are also discussed in Technical Volume 4. Based on these measurements, maps of the radionuclide deposition density and ambient dose rates at a series of locations at different times have been produced.

As well as quantifying the spatial variation in radiocaesium deposition, it was important to quantify how the deposition density declines with time. Data on the rates of loss of radiocaesium from different surfaces in Japan are documented and have been updated in Table 5.2–1 [22]. The loss of caesium from surfaces and the resulting reduction of ambient dose rates depends on: (1) land use (for example the decline is faster in urban areas and over water than over forests) and (2) the magnitude of the initial ambient dose rate.

The reduction of ambient dose rates in areas where initial values were <0.23 μSv/h was slower compared with the reduction in areas of >0.23 μSv/h. The potential influence of remediation varied and was not specifically tested in the above studies. However, the ambient dose rate reduction in areas where the ambient dose rate was in the range of 0.5–2.0 μSv/h was rapid, and there was a significant decrease in ambient dose rate observed at some measurement points (open flat areas of about 10 000 m^2) that were close to, or surrounded by, lands which had presumably been remediated or improved followed by decontamination [22].

TABLE 5.2–1. REDUCTION OF AMBIENT DOSE RATES OBTAINED FROM CAR-BORNE SURVEY DATA RECORDED FOUR TIMES BETWEEN JUNE 2011 AND MARCH 2013*

Land use	Number of samples	Half-life for the reduction of ambient dose rates median and range (y)**
Water	78	1.1 (0.49–2.1)
Urban	1659	1.0 (0.4–3.0)
Paddy	899	1.0 (0.43–2.4)
Crop	767	1.2 (0.54–2.7)
Grass	331	1.2 (0.49–2.8)
Deciduous forest	9271	1.4 (0.68–3.2)
Evergreen forest	1726	1.6 (0.78–5.1)
Bare surface	582	1.1 (0.57–2.5)

* The reduction is quantified by the ecological half-lives which were calculated assuming that the ambient dose rate has decreased according to an exponential function with elapsed time (based on, and extending [22, 23]).
** The range is defined by the 5th and 95th percentile of the distribution.

The ambient dose rates above roads have declined faster than those above undisturbed flat fields (see Fig. 5.2–2 [24]). The movement of radiocaesium down the soil profile in undisturbed flat fields occurs owing to processes such as rainfall and bioturbation, but is slow in most soils [25]. In contrast, roads and paved areas are typically disturbed places where radiocaesium deposited on the surface is displaced laterally as a result of human activities. The impact of such human activities is likely to differ between evacuated and non-evacuated areas.

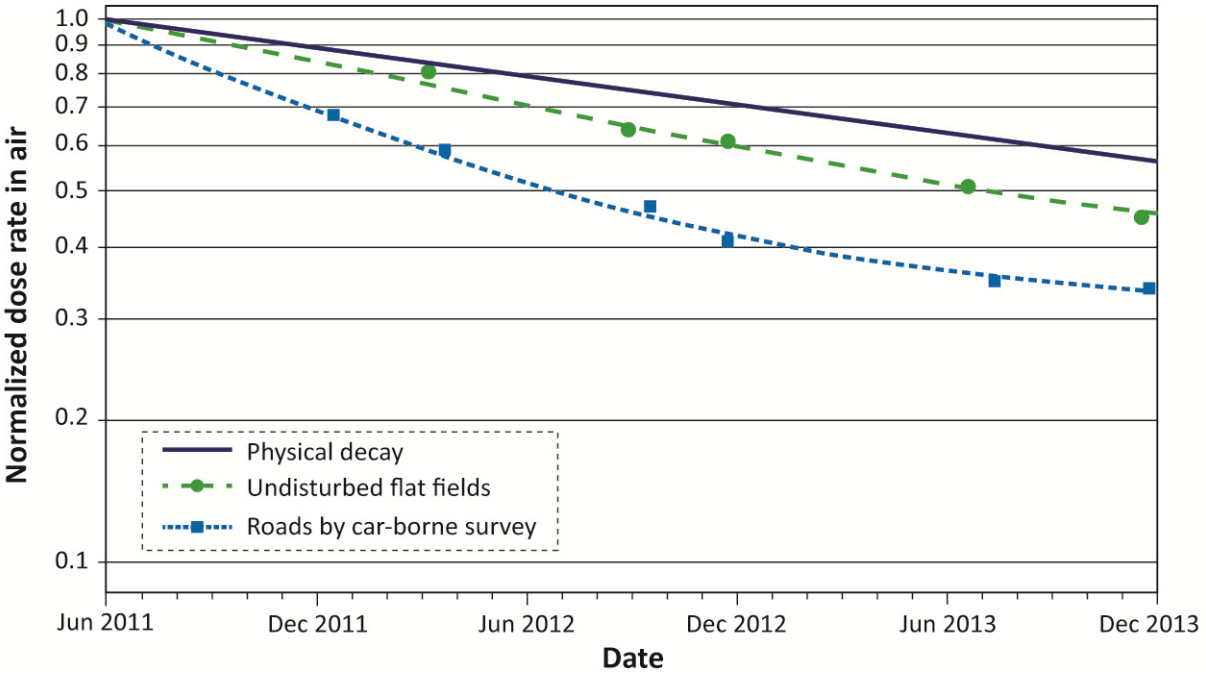


FIG. 5.2–2. Comparison of temporal change over time in the ambient dose rate of physical decay, measurements above roads and above undisturbed fields [24].

Monitoring will ultimately give information on the effectiveness of decontamination. The monitoring strategy will need to be regularly re-evaluated as the situation changes to ensure that remediation is appropriately focused, people are being protected and the remediation strategy is adapted to respond adequately to social considerations.

5.2.3.2. Remediation policies and their development in Japan

IAEA safety standards state that a remediation policy is essential for defining the aims and criteria of remediation [26]. The standards further indicate that policies for environmental remediation should incorporate a set of principles to ensure the safe and efficient management of remediation activities. It is expected that such policies would be established by the national Government. Environmental remediation strategies subsequently lay out the means for achieving the principles and requirements set out in the national policy. Strategies are normally established by the relevant remediation implementer or by the government. Thus, the national policy may lead to the elaboration of several different strategies.

Following the Fukushima Daiichi accident, the Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 [27] (hereafter referred to as the Act on Special Measures Concerning the Handling of Radioactive Pollution) became the main legal instrument to deal with all remediation activities in the affected areas as well as the management of removed materials resulting from the remediation activities. The Act was enacted in August 2011 and took full effect from January 2012.

As decontamination was an urgent issue, the NERHQ established the Basic Policy for Emergency Response on Decontamination Work [28], prior to the Act [27] coming fully into force. The policy permitted the commencement of decontamination in advance of the formal implementation of the Act, and a number of municipalities commenced decontamination work to reduce external doses. This work is described in Section 5.2.5.

Basic principles for environmental remediation based on the Act on Special Measures Concerning the Handling of Radioactive Pollution were published in November 2011, providing an institutional framework to implement remediation activities [29]. The Basic Principles for Environmental Remediation were developed in consultation with relevant ministries and agencies as well as with local authorities.

5.2.3.3. Roles and responsibilities of Japanese organizations

With regard to the responsible organizations, the Act on Special Measures Concerning the Handling of Radioactive Pollution [10] specifies that:

- "The national government shall implement necessary measures in consideration of its social responsibilities associated with the promotional efforts thus far channelled into its nuclear energy policy.
- "Local governments shall carry out their proper role in support of measures by the national government.
- "The relevant nuclear operator shall implement necessary measures in good faith, while cooperating with the national and local governments to implement the measures they have adopted."

In the Japanese administrative system, the national Government, prefectures and municipalities play specific roles in disaster management and environmental protection. The roles and responsibilities of the relevant organizations with respect to remediation since August 2011 are as follows:

- The Nuclear and Industrial Safety Agency (NISA) was the responsible authority in Japan until 19 September 2012, when this role was transferred to the Nuclear Regulation Authority (NRA). The national NERHQ, headed by the Prime Minister and consisting of all the Cabinet members, decides on the overarching policy to respond to the emergency (including the remediation policy). The Support Team for Residents Affected by Nuclear Incidents, under the NERHQ, headed by the Minister of the Ministry of the Environment (MOE) and the Minister of the Ministry of Economy, Trade and Industry (METI), implements the remediation programmes in line with the Decontamination Implementation Policy.
- The Nuclear Safety Commission (NSC) was the responsible authority in Japan until 19 September 2012, when its role was transferred to the NRA. The NSC initially gave advice to the government on technical standards for remediation. With effect from September 2012, this role has been assumed by the NRA. In April 2013, the jurisdiction of radiation monitoring for radioactivity levels, including natural radiation, fallout and so on, was transferred from the MEXT to the NRA, which is responsible for the coordination of activities for monitoring by relevant ministries and other organizations.
- Under the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], MOE is the leading ministry for implementing remediation activities in cooperation with other relevant organizations. MOE is responsible for formulating an implementation policy for off-site remediation activities. In particular, in the Special Decontamination Area (see Section 5.2.4.2), MOE formulates and implements the decontamination implementation plans. It is also responsible for the treatment of contaminated solid waste, including disaster debris and contaminated soil.
- The Ministry of Agriculture, Forestry and Fisheries (MAFF) provides MOE with information on the distribution of radioactive material and technologies for the decontamination of farmlands and forests, which MOE takes into account in formulating a decontamination policy. In addition, MAFF formulates policy about the methods to reduce radioactive material in production processes that are suitable for agricultural and forest products and coordinates fishing policy to ensure distribution of safe fishery products.

— The Ministry of Health, Labour and Welfare (MHLW) is responsible for the formulation and implementation of policy on occupational safety and health (including radiation safety) of workers implementing remediation activities.
— MEXT funds relevant R&D for research institutes, such as the JAEA, which provides technical support for decontamination programmes and monitoring and communicates with local authorities and residents about technical issues.

Fukushima Prefecture assumes the following roles, which are not prescribed in the Act on Special Measures Concerning the Handling of Radioactive Pollution [27]:

— Distribution of resources allocated from the national budget to municipalities in the prefecture;
— Confirmation and management of the progress of decontamination in the municipalities;
— Provision of technical advice to the municipalities;
— Promotion of risk communication in the prefecture;
— Making requests to the national Government as the representative of the municipalities.

Institutional arrangements have been established in Japan to develop policy and implement remediation in the areas affected by the Fukushima Daiichi accident. The national Government, local government (prefectures) and municipalities are involved in the remediation strategy, supported by research organizations that provide technical guidance and other assistance.

In January 2013, a task force was formed, under the Minister for Reconstruction and the Minister for the Environment, to accelerate and integrate decontamination and reconstruction [30]. Decontamination is being carried out jointly by MOE, MAFF and other ministers under the initiative of the Minister for Reconstruction [31, 32]. The aim is to develop measures to achieve the policy goals related to both of these activities, including:

— Simultaneous achievement of remediation of farmland and improvement of agricultural productivity;
— Measures for the decontamination of forests and the development of forestry;
— Promotion of decontamination and reconstruction of infrastructure;
— Expanded use of new technologies for decontamination;
— Consideration of the cost effectiveness of decontamination. [32].

5.2.3.4. Financial provision for remediation

The Act on Special Measures Concerning the Handling of Radioactive Pollution [10] specifies that:

— "The national government shall take measures to finance the costs required for the promotion of measures by local municipalities to deal with contamination by radioactive materials.
— "Measures taken pursuant to this Act shall be considered to be related to damage to be compensated under the Act on Compensation for Nuclear Damage (see Annex III), and are thus to be implemented at the expense of the relevant nuclear operator.
— "Taking its social responsibility into account, the national government shall implement necessary measures to ensure that the relevant nuclear operator makes timely payments to cover the cost of measures taken by local governments etc. under this Act".

The costs associated with the measures taken according to this Act, specifically including decontamination, will be reimbursed by TEPCO. The national Government has allocated the required financing for decontamination and is, therefore, currently paying the associated costs. TEPCO is required to subsequently reimburse the national Government for the costs for decontamination already completed, including those for remediation of the environment. Some of these costs have already been paid by TEPCO.

Remediation costs associated with agricultural production are being paid directly by TEPCO. For example, costs induced by restrictions for food production on contaminated land are paid directly to the farmers by TEPCO as compensation.

The costs associated with remediation up to the end of August 2014 [33] are shown in Table 5.2–2; costs associated with waste disposal are not included. Allowing for an additional 192 billion Yen for decontamination (excluding on-site activities), as requested by the Cabinet Office as reserve funds in the fiscal year (FY) 2011, and taking into account the unused part of the budget in 2011 for remediation only, the total budget is 1487 billion Yen over the four fiscal years since the accident. These values are the budget financed by the Cabinet Office and the MOE for decontamination (excluding on-site activities) and do not include compensation to evacuees. The unit costs of different remediation measures are shown in Section 5.2.4.2.

TABLE 5.2-2. NATIONAL BUDGET RELATED TO OFF-SITE DECONTAMINATION [33]

Item	Budget (billion Yen)	
	Allocated	Unused
FY 2011 third supplementary budget	200	100
FY 2011 reserve funds[a]	192	—
FY 2012	372	13
FY 2013	498	1
FY 2013 [b]/2014	339	—
FY 2015 request	415	—

[a] Additional reserve funds requested by the Cabinet Office.
[b] Supplementary budget.

The total current and future costs of the remediation work in Japan are, and will continue to be, influenced by the policy adopted, the radiological criteria, the intended timescale for implementation and social/cultural aspects.

5.2.4. The remediation strategy and objectives adopted in Japan

In general, a remediation strategy is based on an assessment of environmental radiation sources and exposure pathways that can be modified to reduce public dose. It is a conceptual plan that is a product of the optimization process and includes a set of appropriate remedial measures for which the scale and sequence of their application has also been optimized. A remediation strategy is dependent upon the conditions of the site and the characteristics of the contamination. It can be modified with time as radiological, social or other conditions change. Key features of the remediation strategy adopted in Japan are summarized below.

It was determined that internal exposure to radiation did not play a significant role in the total dose owing to the comprehensive implementation of food restrictions. The remediation efforts were therefore focused on reducing exposures to external radiation. Priority areas for remediation were identified as residential areas, including buildings and gardens, farmland, roads and infrastructure, emphasizing the reduction of external exposures.

The implementation of pilot demonstration projects was a key element of the strategy. Detailed information on these projects is provided in Appendix I. A set of standard operations was developed and applied as full scale decontamination projects, considering contamination level and priority of land use. These projects consisted of experimental or field based activities carried out to identify the

remediation measures that could be considered the most effective and suitable for implementation in Japanese conditions. The information on decontamination techniques obtained during these projects provided the basis for guideline documents, prepared by MOE, to assist municipalities in developing decontamination implementation plans and to decide which remediation measures to apply.

An important element of the strategy adopted was that the national Government and the municipalities decide about the implementation of the remediation approaches that they consider to be most appropriate. It was also decided to conserve the functions of decontaminated entities (houses, farmland, etc.) as much as possible, assuming that they would be used when evacuees return to their original living areas. Topsoil removal was performed and contaminated soil and organic materials that were removed were stored in temporary storage sites. These materials would be subsequently treated and moved to landfill or an interim storage facility depending on their radiocaesium content (see Section 5.4.3).

5.2.4.1. Dose criteria for remediation adopted in Japan

In July 2011, NSC defined the off-site exposure situation to be an existing exposure situation [34]. International recommendations and standards provide guidance on justification and optimization regarding public protection, including implementation of remediation measures [1, 8, 9], as discussed in greater detail in Technical Volume 4, Section 4.3. The Japanese Government based its provisional and long term goals for dose reduction on latest International Commission on Radiological Protection (ICRP) recommendations, in which it recommended dose criteria for such situations (the reference level of annual additional effective dose in the range 1–20 mSv).

The remediation strategy adopted by Japanese authorities was to give the highest priority to the areas in which decontamination is most urgently required from the point of view of human health protection. The remediation strategy was incorporated into the purpose of the Act on Special Measures Concerning the Handling of Radioactive Pollution [27]. In effect, the Act underpinned the remediation strategy for Japan, as it sets out the means for achieving the principles and requirements stated in the national policy.

In accordance with the Basic Principles of the Act, the goals for dose reduction were outlined as follows [29]:

> "In the area where the additional dose is 20 mSv/y or higher, measures shall aim to decrease the size of the area. The following shall be aimed at areas where the additional radiation dose is less than 20 mSv/y:
>
> — To reduce the additional radiation dose to 1 mSv/y or lower over the long term;
> — To reduce the additional annual radiation dose the public is exposed to by around 50% (including the physical attenuation of radioactive materials) by the end of August 2013 from the level at the end of August 2011; and
> — To reduce the additional annual radiation dose affecting children by around 60% (including the physical attenuation of radioactive materials) by the end of August 2013 from the level at the end of August 2011 by decontaminating the living environment of children, such as schools, playgrounds, etc., on a priority basis, since it is crucial to recover the environment under which children can live safely and securely.
>
> "These targets shall be reviewed from time to time based on the effects of measures for the decontamination of the soil, etc. and so forth."

A report of the working group on risk management of low dose exposure [35] stated:

> "For example, the government's policy regarding its announced measures for decontamination aims at a situation in which additional radiation doses on an annualized basis for the general public are reduced around 50% by the end of August 2013, compared with the figures at the end of August 2011, including physical decay of radioactive substances, setting the long-term target for additional exposure doses at a level of no more than 1 mSv per year. For residents in areas estimated to have exposure levels at 20 mSv per year, this policy would mean reduction in radiation exposure to an annual 10 mSv in two-year period, which could be considered an intermediate reference level. Moreover, even after such targets are attained, it would be necessary to continue making stepwise progress in decontamination efforts, leading to possible targets of the further halving of exposure doses, for example (at that point, 5 mSv per year for areas with annual exposure to residents of 10 mSv)."

The above approach had not been implemented at the time of writing.

An upper level for the additional annual effective dose of 20 mSv from external pathways was initially applied in 2011, and corresponds to a conservatively derived ambient dose equivalent rate[8] of 3.8 μSv/h (radionuclide decay is not taken into account).[9] The action level of the ambient dose rate for remediation was initially established by Japanese authorities as being equal to 3.8 μSv/h in connection with the start of the educational year at schools and universities (in April 2011). The additional dose excludes contributions from natural background radiation.

From the end of May 2011, the action level applied to decontamination of schools and their surrounding areas was reduced to 1 μSv/h. From autumn 2011, the associated lower dose rate criterion of 0.23 μSv/h (including 0.04 μSv/h of the background dose rate) was derived from the selected long term criterion of an additional annual effective dose of 1 mSv. The dose rate was based on the lowest reference level of 1 mSv annual effective dose from the range of 1–20 mSv recommended by the ICRP for protection of the public in existing exposure situations [8, 9] and adopted in the revised international Basic Safety Standards (GSR Part 3) [1].

The value of 0.23 μSv/h was applied to identify areas where the additional annual external dose to a resident could exceed 1 mSv. The initial identification of such areas was applied for one year, from the autumn of 2011, without taking into account the reduction in dose rates due to the radioactive decay of radiocaesium. In 2011 and 2012, and afterwards, much more detailed survey data were acquired, and local dose rate measurements were used for decontamination planning and management.

In December 2011, the Government of Japan declared that a cold shutdown state had been achieved and that an existing exposure situation existed that was in accordance with the classification given in the international Basic Safety Standards [1]. The lowest value in the ICRP recommended range of 1-20 mSv/y was selected as a reference value to trigger the implementation of remedial actions, including decontamination of public and commercial facilities, residences, farmlands, roads and forested areas within 20 m of the living environment.

The use of different methodologies to estimate doses to the population has obvious implications for decisions on the remediation of the affected areas and on the potential return of the inhabitants to the SDA. A more recent assessment [13] has shown that the conservative model that was used may

---

[8] Referred to as ambient dose rate (μSv/h) in many Japanese documents and this term is also used in this volume.

[9] The ambient dose rate of 3.8 μSv/h was conservatively derived from an annual dose of 20 mSv by use of an occupancy factor of two thirds in a wooden house that provides a shielding factor of 0.4.

substantially overestimate the annual dose to both typical and representative persons[10], comprising outdoor workers. A highly conservative approach has the benefit of ensuring enhanced protection to members of the public. However, it prolongs the period of evacuation (or relocation) and increases the need for remedial measures to be applied, with a corresponding increase in required resources.

Workers involved in remediation activities (e.g. decontamination) of areas affected by an accident are subject to the relevant requirements for occupational exposure in planned exposure situations [1]. The dose limits to be applied consist of an effective dose of 20 mSv/y averaged over 5 consecutive years (100 mSv in 5 years), and of 50 mSv in any single year. The Japanese authorities adopted these values to control the exposures of workers involved in remediation activities after the Fukushima Daiichi accident. Nevertheless, doses to workers undertaking remediation activities are, if at all feasible, kept below the maximum single year dose limit for occupational exposure [37, 38].

5.2.4.2. Designation of areas to be remediated

According to the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], the estimates of effective dose to individuals used to define the designated areas were deliberately conservative. The contaminated areas were arranged into two categories, based on the additional annual effective dose estimated in autumn of 2011:

- **Special Decontamination Area (SDA)** (Fig. 5.2–3). This area overlaps the former restricted areas, i.e. the evacuation zone within a 20 km radius of the Fukushima Daiichi NPP, and the former Deliberate Evacuation Areas, which are situated beyond the 20 km radius from the plant where the additional annual dose for individuals could reach 20 mSv in the first year after the accident. Within the Special Decontamination Area, the national Government has the responsibility of formulating and effecting remediation plans.
- **Intensive Contamination Survey Area (ICSA)** (Fig. 5.2–3). This area includes those municipalities where the additional radiation dose in the first year was estimated to be between 1 and 20 mSv for individuals in some parts of the municipality. A gamma dose rate of 0.23 μSv/h corresponds to a conservatively estimated additional effective dose of 1 mSv in one year (see Section 5.2.4.1). Municipalities conduct monitoring surveys to identify areas requiring decontamination implementation plans and implement remediation activities in these areas, with the national Government providing financial and technical support to facilitate remediation.

The SDA incorporates land in 11 municipalities. The area includes all of Naraha Town, Tomioka Town, Okuma Town, Futaba Town, Namie Town, Katsurao Village and Iitate Village, and parts of Tamura City, Minamisoma City, Kawamata Town and Kawauchi Village municipalities.

In the ICSA, the organizations responsible for undertaking remediation measures for different types of land are as follows [27]:

- Land under national control: national Government;
- Land under prefectural control: prefecture;
- Land under municipal control: municipality;
- Land under independent control managed by a person or entity under an Ordinance from MOE: the independent administrative agency;
- Other land: municipality.

[10] The representative person is "an individual receiving a dose that is representative of the doses to the more highly exposed individuals in the population" [36]. The most exposed group identified from Japanese census data for 2010 are likely to be outdoor workers living in 1–3-storey wooden houses (about 10% of the population).

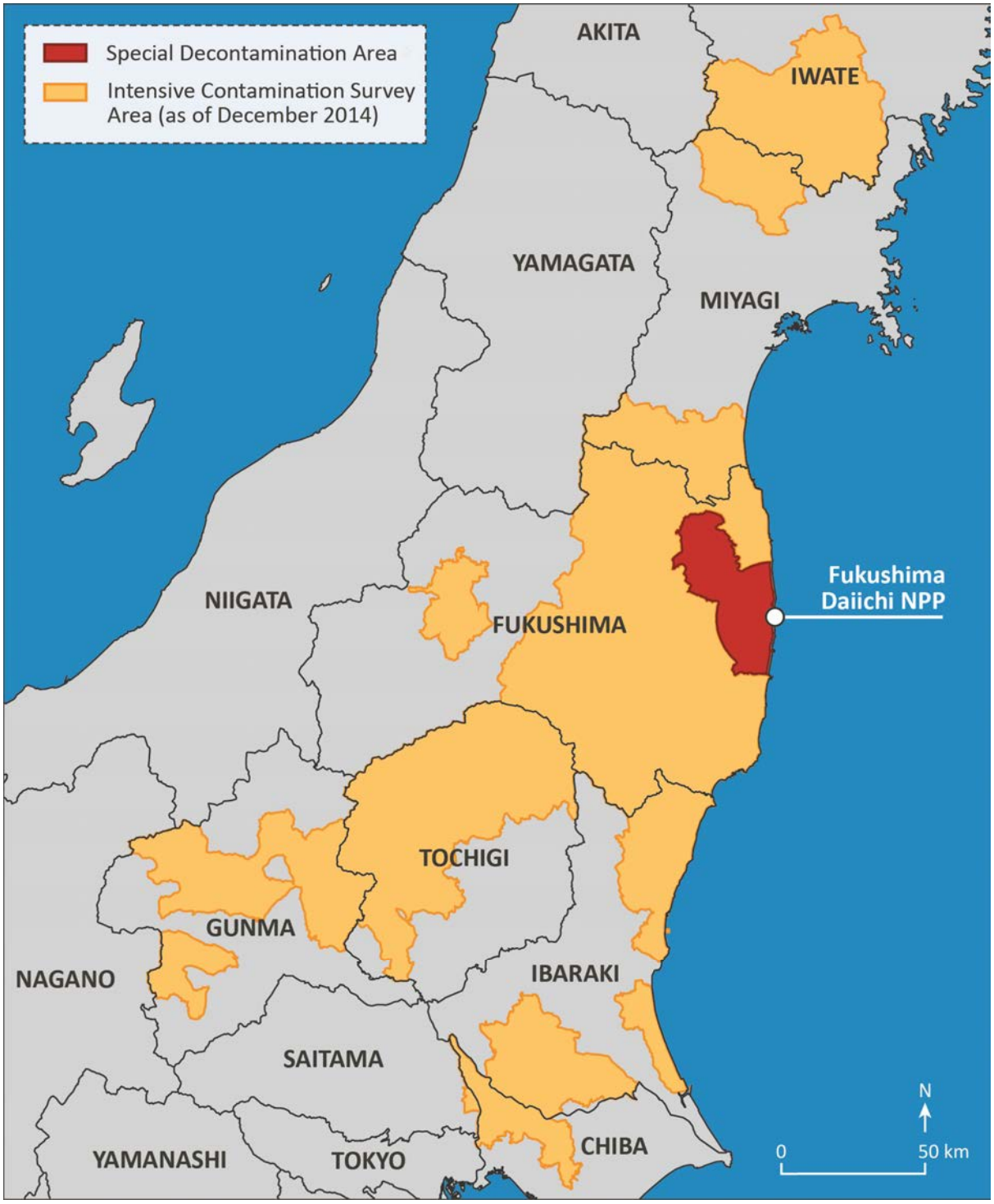


FIG. 5.2–3. The SDA and the ICSA

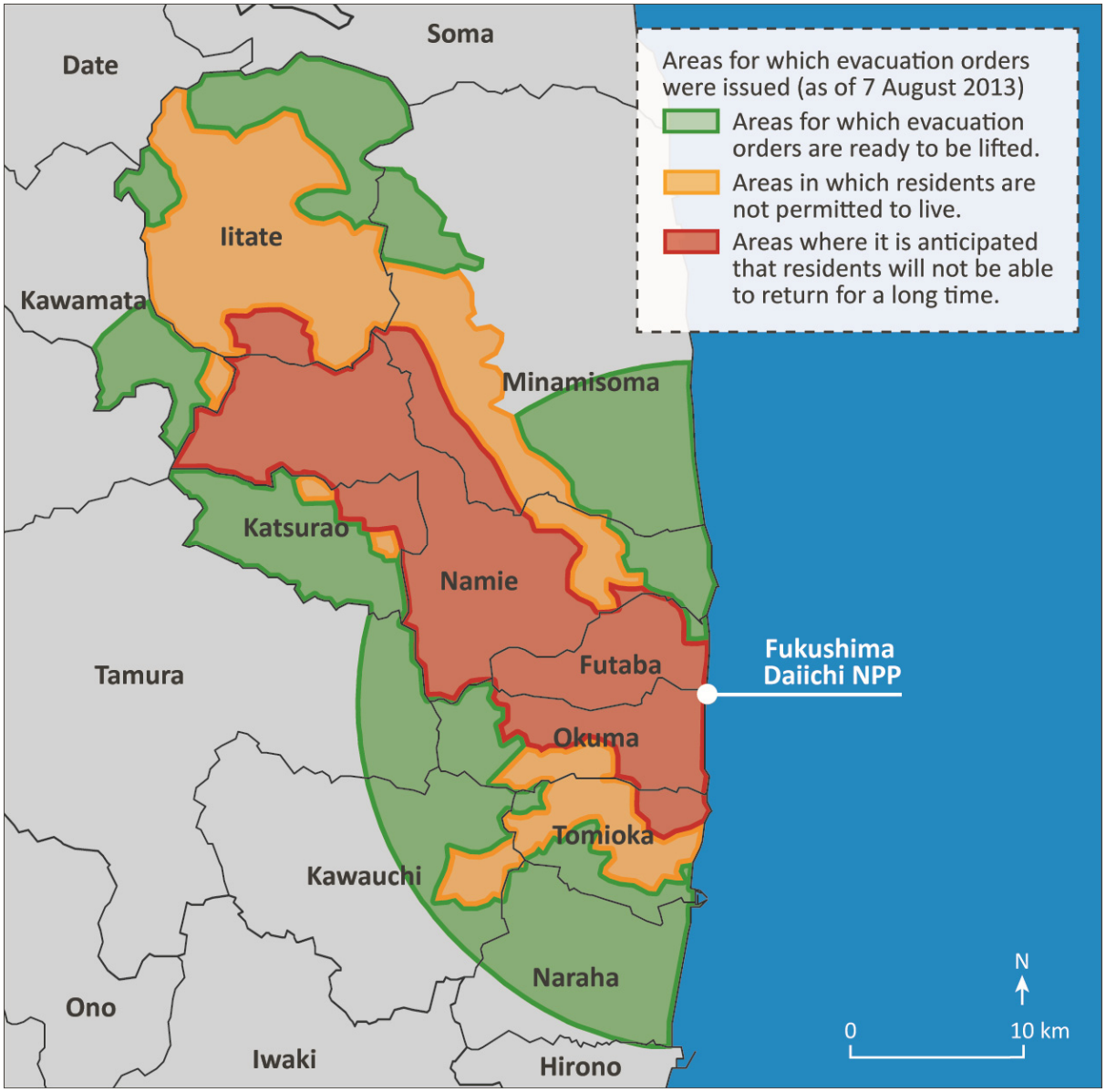


FIG. 5.2–4. The sub-division of the evacuation zone (as of 7 August 2013) [39].

The evacuation areas were rearranged into three categories (see Fig. 5.2–4), based on a decision of the NERHQ in December 2011, according to the cumulative dose in one year (calculated to 31 March 2012) estimated from the ambient dose rates. The categories were specified as follows:

— **Area 1 (SDA 1) (Green).** The area for which evacuation orders are ready to be lifted. The estimated annual dose is above 1 mSv and below 20 mSv.
— **Area 2 (SDA 2) (Yellow).** The area in which residents are not permitted to live. The estimated annual dose is between 20 mSv and 50 mSv.
— **Area 3 (SDA 3) (Red).** The area where it is anticipated that residents will will not be able to return for a long time. The estimated annual dose level is over 50 mSv and the annual effective dose is expected to be more than 20 mSv over a period of six years after the accident.

In SDA 1 and the ICSA, the goal was to reduce the radiation dose of resident adults and children over a two year period by 50% and 60%, respectively, by August 2013. The decline in the ambient dose rate as a consequence of physical decay and natural processes (e.g. weathering) over this period was

about 40%, assuming a ratio of ^{134}Cs:^{137}Cs of 1:1 as of 11 March 2011. In SDA 1, supportive actions for restoring and re-establishing the areas — such as decontamination, restoring infrastructure and employment measures — are being implemented for the early return of residents. For all areas where the estimated additional annual dose was between 1 and 20 mSv, large scale surface decontamination was planned for relatively high dose rate areas, whereas in other, less contaminated areas, intensive decontamination was limited to hot spots such as road ditches and gutters.

In areas where the estimated annual effective dose to people was 20–50 mSv (SDA 2), the goal was to reduce the annual effective dose in residential areas and farmland to less than 20 mSv. Certain measures, such as decontamination or infrastructure restoration, are being conducted according to the plan for the return of residents and the rebuilding of their communities.

In areas where the estimated annual effective dose to people was more than 50 mSv (SDA 3), actions to be taken are being considered through dialogue with local governments and residents. These actions include providing the best possible living environment for residents facing prolonged evacuation, rebuilding their livelihoods and sustaining the functions of municipal governments. Remediation is being implemented, together with testing and evaluation of remediation techniques. Technical details arising from these demonstration projects will guide the implementation of remediation measures in these areas.

5.2.4.3. Predicting trends in external doses

External dose rates decline due to physical decay, weathering from surfaces and vertical migration down soil and sediment profiles. The rate at which the latter two processes occur varies for different types of contaminated surface and soil. Remediation decision making generally involves an assessment of future doses following and in the absence of remedial actions. It is therefore helpful to be able to make predictions regarding the variation in external dose rates, and doses to defined groups of the population, with time. It is possible to use information gathered following the Chernobyl accident [40] to infer trends in the mid to long term. The fractional decline in external dose rates, inferred from data measured in the Russian Federation and Europe following the Chernobyl accident [38] is illustrated in Fig. 5.2–5 for the period 2012–2015. This figure demonstrates that, on average, the external dose to the public would be projected to decline by a factor about four without remediation.

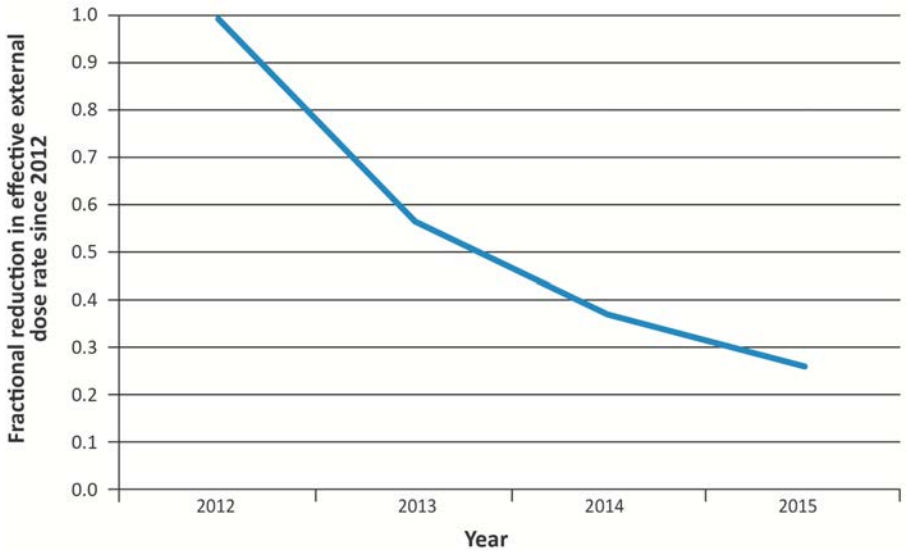


FIG. 5.2–5. Changes with time, relative to 2012, in the effective dose from external exposure to the representative person due to gamma emitting radionuclides.

For the purposes of comparison, the district average annual dose to a representative person in the first few years following the accident was estimated on the basis of deposition and dose rate information measured during the first year, using the methodology presented in Appendix C of the UNSCEAR report [13].

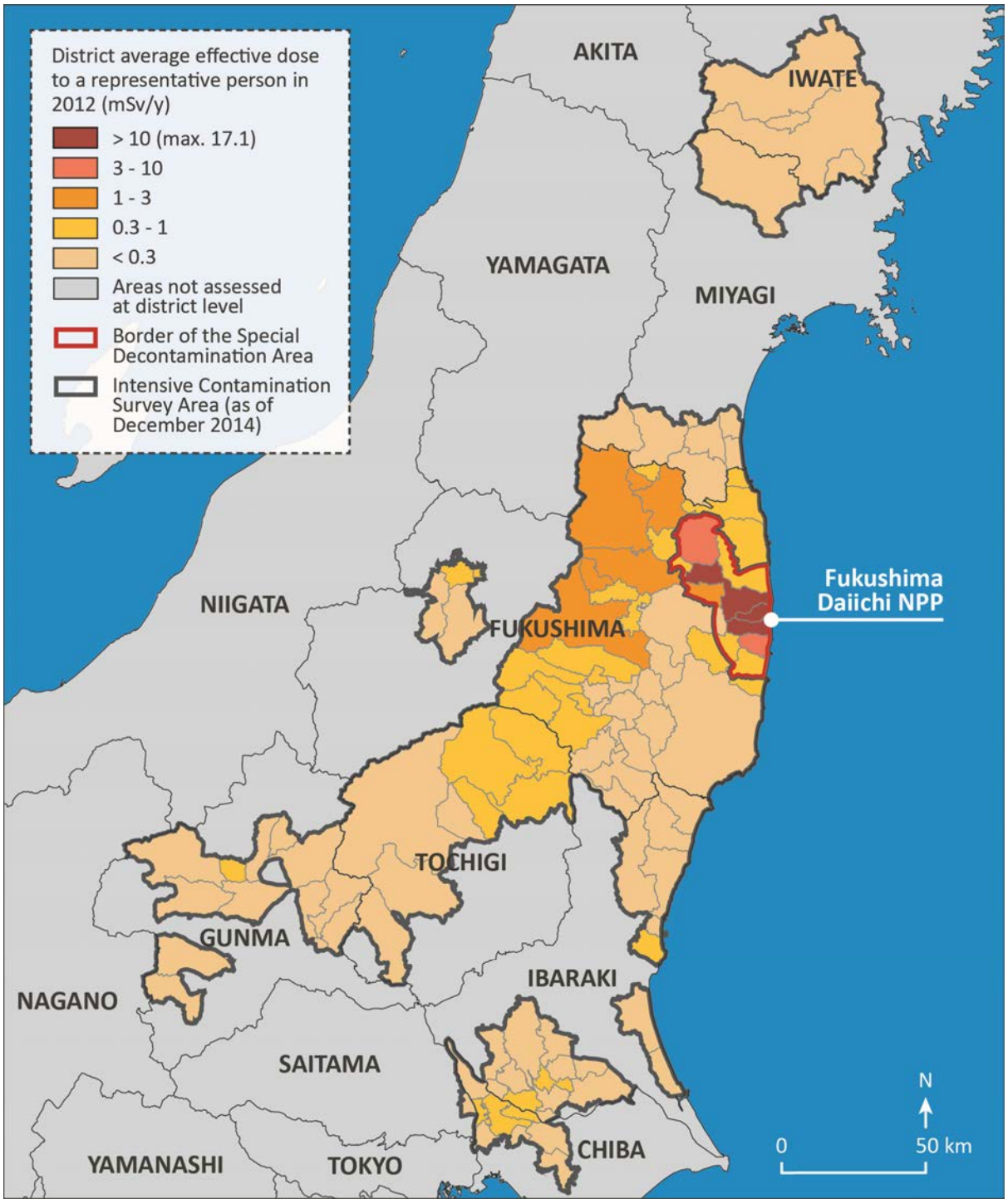


FIG. 5.2–6. Map showing the designation of the Special Decontamination Area and the ICSA (as of December 2014) [41]. Estimated district-average effective doses of a representative person in 2012 are provided based on the methodology used by UNSCEAR (See Section 5.2.6) [13, 40].

The external doses from deposited material were assessed on the basis of measurements of the deposition density of radionuclides measured in June–July 2011, when soil was sampled on a 2 × 2 km grid within 80 km of the Fukushima Daiichi NPP and on a 10 × 10 km grid up to a distance of 100 km and over Fukushima Prefecture. The ambient dose rates were then estimated for given locations and the weighted values for typical locations within settlements were determined. The dose rates experienced by the population were then estimated by using dimensionless occupancy factors. The external effective doses to a representative person (outdoor worker living in a wooden house) for 2012, inferred from district average dose rate data measured in 2011, are plotted in Fig. 5.2–6 [13, 41, 42]. These differ substantially from those produced by the Japanese authorities, which formed the basis for classifying the ICSA and SDA areas in December 2011. On the basis of this approach, the maximum district average annual dose to the representative person in 2012 would not exceed 20 mSv, a value that is five times lower than the highest dose estimated by the Japanese authorities.

5.2.5. Procedures for implementation of remediation

The pilot demonstration projects were experimental or field based projects carried out in 2011 to identify the remediation measures that are most effective and suitable for implementation in Japanese conditions. A variety of factors led to the decision to test the measures in Japan, including: (1) the need to access the effectiveness and applicability of remediation solutions to the site specific conditions prevailing in Japan; (2) the lack of experience in Japan in dealing with the remediation of large areas affected by this kind of accident, including inhabited areas; (3) the need to collect information on site specific data on effectiveness in dose rate reduction associated with individual remediation measures; and (4) the need to test and train the work force on the use of different equipment to be used in remedial work, with a focus on ensuring worker safety.

The Japanese authorities were also aware, and made a critical assessment of, the wide range of remedial measures that have been developed, tested and implemented in the remediation of legacy sites and areas contaminated by nuclear and radiological accidents, notably the accidents in Kyshtym, Chernobyl and Goiânia [42-48]. Aspects related to the effectiveness of remediation measures in terms of dose reduction, technical feasibility, cost, public acceptance, worker safety, operational safety and long term environmental protection were particularly scrutinized.

The range of activities described in Appendix I shows that the implementation of remediation was supported by an extensive research programme in Japan to test and develop appropriate remediation technologies for the contaminated areas. Within these pilot demonstration projects, remediation measures to be potentially applied in residential areas, on roads and in forests were tested with regard to their effectiveness in reducing surface contamination and resulting gamma dose rates. Those measures included a variety of cleaning procedures for roofs, walls and roads, removal of vegetation, litter and topsoil and pruning trees. For agricultural areas, in order to reduce activity levels in the agricultural products, the effect of ploughing, soil treatment and the enhanced application of fertilizer was tested. The results of the demonstration projects are described in detail in Appendix I.

The results of the pilot projects were used for selection and optimization of remediation technologies implemented in the SDA and ICSA.

A set of guideline documents was prepared by MOE and MAFF to assist municipalities to develop their decontamination implementation plans and decide which remediation measures they wished to apply. Most, but not all, remediation procedures involve decontamination of residential areas and removal of topsoil. Decontamination was highly labour intensive, as the areas to be remediated included many surfaces that were irregular and not suitable for the use of mechanized equipment.

5.2.5.1. The Decontamination Guidelines

The Decontamination Guidelines were initially provided by MOE in 2011 and revised in 2013 [49]. The documents provide technical information on carrying out decontamination measures based on demonstration projects and international experience. They constitute a reference source for defining and implementing decontamination projects.

The documents include guidelines on:

— Methods of investigating and measuring the status of environmental radioactivity in the ICSA;
— Decontamination and other remediation measures;
— Collection, transportation and storage of removed soil and other contaminated material.

Remediation measures implemented in contaminated areas are shown in Table 5.2–3. The table lists those remediation measures that have been most commonly implemented in Japan since the accident.

TABLE 5.2–3. COMMONLY IMPLEMENTED REMEDIATION MEASURES [31, 49]

Target	Remediation measures
Houses, buildings	Removal of deposits from the roof, gutters and any decking Wiping roofs and walls Vacuum sanding High pressure washing
Schoolyards, gardens and parks	Topsoil removal Weed/grass/pasture removal
Roads	Removal of deposits in ditches High pressure washing
Gardens and trees	Mowing Removal of fallen leaves Removal of topsoil High pressure washing Paring of fruit trees
Farmlands	Tillage reversal Topsoil removal Soil treatment (e.g. enhanced application of fertilizer) Soil hardening and removal Weed/grass/pasture removal
Animal production	Control of radiocaesium levels in animal feed
Forests and woodland	Removal of fallen leaves and lower twigs Pruning

5.2.5.2. Contract implementation and associated costs

Municipalities and the national Government have appointed contractors to implement remediation. For the national Government contracts, the tender notice is issued in both Japanese and English and is not limited to domestic companies. However, up to the end of 2014, only Japanese companies had received contracts for remediation. The contractors have a responsibility to measure and report the dose rate reduction achieved in the area where the decontamination measures are controlled directly by the national Government. For remediation carried out for municipalities, photographs of the work are taken, the site is inspected and the fulfilment of contracted work confirmed. The remediation costs for the SDAs are given in Table 5.2–4.

TABLE 5.2–4. UNIT PRICES FOR DECONTAMINATION IN THE SDAs DIRECTLY CONTROLLED BY THE NATIONAL GOVERNMENT [50]

Decontamination target	Unit price for decontamination (Yen/m^2)
Residential areas	4300
Schools	3600
Parks	5500
Roads	1700
Agricultural arable land	1500
Grass fields, lawn, pastures	1100
Orchards	2600
Forests	1100

The contractors who are implementing the major decontamination work have gained considerable experience on the ground, and their improved understanding of ways to enhance effectiveness and in developing further innovations is being captured. The web site Decontamination Technology Options eXploration [51] provides information on new decontamination measures developed by companies, including registered technology related to decontamination that has been evaluated by experts using information related to effectiveness, cost and efficiency. The web site promotes the use of new technologies for decontamination and cooperation between developers and implementers to improve procedures.

5.2.5.3. Implementation for different targets

Large scale decontamination work is in progress at numerous locations in both the ICSA and SDAs 1 and 2 (see Fig. 5.2–7).

Residential areas

The vast majority of remediation measures implemented involve decontamination and are aimed at reducing external doses to people in residential areas. Monitoring data are used to define the surfaces that need to be decontaminated. The main targets are topsoil and pavements, but also building roofs when deemed necessary. Decontamination of various surfaces is carried out using a unified scheme involving several different measures.

Topsoil removal has focused largely on private gardens in inhabited and previously inhabited areas (including farmsteads) to ensure the reduction of dose rate. It is aimed at the reduction of the external dose by removal of radioactive contamination. This also reduces the internal dose through the consumption of privately grown food.

In contrast to the situation after the Chernobyl accident, topsoil removal of residential gardens has been implemented widely in Japan. The differences in approaches following the two accidents reflect the specific situations but also provide an example of how the advantages and disadvantages of a remediation action may be valued differently in different countries. The importance attached to the high logistical requirements and waste disposal costs associated with topsoil removal varies between countries. The decision on whether to carry out topsoil removal and other remediation procedures needs to reflect a balance of many factors including:

— Achievable averted doses;
— Cost;

— Availability of suitable alternative remediation measures;
— Attachment of the local communities to their land and the availability and economic value of agricultural land;
— Importance of maintaining consumer confidence in food produced in the contaminated areas;
— Availability of disposal sites;
— Social and cultural perspectives.

Agricultural areas

MAFF has provided handbooks on technologies to remove radioactive material from farmland soil [52] and technical guidelines on decontamination measures based on pilot projects [53]. It has also provided technical guidelines for removing and preventing the spread of radioactive material in forests (March 2012) [54]. A manual for workers is in preparation, which will give information on doses received for all remedial measures.

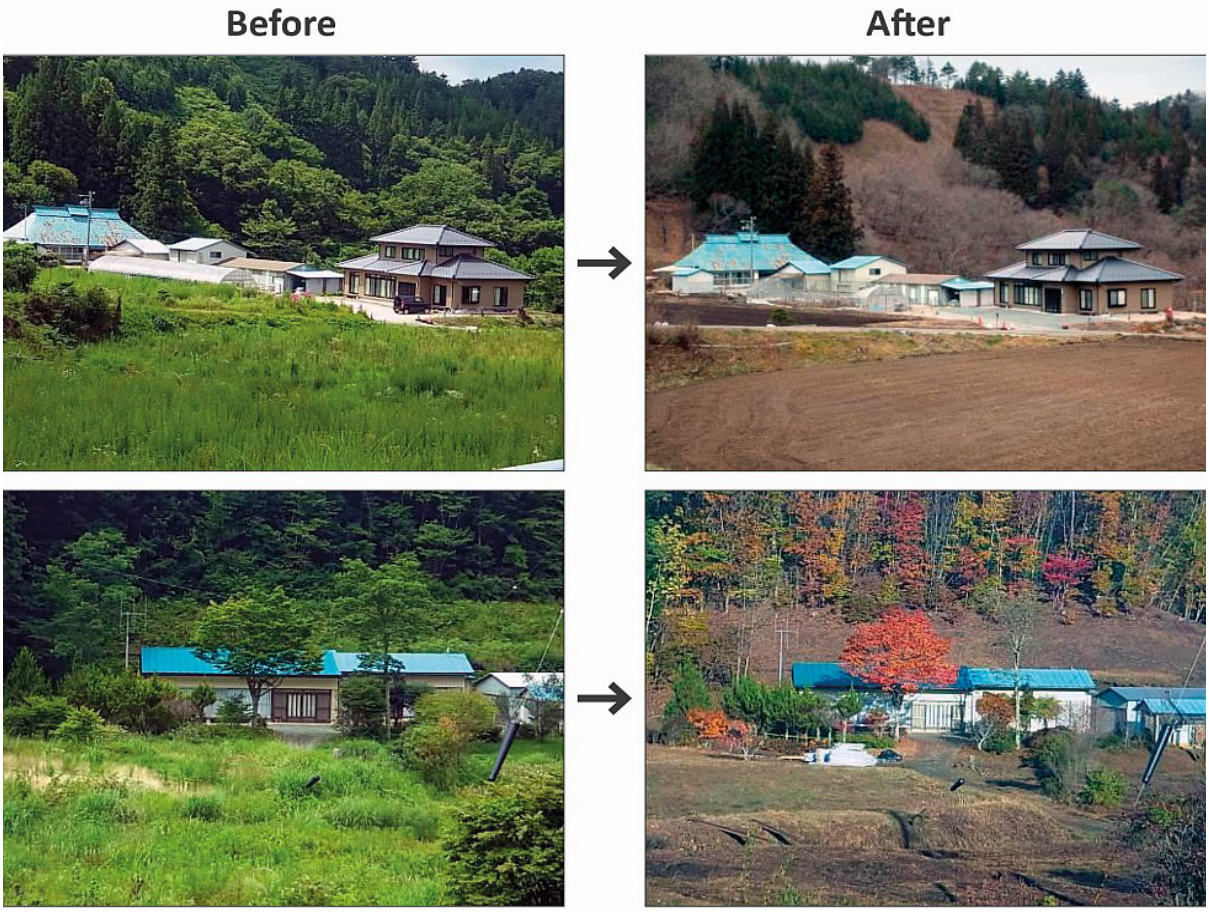


FIG. 5.2–7. Landscapes before and after remediation in Tamura City (Photographs courtesy of the Ministry of the Environment).

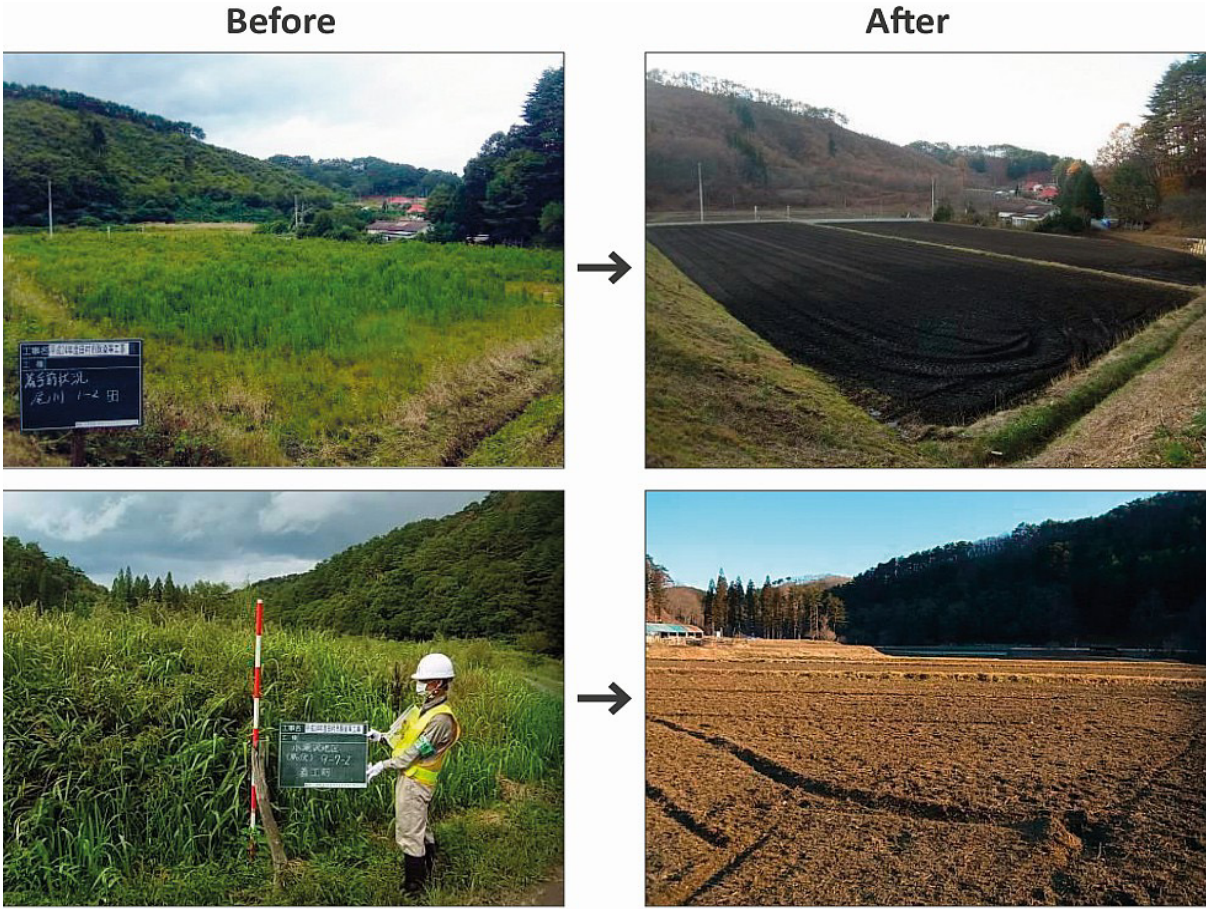


FIG. 5.2–7. Landscapes before and after remediation in Tamura City (Photographs courtesy of the Ministry of the Environment) (cont.).

The major types of remediation applied to farmland, applicable to both the ICSA and SDA, depend on the extent of radiocaesium contamination. The scheme used to determine the applicability of the measures is shown in Table 5.2–5. Remediation measures for each area of farmland are selected on a case by case basis, taking into account the farmer's preference.

TABLE 5.2–5. SCHEME FOR APPLICABILITY OF REMEDIATION MEASURES TO REDUCE BOTH INTERNAL AND EXTERNAL DOSE FROM UTILIZATION OF FARMLAND [31]

Applicable techniques	Radiocaesium activity concentration in soil (Bq/kg dry weight)			
	<5000	5000–10 000	10 000–25 000	>25 000
Cultivation with reduced transfer of ^{134}Cs and ^{137}Cs using potassium, fertilizer	✓			
Reversal tillage (fields, rice paddies, grassland)	✓	✓		
Soil suspension in waste and/removal with extracted water (rice paddies)		✓		
Topsoil removal (fields, rice paddies, grassland)		✓	✓	
Soil removal using a solidification agent		✓	✓	✓
Weed/grass/pasture removal		✓	✓	✓

Fruit trees are decontaminated by high pressure washing and whittling (paring shavings from wood) of tree surfaces to remove radiocaesium.

In the ICSA, agricultural remediation measures have been applied to produce safe foods without topsoil removal. This has been achieved by taking account of the natural processes leading to reduced availability of radiocaesium to crops and the close correlation between potassium status and radiocaesium uptake. This approach has the added benefit of conserving the nutrients in the soil and reducing the amount of contaminated soil.

Forests

Decontamination of forests surrounding residential areas to reduce the dose rate at nearby houses (Fig. 5.2–8) is generally limited to forest areas within 20 m of the residential area. The area of decontamination can be exceptionally extended beyond 20 m when the following two conditions are met:

— The place of residence is surrounded by forest, and the dose at the place of residence is higher than neighbouring average doses even after decontamination.
— The ambient dose rate at 20 m beyond the edge of the forest is considerably higher (two or three times) than the dose rate within 20 m of the edge of the forest before the decontamination [55].

Decontamination techniques similar to those recommended for forest surrounding residential areas were also considered for areas used for cultivating mushrooms if production was expected to continue.



FIG. 5.2–8. Remediation of forests around residential areas.

Aquatic ecosystems

The contaminated sediments of rivers and lakes do not generally have an impact on the ambient dose rate of the surrounding environment owing to the radiation shielding effect of water. Consequently,

decontamination will only be implemented where there is the possibility of the shielding becoming ineffective owing to the water drying up, and the ambient dose rate at the surrounding living environment is significantly increased. Continuous monitoring, and associated R&D, will be conducted to better understand the environmental behaviour of caesium throughout the entire river basin.

5.2.5.4. Generation of contaminated material

In both evacuated and currently inhabited areas, decontamination produces substantial amounts of contaminated material with elevated radiocaesium activity concentrations. Prior to remediation, each municipality was required to identify sites for temporary storage, which are intended to be used prior to the removal of the contaminated material to the interim storage facility (see Section 5.4). The need to identify such sites has been challenging in many municipalities owing to the concerns of land owners and logistical constraints in gaining consent, as many owners were evacuated and relocated to distant areas of Japan.

The storage and disposal of the radioactively contaminated material generated following remediation is a key challenge. Some of the contaminated material that was removed is being temporarily stored in covered piles in weatherproof sandbags or waterproof bags or containers near the decontaminated sites (Fig. 5.2–9(a)) before being transported to temporary storage sites (Fig. 5.2–9(b)).



(a) *(b)*

FIG. 5.2–9. (a) Bags of soil and other organic material after decontamination awaiting transit to the temporary storage area in Tamura municipality in October 2013; (b) Temporary storage sites in Date City. (Photographs courtesy of" B. Howard, Centre for Ecology & Hydrology and M. Balonov, St Petersburg Institute of Radiation Hygiene).

5.2.5.5. Effectiveness of the implementation of remediation

The effectiveness of decontamination is generally expressed in terms of a decontamination factor (DF)[11]. In this report, two variants on this factor are discussed. According to contractor reports, ambient dose rates in the vicinity of dwellings were usually reduced by a decontamination factor (DF_a)[12] of 1.5–2; the DF_a achieved for large areas (such as soccer fields) was about 10. A reduction in

[11] The IAEA Safety Glossary defines the DF as "the ratio of the activity per unit area (or per unit mass or volume) before a particular decontamination technique is applied to the activity per unit area (or per unit mass or volume) after application of the technique" [2].

[12] Decontamination factor (DF_a) is defined as the ratio between the ambient dose rate 1 metre above the ground before and after decontamination. For more detailed information, see Appendix I.

individual doses to residents has been observed. However, the decontamination efficiency in terms of reduction of annual external effective dose of residents has not been comprehensively assessed.

The DF_s [13] and DF_a achieved by both national efforts and those of municipalities have been summarized based on data collected from March 2012 to October 2013 [55]. Data came from 10 municipalities under national Government auspices and 90 municipalities from 8 prefectures. In total, about 250 000 data points were included, with most measurements made at heights of 1 m and some at 50 cm.

The DF_s values achieved for asphalt paved roads were 2–3.3 by washing, and 1.4–3.3 by high pressure washing; for playgrounds the DF_s was 5–10 for stripping off surface 'dirt' [55]. The summarized data showed a reduction in the 25–75 percentile ambient dose rate at 1 m from 0.36-0.93 μSv/h before decontamination to 0.25–0.57 μSv/h after decontamination. When subdivided into different ranges of ambient dose rates of <1, 1–3.8 and >3.8 μSv/h before decontamination, the DF_a values achieved were 1.5, 1.8 and 2.0, respectively [55].

Measurements of ambient dose before and after decontamination are useful to guide remediation. However, they are not a direct measure of the reduction in individual dose, which is influenced by a wide range of factors, including personal habits (e.g. how much time an individual spends outdoors compared with indoors) and the shielding provided by different structures.

5.2.5.6. Radiation protection of decontamination workers

The Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works [58–57] provide detailed information on safety issues related to occupational exposures during implementation. The intention of these guidelines is to protect workers from radiation hazards. However, they are also relevant for individual proprietors, self-employed workers and volunteers.

A committee, consisting of primary contractors of decontamination work, established the systems for integrated dose control of radiation exposure for decontamination workers. The control system operates a radiation passbook control system and a central dose registration database, which can conduct name based aggregation of doses. To ensure the enforcement of the system, the MHLW amended the guidelines for requesting contractors to participate in this system. MOE included a statement requesting contractors to participate in this system as part of the relevant specifications of contracts for decontamination work [59–61]. This system is illustrated in Fig. 5.2–10.

[13] The surface decontamination factor (DF_s) is the ratio between the ambient dose rate measured at the surface (1 cm) of the object being contaminated before and after decontamination. For more detailed information, see Appendix I.

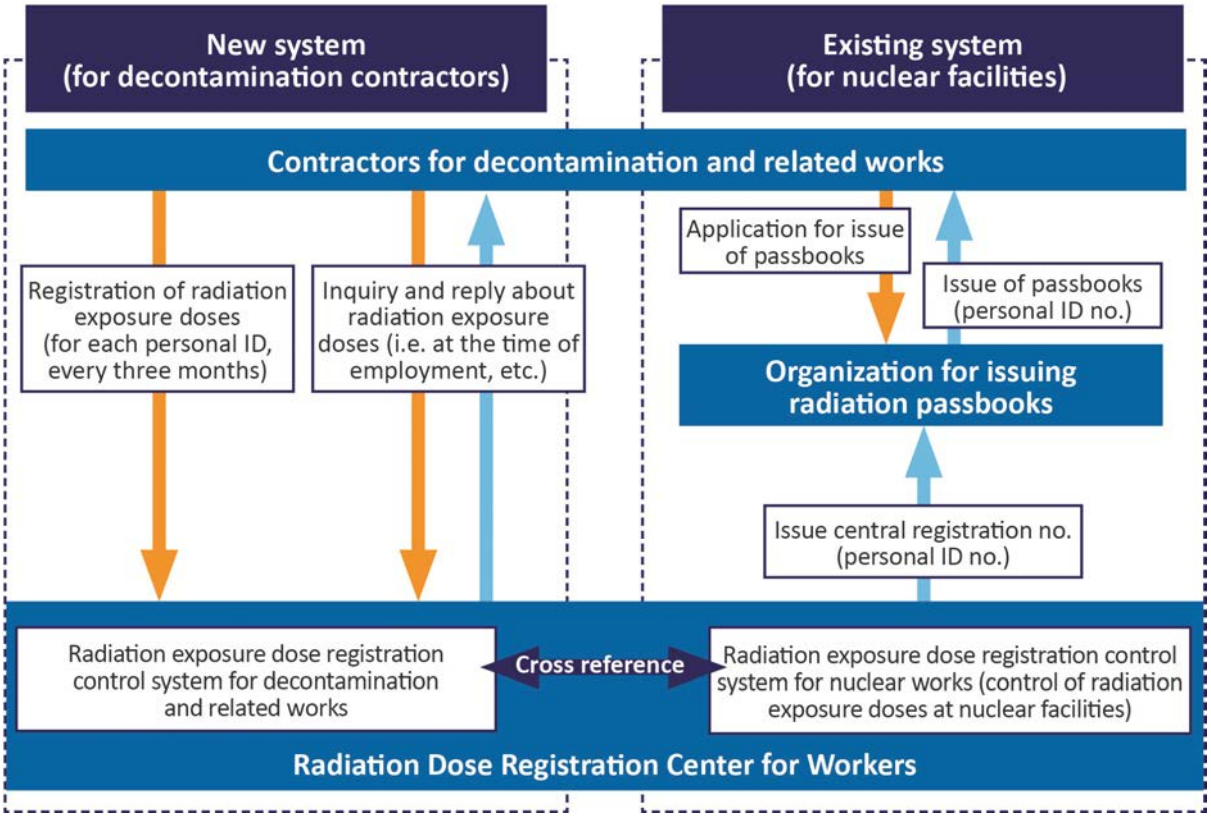


FIG. 5.2–10. System for decontamination contractors [61].

The function of the established system includes the following measures:

(a) Issue of ID numbers and radiation passbooks based on the existing system for workers in nuclear facilities;
(b) Registering and inquiring about radiation exposure doses during decontamination works;
(c) Enabling cross-reference of radiation exposure doses data between the new system and the existing system for nuclear facility workers.

Furthermore, in April 2015, the Radiation Effects Association summarized the exposure dose statistics for workers engaged in decontamination work from 2011 to 2013 [62]. Major findings are as follows:

— The numbers of workers tended to increase quarterly. The mean dose was the highest (0.8 mSv) for the period of January–March 2012, and then remained almost steady at 0.2 mSv–0.3 mSv after the final quarter of 2012.
— The distributions of numbers of workers by age displayed peaks for work age groups of 55–59 and 60–64 in both 2012 and 2013; however, the mean doses were almost the same at about 0.5 mSv irrespective of age.
— With regard to the dose distribution according to calendar years, the percentage of workers who received a dose that exceeded 5 mSv decreased from 1.5% in 2012 to 0.2% in 2013, while the percentage of workers who received a dose that exceeded 1 mSv increased from 9.7% in 2012 to 14.6% in 2013.

5.2.6. Remediation in the Intensive Contamination Survey Area

The ICSA was identified as including those municipalities where the ambient dose rate in some areas exceeded 0.23 μSv/h in the autumn of 2011, which was equivalent to over 1 mSv/y of additional dose, which was conservatively estimated at that time. It initially included 104 municipalities in 8 prefectures (Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma, Saitama and Chiba). By December 2014, the ICSA designation had been lifted for 5 municipalities as a result of decreases in dose rates, and 99 municipalities remained part of the ICSA.

Applying the methodology used in an assessment of radiation doses for the typical person described by UNSCEAR [13], the district average effective dose to a representative person in the ICSA in 2012 has been estimated and was below 1 mSv in all prefectures except Fukushima (see Section 5.2.4.3). Within Fukushima Prefecture, in the ICSA districts, the district average effective doses were below 2 mSv. However, in some areas within these districts, external annual doses above 1 mSv may occur, as the definition of ICSA was based on dose rates within smaller areas than the district average dose rate values used in this assessment methodology.

Estimated district average annual doses to the representative person for 2012–2015 for the ICSA districts in Fukushima Prefecture are shown in Fig. 5.2–11. It is predicted that by 2015, all district-average annual effective doses will be less than 1 mSv. However, higher doses may occur in certain localities owing to the spatial variation in the radiocaesium deposition density within each district.

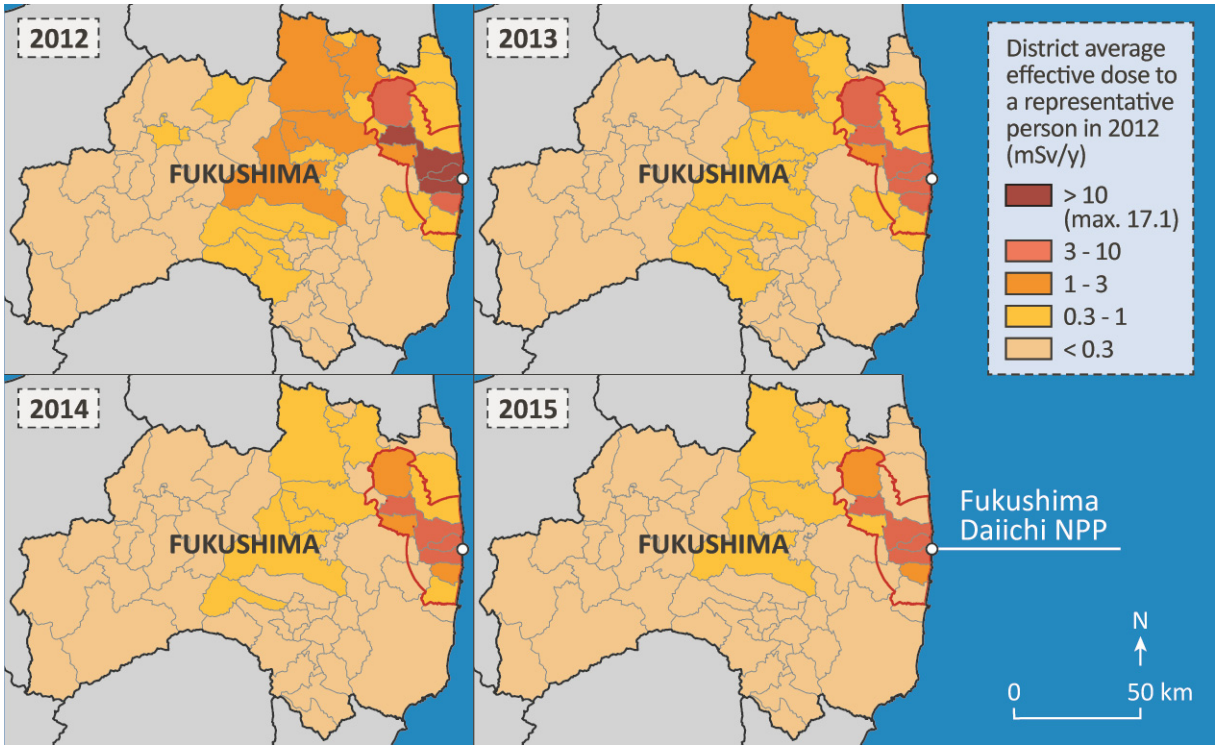


FIG. 5.2–11. Estimated district averaged annual doses to the representative person between 2012 and 2015 for ICSA districts in Fukushima Prefecture adopting the methodology used by UNSCEAR [13].

5.2.6.1. Remediation planning in the Intensive Contamination Survey Area

In advance of the enforcement of the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], some municipalities, such as Fukushima City and Date City, prepared

decontamination plans between September and December 2011. The plans were approved and funded under the Basic Policy for Emergency Response on Decontamination Work [28], which was succeeded by the Act on 1 January 2012.

Local authorities at prefectural and municipal levels have a key role in mitigating the impacts of the radioactive contamination in the ICSA in cooperation with the national Government. Remediation is implemented by each municipality with the financial and technical support of the national Government and according to locally set objectives and priorities for the protection of human health. Municipalities developed their decontamination implementation plans, the plans were approved by MOE and the municipalities gave public notice of the intended remediation work. The specific characteristics of each municipality were taken into account, and its environmental, agricultural, residential and social conditions were considered.

Under the Act, official dates for the commencement of remediation varied for different municipalities, with the first being Fukushima City on 21 May 2012 (although, as has been pointed out, many municipalities had started remediation under the previous Basic Policy for Emergency Response on Decontamination Work [28]). Each municipality was responsible for preparing its own remediation plan and hiring subcontractors to carry out the remediation. Of the 99 municipalities in the ICSA, 94 had formulated decontamination implementation plans by December 2014. The intention is to complete most of the plans in Fukushima Prefecture by fiscal year 2015–2016 [55].

The implementation of decontamination campaigns in the ICSA is based on the results of ambient dose rate monitoring. An individual annual dose in addition to background of less than 1 mSv is the long term goal of the national Government [41]. The action level of 0.23 μSv/h was used to designate the ICSA, but it was not established as the target level for remediation.

The objective of reducing annual additional dose to the general public and children by 50% and 60%, respectively, by August 2013, set out in the Basic Principles for Environmental Remediation [29], was evaluated by the use of monitoring data from sites where decontamination had been completed. Analyses suggested that the planned remediation would achieve the target reduction [55].

The municipalities carry out monitoring surveys to identify areas requiring remediation and to designate and formulate a decontamination plan, which stipulates the area to be remediated (the so-called decontamination implementation areas) and the measures to be used [55].

The approximate budget associated with remediation in the ICSA is given in Table 5.2–6 for the financial years up to March 2015.

TABLE 5.2–6. APPROXIMATE MOE BUDGET RELATED TO REMEDIATION IN THE INTENSIVE CONTAMINATION SURVEY AREA [63]

Financial year (April–March)	Approximate budget (billion Yen)	
	Allocated	Unspent
2011	104.7	19.0
2012	104.3	3.1
2013	202.9	0.3
2013[a]/2014	219.4	—

[a] Supplementary budget

A large amount of contaminated material is being generated from remediation in the ICSA, since the majority of measures taken involve decontamination. However, some remedial measures reduce dose

without creating contaminated waste (e.g. placement of topsoil at lower depths), and the advantages and disadvantages of possible options are considered on a case by case basis.

A review of remediation was conducted after the initial two years in September 2013. In response, additional post-remediation procedures have been implemented [55]. These include:

- Conducting monitoring to determine whether the reduction in the ambient dose rate due to decontamination has been maintained.
- Follow-up remediation work in previously remediated areas or in those that have not been remediated. For instance, the ambient dose rate in certain areas may be higher than that in surrounding areas because they receive contaminated material such as soil, fallen leaves or rain water from a catchment or via other lateral redistribution mechanisms.

Relevant measures on radiation protection, including risk communication, are being considered [55].

The municipalities that were making most progress with remediation work have gained considerable experience of the strengths and weaknesses of implementation. They have also developed novel approaches and explored the best ways to communicate with local residents. The importance of sharing information on the most effective measures with other municipalities was recognized, and, as a result, MOE's Fukushima Office for Environmental Restoration compiled a Good Practice Collection [64]. The document will be updated as appropriate, and other mechanisms to share and exchange information are being used.

5.2.6.2. Progress of remediation in the Intensive Contamination Survey Area

The government of Fukushima Prefecture initially coordinated the application of potentially practicable and effective remediation measures in areas with an estimated additional annual effective dose of 1–20 mSv. The resultant technical data were then used to identify decontamination measures to be implemented by each municipality in the ICSA.

In 2011, initial tests of remediation were implemented; examples of such activities included:

- Decontamination tests at the school and kindergarten affiliated with Fukushima University, Tominari primary school; three houses in Date City; and outdoor school pools and Fukushima University. Decontamination tests at various schools in Fukushima City were used to develop a decontamination manual.
- Decontamination and incineration technology tests at Iitate Village by research institutes under the direction of MEXT.
- Remediation tests of farmland in Iitate Village by MAFF.
- In May 2011, topsoil removal from the playgrounds of schools in the Fukushima Prefecture to reduce external exposure for children commenced, based on initial tests by JAEA at Fukushima University Junior High School and Kindergarten.

The municipalities developed their own decontamination implementation plans, based on the MOE's Decontamination Guidelines [49] and frequently updated web based information [65]. In implementing their plans, municipalities may adopt alternative technologies/methods, in consultation with the MOE, which determines on a case by case basis whether these plans will be supported and funded [65].

During the early stages of remediation, systematic analyses of exposure pathways and exposures, averted doses, social benefits and remediation costs were not conducted in order to select an optimized remediation strategy for each settlement. Nevertheless, the best available technologies were selected for large scale remediation, partially based on information on effectiveness and cost from the outcomes of the Step 1 and 2 demonstration projects. Remediation efforts have focused on those

measures that reduce human radiation exposure and are understandable to the general public; special attention has been paid to the public perception of remediation activities.

Most of the planned remediation activities have focused on decontamination of homes and public areas. A self-help approach was adopted in many places, whereby local residents assisted with remediation of public spaces and their own kitchen gardens in 2011 and early 2012. Thereafter, the appointment of subcontractors has meant that local residents have become less involved.

The progress of remediation in the ICSA for the area immediately outside and inside Fukushima Prefecture is shown in Fig. 5.2–12, which gives detailed information on the numbers of planned and completed remediation activities in Fukushima Prefecture and other prefectures by the end of March 2015.

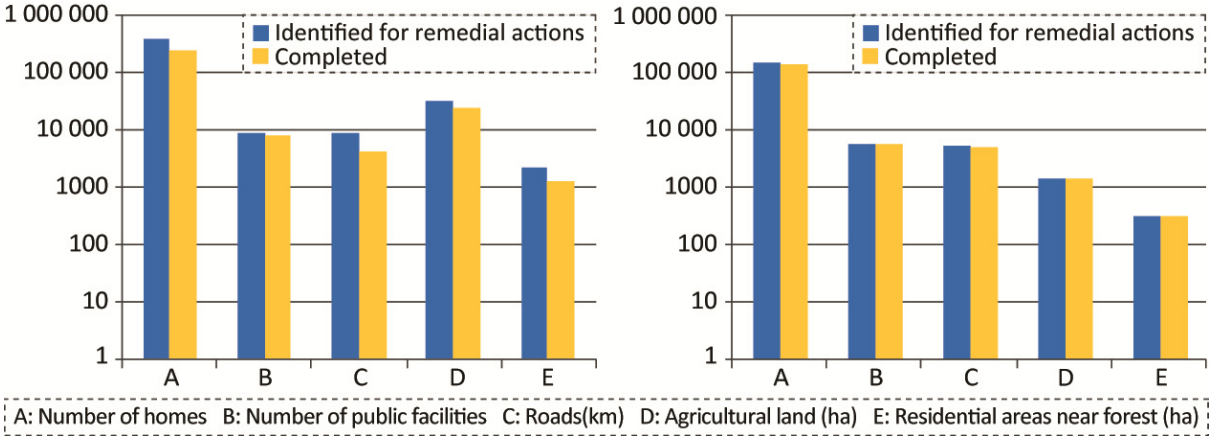


FIG. 5.2–12. Number of planned and completed remediation activities in Fukushima and other prefectures (in Fukushima Prefecture on the left and outside Fukushima Prefecture on the right) by the end March 2015 [66].

The progress of remediation has been affected by many different factors. Remediation measures have progressed rapidly in municipalities where the dose rate is relatively low and the quantity of decontamination work is relatively small. Progress has been delayed in some municipalities where it has taken longer to identify suitable sites for temporary storage and/or to obtain agreement of inhabitants/owners of the storage sites.

By the end of March 2015, planned remediation measures had been completed in 19 of the 94 municipalities that had formulated decontamination implementation plans, and remediation was almost complete in a further 26 municipalities [55].

By the end of March 2015, decontamination in most parts of the ICSA outside Fukushima Prefecture was almost complete (in about 80% of the municipalities). In the ICSA within Fukushima Prefecture, around 90% of the public facilities, 60% of residential houses and 50% of roads had been decontaminated [55].

In the ICSA, the objective is to reduce dose rates as much as practically possible. Initial analysis suggests that individual dose data collected by municipalities have a tendency to be lower than the exposure doses estimated from the ambient dose rates using the conservative approach adopted in Japan [55, 67].

The predictions presented in Section 5.2.4.3 indicate that the additional dose rates in the ICSA, including Fukushima Prefecture, were below the level that would imply an annual effective dose of

1 mSv for the representative person in all but one district by 2013, and in all districts by 2014. By the time that remediation was conducted, the averted dose in much of the ICSA, especially in municipalities outside of Fukushima Prefecture, would have been small, although relevant data on averted dose are not currently available. Nevertheless, the remediation measures addressed important social concerns, providing reassurance to the local communities and allowing the maintenance of economic activity.

5.2.7. Remediation in the Special Decontamination Areas

This section presents the environmental remediation specifically applied in the SDA located within Fukushima Prefecture, covering the period up to December 2014. The SDA includes land in the (former) restricted zone and/or Deliberate Evacuation Area within 11 municipalities of Fukushima Prefecture, which has been subdivided into Areas 1, 2 and 3 (Fig. 5.2–4).

For evacuated towns in the SDA, the objective is the reduction of potential doses to people, upon their return, to below established reference levels and further optimization of radiation protection of the public where justified. Reduction in dose is an important aspect of the reconstruction and revitalization activities, aimed at facilitating the return of the evacuated population. The particular reference levels of annual dose in the range of 1–20 mSv recommended by the ICRP [3, 8] and IAEA [1] for protection of the public in existing exposure situations were applied in Japan by the specification of an additional annual effective dose of 1 mSv as a long term goal.

5.2.7.1. Assessment of doses to people related to remediation criteria

As stated in Section 5.2.4.1, the current criterion for designation of the ICSA established by the Government of Japan is a deliberately conservative ambient dose rate of 0.23 μSv/h. This criterion is based on the long term goal of an additional annual effective dose of 1 mSv and a conservative calculation of external exposure from radionuclides deposited on the ground.

The predicted district average effective doses for the representative person in 2012 for the SDA are shown in Fig. 5.2–13. The predicted annual effective dose for the representative person is estimated to have been 10–17 mSv in Okuma Town, Futaba Town and Namie Town, and below 6 mSv in the remaining areas of Iitate Village, Katsurao Village and Kawauchi Village. By 2015, the maximum district averaged effective dose is estimated to be less than 5 mSv in that year. These district average estimates do not allow for the spatial variation in each municipality in the radiocaesium deposition, and therefore, as for the ICSA, actual doses will vary below and above the district average estimate.

A series of maps illustrating the time series of deposition density of ^{134}Cs and ^{137}Cs are presented in Technical Volume 4, Section 4.1.

UNSCEAR has estimated the effective doses from external exposure to typical adults who were evacuated from locations in Fukushima Prefecture if they were to return to their homes[14] in the period 11 March 2012–11 March 2013 to range from 0.19 mSv to 11 mSv [13]. A comparison of UNSCEAR effective doses for a typical person and those estimated here for the representative person for 2012 shows that the latter are larger by a factor of 1.4 to 1.5. A similar comparison with the predicted effective doses used to define Area 1, 2 and 3 of the evacuation areas by Japan shows that the methodology used is significantly more conservative than that for the ICRP representative person. The comparison highlights the conservative approach used by Japanese authorities for the assessment of exposures to the public arising from ^{134}Cs and ^{137}Cs deposited on the ground.

[14] In the absence of remediation

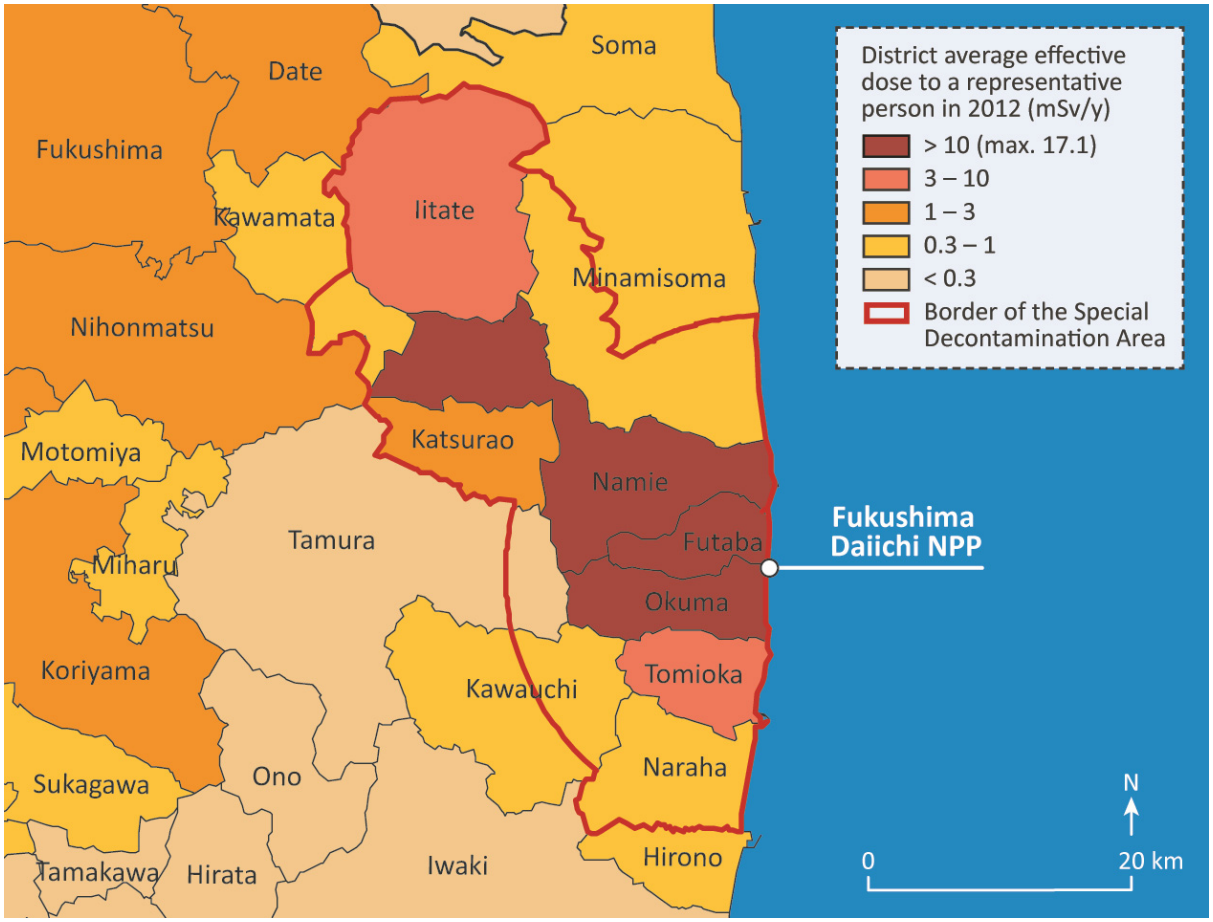


FIG. 5.2–13. Predicted district average effective dose to the representative person in 2012 in the SDA based on the UNSCEAR methodology.

Physical decay of the radiocaesium isotopes over the four year period from January 2012 to December 2015 will lead to a roughly four fold reduction (see Fig. 5.2–5) in dose rates to people, even without remediation efforts. Predictions of additional effective dose, estimated for district average to a representative person, suggest that, for 2015, doses will have declined in most parts of SDAs 1 and 2 to below the current reference levels of annual effective dose established in Japan for the post-accident existing exposure situation (1–20 mSv). Without remediation, the annual effective district average dose in municipalities with the most land in SDAs 1 and 2 is predicted to be 0.2–3.0 mSv in 2015. This means that with remediation, the actual doses of a returning representative person would be less than these values. The predicted annual district average doses for municipalities with the most land in SDA 3 were <5 mSv without remediation.

5.2.7.2. Planning remediation activities in the Special Decontamination Areas

In each municipality, an implementation plan for remediation — i.e. selection of targets and technologies, scheduling and implementation and monitoring of results — was prepared by the MOE in collaboration with local authorities and stakeholders, including local residents (see Section 5.5.5).

Because of the absence of the population in the evacuated villages and towns for an extended period of time, the infrastructure (buildings, roads, water supply, sewage, etc.) will be gradually degraded and may need substantial restoration before people can return. The need for extensive non-radiological restoration could delay the return of people to the evacuated towns, even after radiation conditions have substantially improved.

The remediation roadmap for the SDA was released by the MOE on 26 January 2012 and included the following specifications [68]:

— A specific decontamination plan should be developed by the end of March 2012 for the 11 affected municipalities.
— The plan should correspond to the rearrangement of the restricted area and Deliberate Evacuation Area.
— Advance decontamination work should be carried out for public facilities, such as city and town halls, and infrastructure, such as highways and water facilities.
— Priorities for full scale remediation should be given to areas estimated to give rise to an annual effective dose of 1–20 mSv and 20–50 mSv (estimated for 2011), with the aim of realizing the earliest possible return of evacuees.
— Demonstration projects should be implemented in areas estimated to give rise to an annual effective dose of >50 mSv.
— Implementation policies should be developed for each part of the SDA, and should include priorities and goals for remediation.

The overall remediation roadmap for the SDA up to the end of the financial year 2013 is shown in Fig. 5.2–14.

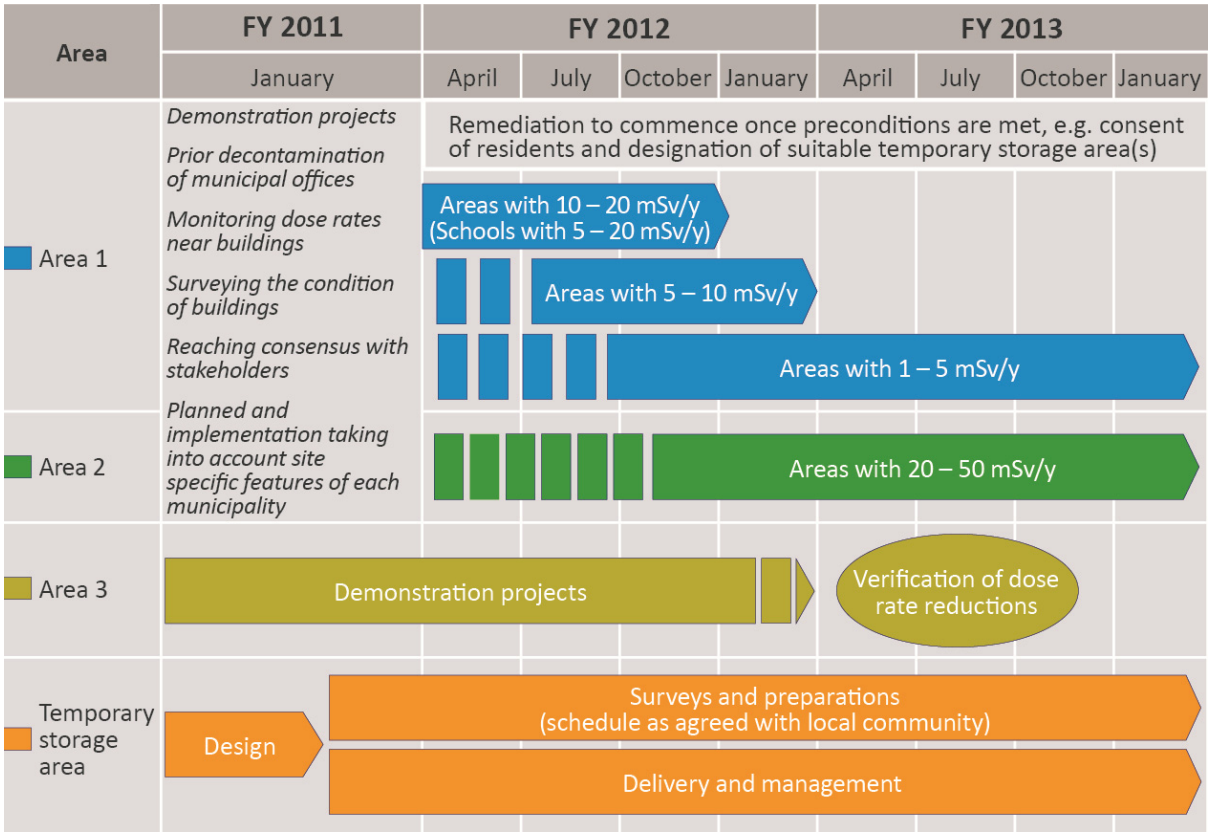


FIG. 5.2–14. Planning for remediation as of September 2013 [55, 69].

New policies were announced by the MOE in September 2013, which stated that decontamination work would be implemented in cooperation with reconstruction measures, depending on the situation in each municipality [55, 70]. This meant revision of plans and schedules of work in some municipalities and the introduction of additional measures to speed up and facilitate remediation. A set of standard remedial actions was developed and applied for each full scale decontamination

project, considering the contamination level and priority land use [55, 70]. To allow evacuees to return home, decontamination has been prioritized for residential areas and their surroundings and for infrastructure essential for habitation, such as water supply, sewage systems and major roads. Topsoil removal has been applied only to schoolyards/parks or relatively highly contaminated areas. Emphasis is being placed on rapid implementation, strict control procedures and open reporting of progress to the public.

5.2.7.3. Progress of remediation in the Special Decontamination Area

Beginning in January 2012, the evacuated areas were divided into three zones, with the intention of initiating remediation, revitalization and reconstruction activities by March 2012. However, the preparatory phase, involving considerable rearrangement of activities, was not completed until August 2013. The rate and extent of progress in the remediation of the SDA has differed in the various municipalities and has been influenced by such factors as the extent of the contamination present, the condition of the evacuated areas in each municipality and the need to agree on the details of the implementation with stakeholders. Some natural features beyond human control, such as the amount of snow in recent winters, have also delayed implementation. The reasons for the delays have been complex and challenging [71] and have included the need for the following:

- Rearrangement of the evacuation areas into three categories, according to the annual cumulative dose estimated from the ambient dose rate;
- Formulation of compensation guidelines;
- Securing of temporary storage sites;
- Obtaining stakeholder and regulatory consent for remediation.

The distribution of the different areas of land of different municipalities among the SDA areas and ICSA categories is shown in Table 5.2–7.

TABLE 5.2–7. AREA OF LAND AND PERCENTAGE OF TOTAL LAND AREA IN THE SDA 1, 2 AND 3 AND IN THE ICSA IN THE AFFECTED MUNICIPALITIES [72, 73]

Municipality	Total area of the municipality (km^2)	SDA 1 (km^2)	SDA 2 (km^2)	SDA 3 (km^2)	ICSA (km^2)
Tamura	458	42 (9%)	0	0	416 (91%)
Naraha	103	103 (100%)	0	0	0
Kawauchi	197	69 (35%)	12 (6%)	0	116 (59%)
Okuma	79	18 (23%)	12 (15%)	49 (62%)	0
Kawamata	128	29 (23%)	3 (2%)	0	95 (74%)
Katsurao	84	64 (76%)	5 (6%)	16 (19%)	0
Iitate	230	62 (27%)	157(68%)	11 (5%)	0
Minamisoma	399	91 (23%)	56 (14%)	24 (6%)	228 (57%)
Tomioka	69	25 (36%)	35 (51%)	8 (12%)	0
Namie	224	21 (9%)	23 (10%)	180 (80%)	0
Futaba	51	2 (4%)	0	49 (96%)	0

Many of these issues, for example, those concerning temporary storage sites and stakeholder engagement are considered in this Technical Volume in Sections 5.4 and 5.5, respectively. Of particular relevance to remediation were the difficulties in adequately explaining to stakeholders:

— The dose criteria and the application of the principle of optimization;
— The criteria used to justify activities such as the felling of trees, demolishing of buildings and renewal of building materials;
— The strategies for removing soil from highly contaminated areas and securing adequate new soil.

Decontamination implementation plans were completed in April 2012 for Tamura City, Naraha Town, Kawauchi Village and Minamisoma City, and between May 2012 and December 2012 for Iitate Village, Kawamata Town, Katsurao Village and Namie Town. For Tomioka Town and Futaba Town, the plans were finalized in June 2013 and July 2014, respectively.

The remediation measures used in the SDA are being implemented by contractors to the national Government in cooperation with reconstruction measures, depending on the situation of each municipality. Since July 2012, there has been substantial progress in remediation of the SDA, including the completion of demonstration projects [46, 74, 75] and implementation of large scale remediation projects in a number of settlements in Areas 1 and 2.

Generic issues concerning implementation, in addition to those mentioned above, which have led to the need to reschedule implementation [71] include:

— Difficulties in securing large numbers of qualified workers and foremen. The use of unqualified workers has not been well accepted in the local communities, and the labour market is limited. This also impacts on other reconstruction or decontamination work in non-evacuated areas.
— Limited logistical capacities of the region — such as reduced traffic capacity leading to road congestion and traffic accidents, accommodation for workers and facilities for non-contaminated solid waste management.
— Increased risk of occupational accidents.
— Increased workload for some activities. For example, allocation of additional compensation to people owning houses and adjacent forests for trees cut down.

Local circumstances vary from one area to another, with the result that there were differences in the preparation and operation of remediation measures between municipalities. For example, decontamination plans of the six municipalities of Minamisoma City, Iitate Village, Kawamata Town, Katsurao Village, Namie Town and Tomioka Town were revised in December 2013 and work continued into the financial year 2015. The revised schedules take into account the current condition of each area and were set up in consultation with each municipality and community (Table 5.2–8).

Within the SDA, decontamination plans were completed in four municipalities in March 2015 (Tamura City, Kawauchi Village, Naraha Town and Okuma Town). Decontamination of residential areas were also completed in two more municipalities (Katsurao Village and Kawamata Town) and were almost completed in Iitate Village [55]. Most decontamination plans in both SDAs 1 and 2 within Fukushima Prefecture were due to be completed before the end of March 2016, although some were planned to continue into 2017.

The information in Table 5.2–8 relates to land in each municipality which is within SDA 1 and 2. The rate of progress depends on the amount of land and number of decontamination targets within each SDA. The extent of land in Area 1 and Area 2 in Okuma Town is small, so it was decontaminated quickly. Futaba Town has some land in Area 1, but most of its land is in Area 3. The progress of remediation for the different municipalities in Areas 1 and 2 is shown in Table 5.2–9 and Fig. 5.2–15 [55].

TABLE 5.2–8. TIMESCALE OF REVISED PLAN FOR REMEDIATION OF MUNICIPALITIES IN SPECIAL DECONTAMINATION AREAS 1 AND 2 [55]

Municipality	Targets	Planned completion of remediation (end FY)			
		2013	2014	2015	2016
Land in Special Decontamination Area 1					
Tamura, Naraha	All				
Futuba	All				
Land in Special Decontamination Areas 1 and 2					
Kawauchi	All				
Kawamata	Residential[a]				
	Other				
Okuma	All				
Katsurao	Residential[a]				
	Other				
Tomioka	Residential[a]				
	Other				
Namie	Residential[a,b]				
	Other				
Minamisoma	Residential[a]				
	Other				
Iitate	Residential[a]				
	Other				

[a] Including surrounding areas.
[b] Excluding areas devastated by the tsunami.

TABLE 5.2–9. PROGRESS OF REMEDIATION FOR THE DIFFERENT TYPES OF AREA IN EACH MUNICIPALITY (PERCENTAGE COMPLETED FOR AREAS 1 AND 2) AT THE END OF MARCH 2015 [76]

Municipality	Special Decontamination Area	Remediation target (percentage completed)			
		Residential areas	Farmland	Forest	Road
Tamura	1	100	100	100	100
Naraha	1	100	100	100	100
Kawauchi	1 and 2	100	100	100	100
Okuma	1 and 2	100	100	100	100
Kawamata	1 and 2	100	19	58	4
Katsurao	1 and 2	100	68	99.9	32
Iitate	1 and 2	96	34	39	26
Minamisoma	1 and 2	8	10	38	6
Tomioka	1 and 2	24	5	41	65
Namie	1 and 2	11	14	18	21
Futaba	1	—	—	—	—

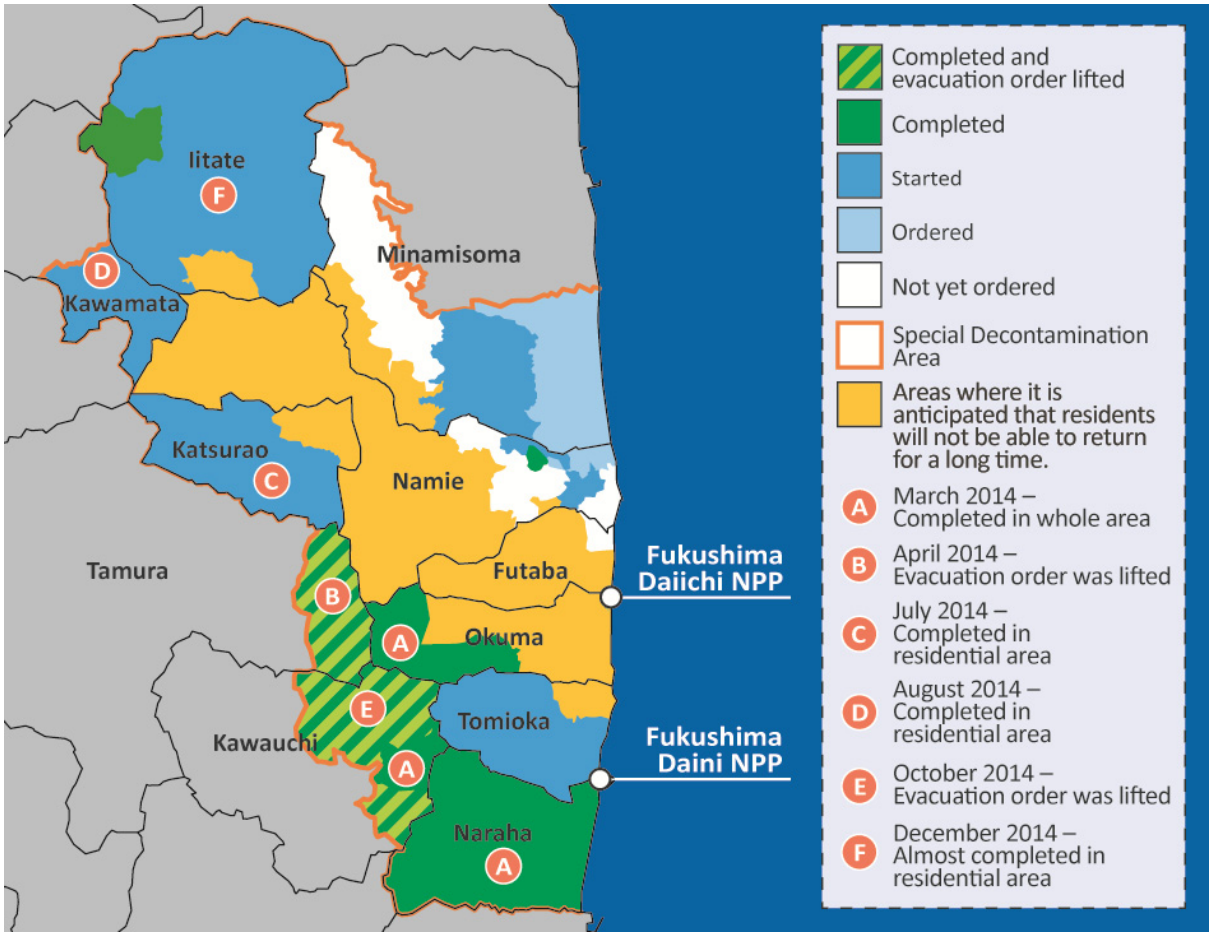


FIG. 5.2–15. Progress in remediation in SDAs up to December 2014 [55].

For Futaba Town municipality, which contains the Fukushima Daiichi NPP, and most of which is situated within SDA 3, the decontamination implementation plan was formulated in July 2014. The decontamination model evaluation project of MOE [51, 77] has provided relevant information on the likely DF_a values that will be achieved in each of the municipalities with land within SDA 3 and gives information on worker doses and their limitation.

A new policy for SDA 3 was announced by Cabinet Decision in December 2013 [55, 78]. It stipulated that the treatment of SDA 3 was to be determined through discussion with relevant local parties, based on the following aspects:

— The estimated future reduction of dose based on the MOE demonstration projects in SDA 3;
— The vision for future industries;
— The blueprint of reconstruction;
— The willingness of evacuees to return to the area.

Significant resources have been devoted to the remediation efforts and good progress has been made. The revised policy of combining reconstruction with remediation is a constructive measure that will enhance living conditions and encourage the return of people to the evacuated towns in the SDA.

The Joban Expressway is a key transport route running parallel to the eastern coast of Japan, which bisects the SDA. Decontamination of the expressway, mainly by removing vegetation from adjacent land and the use of high pressure washing on road surfaces and ditches, was completed in June 2013 [55]. The highway was fully opened for traffic in March 2015.

While the target ambient dose rate for the route between Joban-Tomioka Town and Hirono City, re-opened in February 2014, and for the route between Namie Town and Minamisoma City, opened in December 2014, was 3.8 μSv/h, the actual ambient dose rates based on vehicle mounted monitoring after decontamination in October 2014 were, respectively, 1.3–1.5 μSv/h and 0.6–0.7 μSv/h on average, which were much lower than the target value. The decrease in ambient dose rates is attributed to the combined effects of decontamination and shielding by road paving.

5.2.7.4. A case study: Remediation in Tamura City

The first municipality with land inside the SDA to complete its remediation plan was Tamura City. The remediated parts of Tamura City are relatively small and are located in SDA 1, which was less contaminated than other areas in the SDA. Therefore, it is not representative of other municipalities in the SDA.

Remediation was initially focused on residential areas, farmland and the border strip of forests in the Furumichi and Miyakoji districts in the north-western part of the municipality, which were originally within the 20 km restricted area [55]. A total area for building surfaces of about 23 ha (for 121 family units), 95.6 km of road, about 130 ha of farmland (see Fig. 5.2–16) and about 190 ha of forests were remediated. Remediation took nearly one year, lasting from 5 July 2012 to 28 June 2013. The amount of labour involved was substantial, with a maximum of 1300 workers per day and a total of 120 000 person-days of effort.



FIG. 5.2–16. Remediated paddy fields in Tamura City in SDA 1.

The reduction in ambient dose rate achieved by large scale remediation work in Tamura City is shown in Fig. 5.2–17, as measured at approximately 15 000 monitoring points just before (July 2012–May 2013) and soon after (August 2012–May 2013) remediation. The data show that the frequency distribution of ambient dose rate shifted to lower ambient dose rates after remediation. The average reduction factor in the ambient dose rate was about 1.5.

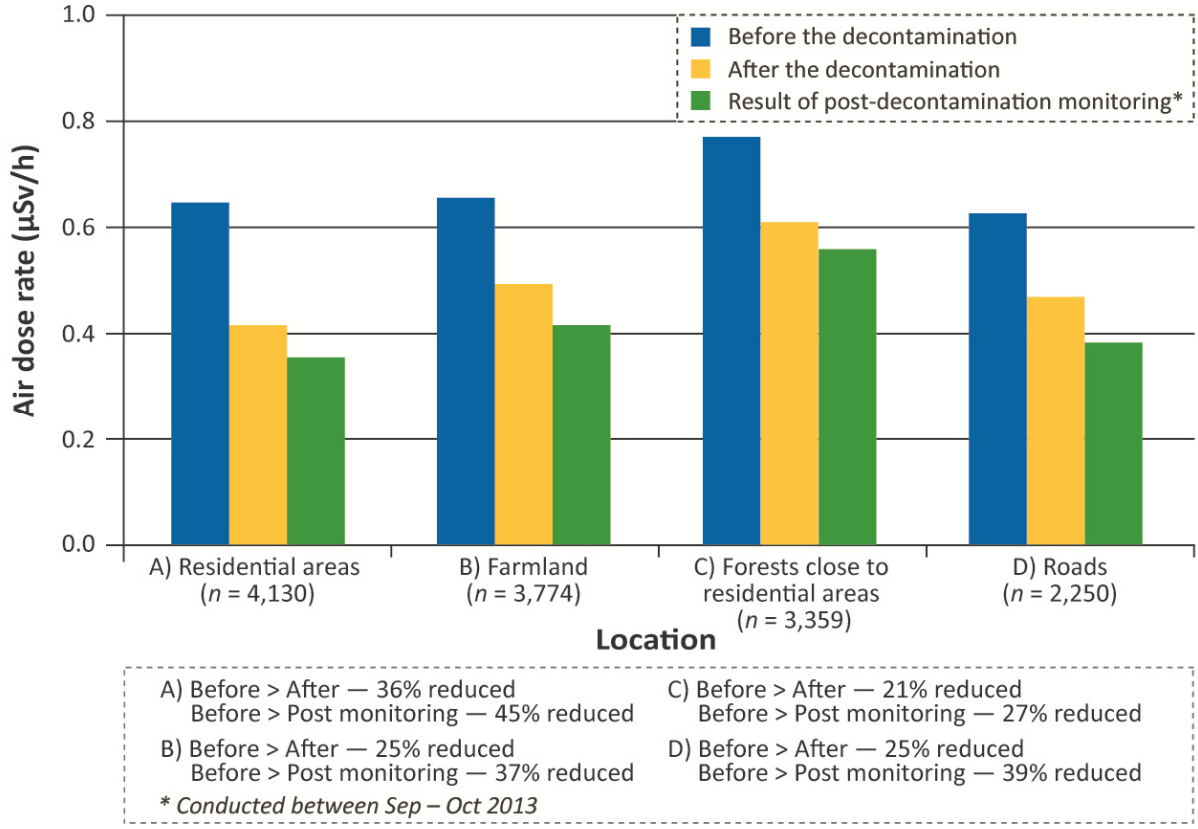


FIG. 5.2–17. Reductions in ambient dose rate achieved in Tamura City in Special Decontamination Area 1 [55].

After the completion of decontamination works in Tamura City in June 2013, postmonitoring was carried out as of September 2013 to confirm the continuation of decontamination efficiency. In addition, explanatory meetings for residents were held. The returning people were given individual dosimeters to measure dose rate and accumulated dose. They also had consultations with medical counsellors, who explained the relationship between their daily activities and their exposure to radiation. The evacuation order was officially lifted in Tamura City on 1 April 2014 [55].

5.2.7.5. Estimation of doses for people returning to the Special Decontamination Area

The criteria for lifting the evacuation order [28] are given as follows:

- Confirmation that the annual effective dose of radiation will be 20 mSv or less;
- Confirmation that sufficient progress has been made in the general restoration of essential infrastructure, especially with regard to children's living environments (see also Section 5.5);
- Comfirmation that extensive talks had been held with prefectural and local governments and residents.

The committed dose to the public upon their return to the remediated settlements will be prospectively assessed by means of environmental measurements and appropriate dosimetric models, such as the ICRP approach using the representative person [36].

The demonstration projects have provided significant reductions in dose rates within the settlements. However, comprehensive analyses of remediation effectiveness and assessment of averted doses are not currently available. For retrospective dose assessment and public reassurance, it is important to focus on measurements of individual dose. For the evacuees to return home, arrangements that

contribute to measurement, management and reduction in individual dose have been suggested [67]. The individual dose measurements need to address both external and internal exposures of the public.

Retrospective (post-remediation) monitoring of individual dose provides valuable information for evaluating the effectiveness of remediation and assessing whether the long term goal of an annual effective dose of 1 mSv is likely to be achieved. Such individual dose monitoring can improve remediation measures and can possibly accelerate remediation through the better use of resources. It also provides reassurance to people, especially those who return to the remediated areas.

The individual external exposure doses are being measured by means of direct-reading electronic dosimeters or thermoluminescent dosimeters for longer term exposures. To assess individual internal dose, whole body counters that reflect both ingested and inhaled radionuclides in the body are employed.

Current experience suggests that careful instruction and communication is needed to ensure that dosimeters are used correctly so that the estimated individual doses reflect those actually received.

Research performed in residential areas of Tamura City and Naraha Town municipalities showed that ambient gamma dose rates had been reduced by an average of 36% and 46%, respectively. Gamma dose rates were determined by measuring ambient dose rates at a distance of 1 metre from the decontaminated surfaces, both before and after remediation actions. Average dose rate reductions in these two municipalities following remedial actions in farmlands, forests and roads were between 21% and 44% [55].

The data indicate that the reduction of ambient gamma dose rates is more significant in areas with higher initial dose rates. After remediation, the gamma dose rates will continue to decline owing to the natural processes of weathering and radioactive decay.

Prior to the return of the public to remediated settlements, and at the early stage of their return, measurements of the activity concentrations of radionuclides in components of the diet, in local drinking water and in the air are important to quantify their contribution to internal doses.

5.2.8. Implementation of action levels in foods and other materials

An action level is the level of dose rate or activity concentration above which remedial actions should be carried out to reduce chronic exposure, if deemed necessary [2]. The activity concentrations applied in Japan after the Fukushima Daiichi accident for food are given in Technical Volumes 3 and 4. Here, information is provided on the implementation of action levels and how compliance with the action levels is ensured.

In 2012, the Japanese authorities decided to reduce the maximum annual additional effective internal dose to 1 mSv in order to achieve further food safety and to build consumer confidence. Accordingly, on 1 April 2012, the Japanese authorities lowered the action levels (termed permissible levels) for radiocaesium in terrestrial and aquatic food products to 100 Bq/kg for general foods such as fruit, vegetables, rice, seafood and meat/fish; to 50 Bq/kg for cattle milk and infant food; and to 10 Bq/kg for drinking water (see Technical Volumes 3 and 4 and Ref. [79]).

Compliance with the action levels for food is demonstrated by an extensive and comprehensive food monitoring programme for foods produced in contaminated areas. The NERHQ restricts shipments if radiocaesium activity concentrations exceed the action level in several municipalities [79, 80]. Food with radiocaesium activity concentration that exceeds the action level is not allowed to enter the food distribution system. Residents of contaminated areas can bring locally produced food from their kitchen gardens, freshwater systems or forests to local measuring facilities.

5.2.8.1. Arrangements for selected products

Rice

In Fukushima Prefecture, specially designed monitoring facilities using scintillation counters have been set up to measure radiocaesium activity concentrations in packaged rice (see Fig. 5.2–18). Labels are affixed to the packaged rice to confirm that it has passed the screening process.



FIG. 5.2–18. Bags of locally grown rice are screened for possible contamination in Motomiya City.

Cultivated mushrooms

Cultivated mushrooms are grown on wood logs in open fields or on commercial mushroom media. Action levels of 50 Bq/kg for these growth media and 200 Bq/kg for logs have been adopted. If radiocaesium activity concentrations exceeding the action level for general foods are detected in mushrooms, the prefectural government requests that mushroom distribution in the relevant municipality be voluntarily restricted. Possible violations are investigated.

Soil used for plant products, including rice

To determine a radiocaesium activity concentration in agricultural soils below which they may be used to grow rice, MAFF applied a conservative transfer factor[15] (TF) for rice. The 90th percentile of the distribution of TF values from a large quantity of Japanese data collected over many decades [81] was determined to be 0.1. By the use of this TF value and the action level for radiocaesium in rice of 500 Bq/kg, established by the Japanese authorities in 2011, an action level for cultivation of rice on paddy soil was set at 5000 Bq/kg in 2011 [81].

From 2012, information on TF values were not used to set criteria based on soil radiocaesium activity concentrations, because of a lack of correlation in the ^{134}Cs and ^{137}Cs activity concentration in soil with that in unmilled rice samples from 432 paddy fields Fukushima Prefecture [82].The data led to the concern that the measurement of radiocaesium in soil was not an accurate predictor of the activity concentration in rice. Therefore, comprehensive inspection of agricultural products continued to identify areas where crops exceeded the action levels and where land required remediation.

Further research is continuing to quantify the variation in different factors which may have led to the lack of correlation and to determine whether such a correlation, as previously reported elsewhere [25, 48], will emerge in the longer term. Such studies include ^{134}Cs and ^{137}Cs uptake from different types of soil to rice, the impact of irrigation or previous treatment of the paddy field, exchangeable potassium status and the mechanisms of ^{134}Cs and ^{137}Cs sorption in different types of soil in the contaminated areas.

To ensure that ^{134}Cs and ^{137}Cs in soil used for agricultural production is not artificially enhanced by the addition of fertilizers, an action level of 400 Bq/kg has been applied for fertilizers, soil conditioners and compost used to grow seedlings [83].

Animal products

The procedures put in place for beef are described in Ref. [84]. In seven prefectures (Iwate, Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba), inspection of beef to verify that radiocaesium activity concentrations do not exceed the designated action level is conducted at least once every three months on all farms. If a sample exceeds the action level for beef, the origin of the animal is traced using cattle identification and traceability systems set up in 2003 and 2004 [85].

Most raw milk is sterilized and then processed into milk and dairy products and is therefore not directly consumed by people in Japan. Raw milk is sampled and analysed at the cooler stations or dairy factories. Up to March 2013, sampling was conducted weekly and, thereafter, more than once every two weeks. When restrictions are lifted, raw milk is sampled and inspected once a week. For traceability, the dairy factory origin is stated on the label.

The action levels for activity concentrations in feed for animals producing meat, milk and eggs were derived by using data on transfer rates between feed and animal products [48] and by experiments conducted by the Japanese Government. MAFF revised the designated action levels for cattle feed and other animal feed in February and March 2012, respectively [86, 87], to be consistent with the reduction of food products action levels in April 2012 (see Table 5.2–10) [88].

[15] The ratio of the activity concentration of radionuclide in the plant (Bq kg^{-1} dry weight (dw) to that in the soil (Bq kg^{-1} dw).

TABLE 5.2–10. ACTION LEVELS FOR RADIOCAESIUM IN ANIMAL FEED[a] (Bq/kg fresh weight) [83, 86, 87]

Animal	Action levels for radiocaesium in feed (Bq/kg fresh weight)
Cattle/horses	100
Pigs	80
Poultry	160
Aqua-cultured fish	40

[a] Assuming 80% water content for forage and fresh weight for other feeds.

Forest products

Forest management includes monitoring of radiocaesium in forest products to identify practical measures to mitigate the impact associated with their use. Consumption of wild foods collected from forests, which often contain high radiocaesium activity concentrations (e.g mushrooms, wild plants and game), has been restricted [48, 89, 90]. These restrictions are likely to continue owing to the expected high and sustained uptake of radiocaesium into many of these foods [44, 91]. Additionally, people are prohibited from visiting the most affected areas and from collecting firewood that exceeds the permissible level (40 Bq/kg).

5.2.8.2. Application of action levels

The low action levels applied in Japan led to extensive restrictions on the use of agricultural land, especially in 2012. To produce food below the action levels, it has been necessary to remediate some agricultural land.

After the accident, the Japanese Government had restricted the distribution of food products from Fukushima and other affected prefectures [92]. There were also restrictions on fishing in some marine areas close to the Fukushima Daiichi NPP.

The areas where rice production was restricted was reduced between 2012 and 2014, as shown in Fig. 5.2–19 [93]. The restrictions in rice production are now confined to Fukushima Prefecture, with all of the municipalities within the ICSA able to produce rice without restriction since the end of 2013.

Overall, the comprehensive implementation of food restrictions and monitoring has protected people and improved confidence in farm produce, as reflected to varying extents by the improving market price of some crops (see Section 5.5.3). The effectiveness of these measures and natural radiological decay processes have contributed to low internal doses to people compared with those from external pathways.

Japanese authorities have made a considerable effort to ensure that clear explanations are given of the derivation of the food action level. Information on the application of the food inspection systems is available on the MAFF web site, and at information centres (see Section 5.5.4).

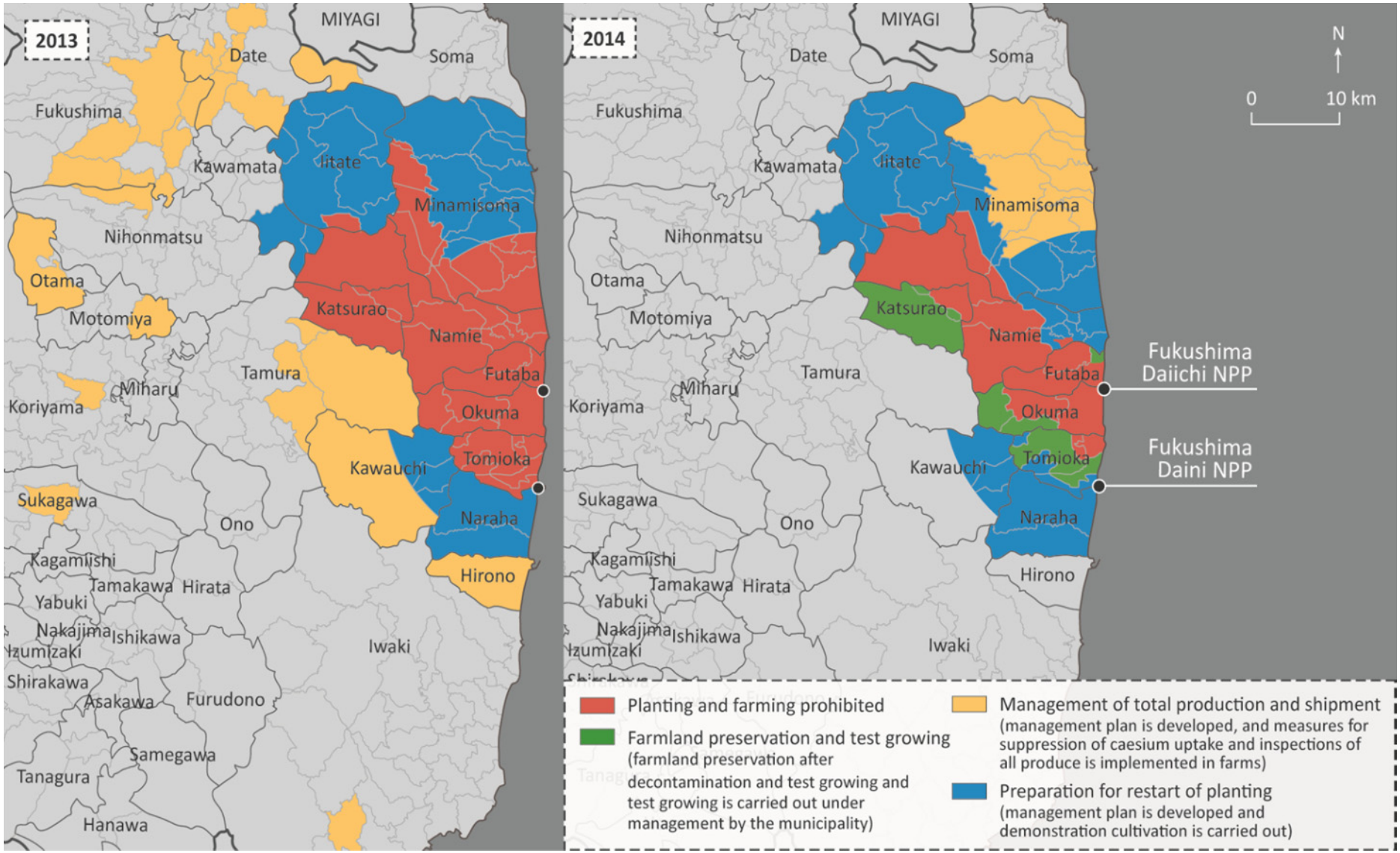


FIG. 5.2–19. Change over time in the area where rice production was restricted [93]

5.2.8.3. Characterization and monitoring of internal dose pathways for remediation planning

Surveys and measurement of the spatial and temporal variation in radiocaesium contamination are being used by national organizations and municipalities to formulate remediation plans. The data have included aerial surveys and/or measurement of radiocaesium activity concentrations in soil, water, sediments and foods, and assessment of individual ingestion doses to humans. Characterization of the contaminated areas in Japan has resulted in the identification of areas where food or other products may have radiocaesium contents that exceed the criteria adopted. Depending on the deposition density, the appropriate type of prohibition or remediation can then be applied.

Terrestrial pathways

The landscape in both types of designated contaminated areas, SDA and ICSA, (see Fig. 5.2–20) generally consists of about 70% forest, but the proportion is even higher in some municipalities, e.g. about 90% forest in Kawauchi Village. Much of the contaminated area is mountainous with forests on mountain slopes. The valleys and other low lying land are dominated by paddy fields, and rice is a key crop in the area, together with fruit, soy bean and flowers.



FIG. 5.2–20. Typical landscape in the contaminated area surrounding the Fukushima Daiichi NPP (Source Brenda. Howard, Centre for Ecology and Hydrology).

Agricultural areas

The radiocaesium activity concentration in soils in farmland areas was measured to a depth of 15 cm to determine the spatial distribution decay corrected to 14 June 2011. Measurements were made from April to July 2011 for soil from six prefectures (Miyagi, Fukushima, Ibaraki, Tochigi, Gunma and Chiba). Overall, in the areas measured, the size of paddy fields with activity levels of 0–5000, 5000–25 000 and >25 000 Bq/kg was 991 km^2, 45 km^2 and 17 km^2, respectively. The equivalent values for other agricultural land were 367 km^2, 15 km^2 and 6 km^2, respectively. More recent information on the radiocaesium activity concentration in farmland soil for the end of December 2012 in the seven prefectures (and focused on contaminated areas in some cases) is summarized in Table 5.2–11. The estimated area of agricultural land where the contamination level exceeded 5000 Bq/kg was about 75 km^2 on 28 December 2012 [94].

Radiocaesium was retained mainly in the upper soil (to a depth of 0–5 cm) in paddy fields which had not been disturbed after the accident [95–97]. Such retention in the upper soil rooting zone is a well

established feature of radiocaesium [8]. However, for the majority of fields where soil was ploughed after the accident, radiocaesium was distributed in soil within the ploughing depth.

There is a wide range of soil types in the contaminated areas; the most commonly present soil groups are fluvisols, andosols and cambisols. International compilations of data show that plant uptake of radiocaesium is highly variable among different soil types [25, 48]. It also differs for various crops and decreases over time. From 2012, the contamination of agricultural produce in Japan, and hence the need for continued food restrictions or remediation, would have been expected to depend not only on the density of ground deposition but also on the soil type and the crop type associated with the different types of land use [47]. Initial studies by MAFF since the accident indicate that, at farms where the action level was exceeded, there were generally low amounts of exchangeable potassium in soil, and clear differences due to the soil types were not evident [98].

The transfer of radiocaesium to brown rice was determined in 2011 and 2012 for four soil types representative of agricultural soils present in Fukushima Prefecture, with geometric mean TF values varying in the range of 0.005 to 0.04 in 2011 and 0.004 to 0.009 in 2012 [99]. The highest transfer was from Brown forest soil, but the difference between the four soil types was not large [99]. The small variation in TF with soil type observed from early data is in agreement with the early findings of MAFF, as presented above. In experimental laboratory studies, the TF values for radiocaesium were lower in soil rich in vermiculite, probably due to the high sorption of caesium to the clay material [82].

TABLE 5.2–11. RADIOCAESIUM ACTIVITY CONCENTRATIONS* (^{134}Cs AND ^{137}Cs) IN PADDY FIELDS AND OTHER AGRICULTURAL LAND ON 28 DECEMBER 2012 (FOR FUKUSHIMA PREFECTURE, DATA ARE FOR NOVEMBER 2013) [94]

Prefecture	Radiocaesium activity concentration* (Bq/kg dry weight)				Number of plots of land in different contamination bands									
	Paddy fields		Other land		Paddy fields					Other land				
	Minimum	Maximum	Minimum	Maximum	Total	0–5000	5000 –10 000	10 000–50 000	>50 000	Total	0–5000	5000–10 000	10 000–50 000	>50 000
Fukushima	48	62 000	37	86 900	152	141	6	4	1	189	184	2	1	2
Tochigi	110	1040	62	2630	12	12	0	0	0	9	9	0	0	0
Miyagi	72	1310	110	860	21	21	0	0	0	6	6	0	0	0
Gunma	85	170	49	560	5	5	0	0	0	20	20	0	0	0
Ibaraki			230	560	0	0	0	0	0	2	2	0	0	0
Chiba	67	120	<16	190	3	3	0	0	0	8	8	0	0	0

*The radiocaesium concentration values are not average or typical values in the prefecture; the sampling points were selected by prefectures; higher contaminated locations were chosen in some prefectures. Soil samples include those from fields or lands in which farming is not operated due to the restriction of entering into the areas.

Information on TF for radiocaesium in different crops (other than rice) has been compiled by MAFF based on information in the scientific literature in Japan before 2011 [100]. Overall, the data are in

good agreement with the equilibrium TFs suggested by IAEA Technical Reports Series No. 472 [48], which suggests that dependency on the soil type will become evident in the longer term.

The lower radiocaesium activity concentration in food crops cultivated in the contaminated areas in subsequent harvests may be explained by the increased fixation of the radionuclide in the soils — most probably in the clay fraction. The ploughing of many kitchen gardens and orchards soon after the accident contributed to a reduction in the levels of radiocaesium in soils (through the dilution of the upper contaminated layers with deeper uncontaminated soil layers) [95].

Forests

Radionuclide deposition in forests can result in internal exposure of the general public through the consumption of wild foods, such as game (e.g. deer and wild boar), fungi, berries and other edible plants that contain elevated radiocaesium activity concentrations [101].

As some forested areas were partly abandoned, the population of some game species has substantially increased. Press reports indicate that the increased population of wild boar has led to the increased incidence of boar feeding on plants in abandoned agricultural fields and causing significant damage [102]. Similar effects were observed in the areas abandoned after the Chernobyl accident [44].

The high and sustained transfer of radiocaesium to various wild foods in forests means that particular attention needs to be paid to the utilization of the extensive forests for collection of these foods. To determine the need for prohibition of these types of food which people tend to collect for themselves, it is essential to understand and quantify the specific transfer characteristics of species in Japanese ecosystems [48].

Radiocaesium activity concentrations were measured in June 2012 in wood based commodities from forests, such as timber produced at 28 factories within 400 km of the accident, and they were consistently very low. Monitoring of radiocaesium in wood products continues to provide reassurance to the population and confidence in the safety of wood. Remedial measures are not currently required to decrease contamination of wood products [103].

Aquatic systems

Aquatic environments in Japan include freshwater and marine ecosystems. Forested catchments are steep and complex, and are linked to an extensive network of weirs and irrigation channels that support agriculture in floodplains (including paddy fields) and lowlands. Radiocaesium can migrate into downstream aquatic systems (initially freshwater and eventually marine) through erosion of soils and runoff from the catchments, primarily as suspended organic and mineral particulates [104–106].

Overall, radiocaesium activity concentrations in freshwater and marine ecosystems have been declining since the accident (see Technical Volume 4, Section 4.1). Nevertheless, monitoring is being continued, as levels may increase in the future due to erosion and runoff from contaminated catchments. This information will help to inform decision making processes relevant to remediation, while providing clear and understandable information that is widely available to both experts and the public.

5.2.9. Summary

Remediation policy

The release of large amounts of radioactive substances after the Fukushima Daiichi accident resulted in extensive contamination of the NPP and its surrounding areas. The external pathway was the

predominant route of exposure to radiation. Remediation activities to reduce exposures to radiation started in some areas during 2011. The remediation policy enacted by the Japanese Government, especially the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], was a key step in allowing the implementation of the remediation measures in the affected areas. Among other things, it created the necessary institutional arrangements for the implementation of a coordinated work programme involving different organizations at the national level. Issues addressed by the Act also include the prioritization of sites to be remediated and the allocation of funds to carry out the remediation works. The Act recognized the need to involve different stakeholders in the overall remediation process.

Remediation strategy

The relative importance of external dose as the main exposure pathway in the aftermath of the accident had a great impact on the definition of the remediation strategies implemented in the affected areas. Radiation doses from the intake of food were largely avoided owing to an extensive and comprehensive food monitoring programme and restrictions on the sale and distribution of foods. The remediation of residential areas and agricultural and forest systems has been labour intensive, and mechanization or automation has only been effective for large flat surfaces such as schoolyards. The diversity of contaminated surfaces has required a situation specific selection of various decontamination methods. Integration of the management of contaminated material derived from removal of soil into the overall strategy has been crucial. Consultation and agreement with concerned parties on remediation work has been essential for the establishment of the strategy, planning and commencement of remediation activities.

Continued optimization is appropriate for the planning of remediation, by concentrating efforts on measures which bring the greatest benefit in reducing doses to the public while avoiding unnecessary ecological and economic damage. The occupational hazards for remediation workers need to be balanced against the benefit of the procedure in terms of public dose reduction and the concerns of residents.

Application of radiation protection principles

The process of setting radiological criteria after the Fukushima Daiichi accident included the results of public and political debates. The authorities adopted a conservative reference level in the strategic planning of remediation (i.e. a long term goal of the additional dose of 1 mSv/y).

Human exposure pathways

In the context of the Fukushima Daiichi accident, external exposure was the dominant exposure pathway of people living in the affected areas. Internal exposure from ingestion of foods containing radiocaesium has been relatively small owing to the widespread restrictions on the sale of contaminated food and the comprehensive monitoring of its distribution, as well as the generally low bioavailability of radiocaesium in agricultural soils. In this circumstance, a reduction of the external dose of the general public by a decontamination of residential, industrial and educational facilities was an effective way of reducing dose rates for the public. Monitoring before and after the application of specific remedial action provided crucial site specific information on its effectiveness. In a limited number of cases, the effectiveness of the remediation was checked by the use of personal dosimeters that allowed the assessment of radiation doses for individual persons.

Dose assessment for guiding remediation activities

In the early phase of remediation in Japan in 2011, conservative approaches were applied to managing uncertainties and reference levels. The decision on the method used to estimate doses to people, and

the degree of conservatism, had consequences for the remediation strategy after the accident. In general, the decision led to an overestimation of predicted dose rates and relatively low derived reference levels. This, in turn, has the effect of increasing the quantity of contaminated materials generated in remediation activities, thereby increasing the costs and the demands on limited resources.

Environmental monitoring

The results of monitoring gamma dose rates and radiocaesium activity concentrations in food, soil and other environmental media provided the possibility for review and update of the remediation plans. Monitoring of both radionuclide deposition densities and ambient dose rates in the affected areas was crucially important in making decisions. To collect relevant data as fast as possible, various methods were developed and implemented in a concerted manner, such as car-borne monitoring, hand-carried walking monitoring, fixed points monitoring with portable survey meters and prediction codes for decontamination effectiveness. The detailed planning of the decontamination of residential areas was based on precise and detailed characterization. Local stations for the monitoring of foods allowed people in affected areas to bring food to be measured for radiocaesium content. Furthermore, facilities were also provided for whole body measurements.

Demonstration projects

Demonstration pilot projects to test the implementation of remediation techniques were useful for providing training and assessment of site specific effectiveness and applicability of remediation measures, as well as for building public trust and confidence (see Appendix I for more information). They also allowed comparison with previously reported data from other situations such as the Chernobyl accident. Two types of experiments were conducted. During small scale decontamination studies, the effectiveness of the decontamination of various types of surfaces was assessed. Later studies considered the feasibility of decontamination on larger areas to estimate the ambient dose rate reduction. The decontamination guidelines provide detailed information on how to carry out remediation for a wide population for residential areas, agricultural land and forests.

Remediation measures for aquatic ecosystems have been evaluated. Experience and information on best practices of remediation measures have been shared through various communication channels. As contaminated sediments of rivers and lakes do not generally impact the ambient dose rate of the surrounding environment owing to the radiation shielding effect of water, decontamination will only be implemented where there is the possibility of the shielding becoming ineffective owing to the drying-up of rivers or lakes and where the air dose rate in the surrounding living environment is significantly increased. Continuous monitoring, and associated R&D, will be conducted to better understand the environmental behaviour of radiocaesium throughout the entire river basin.

Return of the public to evacuated areas

Prioritization of remediation activities in the Special Decontamination Area (SDA) is based on estimations of radiation doses potentially received by the people living in those areas and the radiation doses to workers involved in remediation activities. The reduction of radiation doses due to natural processes such as physical decay, weathering and migration is taken into account. Current remediation conducted in the SDA is being complemented by restoration of infrastructure. Prospective planning for the return of residents to the SDA is carried out on the basis of post-remediation environmental measurements and appropriate assessments of radiation doses to be received in those areas. Individual doses of the returning residents will be reduced as low as reasonably achievable and will comply with national regulations. The most effective way to determine residual individual doses is based on personal dosimeters and whole body measurements.

Progress and effectiveness of remediation

There has been a large effort in implementing remediation in both the ICSA and in two zones of the SDA. Priority has been given to public and residential areas. With regard to ICSA areas outside Fukushima Prefecture, decontamination works were completed in about 75% of all municipalities as of November 2014.

For the ICSA areas inside Fukushima Prefecture, decontamination works were completed in about 60% and 80% of planned residential areas and public facilities, respectively, by November 2014. For SDA 1, decontamination has been fully completed in four municipalities, and it was completed for residential areas in two other municipalities by November 2014. In SDA 1 and 2, decontamination of all other residential areas is planned to be completed by the end of March 2016. In large parts of the ICSA, in 2012, the additional average doses to the public from radiocaesium deposition, estimated on the basis of the methodology used in the UNSCEAR report of 2014 [13], were below 1 mSv/y. By the time that remediation was conducted, the residual doses in these areas, especially in municipalities outside of Fukushima Prefecture, were lower than 1 mSv/y. Nevertheless, the remediation measures have addressed the protection of human health and important social concerns, providing reassurance to the local communities and maintaining economic activity.

The initial demonstration projects provided useful information on the effectiveness of various decontamination techniques in achieving reductions in dose rate for various types of surfaces. Later studies considered the feasibility of the decontamination of larger areas in the evacuated zones and estimated the effectiveness of these measures in reducing ambient gamma dose rates and exploring the implications for worker safety and waste management. For example, research performed in residential areas of Tamura City and Naraha Town municipalities (within the SDA) showed that ambient gamma dose rates had been reduced by an average of 36% and 46%, respectively. Average dose rate reductions in the two municipalities following remedial actions in farmlands, forests and roads were between 21% and 44%.

The data indicate that the reduction of ambient gamma dose rates was more significant in areas with higher initial dose rates. After remediation, the decline of the gamma dose rates continued owing to the natural processes of weathering and radioactive decay.

Generation of contaminated material and initial management

A large amount of contaminated material and waste has been generated from remediation activities in the affected areas, partly as a consequence of the conservative radiological criteria established as part of the remediation strategy. Because of the time required to establish the Interim Storage Facility, the initial waste storage was implemented in numerous temporary storage sites in each of the affected municipalities. Most, but not all of the contaminated material was generated by topsoil removal in residential areas and farmland, and much of the contaminated material has low radiocaesium activity concentrations.

Predicting the environmental behaviour of radiocaesium for remediation purposes

The data on the environmental behaviour of radiocaesium were analysed after the Fukushima Daiichi accident and used to set some action levels in a conservative manner. To guide remediation in agricultural areas, site specific scientific data on radiocaesium mobility in different soil types and the effect of remediation measures are now being reported. The long effective half-life of ^{137}Cs in some ecosystem compartments such as mushrooms and game animals, as well as the potential for redistribution of radiocaesium in steep, forested catchments, requires special monitoring activities as an important component of sustainable future remediation strategies.

5.2.10. Observations and lessons

— **It is necessary to prepare in advance for post-accident recovery in situations that require the remediation of large areas, for example, in the event of a major nuclear or radiological accident.**
Remediation preparedness would include planning, prior to any accident, for the implementation of generic remediation policies and the establishment of criteria for residual doses and contamination levels. Generic remediation plans must be readily adaptable to specific situations.

— **Further international guidance is needed on effective implementation of the radiation protection principles of justification and optimization in existing exposure situations.**
This could include methodologies for assistance in the selection of case specific remediation action levels defined in terms of residual doses or derived quantities as well as procedures for a periodic review of action levels adopted in the early post-accident period to take account of changing radiological conditions. It could also include guidance on appropriate decontamination and remediation techniques. The guidance needs to address technical and scientific issues in addition to socially relevant factors and could promote the development of a coherent, transparent and collectively accepted decision making process.

— **In choosing the reference level to guide the overall remediation strategy following a nuclear accident, it must be clearly understood by the government, the regulator and the affected public that this level is a long term target (often based on equity and ethical considerations),** whereas short term remediation targets must be realistic and economically defensible, based on sound optimization processes. The challenge is to achieve understanding among the affected public of the short term goals that are most beneficial socially. The choice of the additional dose of 1 mSv/y as a long term objective in post-accident recovery is ethically defensible on equity grounds, but will often be inappropriate for use as a short term target on grounds of feasibility and optimized social benefit.

— **Large scale radiation mapping created from aerial or systematic ground monitoring has value in identifying major areas requiring remediation planning.**
However, the detailed remediation strategies depend on a more specific evaluation of local radiological conditions supported by area specific monitoring.

— **Remediation strategies need to be developed on a case by case basis and need to be flexible to enable adjustment to the situation as it develops.**
They must take into account:
- The doses received by the most exposed groups of the population.
- Natural decay of the radionuclides that comprise the contamination, as well as anticipated natural weathering processes. These processes should be taken into account in determining the remediation strategy, including the timescale over which, in the absence of active remediation activities, these factors will reduce doses to acceptable levels.
- The scale of remediation efforts and site specific factors, such as the effectiveness of dose reduction and the doses received by workers.
- The amount of contaminated material generated.
- The various resource constraints (e.g. financial resources, storage and disposal facilities, logistics and qualified human resources).

— **As part of the remediation strategy, the implementation of rigorous testing and controls on foods is necessary to prevent or minimize ingestion doses.**
The systematic implementation of rigorous testing of and controls on food after the accident demonstrated that ingestion doses can be kept at low levels.
To establish confidence in locally produced food, local monitoring stations were set up to allow people in affected areas to bring food to be measured. This control of ingestion doses simplified the recovery by allowing remediation to focus on techniques that reduce external doses.

— **Information from pilot projects for testing the effectiveness and feasibility of remediation measures plays an important role in the planning of remediation strategies.**

The pilot projects provide training and experience in site specific decontamination and facilitate the development of guidelines for carrying out decontamination activities and procedures for ensuring worker safety. The involvement of stakeholders helps promote understanding and acceptance of remedial actions.

— **Decontamination in residential areas and public facilities is an effective way to reduce doses to the public for gamma emitting radionuclides.**
This applies especially to situations where internal exposure is not a major component of the dose received by the population due to the implementation of restrictions on the production, sale and distribution of agricultural products.

— **The dose assessment approaches used in the decision making for existing exposure situations must be regularly re-evaluated at different stages of the remediation process.**
In general, the models need to be sufficiently conservative to be acceptable to all parties involved; at the same time, they need to be sufficiently realistic to allow appropriate optimization of protection from remediation.

— **Data must be obtained from environmental and individual monitoring and characterization to provide necessary inputs to dose assessment models.**
Use of these data is essential for enhancing the reliability of dose assessments and predictions and for allowing remediation strategies to be tailored to site specific conditions.

5.3. ON-SITE STABILIZATION AND PREPARATIONS FOR DECOMMISSIONING

5.3.1. Introduction

Under normal circumstances, the decommissioning of an NPP is a planned activity that is initiated when the decision is made to end operations. Post-accident decommissioning presents a completely different set of circumstances. There are unknowns regarding the condition of the facility, fuel and equipment. Determining the path forward for these unknown or uncertain conditions will take longer than normal decommissioning and may require the development of new technology. The decommissioning of the facility, that is, removal of the systems and structures, cannot begin until fuel and fuel debris removal has been achieved, and other stabilization end conditions have been established. Stabilization comprises the planning and actions required to ensure that the NPP structures (such as the buildings that house the damaged reactors), systems (such as electrical supply) and components (such as pumps or motors) are placed in a stable condition and can function and operate for as long as may be required.

On 17 April 2011, TEPCO released the Roadmap towards Restoration from the Accident at TEPCO Fukushima Daiichi Nuclear Power Station [107].This roadmap detailed immediate actions to address the emergency, including cooling the reactors and spent fuel pools, management of contaminated water, mitigation of the release of radioactive materials to the atmosphere and soil, radiation monitoring and decontamination. The roadmap identified two targets, to be known as steps, in managing the emergency:

— Step 1 was “Radiation dose is in steady decline” [107];
— Step 2 was “Release of radioactive materials is under control and the radiation dose is significantly being held down” [107].

On 16 December 2011, the Government of Japan and TEPCO declared that Step 2 had been achieved. On 21 December 2011, TEPCO issued its Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO’s Fukushima Daiichi Nuclear Power Station Units 1–4 (hereinafter referred to as the ‘Roadmap’) [108]. The issuance of this comprehensive strategic plan marks the beginning of the time period covered by this section. Its focus is solely on on-site activities conducted within the boundaries of the Fukushima Daiichi NPP.

This section describes the process, progress and planning undertaken by TEPCO and the Government of Japan at the Fukushima Daiichi NPP to achieve a decommissioned end state[16]. In this context, 'on-site' refers to the 348 ha area of the Fukushima Daiichi NPP.

The time span for the activities leading to and including decommissioning is presently estimated to be 30 to 40 years. These activities and the schedule estimates are given in the Roadmap. Its provisions, including those for R&D, are outlined. In addition to R&D, these provisions include: stabilization and reliability improvements; controlling water ingress; spent and new fuel removal and storage; and fuel debris removal and storage. In addition, decommissioning alternatives based on past experience at other facilities and potential end states are described.

5.3.2. Management and regulation of on-site activities

5.3.2.1. Management of and funding for on-site activities

Since the accident, TEPCO and the Government of Japan have had distinct roles in on-site decommissioning actions. In the broadest terms, TEPCO is responsible for implementing actions toward decommissioning, while the government is leading R&D activities that will be needed to accomplish the decommissioning. The government has also taken a proactive role in implementing measures to achieve a timely resolution of issues associated with contaminated water and decommissioning planning.

TEPCO is responsible for funding activities and operations that lead towards decommissioning. The R&D work is funded directly by the government and executed by contractors, who are subject to a selection process.

Main roles of the Government of Japan

The main roles of the Government of Japan include: (1) development of basic policy; (2) identification of potential risks and development of preventive and multilayered measures; (3) assessing and monitoring progress; (4) providing financial support; and (5) providing information domestically and internationally.

TEPCO organizational structure

On 1 April 2014, TEPCO created a new organizational entity to focus solely on the cleanup activity at the NPP. Known as the Fukushima Daiichi Decontamination and Decommissioning Engineering Company, it provides a focal point for the management and coordination of the many fields of science and technology that will be involved in the decommissioning efforts and the number of support organizations that will be needed over the long term. The new organization is led by the Chief Decommissioning Officer, who reports directly to the President of TEPCO [109].

5.3.2.2. Regulation of on-site activities

After the accident, the National Diet of Japan (the national parliament) established the Fukushima Nuclear Accident Independent Investigation Commission to investigate the causes of, and the emergency response to, the accident and to make recommendations on how to prevent future nuclear accidents. As a result of this investigation, the NRA was established on 19 September 2012 as an independent commission affiliated with the MOE, responsible for the regulation of the safety of the

[16] The term end state is used in relation to decommissioning activities as the final state of decommissioning; see the IAEA Safety Glossary [2].

decommissioning process of the Fukushima Daiichi NPP [110]. The Prime Minister appointed the chairman and commissioners of the NRA. On 1 March 2014, the Japan Nuclear Energy Safety Organization (JNES) was abolished and absorbed by the NRA. The NRA also holds jurisdiction over part of the affairs of the National Institute of Radiological Sciences (NIRS) and the JAEA.

The Act for Establishment of the Nuclear Regulation Authority [110], which was promulgated on 27 June 2012, came into force on 19 September 2012. The NRA was officially inaugurated on the same day. The NRA developed a new regulatory framework for the regulation of so-called 'disaster-experienced facilities', which need special measures to prevent further accidents and to ensure nuclear security. On 7 November 2012, the NRA designated the Fukushima Daiichi NPP a 'Specified Reactor Facility', which is a facility where a nuclear accident has occurred and special regulations commensurate with the condition of the equipment are stipulated for the designated facility.

On 7 November 2012, the NRA presented TEPCO with a document concerning measures to be taken for the specified reactor facilities to be installed at Fukushima Daiichi Nuclear Power Station [111], which required TEPCO to develop and submit to the NRA an implementation plan to address those matters.

The Implementation Plan consists of seven sections corresponding to the measures to be taken as specified by the NRA [112, 113]. Although the Implementation Plan addresses all six units at the Fukushima Daiichi NPP, only Units 1–4, which were damaged by the accident, are discussed here. The Implementation Plan describes the design and operating specifications for each facility, including their operational limits and controls. These limits and controls are based on the results of safety analyses conducted by TEPCO and establish a basis for compliance. The plan also develops and reviews procedures and describes the actions to be taken in response to an emergency. On 7 December 2012, TEPCO submitted the Implementation Plan to the NRA, which reviewed it to verify that the matters defined had been appropriately addressed. To aid in the review, which was open to the public, the NRA formed the Supervision and Evaluation Committee for the Specified Reactor Facilities, comprised of knowledgeable and experienced individuals. The Implementation Plan was approved on 14 August 2013. TEPCO is responsible for carrying out the activities stipulated in the Implementation Plan. The NRA will conduct inspections and reviews to confirm that the measures described in the plan are being applied [114].

Once approved by the NRA, the Implementation Plan became the operating licence. In Japan, under normal circumstances, the laws require a decommissioning plan be developed after the fuel has been removed, consistent with international standards [115] and Article 38 of the Reactor Regulation Act [6], which prescribes that a report be submitted to the competent minister in advance of decommissioning. Nevertheless, in recognition of the fact that conditions will change as work toward decommissioning advances at the Fukushima Daiichi NPP, TEPCO will develop and submit applications for changes to the Implementation Plan, continuously ensuring safety commensurate with the prevalent conditions. The NRA retains review and approval authority for such changes.

An example of this process was the authorization for the removal of spent fuel from Unit 4. The NRA's measures to be taken established requirements for TEPCO to develop a plan and implement actions to transfer fuel from the reactor spent fuel storage pools to the common spent fuel pool. These required TEPCO: (1) to maintain the subcritical condition of the fuels; (2) to take measures to prevent the fuel assemblies from falling and to mitigate radiation effects to the environment in case of falling; and (3) to store the removed fuels in appropriate conditions, including cooling [111].

Based on these requirements, TEPCO prepared an amendment to the Implementation Plan for fuel removal from the Unit 4 spent fuel storage pool [116] and submitted it to the NRA for review and approval. Details on equipment design for the spent fuel removal and technical procedures for

conducting the work were included. After a review, the NRA approved the amendment in October 2013, with some modifications to the methods to assess fuel integrity.

Subsequently, pre-operational inspections of worker training, safety administration, emergency response measures and other safety aspects of fuel removal were conducted by NRA staff on-site. The spent fuel removal operations started on 18 November 2013, and were inspected regularly by the NRA (for more information on fuel removal see Section 5.3.4.3).

The current approach is to apply a similar licensing procedure to the future activities of fuel removal from Units 1–3, fuel debris removal and the subsequent decommissioning of Units 1–4 [117].

Additionally, the NRA identified a regulatory requirement for managing the additional effective dose at the site boundary in February 2014, and Measures for Mid-term Risk Reduction at TEPCO's Fukushima Daiichi NPS[17] in February 2015, to be actively involved in regulation as compared to regulation for normal plants [118].

5.3.3. The mid- and long term roadmap towards decommissioning

5.3.3.1. Background

On 9 November 2011, the Minister of Economy, Trade and Industry and the Minister for the Restoration from and Prevention of Nuclear Accident[s] issued a joint ministerial order directing the development of a document [108] that would become the strategic plan for recovery and decommissioning. This document, known as the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4, was developed jointly by TEPCO, the Agency for Natural Resources and Energy (ANRE) and NISA, the regulatory body at the time; it was issued on 21 December 2011.

The Roadmap is a comprehensive, high level strategic plan for those supervising the recovery. As a strategic plan, it provides policy and broad guidance to those responsible for carrying out the work. It also provides a source of information for those not directly involved but who need to be informed. It is based on four basic principles:

- Systematically tackle the issues while placing top priority on the safety of local citizens and workers.
- Move forward while maintaining transparent communications with the local population and citizens of Japan to gain their understanding and respect.
- Continuously update the Roadmap in consideration of the on-site situation and the latest R&D results.
- Harmonize the efforts of TEPCO and the Government of Japan to achieve the goals indicated in the Roadmap.

The first Roadmap was based on what was known about Fukushima Daiichi NPP conditions at that time combined with available information from around the world for recovery from other major accidents. The Roadmap had been revised twice since 2011, at the time of writing, with the most

[17] The term NPS (nuclear power station) is used in the title of this document and is therefore reproduced here, although the term NPP (nuclear power plant) is used elsewhere in this volume.

recent version available issued on 27 June 2013 [119, 120]. [18] The update reflects the increased experience gained from the previous two years of work at the site and the resultant improved understanding of the actual conditions, as well as the magnitude of the challenge that lies ahead. The planners of the Roadmap have taken into consideration the results of international events organized in Japan, such as experience and technology workshops with participation by international experts.

5.3.3.2. The Roadmap

The Roadmap defines the work to be executed and the associated schedule for execution. With respect to scheduling, the Roadmap describes three phases of work:

— **Phase 1** — the period of time until retrieval work from the spent fuel pool (SFP) is initiated. Phase 1 was declared complete when removal of fuel from the Unit 4 SFP was initiated in November 2013.
— **Phase 2** — the period of time until the fuel debris removal work is initiated. This is the present phase of the effort. Phase 2 is projected to be completed within ten years, and started after the achievement of the cold shutdown condition. At the time of writing, it is anticipated that Phase 2 will last for another eight years.
— **Phase 3** — the period of time until the completion of decommissioning. This phase is projected to be completed in 30–40 years.

With respect to the scope of work, the Roadmap describes the strategic approach for areas of work concerning:

— The approach to ensuring safety;
— Mid term and long term measures relating to decommissioning;
— Systems and environment to facilitate work;
— R&D requirements.

The Roadmap also addresses issues including: human resource development, cooperation with the international community and communication. An overview and brief description of elements 1–4 of the current Roadmap are given below.

Approach to ensuring safety

TEPCO is responsible for ensuring on-site safety. The Roadmap provides the strategic objectives for safely meeting the aim of reducing risks and optimizing the removal of fuel and fuel debris. The Implementation Plan (Section 5.3.2.2), which is prepared by TEPCO and approved by the NRA, describes how the goals will be achieved.

For risk reduction and optimization in the Fukushima Daiichi NPP as a whole, TEPCO conducts assessments including off-site environmental impacts, confirms that their risk reduction and optimization efforts are sufficient to ensure safety both on-site and off-site and carries out risk assessments for hypothetical emergency events involving the release of large amounts of radioactive materials. In addition, TEPCO identifies the risks that may exist depending on the volumes and types of radioactive materials and conducts assessments of the possibility of occurrence of those events, their temporal progression and the potential impact if they occurred. Based on these assessments,

[18] It is anticipated that there will be further revisions to the Roadmap as plans are adapted in response to changing conditions and new information. The third revision of the Roadmap was issued during the final preparation of this Technical Volume (June 2015). This modified the schedule and the approach for fuel and debris removal and refined approaches for risk reduction, communication with local stakeholders, reduction in workers' exposures, and management of research and development [121].

multilayer and redundant measures for protection are established to protect against the possible risks. There are also measures to reduce dose to workers, to ensure medical support and to reduce and control radiation dose levels at the boundaries of the NPP (see Section 5.3.4.2).

For emergency preparedness, TEPCO has established a disaster prevention operations plan for nuclear operators for the Fukushima Daiichi NPP. Should a new emergency occur, TEPCO would respond by using this plan combined with experience following the Great East Japan Earthquake (see Technical Volume 3 for more information on emergency response).

Mid- and long term measures relating to decommissioning

The central element of the Roadmap is the schedule and description of the work that must be completed to decommission the accident damaged reactors. Given that the accident affected each of the four units to a different degree, there are separate schedules for each unit as well as a general schedule for the activities that are common to all four units (such as water management, waste process and disposal and radiation dose reduction).

For each reactor unit, plans for removal of fuel and fuel debris are described. Plans are proposed to account for the possible range of conditions that may be revealed as more information is gained in the processes of removing fuel and debris.

A key feature of the schedule is the identification of 'holding points'. These holding points are defined as "important junctures at which decisions must be made regarding the transition to the next step" [120]. These decisions may concern a choice of technology, a decision regarding the need for additional R&D or consideration of whether the next step or operation should be changed based on results of preceding actions. The holding points offer a key opportunity to demonstrate transparency in the process and communication of key decisions.

Five technical plans continue to be implemented or developed to provide more specific strategies for key technical activities. These include plans for:

- Continuous monitoring of cold shutdown status of reactor cooling, reducing hydrogen explosion risk and improving reliability of circulating water cooling capability;
- Contaminated water treatment, including measures to reduce the volume and inflow and to improve the decontamination capability of the water treatment facility;
- Reduction of radiation dose levels in the entire plant, preventing dispersion of contamination, including ocean pollution, and reduction of radiation dose at the site boundaries;
- Management and processing and disposal of solid radioactive waste;
- Decommissioning the reactor facilities, including consideration of multiple decommissioning scenarios that will be reviewed within Japan and by the international community.

Systems and environment to facilitate work (human and organizational factors)

Measures toward decommissioning and final decommissioning will be ongoing for several decades. Even as the work progresses, areas with high radiation doses will continue to exist. To this end, TEPCO has established an organization for centralized monitoring of the health and radiation exposure of workers inside and outside the company (Nuclear Power Health and Safety Centre).

Efforts to improve worker safety are ongoing. There is a downward trend in the number of injuries and incidents related to heat stroke [19] [120]. Policies and guidance include such measures as involving the work supervisor in reviews, improving rest areas and optimizing the use of protective gear.

Plans for managing and ensuring the availability of a trained workforce have been established. Actions are scheduled to coincide with the phases described for the measures toward decommissioning. A review of workforce needs will be included with future revisions of the Roadmap.

The Government of Japan recognizes that addressing the workforce needs for decommissioning will require a long term effort. In order to maintain technological expertise and knowledge, the government considers education and training to be a long term commitment. Universities and research organizations will support meeting these needs through funding provided by the government.

Research and development

Much of the work to be accomplished at the Fukushima Daiichi NPP is first of a kind and will be dependent upon equipment and technology that is yet to be developed or has yet to be implemented on such a large scale. Therefore, a parallel R&D programme has been established in coordination with the work efforts described in the decommissioning Roadmap. In this regard, the Government of Japan will play a leading role.

On 8 August 2013, METI authorized the establishment of the International Research Institute for Nuclear Decommissioning (IRID).[20] It is composed of 17 founding members representing Japanese incorporated administrative agencies and Japanese manufacturers and electric utilities. The aim of the IRID is:

— Researching and developing technologies for nuclear decommissioning;
— Promoting cooperation with international and domestic organizations on nuclear decommissioning;
— Developing human resources for R&D [124, 125].

The IRID seeks to promote cooperation with related organizations worldwide to ensure access to the broadest range of ideas and technological proposals.

R&D projects are broadly categorized into activities related to (see Table 5.3–1):

— Removal of fuel from the SFP;
— Preparation for fuel debris removal;
— Processing and disposal of solid radioactive wastes.

Additional R&D activities concern the identification of backup plans and solutions using the latest remote control technology for work processes that are expected to be very challenging (e.g. owing to high radiation dose rates).

[19] Heat stroke occurs when the body becomes unable to control its temperature: the body's temperature rises rapidly, the sweating mechanism fails, and the body is unable to cool down. [122].

[20] In 2014, IRID was reorganized into the Nuclear Damage Compensation and Decommissioning Facilitation Corporation [123].

TABLE 5.3–1. PROJECTS RELATED TO THE THREE BROAD R&D AREAS [125]

	R&D Activities
1	*Removal of fuel from the spent fuel pool*
	Evaluation of long term integrity of fuel retrieved from SFP
	Examination of the processing methods of damaged fuel etc. retrieved from SFP
2	*Preparation for fuel debris removal*
	Development of remote decontamination technology for the inside of the reactor buildings
	Formulation of a comprehensive plan for dose reduction
	Development of technology for inspection and repair to stop leakage of water from the primary containment vessel (PCV)
	Development of technology for inspecting the inside of the PCV
	Development of technology for inspecting the inside of the reactor pressure vessel (RPV)
	Development of work methods and devices for removing fuel debris and in-core structures
	Development of technologies for the loading, transfer and storage of in-core fuel debris
	Development of techniques for evaluating the integrity of the RPVs/PCVs
	Development of technologies for controlling fuel debris criticality
	Analysis of the status in the core by means of advanced accident sequence analysis technology
	Establishment of the characteristics of debris using simulations and development of fuel debris treatment technology
	Establishment of nuclear material accountancy and control measures for the fuel debris
	Development of technologies for in-core fuel debris detection
	Development of technologies for radioactive material detection in the suppression chamber
3	*Processing and disposal of solid radioactive waste*
	Processing and disposing of the materials contaminated with radioactive nuclides originating from damaged fuels that could contain seawater, zeolite and sludge

5.3.4. Preparations for decommissioning

Under normal circumstances, decommissioning of an NPP is a planned activity that is initiated when the decision is made to end operations. To prepare, fuel is removed, it is ensured that the status of any contamination is well known and documented, the licence condition for decommissioning is well defined and the necessary industrial experience is well established. It is therefore possible to schedule and contract with capable and experienced companies, and technology is sufficient for achieving the required end state in a safe manner [126].

Post-accident decommissioning presents a completely different set of circumstances. There are unknowns regarding the condition of the facility, fuel and equipment. Determining the path forward for these unknown or uncertain conditions will take longer and may require development of new technology. As described below, this includes actions to reinforce the structural stability of the facility and design and installation of systems to ensure that cooling needs are met. Decommissioning of the facility, that is, removal of the structures, systems and components (SSCs), cannot begin until fuel and fuel debris removal has been achieved and other stabilization end conditions have been established [126].

5.3.4.1. Stabilization and reliability

Preparation for decommissioning of an accident damaged facility such as the Fukushima Daiichi NPP first involves establishing stable conditions (that is, stabilization) and ensuring that there are SSCs in place that will reliably maintain those conditions for the long term or until their functions are no longer needed. Experience has shown that there is significant variability in the conditions following a nuclear accident [126]. Hence, it is not possible to formally define the stabilization phase in a way that is applicable to all post-accident conditions. Stable conditions are a prerequisite for the objective of removing nuclear fuel and the nuclear fuel debris resulting from the reactor core meltdowns. Stabilization also serves to reduce radiation levels within work areas and contributes to lower off-site doses.

The Roadmap shows that preparation for decommissioning is anticipated to take about three decades. Maintaining and improving the conditions achieved with stabilization includes programmes and methods to ensure the long term reliability of SSCs needed for the recovery and cleanup leading to decommissioning. The reliability of SSCs is ensured in several ways. Diversity of systems for individual functions (such as cooling) and redundancy of components within systems are two strategic approaches for such assurance. These are implemented, for example, by installing multiple backup features and by replacing and/or upgrading mobile and temporary SSCs to augment permanent ones. To understand the threats to reliable performance over the long term, inspections, monitoring activities and evaluations are conducted to account for aging effects, degradation of components owing to corrosion (e.g. as a result of the salt environment) and the impact of any future tsunamis, earthquakes or other natural events [126].

The measures to carry out stabilization and ensure reliability of SSCs at the Fukushima Daiichi NPP that are of particular importance for an accident damaged NPP are described below. There are other functions typical of any power plant that must also be maintained and operated by the plant staff (for example, non-essential water supply systems, non-essential electrical power and non-emergency communications). The following subjects are described in this section to illustrate their importance to the Fukushima Daiichi NPP on-site recovery:

— Monitoring plant conditions;
— Cooling the fuel and fuel debris;
— Maintaining nuclear subcriticality;
— Controlling hydrogen;
— Ensuring reactor building structural stability;
— Controlling water ingress and preventing leakage to the environment;
— Assuring essential electrical power feed;
— Assuring the performance of major safety functions over the long term.

Monitoring plant conditions

A severe accident causes the destruction of many of the plant's normal instruments. Both during the emergency phase of accident response and for subsequent recovery activities, many of the functions for which these instruments were designed must nevertheless continue to be monitored. It is important to determine vital parameters that must be monitored (such as temperature, neutron multiplication and water levels in the PCV).

Methods must be established to measure those parameters, either with installed instruments for direct detection or by indirect methods (such as monitoring of short lived noble gas release to detect possible nuclear criticality, as described later). With time, some monitoring may no longer be needed, or other monitoring may need to be improved. For example, as access is gained to fuel debris, it may become possible to directly monitor neutron multiplication with instruments designed for that purpose. Some

parameters will be more difficult to measure than others; for example, establishing an automatic measurement of water level is currently a challenge.

Specific means for monitoring related to particular functions at the Fukushima Daiichi NPP are described in the subsections that follow.

Reliability of monitoring is important. Examples of means to accomplish this include backup systems and components, diversity of detection methods, battery backed power supplies and duplication of monitoring centres at remote locations. Human observation and remote cameras (with or without interpretive software) can also serve as a means of detection.

Presently, monitoring and surveillance of plant parameters is accomplished by use of instrumentation that survived the accident, with portable and permanent monitoring equipment that has been installed, and by replacing degraded instrumentation. The presence of operational personnel in many areas, such as the operational floor of the Unit 4 SFP, augments the monitoring systems [120, 127].

Cooling of the fuel and fuel debris

Maintaining stable conditions for the damaged fuel and fuel debris is one of the most important activities to prevent further release of radioactivity. This applies to the spent fuel in the SFPs, as well as the damaged fuel and fuel debris material resulting from the overheating of the core during the accident. Removal of decay heat is of paramount importance and is a prerequisite for other recovery activities.

Even after a shutdown condition has been reached and nuclear fuel/fuel debris can no longer achieve criticality, decay of radioactive fission products within the fuel continues to produce heat. The decay heat generation rate decreases exponentially with time.

Cooling to prevent overheating must be maintained until the decay heat generation is so low that passive cooling is sufficient. This condition will not be reached for several years after the accident.

Water cover over the top of the spent fuel was ensured immediately after the accident by the use of pumper trucks to initially spray sea water and subsequently fresh water into the spent fuel storage pools of the units using a closed loop cooling system. While underwater video showed that there was building debris in the pools, it also verified that the spent fuel had remained within the storage racks [120, 127].

Immediately following the accident, seawater was injected into the RPVs to cool fuel debris using the fire system piping and fire engines. Since May 2011, cooling has been achieved by the injection of fresh water through the feedwater system piping using the temporary electric pumps in Units 1–3. Temperatures measured inside the PCVs at Units 1–3 exceeded 100°C until mid-July 2011. Thereafter, the monitoring of RPV and PCV temperatures showed a continuous cooling of the reactors. Until early December 2011, control of cooling was performed by adjusting the amount of circulation water injected via the feed water line through the RPV downcomer area and lower plenum into the core region. In December 2011, additional injection paths were established from above the core regions via the core spray systems. During this transition, temperatures were reduced to below 100°C. In order to enhance reliability of water injection to the RPVs, redundancy and diversity of water and power sources have been implemented by the use of multiple pumps, tanks and redundant off-site and on-site power sources [127].

At the time of writing, one filtrated water tank (8000 m^3), two purified water tanks (2000 m^3 each) and condensate storage tanks (CSTs) (1900 m^3 for Unit 1 and 2500 m^3 each for Units 2 and 3) provide cooling water sources. The water injection pump near each CST (20 m^3/h) is used as the primary

water injection pump. For these pumps, two lines of off-site power are available. An additional emergency water injection pump at a higher elevation (20 m^3/h) is available as a backup [117].

Even in the case of loss of off-site power, one of these pumps would be operable through the on-site emergency power supply. The emergency water injection pump and the water injection pump near the purified water tank (37 m^3/h) are available, since the emergency diesel generators dedicated to these pumps are installed at a higher elevation. In addition, water can be retrieved from a nearby hydro dam. Seawater injection by use of fire engines is available as a final option [117].

Spent fuel cooling

It is necessary to cool spent fuel in the pools within the reactor buildings so that the water temperature is maintained below 65°C in the SFPs for Units 2 and 3 and below 60°C in Unit 1. Stable cooling of the fuel in the SFPs of Units 1–4 has been established using part of the original cooling system and newly installed heat exchangers. To maintain this function until all the spent fuel has been removed, and for potential subsequent use of the system when fuel debris removal takes place, the following major necessary measures have been identified:

- Replacement of the secondary pressure hoses with polyethylene pipes and installation of sunscreens on the outdoor pressure hoses;
- Replacement of backup components for the active and main components of the pumps, heat exchangers and the cooling tower;
- Installation of switchboards and panels to provide the means to supply power among units from a variety of sources;
- Installation of a temporary emergency diesel generator (EDG);
- Installation of an additional source of water from an external water injection line directly entering into the pool.

Improvement of the chemical composition of the water in the SFPs for long term stable cooling is important. During the accident, seawater was injected into the SFPs of Units 1–4. In order to mitigate the adverse effects of salt, such as corrosion of structural components, TEPCO used reverse osmosis to return the water to acceptable conditions. Treatment was completed at all units by March 2013. In addition, hydrazine (a reducing agent) has been added, as needed, to the pool water of Units 1–4 to reduce corrosion [128].

Fuel debris cooling

A relatively stable cooling of the fuel debris in Units 1–3 has been established and is adequate for removing heat. The requirement for cooling fuel debris is to keep the RPV temperature below 100°C. However, to account for possible measurement uncertainty, an operating limit of 80°C is used.

The damaged fuel and fuel debris within the RPVs and primary containment are continuously cooled by recirculation of water that is leaking into the turbine building. For this purpose, a circulating water injection line has been installed. This line has a large circulation path in which radioactive caesium is removed by zeolite column (see Fig. 5.3–1). Future plans include creating a shorter loop (not shown in this figure) in which some equipment will be located indoors; this will improve reliability, decrease the risk of leakage and reduce the human and equipment resources required to maintain the systems in a good working condition [128].

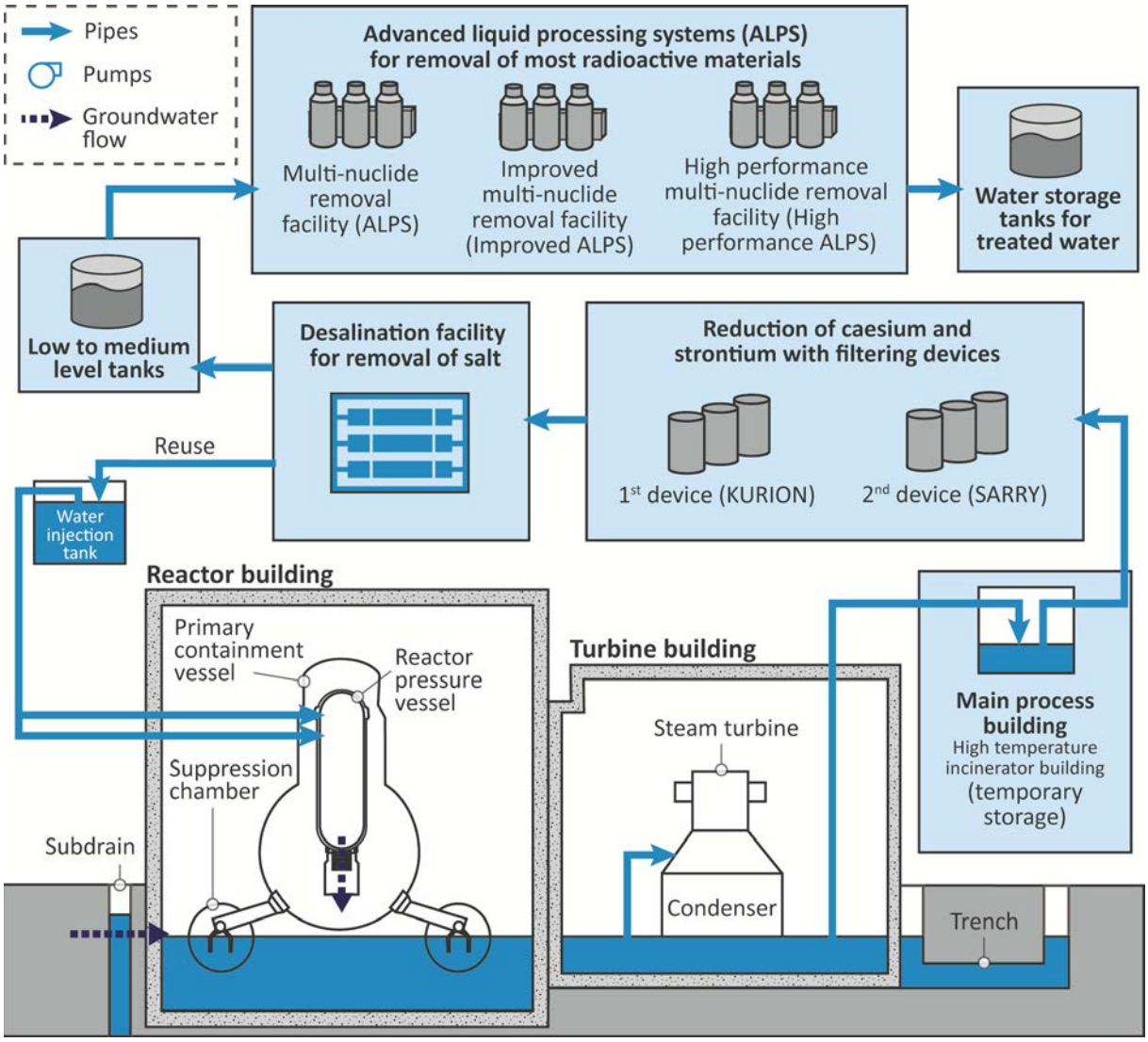


FIG. 5.3–1. Cooling loop and management of contaminated water [128].

In order to maintain reliable water injection for cooling over a long period, in addition to shortening the loop in the future, supplementary major measures taken are that:

— Piping has been interconnected so that water from the CSTs originally dedicated to Units 1, 2 or 3 can be used for any of these units.
— Interim water injection by use of hoses for the RPV and PCV have been replaced with polyethylene pipes.

As a consequence, the water injection function is ensured by a primary system and four backup systems [129].

Maintaining nuclear subcriticality

Criticality is a condition that can be achieved in fissile materials (e.g. uranium and plutonium isotopes), where neutron generation is balanced by neutron loss. For reactor fuel materials surrounded by water, criticality can occur if the concentration of fissile materials is sufficiently high. If criticality is reached and conditions are such that neutron production is not managed in such a way as to control the release of energy, the temperature of the material and the surroundings can continue to increase.

Therefore, an important control function at Units 1–3 is to maintain subcritical conditions within the fuel debris.

Criticality is unlikely in the destroyed fuel because relatively precise configurations of fuel, water and fuel structural materials are required for criticality; nevertheless, to ensure safety, it is essential to prevent any large scale energy generation from a fission reaction.

An important aspect of prevention is to detect the potential onset of such reactions. At the Fukushima Daiichi NPP, the normal operational instruments for monitoring criticality were destroyed by the accident. To compensate for this loss, criticality is monitored by detection of xenon (more specifically ^{135}Xe) in the gas control system. In the event of a nuclear criticality incident, ^{135}Xe would be released to the PCV because of the breached condition of the RPV and would be detected via the PCV gas control system. The reliability of the detection system is described in the subsection 'Controlling hydrogen' below as part of the discussion of hydrogen control.

Should the presence of xenon be detected, borated water would be immediately injected via the cooling water system. Boron-10 is a neutron absorber that prevents neutrons from reaching a concentration required to sustain a critical condition [130].

Criticality within SFPs is unlikely because the fuel configuration and storage conditions are well known and carefully controlled, as are the materials of the storage racks.

Controlling hydrogen

Hydrogen continues to be generated within the reactor vessels and containment vessels, although the generation rates are much lower than during the accident. At that time, the primary mechanism was zirconium metal reacting with water molecules at very high temperatures. Currently, hydrogen is primarily generated from the breakdown of water molecules caused by gamma radiation from sources covered by the water (radiolysis). The hydrogen will pass into the containment vessel because of the breached condition of the RPV. The presence of fuel debris in the PCV will generate hydrogen by the same mechanism.

Hydrogen control is conducted within the reactor systems to prevent its accumulation to a concentration at which it can ignite. The hydrogen concentration in the PCV air space is controlled to less than 2.5% by volume; it provides a conservative margin to the lower limit of flammability, which is 4% by volume in air. This is the lowest concentration capable of igniting in air (an ignition source such as a spark, a flame or high temperature heating would also be required). Monitoring and concentration control for hydrogen is required until it can be shown that hydrogen will only be a trace gas at concentrations much lower than the flammable limit.

At present, nitrogen gas is injected into areas where hydrogen can be generated through gas supply lines in order to exclude oxygen as well as to maintain hydrogen levels below the flammability limit. Nitrogen gas injection was established in April 2011 in Unit 1 and, by June 2011, in Units 2 and 3. This requires a system designed and installed specifically for that purpose. To ensure reliability of the nitrogen injection function, redundant power supplies for the three nitrogen gas supply units have been established, and a diesel generator driven nitrogen gas supply unit has been installed for emergency use [130].

Reliability of gas removal is also important. Gas is extracted from the PCVs and discharged through filters to the outside. The PCV gas control system controls the hydrogen concentration and measures xenon gas to monitor the subcriticality (as described above). The reliability of this system is maintained by the switchgear for the PCV gas control equipment, receiving power from the different stations' common buses. That is, the gas exhaust is provided by two trains of fans and filters for each

reactor unit; each train is powered with different electrical buses, and an emergency bus is available for power in the event of loss of external power. Two measurement instrumentation systems for hydrogen and noble gas concentration are provided for each unit's system [130].

Ensuring the structural stability of the reactor buildings

Because the reactor buildings were damaged by the accident, it is necessary to assess the damage, evaluate the structural integrity of the remaining structures and take practical measures, such as reinforcement, to maintain the structures throughout the stabilization, preparation for decommissioning and decommissioning processes. Continuous monitoring of the building and structures and potential re-evaluation are being conducted.

Controlling water ingress and preventing leakage to the environment

Before the accident, groundwater flowing from the mountainside in the rear of the Fukushima Daiichi NPP was pumped from sub-drains (wells) located around the NPP buildings at a rate of approximately 850 m^3/d from Units 1–4 [131]. These sub-drains functioned to reduce the groundwater levels around the buildings and to arrest the inflow of groundwater into the buildings. Without the sub-drains, groundwater would infiltrate the buildings, as they were built below the groundwater level. The sub-drains and pumping equipment were damaged by the tsunami and ceased to operate. Following the accident, cooling water was injected into the reactor cores. This water becomes contaminated, and it is being collected, treated and stored in on-site tanks.

After the accident, approximately 400 m^3/d of water flowed into the buildings. A further 400 m^3/d flows under the buildings and is flowing into the NPP's port. More information can be found in Technical Volume 4 and Ref. [132].

A total of approximately 400 m^3/d of water is circulated through the RPVs of Units 1–4 for cooling. The groundwater that enters the buildings is mixed with the circulating water used for cooling the RPVs, leading to a total volume of approximately 800 m^3/d of contaminated water being managed. Approximately 400 m^3/d of water is injected back to the RPVs for cooling the fuel debris, and the remaining 400 m^3/d is stored in the contaminated water storage tanks. Two caesium removal water treatment systems (SARRY and KURION) are in operation. A third system, AREVA, and mobile caesium removal systems provide backup. Three treatment systems for the removal of other radionuclides, the Advanced Liquid Processing System (ALPS) in operation (as of May 2015) [133]. Desalination systems are also in operation.[21] The treated water is presently stored on-site in more than 826 tanks [134, 167].

Managing this water is a complex issue. Water levels in the reactor and turbine buildings are currently being maintained to keep the contamination contained. In addition, by maintaining a natural flow into the building, contaminated water is prevented from flowing out to the surrounding soil. This is achieved by pumping water from the turbine buildings so that water levels in the reactor and turbine buildings are maintained below the water level in the ground surrounding the buildings. As long as the current cooling of fuel and fuel containing material is continued, it will be necessary to control the amount of water entering the buildings [135].

TEPCO is also working to identify the location and plug the holes in the PCVs that allow radioactive cooling water to flow out. Many of the leaks are thought to be in the suppression chambers, which are doughnut shaped structures that form a ring around the containment vessel. This system is used to regulate temperature and pressure inside the RPV during emergency situations. The suppression

[21] Water treatment systems are discussed in detail in Section 5.4.4.

chambers and the rooms that contain them are filled with water, complicating the process of identifying the location of the leaks. As of May 2014, the locations of some of the leaks in Units 1 and 3 had been identified. To control and prevent the continued ingress of water, TEPCO is implementing the measures described below.

Installation of a groundwater bypass

A groundwater bypass system is in operation at the Fukushima Daiichi NPP (see Fig. 5.3–2). This work aims at reducing the amount of water flowing into the reactor buildings by first pumping the groundwater from the upstream side of the buildings, transferring it into temporary storage tanks, analysing the quality of the water in the tanks to determine if it falls below the discharge criteria, and finally discharging to the sea any water that fulfils the criteria. TEPCO reported in a press release that bypass operations had begun on 21 May 2014 and acknowledged the acceptance of these discharges by many of the stakeholders, including Fukushima Prefecture and members of the fishing industry [136]. The discharge criteria are: 1 Bq/L of ^{134}Cs or ^{137}Cs; 5 Bq/L for total beta activity; and 1500 Bq/L for tritium.[22]

Restoration of the sub-drains

Inflow of groundwater into the buildings will be suppressed by restoring the ability to pump up and remove groundwater from around the buildings, as had been done before the accident. Restoration of the system is under way.

Stopping ingress by sealing building penetration points

The buildings associated with Units 1–4 have over 800 penetrations in the outer walls. Those that are below the water level or which are in the outer walls are likely pathways for groundwater to enter the buildings. TEPCO is currently undertaking measures to seal these penetrations, including an analysis to make sure that attention is given to those penetrations with the greatest ingress of water.

Landside impervious wall[23]

A landside impervious wall, deploying a soil freezing method, will be installed around the reactor and turbine buildings to suppress the increase of contaminated water attributable to groundwater inflow. The approach is to construct ducts in the ground and circulate a coolant (e.g. at –30°C to –40°C) to form a wall of frozen soil. Soil freezing is an engineering technique that is commonly used in mining and tunnelling (see Fig. 5.3–3). This work is being supported by METI. The NRA has authorized work on the mountainside, on condition that tests were undertaken before full operation commences. The tests on the mountainside started on 30 April 2015, and the operation of the wall as a whole will be examined in the light of the information to be gained from this test. At the time of writing, no completion date had been announced [137, 138].

[22] The agreement with the stakeholders included: third party monitoring to ensure discharge standards are being met; transparency in the release of information by TEPCO; and continuation of the compensation to fishermen for reputational damage (i.e. damage to the reputation of their products in the eyes of the consumer).

[23] Also referred to as an ‘ice wall’ or ‘frozen wall’.

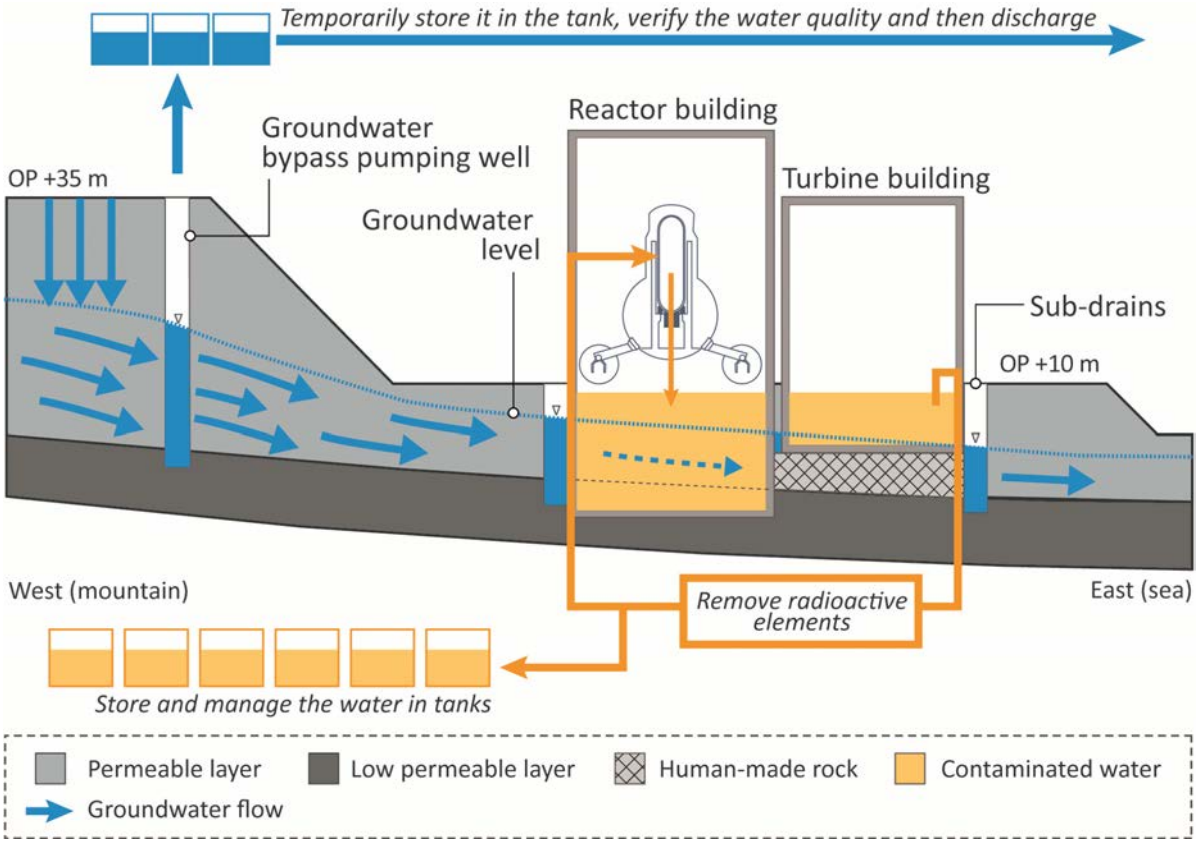


FIG. 5.3–2. Illustration of the groundwater bypass system [131].

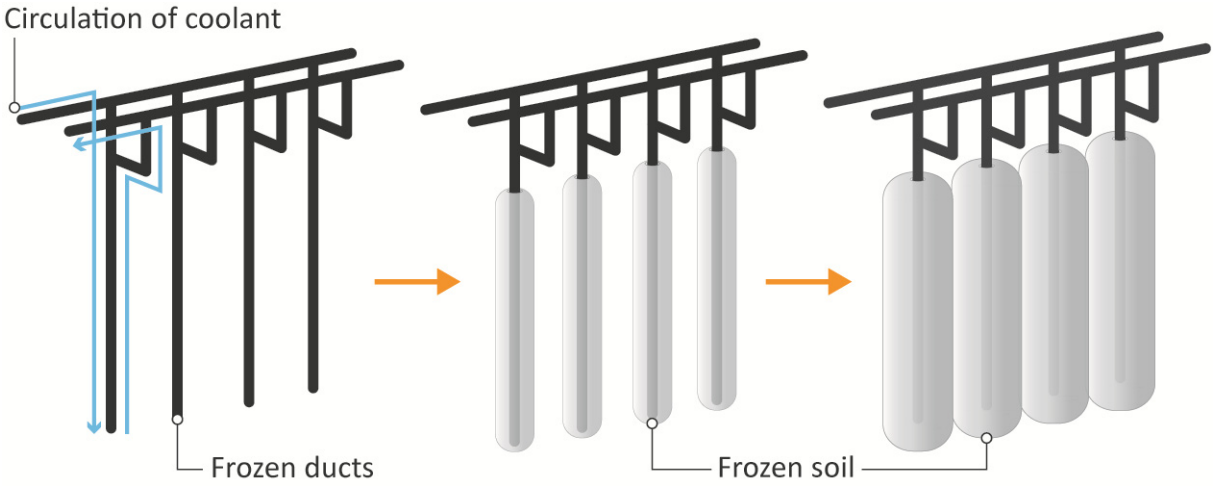


FIG. 5.3–3. Landside impervious wall [137].

Filling in subterranean spaces of the turbine building and other buildings to levels higher than surrounding groundwater levels is being considered as a backup measure for stopping groundwater flow in the event that the flow of groundwater cannot be sufficiently suppressed by the landside impermeable wall and the sub-drains [139].

In July 2013, TEPCO discovered that contaminated groundwater was entering the NPP's sea port, with the source of the contamination suspected to be water from one of the trenches connected to the Unit 2 turbine building [135]. The countermeasures are described briefly below.

Ground improvements

These actions include paving the land surface to prevent infiltration of rainwater; reducing permeability of the oceanside foundation by injecting chemicals into the ground between the water intake locations to prevent the outflow of groundwater to the port; and pumping water from between the oceanside intakes of Units 1 and 2.

Removal of water from the trenches

After the accident, contaminated water leaked into the ocean through the trenches. This leakage has stopped, but the contaminated water remains in the trenches. The estimated volume is approximately 11 000 m^3 [131]. Plans are under way to remove the contaminated water and to block the trenches.

Installation of a seaside impervious wall

A seaside impervious wall (steel sheet piling) to suppress the outflow of groundwater to the sea is being installed at the seaside area of the Units 1–4 reactor buildings (Fig. 5.3–4).

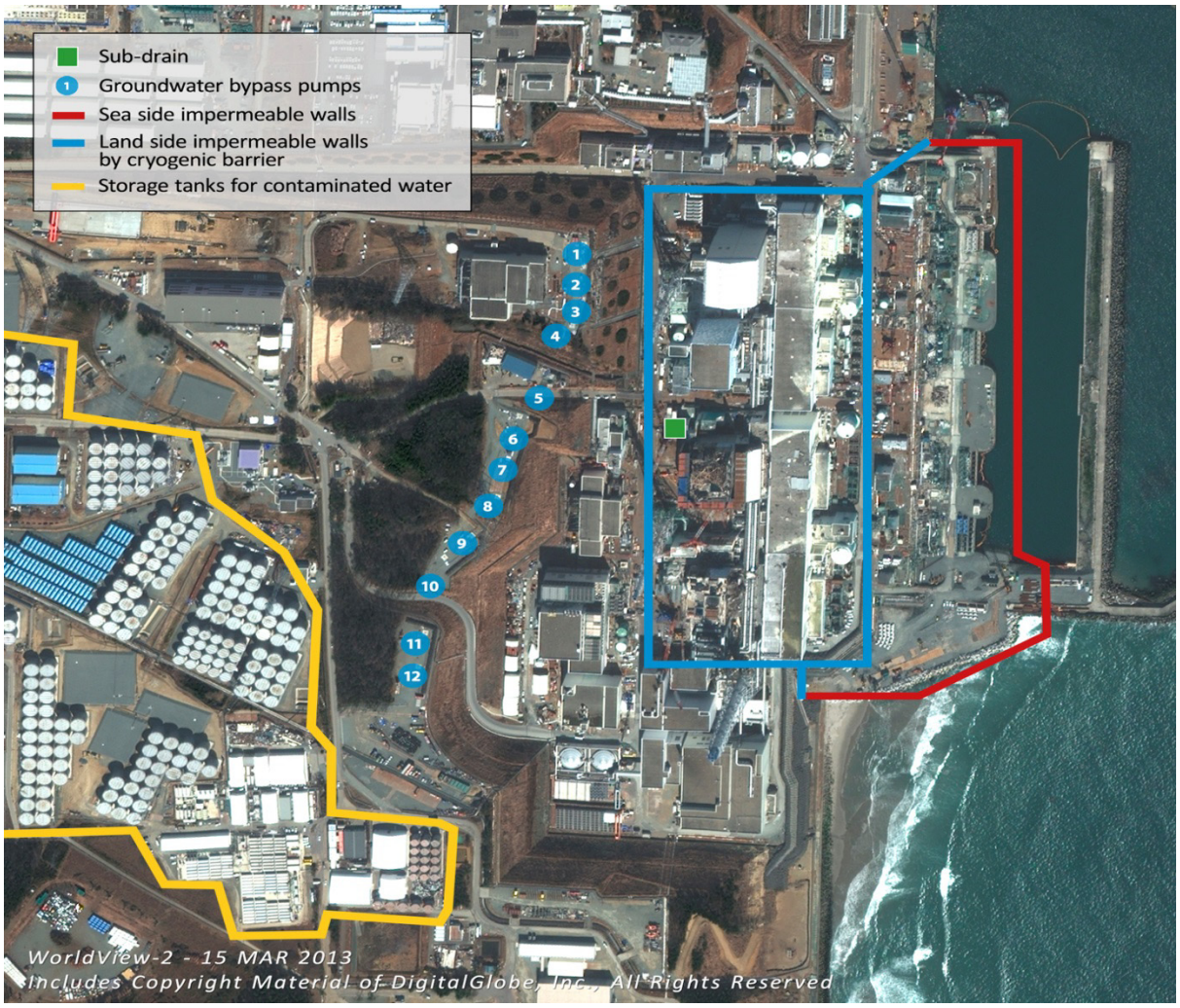


FIG. 5.3–4. Illustration of water management efforts [140].

Ensuring essential electrical power feed

Improvement in the reliability of power sources is being achieved by upgrading temporary equipment to permanent equipment and by ensuring that power for critical equipment can be provided from several electrical buses. The following measures have been taken:

- For the off-site power supply, new switchyards have been constructed and two new 30 MVA transformers have been installed to serve Units 1–4. Parallel operation of key switchyards has been established to prevent on-site power failure when an interruption occurs in one transmission line.
- The second on-site common diesel generator has been restored to operability.
- To provide reliability for on-site high voltage distribution, four new on-site high voltage busbars and a new connection line between common on-site high voltage circuit breakers have been completed. In addition, new remote monitoring/operation equipment for the high voltage circuit breakers has been installed.

Ensuring the performance of major safety functions over the long term

This section describes the requirements and actions taken to provide assurance that the major safety systems will perform as required, even in the case of future natural events.

Japanese regulations require the following measures to be taken:

- All SSCs that have safety functions should have appropriate seismic resistance in accordance with the seismic design guideline. If this is not assured, diversity should be considered, as needed.
- SSCs that have safety functions should not lose their functionality because of anticipated natural events such as tsunamis, heavy rains, typhoons and tornadoes. At the same time, diversity should be considered, as needed. For SSCs that have essential safety functions, it is especially important that the combination of load induced by the most severe condition that occurs during anticipated natural events combined with the load induced by accident conditions should be considered.

To verify the capability of SSCs to withstand an earthquake, a tsunami or a tornado/cyclone, the following assessments and evaluations have been, or will be, conducted.

Earthquake

Based on the results of evaluations, TEPCO determined that there was no significant damage to the reactor buildings, turbine buildings and primary equipment and piping required to meet seismic safety standards that can be attributed to the Great East Japan Earthquake [141].

Furthermore, given the current damaged state of the reactor buildings of Units 1, 3 and 4 due to the explosions, TEPCO conducted additional assessments to determine if the buildings could withstand future large earthquakes. The assessments were conducted in accordance with the Design Basis Earthquake Ground Motion concept based on the Seismic Design Review Guidelines [142]. Computer earthquake simulations were also performed, taking the present building situation into consideration. Based on these analyses, TEPCO has concluded that the reactor buildings would be capable of withstanding a future large earthquake. To further enhance the safety margin at Unit 4, TEPCO installed, in July 2011, a support structure at the bottom of the SFP. This increased the safety allowance (earthquake resistance strength) by an additional 20% [141].

Unit 2 did not experience a hydrogen explosion, and no major damage has been observed to the reactor building. It was evaluated that the level of safety against a future earthquake is adequate [143].

Tsunami

TEPCO took measures against a postulated tsunami with the maximum height of 7 to 8 metres, which is caused by an outer-rise earthquake [141]. As a result of this study, all the pumps for water injection into the RPVs of Units 1–3 were moved to higher locations by July 2011. The mobile emergency power sources, fire engines and other related equipment were also moved to higher locations. TEPCO also constructed a temporary seawall of varying heights of 2.4 m to 4.2 m on the grounds at the 10 m level to protect the major buildings.

In addition to the above mentioned countermeasures against earthquakes and tsunamis, redundant and diversified facilities and equipment, such as power trucks and fire engines, were provided for response to other events, such as multiple equipment failures or off-site power losses.

Based on the experience of the Great East Japan Earthquake, the NRA has developed new regulatory requirements [144]. In accordance with this requirement, TEPCO is in the process of determining new earthquake ground motion parameters and tsunami heights that have to be considered as part of the backfit requirements for the Fukushima Daiichi NPP in its present state. After completion of the evaluation, measures based on the results will be implemented as appropriate at the Fukushima Daiichi NPP.

Typhoon and heavy rain

Buildings that contain highly contaminated water, such as the reactor and turbine buildings, are evaluated by use of past metrological data according to the Building Standards Act [145]. The buildings, and the systems installed in the buildings, are evaluated for their ability to maintain their functions during typhoons.

Regarding heavy rain, an estimation of the amount of contaminated water accumulated in the basement of the building was conducted. The results showed that, even if the total rainfall would add up to 1000 mm/d, which would exceed any amount recorded in past meteorological data in Japan, the water levels would remain sufficiently low to avoid an overflow of the basements [146].

Tornado

Buildings such as the reactor and turbine buildings that have reinforced concrete structures are not expected to be damaged by tornadoes.

The pumps for the RPV/PCV water injection system are distributed to dispersed areas, and the risk of losing the function of all pumps at the same time due to a single tornado is considered very low. Even if all the pumps lost their capability simultaneously, water injection could be provided by fire engines.

As for the power supply system, diesel generators are located inside reinforced concrete buildings. Motor control centres are kept within reinforced concrete or steel beamed buildings at dispersed areas to avoid simultaneous loss of their functions. Outdoor cables are installed with multiple routes, because they could be directly damaged by tornadoes. If all the cables were damaged, dedicated generators are located at dispersed locations and could supply power to the SSCs. In addition, mobile power units are available (similar evaluations are conducted for important safety related SSCs such as the SFPs and the water treatment systems).

Ageing degradation effects

To verify the capability of SSCs to respond to aging degradation effects over a long time, assessments and evaluations include:

- Conducting checks of the reactor buildings of Units 1–4. Repairs and/or reinforcements are carried out as needed.
- Conducting evaluations of the integrity of the RPVs and PCVs that may have been affected by injecting sea water into the reactors, which include corrosion wastage and seismic resistance evaluations.
- Development of a corrosion control system that is applicable to the RPVs and PCVs.
- Continuation of salt removal from cooling water.

SSC specific evaluations

Case specific evaluations and countermeasure implementation, as needed, are described in the implementation plans for SSCs, such as the plan for the RPV/PCV water injection system [146]. In this case, time dependent temperature change of fuel debris and steel structures, the amount of radioactive material and the dose rates are evaluated for the case that the function of the water make-up system is lost. It has been shown that the time needed to restart water injection by the use of fire engines would be short enough to determine whether the result of the loss of function is significant.

5.3.4.2. Measures for reducing radiation levels

The reduction of radiation levels has two main purposes: to limit the dose to workers when performing activities in the plant; and to reduce the annual effective dose to a hypothetical[24] person living in the area surrounding the plant.

With regard to radiation levels inside the NPP boundary, the aim is to reduce the gamma dose rate in the NPP's southern area (except around Units 1–4) to levels below 5 μSv/h. Measures planned to reduce dose inside the boundary primarily consist of removing the radioactive debris scattered by the hydrogen explosions and accumulated within the premises and then performing extensive decontamination of facility structures, components and ground.

Before starting decontamination work inside buildings, obstacles such as rubble and debris must be removed by unmanned equipment not only to reduce dose rates but also to secure access routes for decontamination devices and internal surveys of the PCVs. Decontamination is then performed through the use of remotely operated decontamination devices [147].

With regard to radiation levels outside the NPP boundary, the aim is to reduce the total effective dose at site boundary to less than 1 mSv/y. Reduction of radiation levels at the site boundary is obtained by the following:

- *Limiting the gaseous radioactive release to the environment*. This is accomplished by re-establishing the containment function of buildings and facilities that contain radioactive material and by re-establishing an active ventilation system. This ensures a continuous airflow from lower contaminated to higher contaminated areas and the filtration of potentially contaminated air by high efficiency particulate absorption filters. Major measures implemented are:

[24] The term hypothetical is used here because the reactor site is surrounded by the restricted area, in which nobody is allowed to live.

- Unit 1: Installation in December 2011 of a PCV gas control system allowing extraction of gas from the PCV to the stack through the filters; at the same time, an equal quantity of nitrogen was injected into the building.
- Unit 2: Closure of disrupted blowout panel with a movable panel in March 2013. Releases are continuously monitored through the dust radiation monitor at the reactor building exhaust system outlet.
- Unit 3: Planned installation of a cover over the reactor building work area to limit dispersion of radioactive material during fuel removal operations from the SFP.
- Unit 4: Construction of a cover and installation of a ventilation system. Its exhaust is filtered to prevent the release of radioactive material.

— *Limiting the liquid radioactive release to the environment with particular attention to the discharges of contaminated water to the ocean*. The measures are described in Section 5.3.4.1. The results of seawater analysis undertaken in April 2013 3 km offshore of the NPP outside the port show ^{137}Cs and ^{134}Cs values of around 0.1 Bq/L. Other β emitting nuclides were below detectable limits [148].

— *Limiting direct and skyshine radiation*[25] from secondary waste, i.e. radioactive material generated during accident recovery. Secondary waste is stored in various areas on the site, referred to as the north, west and south areas. The storage function and the specific measures taken to reduce radiation from each area are described below (Table 5.3–2).

TABLE 5.3–2. MEASURES TO REDUCE RADIATION LEVELS AT THE SITE BOUNDARY [149]

	North	West	South
Characteristics	Temporary storage of debris and felled trees	Temporary storage of spent fuel in dry cask storage, solid waste and felled trees	Temporary storage for spent caesium adsorption towers, debris and felled trees
		Advanced Liquid Processing System (ALPS) located in this area	
Actions	Felled trees and debris covered with shielding soil	Removal of trees to install tanks for accumulated and treated water storage	Installation of shields on spent caesium adsorption towers
	Transferred to locations further away from the boundaries	Felled trees covered with shielding soil	Installation of temporary storage facilities with the shield function and movement of adsorption towers to the facilities
		Installation of lead shields with a thickness of 8–10 mm around the ALPS components that contribute significantly to radiation levels	Installation of temporary storage facilities away from the boundaries and transferal of adsorption towers to the facilities

Owing to the present stable condition of the reactors, and assuming no further changes in the facility's condition, the effective dose at the site boundary from the emission of gaseous radioactive material is estimated to be approximately 0.03 mSv/y. A similar dose rate is expected in the future. The effective dose at the site boundary due to direct and skyshine radiation generated by the radioactive wastes was estimated to be approximately 0.91 mSv/y (at the end of May 2014).

[25] Skyshine is radiation reflected back from the sky to the ground.

5.3.4.3. Removal of spent and new fuel from spent fuel pools

Removal of spent fuel and new fuel from the SFPs within the reactor buildings must be conducted as a phase of decommissioning prior to the subsequent operations to remove fuel debris from within the RPVs and PCVs of Units 1–3.

The following sections describe the conditions and actions under way and planned to remove new and spent fuel from the pools, and the status and preparations of actions to address the removal of fuel debris.

Fuel in storage at the time of the Fukushima Daiichi accident

For boiling water reactors (BWRs) of the design used at the Fukushima Daiichi NPP, fuel that is not within the reactor core is usually stored within the individual unit fuel pool during plant operations. This fuel pool is located within the reactor building, as shown in Fig. 5.3–5. Fuel assemblies are stored in racks within the pools.

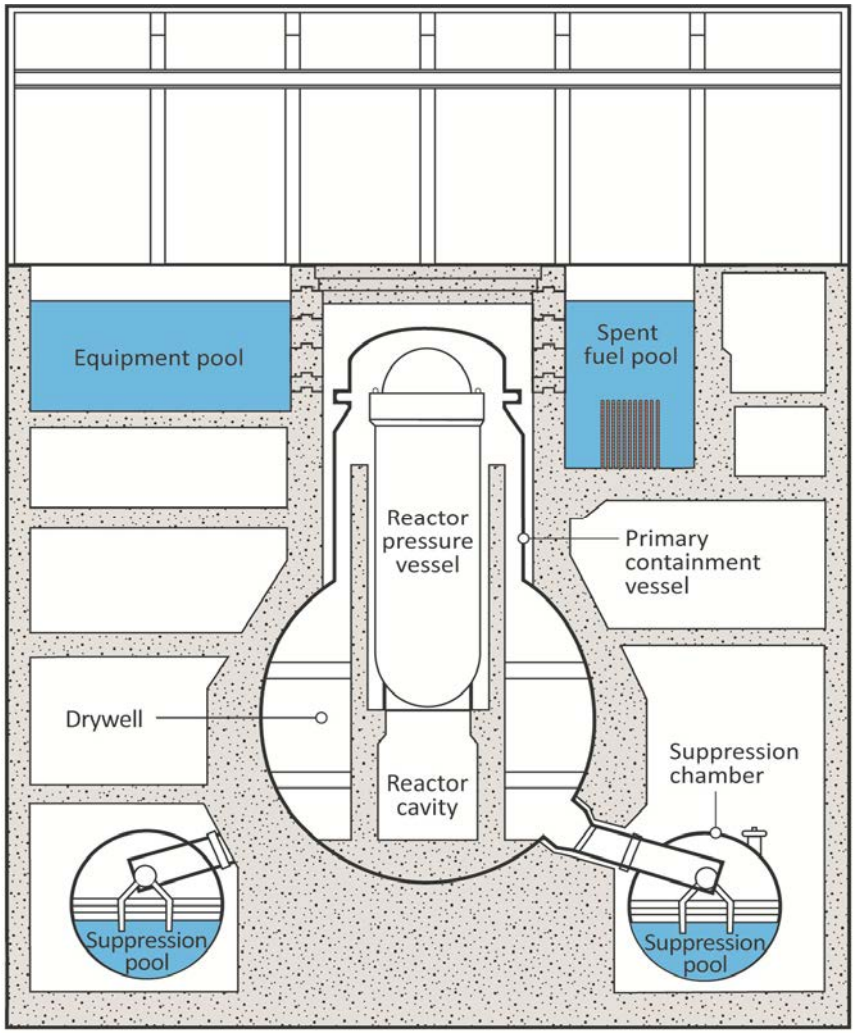


FIG. 5.3–5. Reactor vessel and fuel pool configuration.[26]

[26] This figure illustrates the configuration of Fukushima Daiichi Units 1–5 (Mark I containment). The configuration of Unit 6 (Mark II containment) is described and illustrated in Technical Volume 1, Section 1.2.

The number of spent fuel and new fuel assemblies in the individual unit pools at the time of the accident are listed in Table 5.3–3.

TABLE 5.3–3. USED AND NEW FUEL IN STORAGE POOLS AT THE TIME OF THE ACCIDENT [150][27]

Location	Number of fuel assemblies		
	Used	New	Total
Unit 1	292	100	392
Unit 2	587	28	615
Unit 3	514	52	566
Unit 4[a]	1331	204	1535
Units 1–4 total	2724	384	3108
Common pool	6375	—	6375

[a] The large number of fuel assemblies for Unit 4 is due to the fact that the unit was in a maintenance and inspection shutdown; all its fuel assemblies had been removed from within the reactor and were within the Unit 4 pool.

As a result of the hydrogen explosions that destroyed the upper portions of the reactor buildings of Units 1, 3 and 4, rubble dropped into the pools and on top of the fuel in the storage racks and left them open to the atmosphere (see Fig. 5.3–6 and Fig. 5.3–7). Based on visual verification during the construction and installation of a protective cover over the damaged building at Unit 4, no fuel assemblies in the pool appear to have suffered severe damage from the rubble. The result of water analyses show that no severe damage from the rubble is expected to exist in Units 1 and 3. The campaign to remove fuel from Unit 4 has confirmed this assessment. Nevertheless, as each fuel assembly was removed, it was inspected for damage and for the possibility of foreign material within the fuel rod matrix.

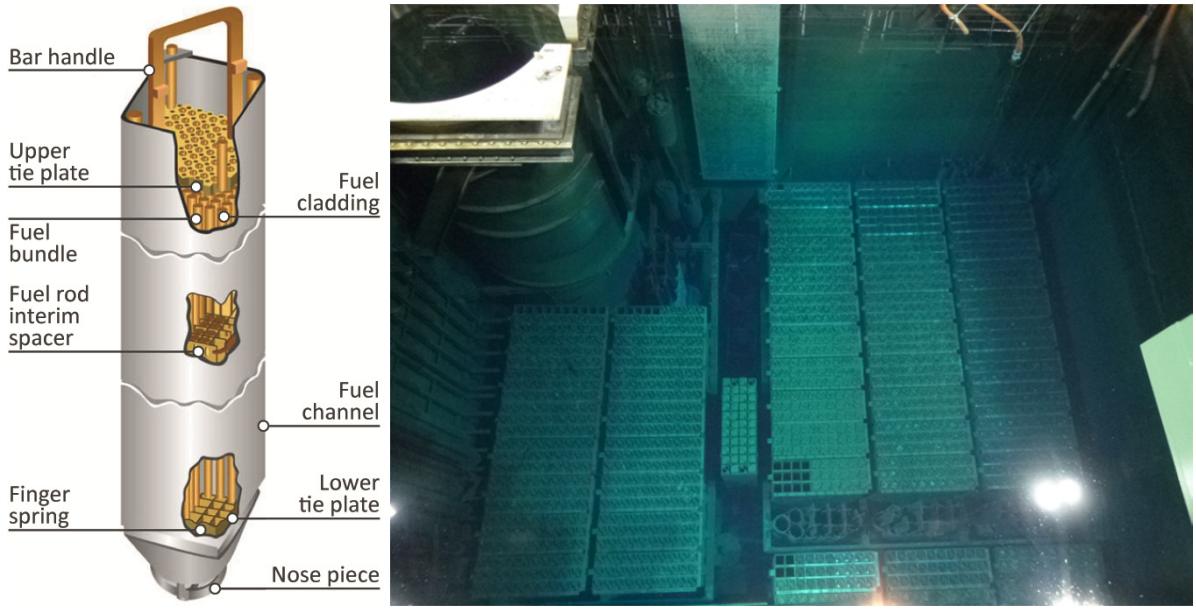


FIG. 5.3–6. BWR fuel assembly diagram and fuel assemblies in storage racks within the spent fuel pool [151].

[27] Prior to the accident, reactor fuel was stored in the reactor pools, then moved to a common fuel pool located on-site.

Fuel assemblies in storage continue to slowly release energy as a result of heat produced during radioactive decay. They are, therefore, cooled by storage under water, which also provides radiation shielding. None of the fuel in the pools suffered damage from overheating as a result of the accident, although the normal cooling systems were disabled by the loss of electrical power. Until these systems were restored, sea water was pumped to the pools to ensure heat removal at Units 1, 3 and 4. The possible corrosion effects from the limited exposure to sea water will be determined during removal inspection and evaluation over the next several years. Because the temperature remained low and the salt has been removed from the cooling water, it is not anticipated that there will have been significant damage from the sea water. Results of inspection of fuel in storage at the Unit 4 SFP indicated only normal levels of corrosion, despite exposure to sea water. Evaluation of the long term integrity of the spent fuel is currently being conducted and will be completed by 2018.



FIG. 5.3–7. Debris in spent fuel pool [153].

Nine dry casks with spent fuel had been stored in the cask storage building at the time of the earthquake. As a result of the earthquake and tsunami, the building was flooded with sea water and sand, combined with earthquake rubble. Visual observation, along with temperature and radiation measurements, confirmed that the integrity of the nine casks had been preserved. One of the casks was opened, and a representative spent fuel assembly was inspected. There were no abnormalities in the cask or in the contained fuel. All nine casks have been removed, inspected, parts replaced as necessary and placed in the new dry storage area.

Overall plan and method for spent fuel removal

The fuel currently within the pools will be removed to ensure its long term safety and to establish conditions within the reactor buildings of Units 1, 2 and 3 for the eventual removal of damaged fuel debris from the RPVs and PCVs. Therefore, an overall objective is to remove all spent and new fuel from the storage pools in Units 1–4 as a major phase of the long term effort. These operations will be conducted from the operations floor area above the reactor vessels, which is adjacent to the fuel pools. The fuel assemblies removed will be transferred to the common pool. The pools may then be used for placement of fuel debris removal equipment and for other operational support. It is too early to say how this might be achieved.

The following activities, shown in approximately chronological order, will be conducted for each unit with varying degrees of applicability. There may be some overlap between the completion of one and the beginning of the next step. See Table 5.3–4 for details.

TABLE 5.3–4. ACTIVITIES TO SUPPORT THE REMOVAL OF SPENT FUEL [154]

Activities in support of spent fuel removal	Status of activities
Remove the explosion damaged structures from the operations floors at the top of the reactor buildings.	Accomplished for Units 3 and 4
Remove rubble from the operations floors. This requires remotely operated equipment, as needed, because of radiation levels.	Accomplished for Units 3 and 4
Re-establish building covers to protect the operations floors from the weather and to establish a physical boundary for future operations.	Accomplished for Unit 4. Unit 1 has an interim cover that will be replaced before fuel removal begins. The need for a cover for Unit 2 is to be decided, based on evaluation of the expected dose rate after decontamination. Unit 3 will require a new cover.
Survey and remove structural debris that fell into the pool.	Accomplished for Unit 4
Inspect fuel storage racks to determine if there was structural debris damage that would impede fuel removal.	Accomplished for Unit 4
Decontaminate the operations floor for the purpose of reducing radiation levels, as feasible.	Completed for Unit 4 and under way for Unit 3 (in March 2014)
Determine the need, specify the requirements and acquire remote technology for fuel removal from the pools of Units 1–3. For example, remotely operated removal equipment may be needed to reduce doses to operators in areas where decontamination and placement of shielding are difficult.	In progress
Create an implementation plan for review and approval by the NRA for licensing of the removal operations. Implementation includes procedures specific to each unit as a result of differences in physical conditions.	Accomplished for Unit 4
Complete the nuclear fuel removal operation for each unit.	Accomplished for Unit 4

Fuel removal was initiated first at Unit 4 for several reasons. These included: relatively low dose rates, greater number of fuel bundles and related concern over heat generation, and a better understanding of the existing rubble.

The basic steps for fuel removal are as follows:

— Relocate the fuel assemblies stored in the fuel rack inside the SFP one by one into a transport container (cask) underwater by use of a fuel handling machine.
— Lift the cask from the SFP using a crane.
— Conduct, at the operating floor level, such activities as closing the lid of the cask and decontaminating the cask.
— Lower the cask toward the ground using the crane to place it on the truck trailer.
— Transport the cask to the common pool.

Fuel removal from the spent fuel pool in Unit 4 began in November 2013 and was completed in December 2014 [155]. Figure 5.3–8 shows the cask being lifted from where it will be moved for placement onto a truck. As of 22 December 2014, all 1331 spent fuel assemblies and 202 fresh fuel assemblies had been transferred from the Unit 4 SFP to the common storage pool and the Unit 6 SFP [156].

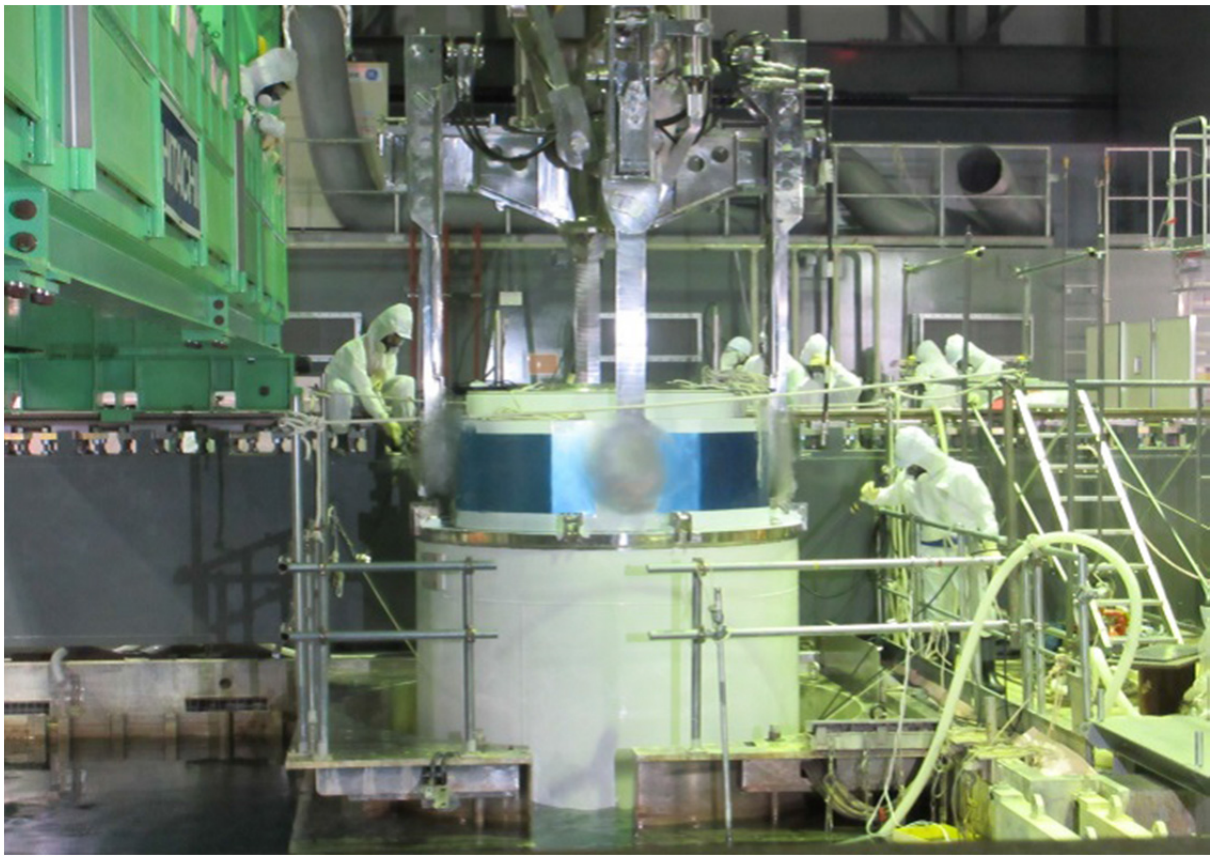


FIG. 5.3–8. Removing the transport cask from the spent fuel pool.

Fuel removal from Unit 3 is planned to start at the beginning of 2018 [121]. Plans and schedules for the removal of fuel from Units 1 and 2 will be based on the experience from Units 3 and 4, the results of facility surveys, the survey/characterization of rubble and internal dose reduction efforts within relevant buildings (e.g. shielding and decontamination).[28] The total time required for the removal and transfer will be several years. There are two on-site options for storage of the spent fuel assemblies. One is in the common pool and the second is in dry storage. Spent fuel generates varying degrees of residual heat from the decay of remaining fission products. As a consequence, such fuel must continue to be stored underwater until the levels of heat generated are sufficiently low to allow dry storage. Therefore, to ensure that there is enough storage space, fuel in the common pool that generates sufficiently low levels of residual heat has been removed to dry storage.

The existing dry cask storage building was unavailable because of damage from the tsunami. During 2013, a new area for the dry storage of spent fuel was completed. The dry storage area is illustrated in Fig. 5.3–9. This area has been utilized to store fuel after it had been removed from the common pool and placed within dry storage casks.

[28] The most recent revised Roadmap, published in June 2015, indicates that removal of fuel from these units is estimated to start between 2020 and 2021 [121].

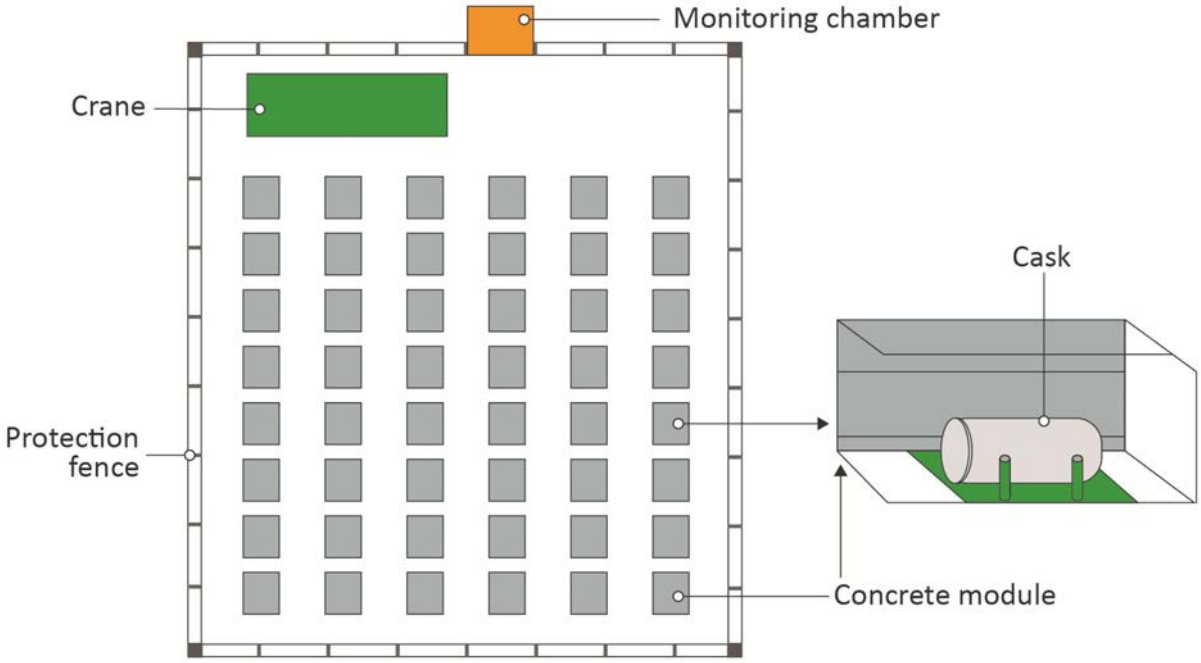


FIG. 5.3–9. Dry storage area [150].

5.3.4.4. Removal of fuel debris

Owing to the pressures and temperatures experienced during the accident, the fuel from the melted cores is no longer in its original locations. The destroyed fuel assemblies and the fuel rods that made up the reactor cores, as well as the core support structure, no longer have their original configuration. Fuel debris refers to fuel that has been severely damaged as a result of the accident.

There have been several accidents resulting in damaged nuclear fuel, some of which have resulted in off-site impacts. These accidents provide experience of fuel damage events that can be drawn upon to assist in the management of fuel debris from the Fukushima Daiichi accident. Table 5.3–5 is a chronological tabulation of such events that have occurred since 1952.

Depending upon the extent of fuel damage, the fuel rods may slump within the assemblies. Conceivably, the corium (a mixture of molten cladding, fuel and structural steel) can drop to the bottom of the reactor vessel. If the hot fuel or cladding is exposed to cooling water en route, it may solidify and fracture, falling to the bottom of the reactor vessel. Given that the melting point of the steel reactor vessel is about 1500°C, there is the possibility of the corium penetrating the steel if it remains at a sufficiently high temperature for a long time. In any event, the BWR pressure vessels have numerous penetrations at the bottom for the control rods and instrumentation, so any molten corium would possibly fall to the bottom of the dry well containment.

To provide a physical perspective of what is meant by fuel debris, illustrations from the accidents at Three Mile Island Unit 2 (TMI-2) and Chernobyl Unit 4 are provided. Figures 5.3–10 and 5.3–11 show the extent of damage to the TMI-2 fuel and views of the fuel debris that consist of partial fuel assemblies, individual rods, and rock-like material. Figure 5.3–12 shows pictures from Chernobyl. On

the left is the cavity where the core initially existed, and on the right are examples of glass-like material consisting of melted fuel and other materials from within the reactor.[29]

TABLE 5.3–5. EVENTS WHICH INVOLVED NUCLEAR FUEL DAMAGE

Plant (year): characteristics	INES level*	Country
NRX (1952): water cooled, heavy water moderated	5	Canada
Windscale (1957): gas cooled graphite pile	5	UK
SL-1 (1961): small prototype PWR	4	USA
Chapelcross (1967): Magnox carbon dioxide cooled, graphite moderated	4	UK
Fermi 1 (1968): sodium cooled	4	USA
Agesta (1968): water cooled	4	Sweden
St. Laurent (1968): gas cooled, graphite moderated	4	France
Lucens (1969): experimental gas cooled, heavy water moderated	5	Switzerland
Jaslovské Bohunice, A–1 (1977): gas cooled, heavy water moderated	4	Slovakia
Three Mile Island (1979): PWR	5	USA
Chernobyl (1986): water cooled, graphite moderated	7	former Soviet Union
PAKS (2003): PWR	3	Hungary
Fukushima Daiichi (2011): 3 BWRs	7	Japan

* The INES is the reference basis for the rating the severity of nuclear events. It is recognized and used by all IAEA Member States [157]. INES can be divided into two principal areas: INES levels 1–4, for which impacts are limited within the site boundaries; and INES levels 5–7, for which off-site impacts are realized.

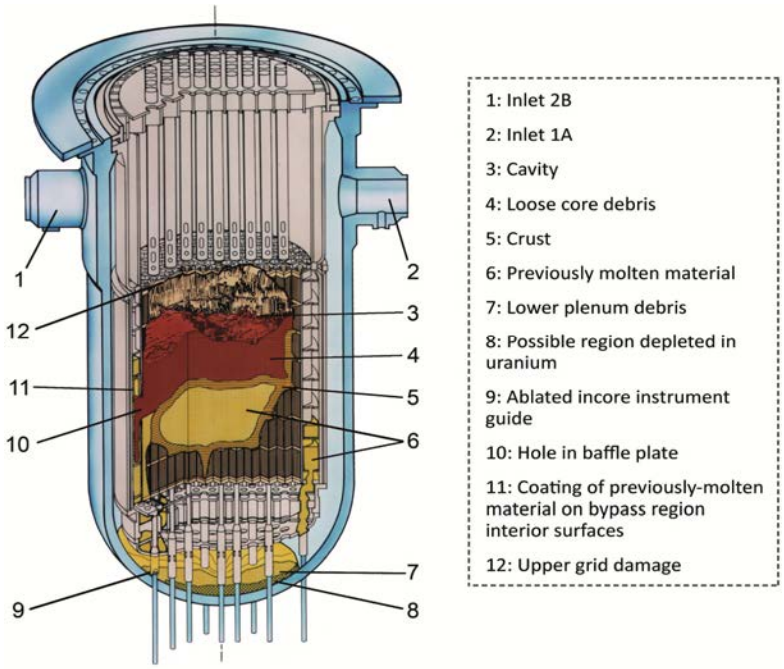


FIG. 5.3–10. TMI-2 core damage [158].

[29] The Chernobyl reactor, although water cooled, is a very different design than the BWRs of the Fukushima Daiichi NPP or the PWRs of TMI-2.

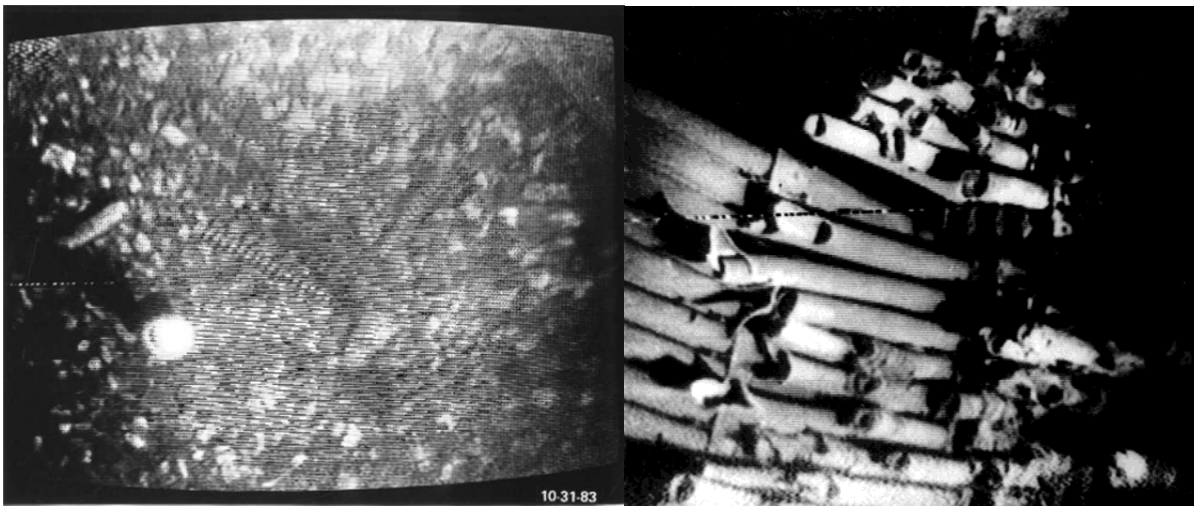


FIG. 5.3–11. TMI-2 fuel debris [159] (photograph on the left courtesy of Pennsylvania State University and that on the right of the Associated Press).

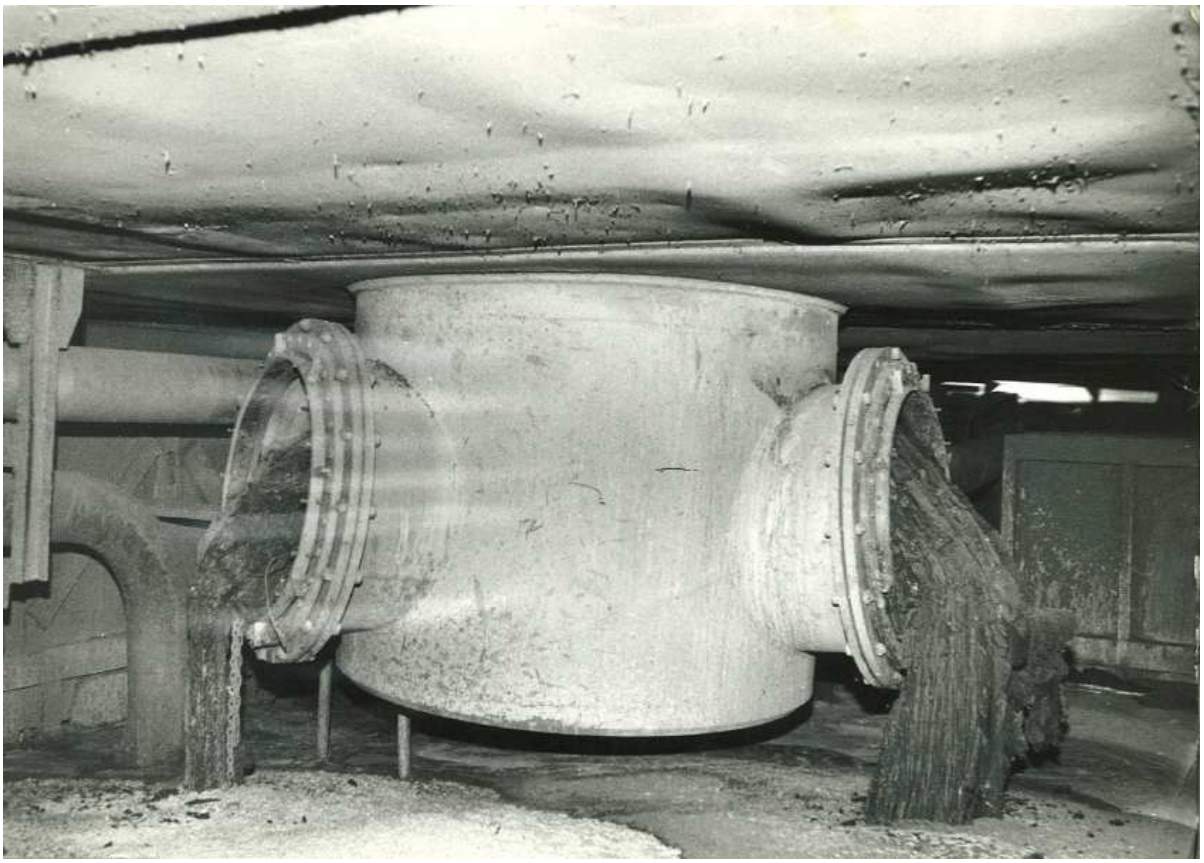


FIG. 5.3–12. Chernobyl Unit 4 core cavity and corium [159] (photograph courtesy of the International Nuclear Safety Project).

Fuel debris removal and storage

Of the fuel damage accidents listed at the beginning of this section, the TMI-2 accident is the closest in terms of precedent for the destroyed reactor cores and fuel at the Fukushima Daiichi NPP. However, the challenge in removing the fuel debris at the Fukushima Daiichi NPP is significantly greater than at TMI-2. Some of the reasons are that:

- The extent of tsunami damage at the Fukushima Daiichi site, its buildings, electrical and water infrastructure, other support systems and the surrounding area requires significant preparatory work before actual fuel debris removal can begin.
- Several days without direct cooling resulted in extended duration of temperatures approaching 3000°C and complete destruction of the cores of three units (compared with one at TMI-2). This resulted in a much greater scale of damage to the fuel, including its movement outside of the reactor vessels.
- Hydrogen explosions that resulted in the destruction of reactor building structures that must be repaired and decontaminated in order to gain access to the reactors. Although there was damage to the reactor buildings, they are expected to be effective enclosures for future operations.
- High levels of radioactive contamination that make access very difficult and result in the need for extensive decontamination operations to reduce the radiation to safe levels for humans within the design basis for equipment.
- While both accidents required water recirculation for post-accident cooling for heat removal and boron concentration control for nuclear reaction prevention, this was more readily accomplished at TMI-2, as there was limited introduction of additional water compared with that resulting from the leakage paths at the Fukushima Daiichi NPP.
- The existence of the SFPs within the reactor buildings at the Fukushima Daiichi NPP, requiring the fuel assemblies stored there to be removed in advance of work within the reactors and containment vessels.
- The vertical distance from the top of the reactor vessel to the location of fuel debris is over 50% greater at the Fukushima Daiichi NPP than at TMI-2 (about 30 m or more compared with 20 m).

As a result, removal of fuel debris from the Fukushima Daiichi NPP is likely to take much longer than at TMI-2, where it was achieved within about 12 years. This is reflected by a current plan of approximately 30 or more years in the Roadmap [160]. Figures 5.3–10, 5.3–11 and 5.3–12 illustrate the fact that the nature and extent of the fuel debris is dependent upon the nature of the accident and the fuel type. This is not only due to the effect of the initiating events and their duration, but is also attributable to the physical differences among the reactors and materials. An important lesson from historical reporting of visual inspection of the fuel conditions at TMI-2 [161] was that the actual condition of the fuel was far worse than initially expected. Visual validation of fuel conditions was essential to the proper planning and execution of fuel debris removal.

At the time of writing, there has been no direct visual confirmation of the configuration and the composition of the fuel debris resulting from the Fukushima Daiichi accident, owing to the high radiation dose levels in the damaged reactors. Based on evaluation, and until more direct evidence is obtained, analysis indicates that most of the fuel in Unit 1 is likely to have melted, some of which has penetrated through the bottom of the RPV and into the PCV [162]. The fuel in Units 2 and 3 is also likely to have melted, but some of it has remained within the vessels. Figure 5.3–13 is an illustration of evaluations, conducted up to February 2014, and it shows the estimated locations of the fuel debris for Units 1, 2 and 3, respectively. The figure illustrates the differences in the degree of fuel melting and the amount that remained within the RPV as well as its location in the PCV.

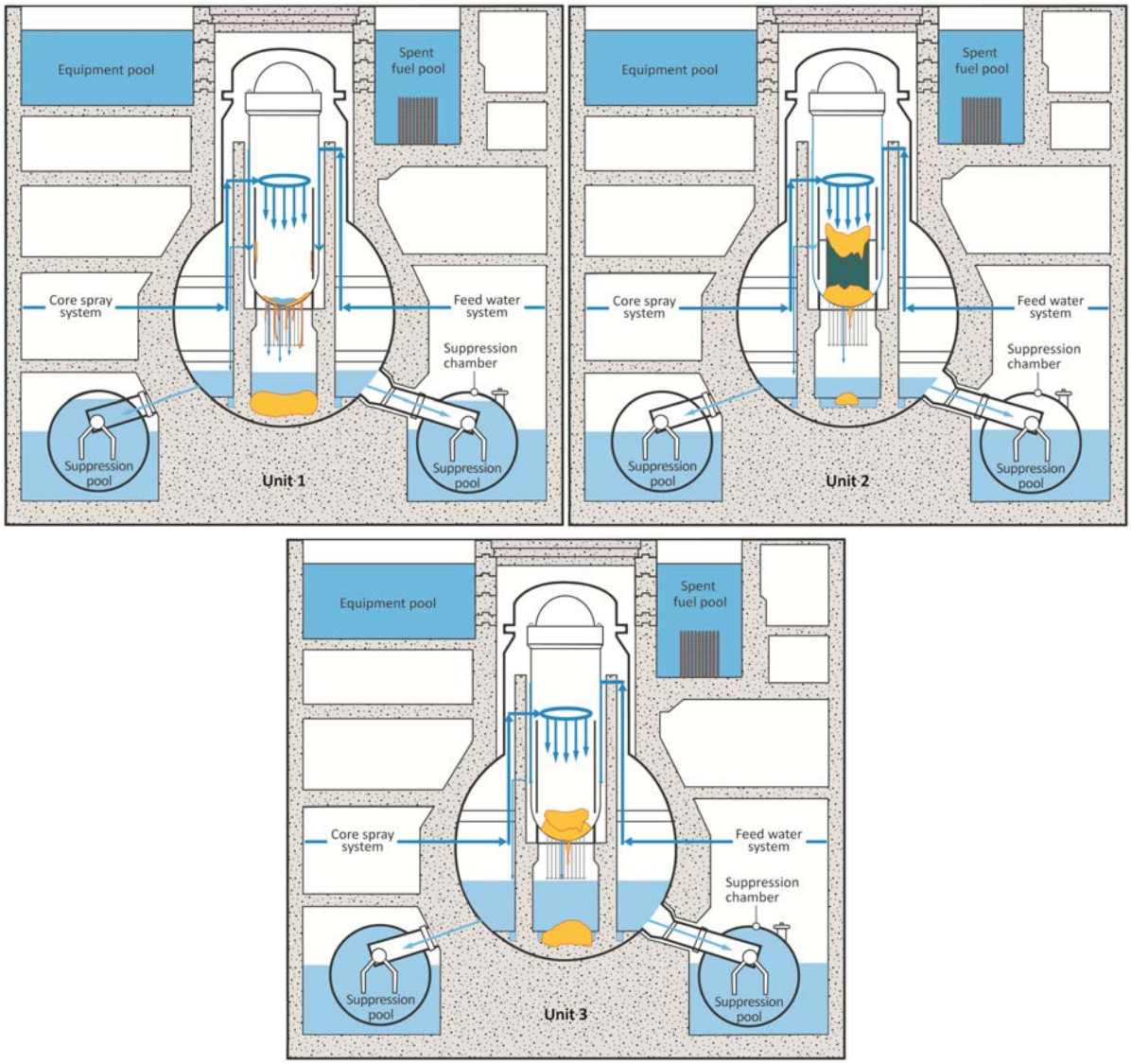


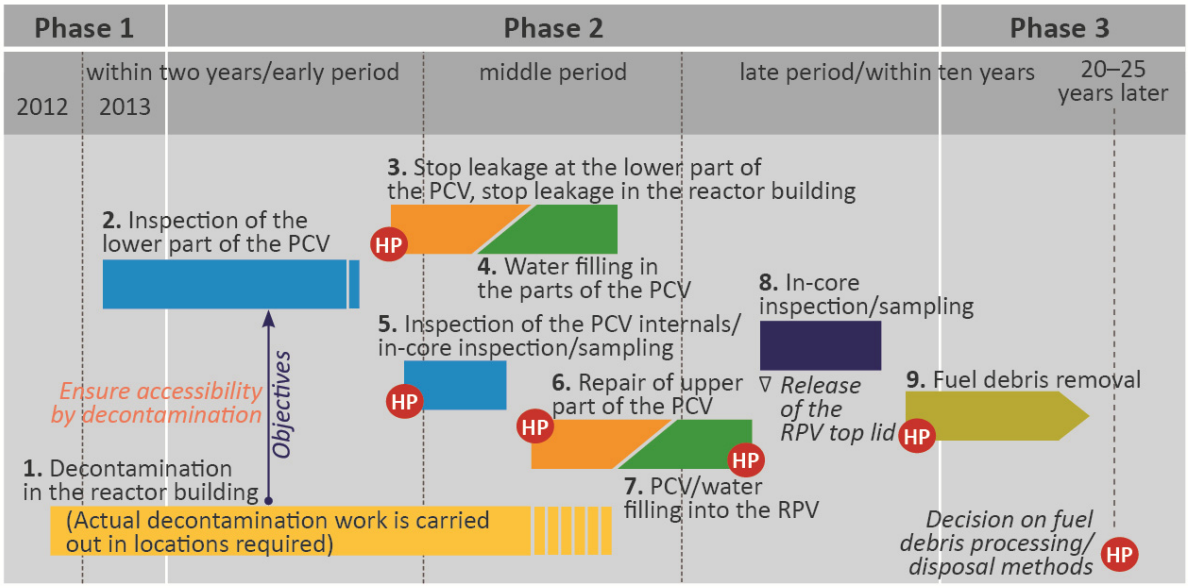
FIG. 5.3–13. Estimated conditions of the RPVs and PCVs of Units 1–3 (clockwise from top left) as of February 2014 [162].

Overall approach for fuel debris removal

Because of the high levels of radiation and contamination, combined with the unknown distribution or in situ properties of the fuel debris, much of the work will need to be conducted with remotely operated equipment. Fuel debris removal will not be conducted for many years. Strategies, planning, engineering, design and construction of equipment for removal will need to be adjusted as data becomes available regarding the actual condition of the fuel debris. [30]

A conceptual model for future debris removal activities is presented in Fig. 5.3–14, recognizing that numerous details will need to be developed in advance [120]. In this concept, a platform is mounted above the top of the reactor vessel with its lid removed.

[30] The revised Roadmap published in June 2015 indicates that a range of approaches will be examined to determine the most appropriate approach for each unit [121].



HP **Technical holding point -** The next and future processes will be reviewed in consideration of actual site conditions and the result of technology development.

3. Defining the stop leakage method of the lower part of the PCV **5.** *Defining the method of inspecting the inside of the PCV* **6.** *Defining the repair method of the upper part of the PCV* **7.** *The upper part of the PCV/Completion of water filling/Defining the method for inspecting inside of the core* **9.** *Completion of the preparation of fuel debris storage cans etc.*

FIG. 5.3–14. Conceptual model for future debris removal activities [120].

Fuel debris removal concept

To reach the point at which this concept can be implemented, many preliminary steps are required. A high level description of the sequence is listed below.

(1) Reduction of radiation levels in the reactor buildings: Access by workers to the spaces inside the reactor buildings is still difficult because of the high dose levels and the rubble and contaminated dust that have been scattered inside them. Decontamination will be conducted as needed to gain access, in many instances with remotely operated equipment.

(2) Repair of the PCVs containing water: An investigation will be conducted and the required equipment developed for stopping the water leakage from the PCVs, after which the water level in the PCVs will be monitored and maintained as needed for subsequent operations.

(3) Characterization inside the PCVs: Removal of the fuel debris requires pinpointing the exact locations of the pieces of fuel debris. The equipment to investigate the conditions inside the PCVs will be developed, and the necessary information, such as the locations, distributions and shapes of the fuel debris pieces, will be obtained. The information must be carefully collected, analysed and recorded.

(4) Characterization of the conditions inside the RPVs: This includes the distribution of fuel debris, as well as the physical configuration, physical properties and damage to the interior of the RPVs, including the distribution and shapes of once molten metal, the levels of radioactivity and other factors.

(5) Development of fuel debris removal technologies: The preconditions for fuel debris removal will be identified, leading to the development of technologies and equipment to open the reactors, remove structural impediments inside the RPVs and remove fuel debris.

(6) As the approach to removal of fuel debris progresses, there will be a need to implement a variety of water management systems beyond cooling and boron control. For example, additional means will be needed for removal of particulate material that becomes suspended as a result of the removal operations.

(7) Packaging, transfer and storage of fuel debris: As debris is removed from the RPVs and the PCVs, it will need to be placed in shielded containers. The containers will need to be removed from the reactor buildings and placed in interim storage on the Fukushima Daiichi site until a final disposition path has been decided.
(8) Prevention of nuclear criticality of fuel debris: Evaluations will be conducted and monitoring techniques put in place to preclude any possibility of nuclear criticality within the debris.
(9) Accounting for, and control of, nuclear material in the fuel debris: Based on the safeguards agreement with the IAEA and Japanese domestic law, accountability is required for fissionable materials. Because the standard methods cannot be applied to the fuel debris, accountability measures will be established before the fuel debris is removed from the reactors.

The Government of Japan is sponsoring conceptual studies that include gaining access to and removing fuel debris [120].

5.3.5. Achieving readiness for decommissioning

As the project progresses, conditions and criteria will be established to signal when the requirements for starting decommissioning have been achieved. Once achieved, they will be followed by immediate dismantlement, deferred dismantlement (long term safe storage), entombment or some combination of the three.

None of the three NPPs elsewhere in the world that experienced the most severe fuel damage in prior accidents have yet achieved the final end state for complete decommissioning [126]:

— The damaged Windscale unit is currently in a care and maintenance condition, with a plan to place it in safe storage in the next several years, withfinal decommissioning to occur around the middle of this century.
— Chernobyl Unit 4 is currently in the process of being placed in a condition of safe storage, with the final decommissioning also projected for the middle of this century.
— At the Three Mile Island site, the undamaged Unit 1 is operating normally, and it is planned to start decommissioning this unit within the next 20 years. The TMI-2 plant is in a safe storage mode, with a plan for complete dismantlement and site remediation as part of a combined decommissioning with Unit 1.

In the case of the Fukushima Daiichi NPP, it is too early to specify the exact preconditions for decommissioning. The purpose here is to provide a general idea of the considerations that are likely to form the basis of planning, once the recovery phase nears completion.

Because the conditions for each accident are unique, there is no standard for decommissioning following an accident. At the Fukushima Daiichi NPP, the Roadmap prescribes that decommissioning will follow the removal of the fuel debris. Once those conditions have been achieved, an analysis will be performed to evaluate and choose an option for safe storage or final decommissioning. In addition, a safety case will need to be made to address any of the following that may remain on-site until the ultimate end state is achieved [120]:

— Nuclear residues, particles and radioactive materials remaining within the facilities;
— Spent fuel in storage;
— Fuel debris in storage;
— Solid radioactive waste in storage;
— Processed water in storage.

When these analyses are completed, their conclusions will be used to determine the conditions to be established. These conditions will be specified for all aspects of the facility’s structures and rooms

and for all systems. As indicated in the range of presentations of the International Experts' Meeting on Decommissioning and Remediation after a Nuclear Accident, issues that will need to be addressed include [163]:

- Requirements for inspection, care and maintenance of any on-site stored waste and fuel bearing materials;
- Periodic inspection with procedures that specify what is to be inspected, the frequency of inspections, criteria for the evaluation of conditions and the walk-through path, including roof inspections;
- The ability to purge closed areas prior to entries for inspection;
- The prevention of serious spread of contamination by airflow pathways, filtered exhaust ventilation may be necessary;
- Preventing or minimizing in-leakage of storm water and snowmelt; removal and treatment of any such in-leakage;
- Ageing management of passive systems and damaged structures;
- Maintaining a fit for service condition of any SSCs required for the continued safety of the NPP;
- Structural integrity against earthquakes and other natural hazards;
- Fire detection and response if there are combustibles remaining;
- Prevention of intrusion by vermin, birds and other wildlife;
- Security of the site.

Electrical supply to support the above listed functions needs to be provided. Records and photographic/video information, along with periodic inspection and repair reports, need to be archived in a retrievable manner.

5.3.5.1. End state alternatives

Under normal (non-accident) circumstances, the end state for a licensed facility is defined and described in the licence application and subsequent supporting documents. Release from regulatory control is the end state condition sought for a facility that has reached the end of its operating life and is beginning the process of a planned, permanent shutdown. Achieving an end state that releases the licensed facility from regulatory controls would typically be achieved through complete dismantlement — an accomplishment achieved by 11 nuclear power production facilities worldwide as of December 2014 [164].

Two strategies for achieving a facility end state are generally accepted: immediate dismantling and deferred dismantling, which is sometimes referred to as safe storage. The accident damaged TMI-2 reactor is at present in safe storage. Former nuclear material production reactors at the United States Department of Energy (DOE) Hanford Reservation are also in a safe storage condition. In either case, once the criteria are established, the end state may allow unrestricted future use or may require restrictions on the future use [1]. It is also possible that a combination of end states that cover the range of possibilities could be achieved for the site.

Under exceptional circumstances, entombment may also be considered as the ultimate decommissioning end state [165]. Entombment involves encasing the facility in a long lived material to make sure that residual radioactivity cannot migrate to the environment. To date, this technique has been used on a smaller scale for research test reactors [166] and most recently on a large scale for former nuclear material production reactors in the United States. In 2011, the DOE completed the entombment of two former nuclear material production reactors at the Savannah River Site. In both instances, all fuel was removed, and the below grade sections of the facility were filled with cementious grout. The above grade structures, built of reinforced concrete, were left in place. To restrict rainwater intrusion, high strength intercrystalline grout caps were installed on the flat roofs

above the production areas. The DOE is also deploying entombment as a decommissioning strategy [18].

At this time, it is unrealistic to predict what the end state will be for the Fukushima Daiichi NPP. A final end state decision will need to consider many factors, including potential dose rates to the decommissioning workers, how much waste would be generated, what conditioning the waste may require and where that waste would be disposed. Expectations and plans for the land will also need to be considered. There is much yet to be learned regarding site conditions, and there will need to be a comprehensive dialogue with stakeholders before a decision can be made.

5.3.5.2. Release of site

International decommissioning standards recognize a range of alternatives for the release of a site once decommissioning actions are complete [115]. While the stated goals of all decommissioning standards are to release the licensed site from regulatory controls, they also take into consideration that there may need to be restrictions placed on the future use of the site. These alternatives range from reuse of the land for any purpose (including residential), to reuse for limited purposes (such as industrial), to retaining regulatory control over access and use. For a site covering a large area, it may also be possible to employ an end state that includes all these options with different end use restrictions being applied to different parts of the site. Alternatives for the end state and future use of the site are best discussed with stakeholders before the final decommissioning strategy is decided upon and implemented. This approach gives the responsible parties the best possibility of designing a decommissioning plan to support the likely future use of a site.

5.3.6. Summary

Under normal circumstances, decommissioning of an NPP is a planned activity that is initiated when the decision is made to end operations. Post-accident decommissioning presents a completely different set of circumstances.

Strategic planning

Following the Fukushima Daiichi accident, those responsible for the long term activities for stabilization and cleanup created a strategic plan for the overall project. This document is the Mid- and Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4. This Roadmap was developed jointly by TEPCO, ANRE and NISA and was issued on 21 December 2011.

The Roadmap is a comprehensive, high level strategic plan for those supervising the recovery. As a strategic plan, it provides policy and broad guidance to those responsible for carrying out the work. It also functions as a source of information for the general public.

The Roadmap had been revised twice since 2011, at the time of writing and the latest version available was dated June 2013. [31] The updates reflect the increased experience gained from the prior two years of work and an improved understanding of the actual conditions and the magnitude of the future challenges.

[31] It is anticipated that there will be further revisions to the Roadmap as plans are adapted in response to changing conditions and new information. The third revision of the Roadmap was issued during the final preparation of this Technical Volume (June 2015). This modified the schedule and the approach for fuel and debris removal and refined approaches for risk reduction, communication with local stakeholders, reduction in workers' exposures, and management of research and development [121].

Stabilization and long term reliability

Preparation for the decommissioning of an accident damaged facility involves first establishing stable conditions (i.e. stabilization) and ensuring that there are SSCs in place that will reliably maintain those conditions for the long term until their functions are no longer needed.

TEPCO has established stable conditions at the Fukushima Daiichi NPP for many functions needed to maintain safety and to allow progress toward decommissioning. These functions include: (1) cooling to compensate for the decay heat of the spent fuel and core debris; (2) maintaining subcriticality to prevent further nuclear reactions; (3) injecting nitrogen into areas where there is a potential for accumulation of hydrogen gas; (4) filtering ventilation to capture radioactive particulate matter before releasing to the surroundings; and (5) monitoring of these and other functions. Important support functions have been re-established; one example of this is the repair and upgrading of both normal and backup electrical supplies.

To ensure long term reliability of these stable conditions, systematic engineering, operational, and management approaches have been put in place for SSCs needed to provide these functions. TEPCO has also implemented substantial countermeasures in preparation for any future large earthquake or tsunami, including backup facilities and improved emergency preparedness at the site of the damaged NPP [141].

On-site water management

Even after achieving shutdown conditions, cooling of nuclear fuel and fuel debris must be maintained for several years after the accident to prevent overheating until the decay heat generation is so low that passive cooling is sufficient.

Water management at the Fukushima Daiichi NPP is a challenging problem owing to the volume of water and the sources of water now requiring management. As a consequence of the accident, sub-drains (pumps) that previously prevented groundwater from entering into the buildings ceased operation. The water is now entering the buildings and becoming contaminated, thereby continually adding to the volume of water needing to be managed and treated.

Storage tanks and water treatment facilities have been built. As of February 2015, the treated water was stored on-site in 826 tanks [167]. Additional treatment facilities continue to be added or upgraded. A series of water management techniques have been deployed or are in the planning stages, including restoration of the sub-drain system, installation of a landside impervious wall to further prevent water ingress and interception of water uphill of the damaged facilities and bypassing it around the facilities into the ocean.

With the approval of the NRA and after consultations with many stakeholders, including the Fukushima Prefecture and the fishing industry, TEPCO began discharging bypassed water in May 2014.[32] TEPCO was assessing the effectiveness of this measure on groundwater ingress into the buildings [140].

Spent fuel and damaged core fuel debris

TEPCO began removing the spent fuel in the storage pool within the Unit 4 reactor building in November 2013. The operation was completed in December 2014 [168].

---

[32] The requirements are: Discharges of ^{134}Cs or ^{137}Cs must be below 1 Bq/L, 5 Bq/L for total beta activity and 1500 Bq/L for tritium; third party monitoring to ensure discharge standards are being met; transparency in the release of information by TEPCO; and continuation of the compensation to fishers for reputational damage.

It will require several years to remove the spent and new fuel assemblies from the pools in all four units. The exact time is dependent on the progress that can be made in removing debris resulting from the explosions, preparing the upper structures of Units 1, 2 and 3 for access and providing support for equipment and structures for the removal of fuel. The spent fuel will be placed in a common pool and eventually moved to dry storage on the site.

The removal and management of debris from the melted fuel is a much more complex challenge. The debris will need to be characterized, removed, packaged and placed in storage. The major obstacles to achieving this at the Fukushima Daiichi NPP are the high radiation levels and the flow of water through leaks from the primary containments and from the reactor buildings.

Decommissioning

For those NPPs that have experienced severe fuel damage, the Fukushima Daiichi NPP can provide a unique insight into how best to approach decommissioning of multiple fuel damaged units. Plans for decommissioning show a progression from one unit to the next, offering an opportunity to provide lessons learned throughout the process. These lessons can be applied to the Fukushima Daiichi NPP and transferred to other sites. Although decommissioning scenarios tend to be driven by site specific conditions, the lessons learned from the Fukushima Daiichi NPP can provide information for developing multi-unit decommissioning strategies.

There is much yet to be learned regarding the material conditions within the Fukushima Daiichi reactor systems and the resulting site conditions that can be achieved. Once the fuel debris is recovered and rendered safe, it may be necessary to establish a safe storage condition for the facilities and site until the ultimate decommissioning end state is decided. At this early stage of cleanup activities, it is unrealistic to predict the ultimate end state but, in the decision making process, expectations and plans for the land will need to be considered.

Organization and management

Since the accident, the Government of Japan and TEPCO have had respective responsibilities for on-site decommissioning activities. While TEPCO is responsible and accountable for implementation and operation of measures toward decommissioning, the government has also assumed a role in the implementation of countermeasures concerning contaminated water as well as regulatory oversight of TEPCO by the NRA. The organizational structures of the government and TEPCO have evolved in a manner consistent with the circumstances and the changing situation at the NPP. This decommissioning work is estimated to take decades to complete, and a trained and educated workforce will be essential for ensuring success over the long term.

5.3.7. Observations and lessons

- **Following an accident, a strategic plan for maintaining long term stable conditions and for the decommissioning of accident damaged facilities is essential for on-site recovery. The plan needs to be flexible and readily adaptable to changing conditions and new information.** Such a plan serves as guidance for managing and coordinating the activities at the site. It is important that it provides a prioritized approach for completing the critical activities, including identification of key interactions between activities, criteria for decision making and the role of R&D in defining alternatives for future activities. A different regulatory approach for post-accident situations is necessary to allow the required flexibility in response to encountering unforeseen issues.
- **Once on-site stabilization has been achieved, it is important that the long term reliability of SSCs essential for safety is assured and maintained. Alternatives to the pre-accident SSCs**

(including backups) may be needed for many functions. In the long term, installation of new systems may be more effective than attempts to repair existing systems.
A combination of traditional and innovative approaches may be needed to ensure reliability of SSCs. In some instances, they need to be tailored to the unique conditions, including the potential for future damage from natural hazards, in which the SSCs are performing within damaged facilities.

— **Cooling fuel within a damaged nuclear reactor may require the use of large volumes of water that will entail subsequent treatment, conditioning and storage.**
Managing and characterizing cooling water before, during and following its processing will consume resources (money, human resources, time). The selection of treatment systems depends on the type of radionuclides and their concentrations and on other constituents that may be present in the water. The situation is more complex than during normal operations owing to the presence, for example, of boron, sea water minerals, particulate matter and microorganisms.
Waste water management at the Fukushima Daiichi NPP is a challenging problem owing to the volume of water requiring processing, storage and/or discharge. Although international guidance exists for discharges during the normal operation of nuclear facilities, further guidance on its application in post-accident situations is needed.

— **Retrieving damaged fuel and characterizing and removing fuel debris require solutions that are specific to the accident and special methods and tools may need to be developed.**
A reactor accident involving damage to the nuclear fuel results in unique conditions within the reactor and with regard to the fuel debris. Different plans for characterizing and removing damaged fuel and debris will need to be developed and carried forward to various degrees until one of the plans, or a combination of them, is considered to be the preferred method.

— **Decisions on interim stages and the end state of the site and the damaged reactors will need to take into account many factors that are difficult to evaluate at present.**
Such decisions will depend on the condition of the damaged reactors, fuel and debris, which cannot yet be determined in detail. Factors to be considered in the decision making include the potential dose levels for decommissioning workers, the volume and type of waste generated and the efforts required for waste treatment. The decision making process on the end state will need to include a dialogue with stakeholders.

— **It is essential to establish an integrated management structure for maintaining stabilization, preparing for decommissioning and carrying out decommissioning activities.**
The challenges of post-accident preparations for decommissioning are different from those of a normally operating plant. Long term stabilization and preparations for decommissioning depend upon the input from many organizations, and an integrated approach is needed to ensure that these efforts are effectively and efficiently managed. An organizational structure that is focused solely on decommissioning of the damaged site may be necessary.

— **Establishing and maintaining long term knowledge and technical expertise is essential for successful decommissioning.**
Post-accident preparations for decommissioning will take decades. Arrangements for maintaining the necessary expertise throughout this entire period are necessary.

5.4. MANAGEMENT OF CONTAMINATED MATERIAL AND RADIOACTIVE WASTE

5.4.1. Introduction

The Great East Japan Earthquake of 11 March 2011 and the subsequent tsunami and accident at the Fukushima Daiichi NPP resulted in the radioactive contamination of large areas of land and the generation of considerable amounts of contaminated material and radioactive waste both within (on-site) and outside the NPP boundary (off-site).

In the immediate aftermath of the accident, radioactive wastes were generated in the process of gaining access to, and stabilizing, the damaged nuclear facilities. Subsequently, significant quantities of waste were and are being generated during the implementation of the remediation programme (see Section 5.2).

The waste quantities are very much larger and levels of contamination much higher compared with waste originating from routine operations. The physical and chemical composition and characteristics as well as the levels of contamination vary widely. This resulted in the need for extraordinary efforts to identify waste streams and to segregate and characterize them. In order not to delay recovery activities, urgent decisions regarding the construction and operation of treatment and storage facilities for handling and managing this material were necessary.

This section deals with the management of contaminated material and radioactive waste, generated both off-site and on-site, following the emergency phase and beginning with the transition to an existing exposure situation in December 2011. It addresses the particular challenges involved in segregation, characterization, treatment and conditioning (e.g. volume reduction), storage, and future planning for the disposal of the waste.

The aspects of the regulatory and legal framework specific to the management of contaminated material and radioactive waste are addressed in Section 5.4.2.

Outside the boundary of the NPP, large areas of land are in the process of being remediated, generating a significant amount of contaminated material. The activities with regard to pre-disposal management (conditioning, interim storage, etc.) and disposal are discussed in Section 5.4.3.

Section 5.4.4 describes activities related to on-site waste management, including measures to address material such as building debris, trees and the large volumes of water containing high concentrations of radionuclides, oil and salt that were generated during the accident. It also discusses the continuing need for the management of contaminated water, resulting from ongoing reactor cooling and groundwater leakage into the reactors.

Section 5.4.5 presents a summary and, based on experiences from activities to date and measures still to be taken, lessons learned for the international community to strengthen nuclear safety worldwide.

5.4.2. Legal framework and responsibilities

The legal framework and responsibilities prior to the accident at the Fukushima Daiichi NPP have been described in Technical Volume 1. This section provides additional information related to radioactive waste management practices and describes the relevant changes that have taken place since the accident.

5.4.2.1. Radioactive waste management in Japan

Radioactive waste management in Japan is based on the acts and regulations identified in Section 5.4.2.2 [6, 169–171]. The radioactive waste generated at the nuclear facility level was required to be managed in compliance with the Reactor Regulation Act, the Act on Prevention of Radiation Disease Due to Radioisotopes, etc. (also referred to as the Radiation Disease Prevention Act)[33] and other relevant regulations [170].

[33] Act on Prevention of Radiation Disease Due to Radioisotopes, etc., Act No. 167 of June 10, 1957 as last amended by Act No. 69 of June 13, 2014, http://law.e-gov.go.jp/htmldata/S32/S32HO167.html

Waste classification scheme

Radioactive waste in Japan is classified into waste requiring geological disposal and waste requiring sub-surface disposal, near surface pit disposal and near surface trench disposal according to the radionuclide activity levels in the waste. An overview of the classification of radioactive waste and main regulatory system for the promotion of radioactive waste management and spent fuel management is given in Table 5.4–1 and Fig. 5.4–1 [170].

TABLE 5.4–1. CLASSIFICATION OF RADIOACTIVE WASTE [170]

Classification			Examples	Origin of waste
High level radioactive waste (HLW)			Vitrified waste canister	Vitrified liquid HLW that contains fission products such as ^{90}Sr and ^{137}Cs and actinide elements such as ^{241}Am and ^{237}Np, separated from spent fuel during reprocessing
LLW	Waste from power reactors	Waste from Core Structures, etc.	Control rods, core internals	Waste generated at NPPs
		Low level radioactive waste	Liquid waste, filters, used equipment, expendables	
		Very low level radioactive waste	Concrete, metals	
	Long lived low heat generating radioactive waste (transuranic (TRU) waste)		Sludge, filters, used equipment, expendables	Low level radioactive waste (LLW) generated from the operation and dismantling of reprocessing facilities and MOX fuel fabrication facilities
	Uranium waste		Expendables, sludge, used equipment	Radioactive waste generated from enrichment and fuel fabrication facilities
	Waste from research facilities, etc.		Liquid waste, metal, concrete, plastics, filters, disposable syringes	Radioactive waste generated from research facilities, medical, facilities, etc.
Material that need not be treated as radioactive waste (waste below clearance level)			Concrete , metal	Waste generated from the operation and dismantling of nuclear installations and the radioactivity concentration of the waste is so low that no measures to avoid radiation hazards are necessary

The Reactor Regulation Act [6] regulates the on-site treatment of radioactive waste, categorizing the wastes as gaseous, liquid or solid waste, and defines methods for on-site treatment of such waste. It considers:

— Category 1 waste: Radioactivity exceeds the concentration limits (e.g. ^{14}C > 1015 Bq/t, Alpha nuclides > 1011 Bq/t).
— Category 2 waste: Radioactivity does not exceed the concentration limits.

This Act also provides a system for the clearance from regulatory control of radioactive waste originating from nuclear reactors under appropriate conditions.

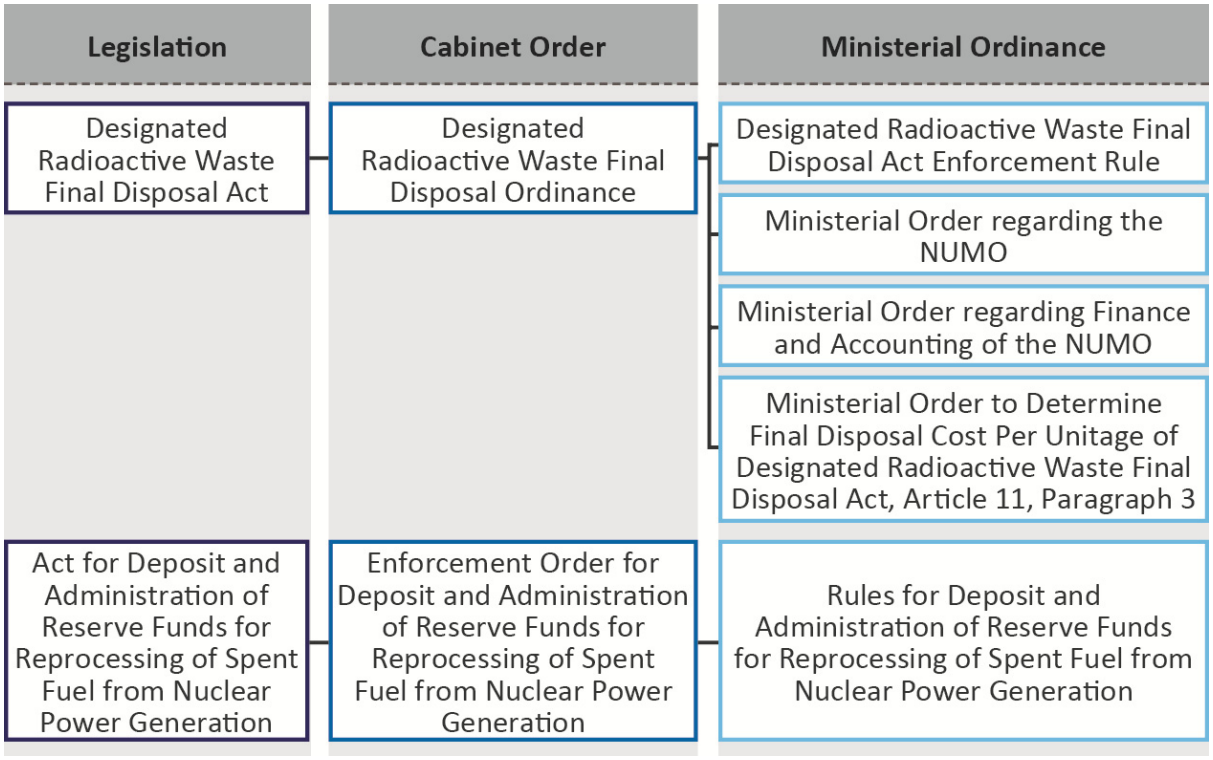


FIG. 5.4–1. Main regulatory system for the promotion of radioactive waste management and spent fuel management for normal waste streams [170].

5.4.2.2. Roles and responsibilities of national and local governments and other agencies before the Fukushima Daiichi accident

The roles and responsibilities of the various sections of government and other organizations involved in ensuring the safety of radioactive waste management are outlined in the National Report of Japan (October 2011) to the Fourth Review Meeting of the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (hereafter referred to as the National Report of Japan to the Joint Convention) [170]. Roles and responsibilities have evolved since the Fukushima Daiichi accident. These evolving roles and responsibilities have been developed from the roles and responsibilities that existed prior to the accident, as follows.

The ministries of the Government of Japan were responsible for developing the waste management policy and the safety regulations. They were also responsible for the supervision of waste management activities. Other government organizations, such as the Japan Atomic Energy Commission (JAEC), ANRE and JAEA, assumed responsibility for the promotion and implementation of radioactive waste management activities [170].

NISA and the NSC were responsible for the implementation of the regulations provided by the Reactor Regulation Act and other relevant acts. NISA was established in 2001 to integrate the regulatory functions of the METI. NISA was given the responsibility of administering the safety regulations for nuclear installations related to the utilization of nuclear energy. The structures and duties of the regulatory bodies were clearly specified in the applicable legislation and financed by the government budget. The regulatory bodies were responsible for the regulation of nuclear safety depending on the type of nuclear energy used. They also conducted inspections to confirm compliance with the regulations and associated technical standards. Radioactive waste management facilities for waste generated from commercial power plants were regulated by the regulatory body, NISA, to ensure proper performance of the facilities and compliance with the required operational safety

programme. Periodic assessment was implemented to ensure the safety of nuclear facilities. Existing waste management facilities were described in the National Report of Japan to the Joint Convention [170].

JNES was established in October 2003 as a technical support organization for NISA in ensuring safety in nuclear energy use [170].

The Nuclear Waste Management Organization of Japan (NUMO) was established as an organization to implement disposal as required by the Final Disposal Act [169] and the Basic Policy for the Final Disposal of Designated Radioactive Wastes [34] and the Plan for Implementation of Waste Disposal [170]. NUMO works in close cooperation with the government. The electricity utility companies plan for implementation of safe disposal of high level radioactive waste (HLW) and transuranic (TRU) waste[35] in geological repositories. NUMO is also responsible for site selection and characterization, construction, modification and maintenance of repository, closure and post-closure management [170].

Japan Nuclear Fuel Limited (JNFL) is responsible for the disposal of low level radioactive waste (LLW) generated at NPPs. The waste is buried at the LLW Disposal Center at Rokkasho Village in Aomori Prefecture, which is owned by JNFL. The radioactive fuel cycle waste is stored at the facilities where it was generated [170].

The operators of the nuclear facilities that generate the waste are responsible for the management of radioactive waste on-site. Non-compliance with the stipulations given in a licence could result in its revocation.

5.4.2.3. Funding of radioactive waste management before the Fukushima Daiichi accident

The application to license a nuclear facility, including a waste management facility, requires the availability of the necessary financial resources. This is an essential requirement for obtaining a licence for waste management [6, 169–171].

Pursuant to the Final Disposal Act, operators of power reactors are required to deposit funds with NUMO for the disposal of HLW. NUMO is the implementing body for disposal. The management of the funds has been entrusted to the Radioactive Waste Management Funding and Research Centre. Payments are made by each company and are adjusted on an annual basis, the amount being based on the previous year's production of HLW. Every year, NUMO notifies the companies of the amount to be deposited into the fund [170].

5.4.2.4. Creation of new responsibilities after the Fukushima Daiichi accident

The Fukushima Daiichi accident led to a number of modifications of the nuclear safety regulatory authorities in Japan, including those with responsibility for the regulation of radioactive waste management, as described in more detail in Technical Volume 1. The findings and the lessons learned from the accident led to a reform of the regulatory authorities in order to separate regulatory functions with respect to nuclear safety, security, safeguards, radiation monitoring and radioisotope regulation from promotional functions. The reform was based on the Cabinet Decision of 15 August 2011 and the Recommendation from the Advisory Committee for the Prevention of a Nuclear Accident of 13 December 2011 [173–175].

---

[34] The Basic Policy was revised during the final preparation of this volume (22 May 2015). In the revised plan, the Government of Japan will "play a proactive role in resolving the issue of designated radioactive wastes". [172]

[35] That is, long lived low heat generating radioactive waste.

Following the accident, the government established new legislation clearly defining the responsibilities for off-site waste management. The Ministry of the Environment (MOE) was appointed the responsible body for developing acts and implementing off-site remediation activities. Accelerated licensing processes were needed to support initial recovery activities. In cooperation with relevant interested parties, the MOE developed specific regulations and guidelines to address these needs. In addition, institutional arrangements were made and implemented with the extensive involvement of the national Government, prefectural governments, municipalities and other institutions to provide the financial, technical and logistical support to manage the contaminated material and the radioactive waste resulting from the accident.

With respect to on-site waste management, the existing Reactor Regulation Act was amended after the accident but the basic legal framework did not change. A bill for the establishment of the Nuclear Regulation Authority was subsequently approved by the National Diet, enacted on 20 June 2012, and promulgated on 27 June 2012 [110]. Accordingly, the NRA was established on 19 September 2012 as an independent commission affiliated with the MOE [110]. Thus, on-site activities are clearly defined with the NRA as the regulator and TEPCO as the implementer.

5.4.2.5. Regulations, standards and guidelines for radioactive waste and contaminated material management

Legislative and regulatory instruments have been developed after the Fukushima Daiichi accident for dealing with on-site and off-site waste. Post-accident issues concerning off-site waste management have been addressed in the Act on Special Measures Concerning the Handling of Radioactive Pollution, which was enacted following governmental and ministerial ordinances issued by the MOE [27]. This Act specifies which wastes are the responsibility of the national Government, and which wastes are to be dealt with by the prefectures and municipalities. The national Government is assigned the responsibility for all waste generated inside the SDA and for all waste generated outside the SDA that are designated by the Minister of the Environment. This 'designated waste' has been defined as waste in which the radiocaesium content exceeds 8000 Bq/kg. Details on the selection of the threshold of 8000 Bq/kg for Designated Waste and the reasons for targeting caesium are described in Approaches to Ensuring Safety in the Act on Special Measures Concerning the Handling of Radioactive Pollution [176]. For low level contaminated waste other than designated waste, measures to be taken must be in accordance with the Waste Management and Public Cleansing Law (also referred to as the Waste Management Law) [7].

For radioactive waste generated at the Fukushima Daiichi NPP, the legal framework is described under the Reactor Regulation Act [6].

Legal framework for radioactive waste management during the emergency

Large amounts of waste were generated during and after the Fukushima Daiichi accident. The generated waste includes contaminated material and radioactive waste with a wide range of characteristics that cannot necessarily be processed by the usual waste management conditioning techniques and procedures. The regulatory standards for waste that existed at the time of the accident needed to be adapted to enable adequate management for this type of waste. There was no specific regulation in place for the management of radioactive waste generated during the emergency phase of the accident, as discussed in more detail in Technical Volume 3.

Legal framework for radioactive waste generated on-site and contaminated material generated off-site

Waste generated off-site during remediation activities consists of contaminated soil, organic matter (leaves, branches, etc.), debris and rubble or contaminated consumer products. This material is mainly

managed according to the Act on Special Measures Concerning the Handling of Radioactive Pollution. The Act also specifies the roles and responsibilities of the institutions involved, such as the national Government, prefectural governments and municipalities. Furthermore, it defines responsibilities for monitoring, decontamination and waste management, as well as for the provision of financial resources.

On-site waste is generated mainly from activities that involve the cooling of the reactors, gaining access to the reactors, dismantling, decontamination and cleanup, and demolition. On-site waste is currently regulated by the Reactor Regulation Act [6].

Regulations on clearance levels for on-site and off-site waste

Waste streams for on-site waste arising from the operation and decommissioning of commercial NPPs are defined under the Reactor Regulation Act. In 2005, the concept of clearance levels was added to the Act, conforming to IAEA Safety Standards Series No. GS-R-1 [177], which was valid at that time. The clearance level is based on the fact that the risk of the material containing extremely low levels of radioactivity affecting human health is negligible. After the accident, in June 2011, the NSC provided the additional document Near-term Policy to Ensure the Safety for Treatment and Disposing of Contaminated Waste Around the Site of Fukushima Daiichi Nuclear Power Plants [178]. This document made provisions for the possibility of reuse or recycling of material if the activity concentration is lower than a concentration equivalent to 10 mSv/y. It also includes provisions for waste disposed of as industrial waste after approval and confirmation by the government [6].

As mentioned above, there was no legislation available for waste streams for off-site waste before the accident. The waste streams for off-site waste were established in 2011 under the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], which is the main legal instrument that deals with materials contaminated by the accident, as well as the management of materials that have been generated during remediation activities. The Basic Principles were published in November 2011 [29].

Licensing of storage, treatment and disposal facilities

For off-site waste, the MOE is responsible for establishing facilities for the management (characterization, treatment and conditioning, storage, and disposal) of contaminated waste and soil in the SDA (see Section 5.2) and for the management of designated waste in other areas. In order to facilitate timely implementation of recovery activities, it was very important to rapidly establish a regulatory framework and guidance for the implementation of waste management, including treatment, storage, transport and disposal. The MOE has established advisory committees to assist in the implementation of decontamination, the siting and design of the Interim Storage Facility (ISF) and off-site waste management [29].

Waste generated on-site includes debris resulting from the earthquake, tsunami and the accident, as well as waste from decommissioning and dismantling operations. Secondary waste is generated during water treatment. Licensing of on-site waste management facilities for treatment, transportation, storage and disposal is the responsibility of the NRA, according to the Reactor Regulation Act [6]. For licensing, TEPCO submits an application and an implementation plan that requires approval by the NRA.

Classification and characterization of contaminated materials after the accident

The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] provides a description of the categories of waste generated during the off-site remediation of areas affected by the nuclear accident and arising from the earthquake and tsunami that hit the coastal area of Tohoku.

Contaminated materials are categorized by origin and type. Categories include soil, branches and leaves, waste produced by industrial activities, ash from incineration of combustible refuse collected in the municipalities, sewage sludge and sludge from water treatment plants.

Waste generated within the SDA is the responsibility of the national Government. Designated waste is also the responsibility of the national Government, irrespective of its original location. Waste outside of the SDA, e.g. within the ICSA that has radiocaesium concentrations below the level that would qualify it as designated waste is the responsibility of the municipalities (for activities including storage, volume reduction and disposal).

Each type of waste is controlled through the entire period of management. Temporary storage sites (TSSs) need to be prepared by the waste generator in case of designated waste. In case of waste in the SDA, the sites are selected in consultation with the local municipalities. In the case of removed soils, etc., the storage sites are selected with the involvement of the residents, in cooperation with the local municipalities.

5.4.2.6. Roles and responsibilities of national and local governments and other agencies for waste management after the Fukushima Daiichi accident

Off-site wastes are generated mainly from remediation and other activities following the Fukushima Daiichi accident and comprise contaminated material and disaster waste, i.e. waste generated from the earthquake (wreckage of buildings collapsed by the earthquake and tsunami; cars, ships, etc., damaged by the tsunami). The MOE developed a plan of the basic principles, sought Cabinet approval, and set standards for the processing of contaminated waste and contaminated soil. The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] stipulates actions to be taken and the responsibilities of various institutions and organizations including national and local governments, municipalities and the nuclear power operator, TEPCO. According to the Act, the government is in charge of building a regulatory regime for off-site decontamination and waste management.

The primary responsibility for on-site waste management rests with the nuclear facility operator, TEPCO, with NRA being the regulator. Under the Reactor Regulation Act, TEPCO is required to submit an implementation plan for approval by the NRA. The plan includes the description of waste types, estimated amounts of waste, waste storage methods, and plans for R&D for the future [6, 112].

5.4.2.7. Documentation and record keeping

In order to ensure safety throughout the waste management life cycle after the Fukushima Daiichi accident, it is necessary to understand the interdependencies of the various waste management activities, from generation to disposal. Information on waste characteristics (e.g. origin of waste, radionuclide concentration, physical characteristics and chemical composition) needs to be collected and kept for the purpose of siting, designing and operating of waste management facilities. In line with these internationally accepted principles, Japanese legislation requires detailed record keeping and documentation. Records of activities undertaken during and after the accident are provided in a number of documents that are available at the MOE, TEPCO, NRA, MAFF and METI web sites.

Record keeping and documentation covering all activities relating to on-site waste is primarily the responsibility of the waste generator and the licensee (the organization responsible for waste management). For HLW subject to geological disposal, the licensee is NUMO. For LLW from nuclear power reactors, JNFL is responsible for record keeping. These records are to be kept for a designated period of time.

Reporting on activities regarding off-site areas is addressed by the Act on Special Measures Concerning the Handling of Radioactive Pollution [27]. The Act provides the MOE with broad powers to require reporting on the collection, transfer, storage and disposal of designated waste.

5.4.2.8. Funding of waste management after the Fukushima Daiichi accident

The existing legislation in Japan defines responsibility for the costs of radioactive waste management. Waste originating from the Fukushima Daiichi accident in off-site and on-site areas will be borne by the operator, TEPCO (including activities during and after the emergency), with support from the national Government. The national Government is responsible for taking steps to finance the management of contaminated material and radioactive waste. Provisions made for contaminated material also require that funding is made available for future activities to ensure the safety of TSSs and ISFs.

The Japanese Government has also established a Reconstruction Agency to provide a political and financial framework for actions dedicated to the reconstruction of the areas affected by the Fukushima Daiichi accident. The Reconstruction Agency plans, coordinates, and implements the national policy on reconstruction for the resettlement of the people affected by the Fukushima Daiichi accident. This includes funding of decontamination activities and restoration of infrastructure in areas affected by the accident.

5.4.3. Off-site management of waste and contaminated material

This section describes the management of contaminated material, generated off-site, following the Fukushima Daiichi accident. As a result of various efforts to remediate the affected area described in Section 5.2, large amounts of contaminated material have been generated. In order to protect people and the environment from additional radiation exposure, there was a need to manage these large volumes of contaminated material, including the construction of waste storage and waste treatment facilities, and the means of transport for the waste. In order to implement these activities in a coherent, rapid and safe manner, it was urgently necessary to establish national policies and strategies on waste management for off-site areas, which also required creating or adapting existing laws and regulations.

5.4.3.1. Categorization of waste

The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] defines the contaminated waste within Fukushima Prefecture as follows:

(1) Waste within the Countermeasure Area (former Restricted Area and Deliberate Evacuation Area, which overlaps the SDA). It consists of debris from tsunami, disaster hit house demolition debris and house cleaning waste resulting from long term evacuation.
(2) Designated waste: Contaminated waste above a certain level (8 000 Bq/kg), such as sewage sludge, incinerated ash, etc.
(3) The combination of (1) and (2) is referred to as ‘specified waste’.
(4) Low level contaminated waste other than specified waste: Waste with activity less than or equal to 8000 Bq/kg and which does not originate within the Countermeasure Area. This waste is subject to the Waste Management and Public Cleansing Act [7].
(5) Soil and waste arising from the decontamination activities. This waste includes soil, grass, leaves, branches, surface sediments, etc. Division of responsibility for the management of waste during remediation

As was described in Section 5.4.2, MOE was assigned the responsibility for off-site waste management related to remediation of contaminated land. After issuing the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], the MOE developed the ‘Guidelines for

Waste: Guidelines for Treatment of Waste Contaminated with Radioactive Materials Discharged by the Accident' (Waste Related Guidelines) in December 2011 [179].

The Waste Related Guidelines were developed to help stakeholders involved in waste management (e.g. in waste generation, segregation, transportation and storage), including municipalities, to manage contaminated waste in a safe manner. The document describes the responsibilities and expected treatments for various types of waste and contains six sections:

— Section 1: Contamination level investigation methodology.
— Section 2: Specified domestic waste and specified industrial waste.
— Section 3: Designated waste.[36]
— Section 4: Decontamination waste.
— Section 5: Radioactivity measurement methodology.
— Section 6: Specified waste [180].

The document also presents the responsibilities and the waste management procedures for soils and solid waste contaminated with radioactive material resulting from the Fukushima Daiichi accident. It also includes information on the threshold values, responsibilities for, and types of treatment for various categories of waste.

Additional details on the management of decontamination waste are given in Table 5.4–2.

[36] See Section 5.4.2.5 for details of waste classification.

TABLE 5.4–2. OFF-SITE MANAGEMENT OF CONTAMINATED SOILS AND SOLID WASTES [181]

Category		Generating area	Entity responsible for treatment and disposal	Typical mode of temporary storage	Expected intermediate treatment	Expected treatment after temporary storage and intermediate treatment
Soil	Soil removed from the decontamination work specified in the decontamination plans in the Special Decontamination Area (SDA)	SDA	Ministry of the Environment (implementing decontamination)	Local storage, dedicated temporary storage sites	None	Stored in an ISF, Reuse
	Soil removed from the decontamination work specified in the decontamination implementation plans in the ICSAs	ICSAs (within Fukushima Prefecture) ICSAs, (other prefectures)	Relevant municipalities, prefectures, etc. (implementing decontamination)	Local storage, dedicated temporary storage sites	None	Disposal
Contaminated solid waste	Solid waste generated from the decontamination implementation work specified in the decontamination Plans (grass, leaves, branches, surface sediments, etc., mostly biodegradable and combustible)	SDAs	Ministry of the Environment (implementing decontamination)	Local storage, dedicated temporary storage sites	Existing incineration facilities, incineration at temporary incineration Facilities. Planning and construction are ongoing.	>100 000 Bq/kg: ISF, <100 000 Bq/kg existing controlled waste disposal facility: (Regardless of the activity concentration, incinerated ash generated from decontamination will be stored in the ISF)
		ICSAs (within Fukushima Prefecture) ICSAs (other prefectures)	Municipalities, prefectures, etc. (implementing decontamination)			Existing controlled waste disposal facility

5.4.3.2. Waste management strategy

The key elements of the remediation waste management strategy have been formulated by the Government of Japan, and in particular by the MOE [27, 179, 181]. They include the following:

- Collection of remediation waste in temporary storage sites near the decontamination location;
- Transport of remediation waste material from temporary storage sites to the interim storage facility;
- Volume reduction of combustible material by incineration in available municipal solid waste incinerators equipped with off-gas cleaning systems for the retention of ^{134}Cs and ^{137}Cs;
- Volume reduction of soil by the use of soil washing techniques to separate caesium or caesium-rich soil constituents;
- Disposal, depending on radioactivity content, in the ISF or in commonly used or specially designated municipal landfills or near surface disposal facilities;
- Establishment of an inventory of collected material to keep track of the activity and the amounts accumulated.

This strategy was implemented through the following actions:

- Use of existing infrastructure that is appropriate for management of such large volumes of generated material (including collection and segregation at the source by the activity level);
- Establishment of numerous temporary storage facilities;
- Providing capacity for transport, treatment, volume reduction and disposal at municipal landfills for disposal;
- Identification of potential sites for the interim storage facility appropriate for the storage of large volumes over the required period of time;
- Identification of designated disposal sites for different types of wastes.

In order to conduct remediation activities smoothly in many locations in parallel, the waste management activities needed to be conducted with the involvement of various stakeholders such as municipalities and prefectures. Since it was foreseen that the construction of an interim storage facility would need time, the utilization of temporary storage facilities became very important. However, since there were difficulties identifying locations for temporary storage facilities, the need for reducing waste volume by the proper selection of decontamination techniques became more important.

Following discussions by national and local government officials with local residents and landowners, the plan to construct an interim storage facility was accepted in Okuma Town in December 2014 and in Futaba in January 2015. In January 2015, the MOE confirmed plans and arrangements for pilot scale transport of contaminated soil to the interim storage facility from March 2015 [55]; for testing purposes; these transports started on 13 March 2015.

Details on how this strategy has been implemented are provided in the following sections.

5.4.3.3. Waste types, characteristics and quantities

Waste types

As stated in Section 5.4.3.1, contaminated waste is characterized by the type of material, the area of origin and the activity level. The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] defines waste according to the following criteria:

- The locations where the waste was generated (e.g. SDA and ICSA; see Section 5.2);
- Activity concentration of ^{134}Cs and ^{137}Cs (<8000 Bq/kg, <100 000 Bq/kg, >100 000 Bq/kg);

— Waste types (combustible, non-combustible waste, soil);
— Origin of waste (remediation activities, demolition of houses damaged by earthquakes, waste generated during cleaning of houses in the evacuated zone).

Waste quantities

The quantity of contaminated material per unit area from remediation activities depends on the characteristics of the affected environment (urban, forest, agriculture, etc.) and the decontamination criteria. The remediation techniques selected determine the amount and radioactivity concentrations of the waste that will be generated and transferred to the storage facilities associated with the decontamination work [182].

The estimation of the amount of waste in the SDA is based on the following factors:

— Decontaminated objects, such as roofs, gutters and farms;
— Land use, such as residential areas, schools, parks and farmlands;
— The decontamination methods selected, e.g. removal of deposits, scraping-off surface soil and wiping residues.

According to information given by the MOE, it is estimated that the incineration of combustible materials will reduce the waste volume by approximately 20% [183].

The amount of debris which contains some contaminated material in the SDA (countermeasure area) resulting from the earthquake and tsunami, so called disaster waste, was estimated by volume measurement and assessment of composition through inspection at each location. Disaster waste amounts to approximately 680 000 Mg in coastal areas of Fukushima (Minamisoma City, Namie Town, Futaba Town, Okuma Town, Tomioka Town and Naraha Town). Since most of this debris was generated as a result of the tsunami, it is concentrated in the coastal areas. It has been estimated that up to 30% of such waste is combustible. Table 5.4–3 presents the estimated quantity of waste within the SDA.

TABLE 5.4–3. ESTIMATION OF QUANTITY OF WASTE WITHIN THE SDA AS OF DECEMBER 2013 [184]

	Disaster waste (Mg)	House cleaning waste (Mg)	Total (Mg)
Minamisoma City	247 000	13 000	260 000
Namie Town	263 000	26 000	289 000
Futaba Town	13 000	180	13 000
Okuma Town	3 400	500	3 900
Tomioka Town	91 000	13 000	105 000
Naraha Town	62 000	14 000	76 000
Iitate Village	660	41 000	42 000
Kawamata Town	860	2 400	3 300
Katsurao Village	660	6 100	6 700
Tamura City	1 300	1 100	2 300
Kawauchi Village	1 200	1 300	2 500
Total	684 000	119 000	802 000

The amount of designated waste, such as incinerated ash, was estimated based on data derived from the current fraction of sewage sludge exceeding 8000 Bq/kg that was already specified as such, and the amount of the waste that could exceed 8000 Bq/kg due to future incineration [185]. Table 5.4–4 presents the estimated status of designated waste.

TABLE 5.4–4. CURRENT STATUS OF DESIGNATED WASTE (AS OF DECEMBER 2014) [186]

	Incineration ash (t)		Waste sludge (t) (domestic water)	Waste sludge (t) (industrial water)	Sewage sludge (t)	Agriculture and forestry waste (t)	Other (t)	Total (t)
	Public waste	Industrial waste						
Iwate	199.8	0	0	0	0	0	275.8	475.6
Miyagi	0	0	1 011.2	0	0	2 238.2	74.7	3 324.1
Yamagata	0	0	0	0	0	0	2.7	2.7
Fukushima	99 751.9	3 025.1	2 261.2	168.1	9 447.4	2 481.3	12 534.3	129 669.2
Ibaraki	2380.1	0	0	0	925.8	0	226.9	3 532.8
Tochigi	2 447.4	0	727.5	0	2 200	8 133.0	18.4	13 526.3
Gunma	0	0	545.8	127.0	513.9	0	0	1 186.7
Chiba	2 717.7	0.6	0	0	542.0	0	420.8	3 687.0
Tokyo	980.7	1	0	0	0	0	0	981.7
Kanagawa	0	0	0	0	0	0	2.9	2.9
Niigata	0	0	1 017.9	0	0	0	0	1 017.9
Shizuoka	0	0	0	0	0	0	8.6	8.6
Total	108 483.5	3 026.7	5 563.6	295.1	13 629.1	12 852.5	13 565.2	157 416

5.4.3.4. Waste management during the emergency phase

On 3 June 2011, the NSC issued a near term policy as an immediate measure to ensure the safety of the treatment and disposal of the contaminated material around the site of the Fukushima Daiichi NPP.

The treatment and disposal of contaminated materials were implemented by the MOE for waste in the evacuated area and by municipalities in other areas (areas with low level contamination) [27,81].

The materials generated during the early remediation of land, buildings, agricultural land, forests, dams, and so on, were temporarily stored at designated places. Contaminated materials were packed in weatherproof sandbags or waterproof bags and placed on plastic sheets on the ground. The collection was then covered with plastic sheets, and sandbags were placed on the plastic sheet to provide radiation shielding. Contaminated disaster waste, in particular, was segregated by dose rate. Enhanced shielding measures were also taken to reduce dose rates [176]. A wide range of focused remediation projects were rapidly initiated by municipalities and local communities during the emergency phase for specific areas (schools, playgrounds, public land, trees/forests, roof surfaces and gutters, drainage systems, roads, etc.). The remediation activities were prioritized to reduce the exposure of children first. Although the main effort involved the manual washing and removal of contaminated material using technology that is easily available, other methods that might improve decontamination while decreasing the volumes of waste were also tested [81].

Waste produced from remediation activities was reduced in volume as much as possible, for example, by the grinding or chipping of foliage, concentration of radioactivity from contaminated water or the separation of waste according to activity levels.

Waste from the cleaning of houses has been collected and transferred to temporary storage facilities. In most cases, labelled heavy duty flexible containers were used for solid waste transportation and storage. However, contaminated disaster waste in the SDA, such as the tsunami debris and house demolition debris, has been collected and temporarily stored within the SDA without further treatment.

This experience has shown the importance of establishing effective plans and actions to be taken for safely storing waste within a very short period of time, which is essential in order not to delay the implementation of remediation activities.

5.4.3.5. Efforts in waste management after the emergency phase

The ongoing efforts in the management of contaminated material can be divided into two categories: management of contaminated material in Fukushima Prefecture and the management of contaminated material outside Fukushima Prefecture. The following two flow charts (Figs 5.4–2 and 5.4–3) illustrate the ongoing efforts in both areas [187, 188]. The main difference is due to the fact that, in Fukushima Prefecture, contaminated material above 100 000 Bq/kg is transferred to an interim storage facility and subsequently to disposal, whereas in other prefectures it is transferred to a leachate controlled landfill. In addition, the ongoing efforts for managing disaster waste are shown in Fig. 5.4–4.

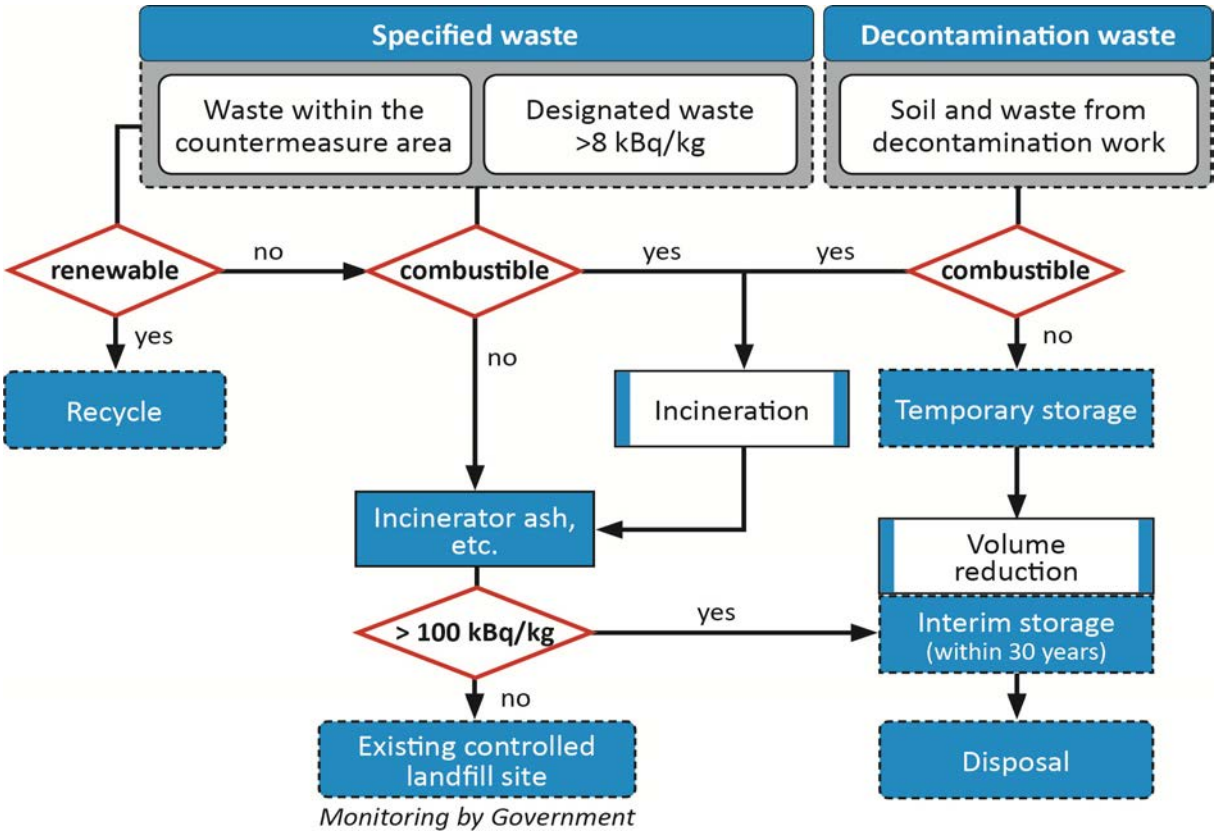


FIG. 5.4–2. Flow chart of specified waste and contaminated soil management in Fukushima Prefecture, as of December 2014 [189][37].

[37] Regardless of the activity concentration, incinerated ash generated from decontamination will be stored in the ISF.

The volume of waste within the Countermeasure Area is approximately 800 000 t (as of 26 December 2013), and that of designated waste is approximately 130 000 t (as of the end of December 2014).

The amount of soil and waste generated from decontamination is estimated to be 16–22 million m^3 after volume reduction (incineration) (as of October, 2013).

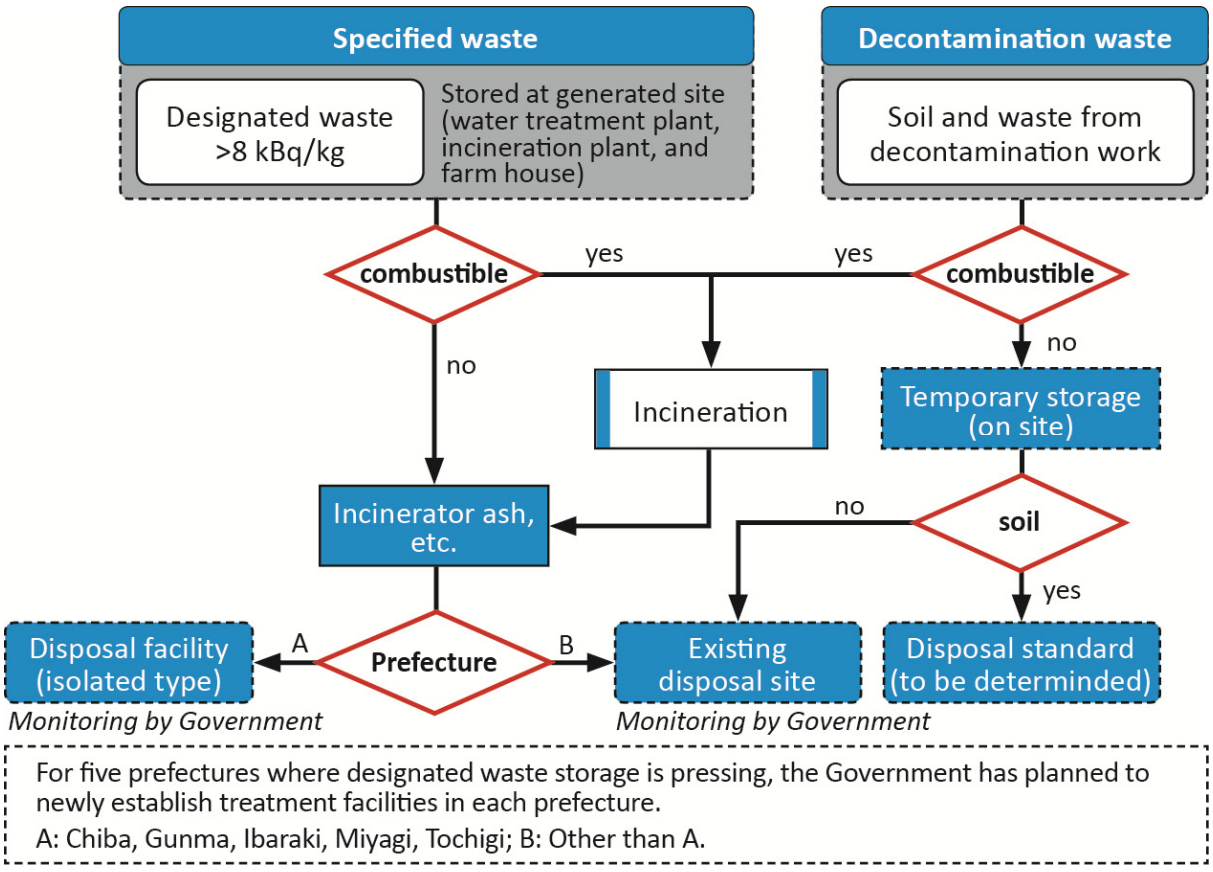


FIG. 5.4–3. Flow chart of specified waste and contaminated soil management in other prefectures [190].

Outside Fukushima Prefecture, the amount of designated waste is approximately 28 000 t (as of the end of December 2014) and the amount of soil and waste generated from decontamination is estimated to be 1.4–13 million m^3 (as of October, 2011).

The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] notes that large volumes of waste will be generated, especially of soil contaminated by radioactive material originating from the accident. Hence, it is advantageous to reduce the volume of material that must be managed through the segregation of highly contaminated material from lightly contaminated material, and through the separation of non-combustible and combustible materials with the subsequent incineration of the combustible material. The ongoing activities are described below.

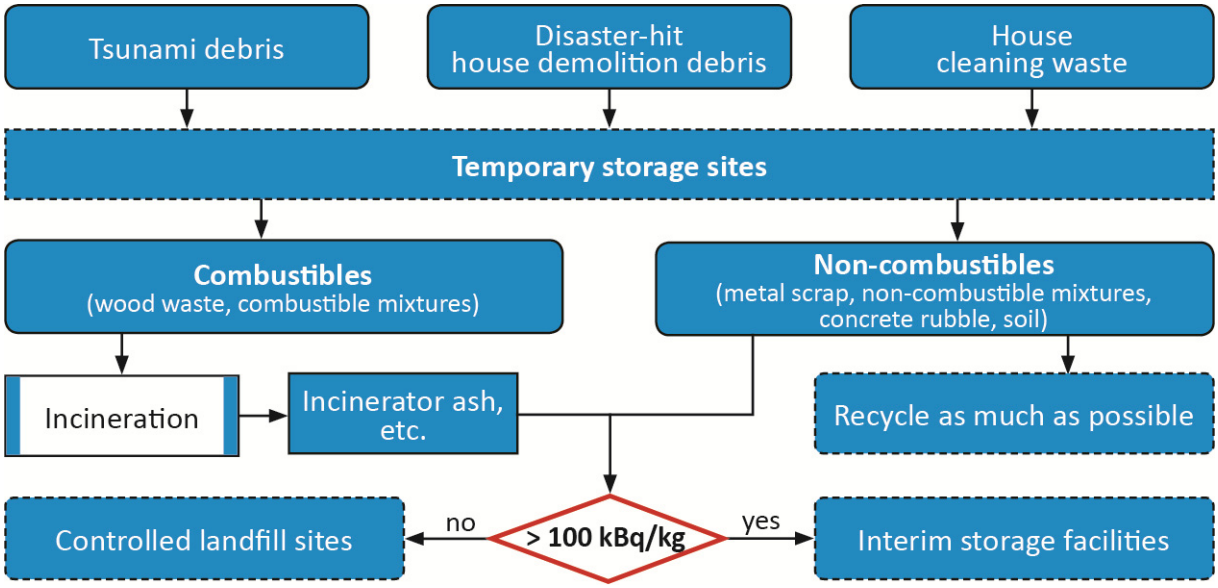


FIG 5.4–4. Processing flow of waste in the SDA [189].

Collection and transport

Solid waste from remediation activities (soil, grass, leaves, branches, surface sediments, etc.) is collected and, after volume reduction, placed into containers, labelled and then transported to temporary storage sites. There are two kinds of container to store removed soil, etc., namely a large weatherproof sandbag and a flexible container. Both containers are subject to performance requirements related to the material and container and to certification by authorized examining bodies. In the case of a flexible container, the maximum loading is 1.5 t. Neither the sandbags nor the flexible containers can be considered to be gas or watertight.

The bags are labelled with either a robust conventional tag or an electronically readable chip that contains a sample location code, date, description of contents, estimated ^{134}Cs and ^{137}Cs activity concentrations and surface dose rates. In addition, waste is either bagged at the point of remediation work or shipped by trucks to a central bagging location. Waste bags are then stored for a short period with minimum cover (tied/weighted down heavy plastic sheeting) and control (barrier to prevent close approach), until they are transported to the temporary storage sites (TSSs) [81, 186, 191].

In the case of waste in the coastal areas of the SDA, tsunami debris and house demolition debris were piled up temporarily at the site after disaster rescue activities Once TSSs have been acquired, this waste will be collected, transferred to the TSSs and segregated, according to the process shown in Fig. 5.4–4.

For transportation of the decontamination waste, the following essential measures have been considered:

— Set-up and operation of a data management system to control loading, transport, storage and disposal;
— Definition of transportation routes and truck control points to ensure compliance with the routing plan;
— Set-up of cleaning areas and monitoring points for trucks, either at storage or disposal sites or between the contaminated and clean zones;
— Set-up of an emergency response plan for the event of a transportation accident;

— Measures to prevent dispersion of decontamination waste to the air, such as the use of airtight flexible containers and secondary contamination prevention measures.

Segregation

Segregation of contaminated material based on activity concentrations of caesium (<8000 Bq/kg, <100 000 Bq/kg, >100 000 Bq/kg) takes into account waste forms (combustible/non-combustible/soil) at the point of collection.

Waste with an activity concentration below 8000 Bq/kg is treated by the normal treatment methods used for non-radioactively contaminated waste (combustion, recycling of metals and plastic, composting organic materials, etc.).This waste is managed as municipal solid waste, utilizing the existing infrastructure for transportation, handling, volume reduction and disposal in municipal solid waste landfills.

As noted previously, waste with an activity concentration exceeding the threshold value (8000 Bq/kg) is categorized as designated waste. It requires special arrangements for transport, treatment, eventual recycling and reuse or disposal in designated landfills equipped with systems for leachate collection, control of gases and adequate monitoring [192].

Processing (pretreatment, treatment and conditioning)

The treatment standards of contaminated waste have been defined in Ref. [182]. Combustible designated waste such as sewage sludge, as well as agricultural and forestry by-products, are reduced in volume and stabilized through incineration or de-watering.

The management of incinerator ash and sewage sludge depends on the activity levels:

— Ash with caesium activity concentrations of 8000 Bq/kg or less is to be disposed of at conventional leachate controlled landfills.
— For ash with activity levels between 8000 and 100 000 Bq/kg, the proposed disposal pathway is in designated landfills equipped with leachate control systems that can be further monitored. Ash is to be fully immobilized, e.g. by the use of cement or other suitable matrix material prior to disposal [81, 193].

For solid wastes, volume reduction has also been implemented wherever practical. For trees, high pressure washing is also an option but for most other vegetation, cutting, trimming or uprooting have been widely applied. Incineration reduces the volume of branches and leaves very effectively. The ^{134}Cs and ^{137}Cs concentrations in the exhaust air are kept below the regulatory limit through flue gas treatment using bag filters (high efficiency flue gas treatment equipment) to remove particulates in the discharged effluent [193].

For foliage, significant volume reduction was achieved by mechanical shredding/chipping, a process that was implemented at several demonstration sites [81, 193].

The strategy for the management of disaster waste, and waste from decontamination, aims to use existing municipal incinerators, subject to the provision of adequate off-gas cleaning systems for the retention of caesium (Fig. 5.4–5). In addition, the following measures were considered in order to protect people and workers from radiation exposure:

— Set-up of training and occupational exposure limits for workers involved in the collection of material for temporary storage and segregation into different activity categories at the point of collection by the Ordinance of MHLW revised in July 2013 [57, 194].

— Establishment of limits for direct recycling and reuse of less contaminated material (e.g. rubble, metal, soil, etc.).
— Transportation of non-processable contaminated material directly to disposal facilities, and of soil to either treatment or disposal facilities.
— Set-up of acceptance requirements for contaminated material for purposes of incineration, and provision of radiation protection measures for workers by the Ordinance of MHLW revised in July 2013 [57, 194]. Effluent release limits at incineration facilities, and conditions for the transport of radioactive ash to disposal facilities.

To reduce the volume of contaminated soil requiring disposal, several methods have been implemented, such as optimization of soil removal thickness based on measurements to determine the depth of ^{134}Cs and ^{137}Cs penetration so as to remove only the most contaminated material. In addition, soil decontamination treatment methods were tested at the laboratory scale [195].

For liquid waste generated by the cleaning of surfaces, the treatment methods are described in Refs [196–198]. For dissolved caesium isotopes, removal by selective ion exchange and approaches using both ferric ferrocyanide and zeolites are also used [199].

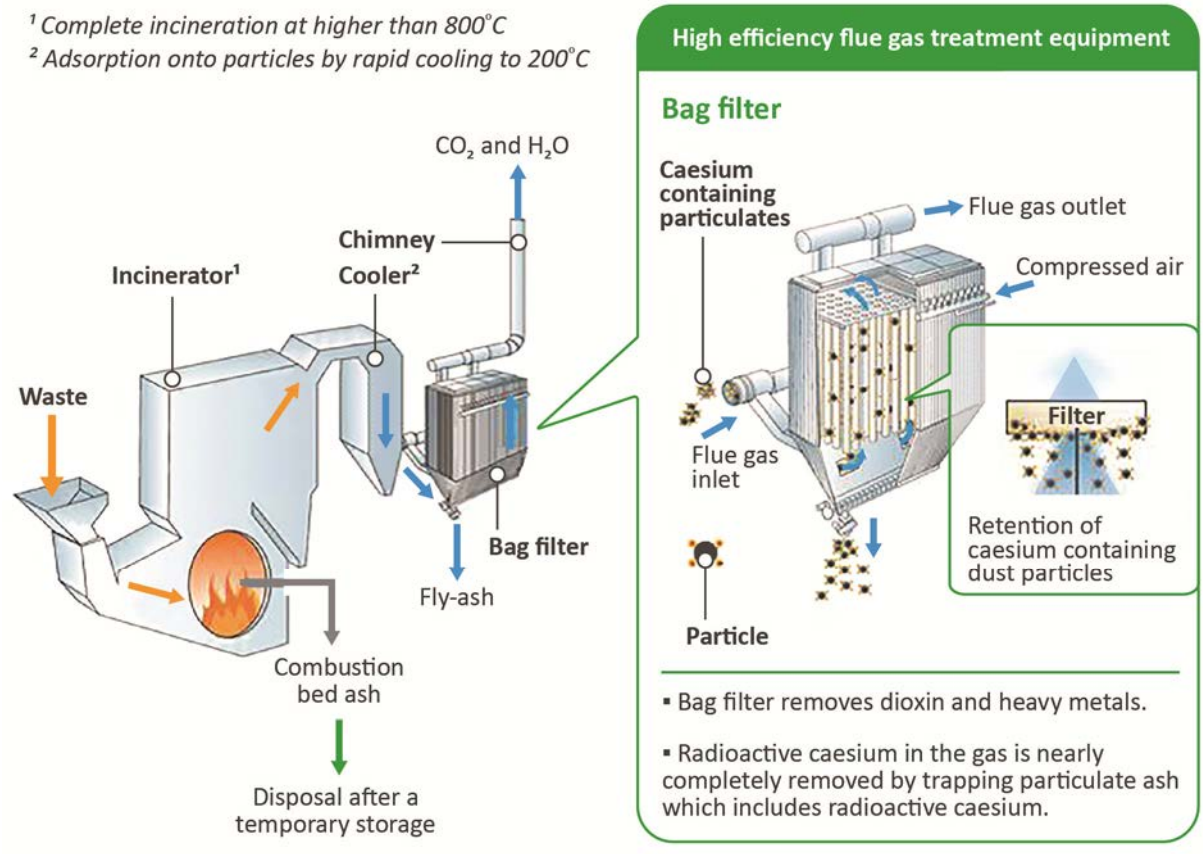


FIG 5.4–5. Schematic diagram of incinerator and off-gas cleaning systems [185].

Incineration has advantages in cases where large volumes of contaminated material have to be managed. Nevertheless, the use of incinerators requires the fulfilment of various conditions and prerequisites. The incinerator design must include features to protect the public from discharges of radioactivity. The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] requires the monitoring of air quality, exhaust gas and water quality of the discharged water from the

incinerator. To avoid spreading the radionuclides, especially ^{134}Cs and ^{137}Cs, the incinerator should be fitted with high performance dust removal equipment. The MOE proposes to use bag filters or electrical dust chambers [200]. Ash is collected and monitored for radioactivity content before dispatch to disposal.

A fluidized bed incineration facility at the Ken-Chu sewage treatment centre was used to demonstrate the incineration of contaminated sewage sludge. The results of one month's trials showed that the process was effective in reducing the volume by a factor of about 20 and that the bag filters were effective in trapping fly ash and limiting the release of caesium within site stipulated limits [41].

Temporary storage

According to the decontamination plan formulated by the MOE, contaminated soil and waste generated from remediation in Fukushima Prefecture are to be collected and stored at, or near, the sites undergoing remediation in temporary storage facilities. Afterwards, the material will be placed in the ISF. After interim storage for up to 30 years, final disposal will be take place outside Fukushima Prefecture [179, 191].

In order to facilitate the implementation of the decontamination plan, the MOE prepared guidelines for the design and implementation of such facilities, the Waste Related Guidelines [179]. Based on these guidelines, TSSs to store contaminated material generated from the ongoing remediation activities have been constructed by the national Government or municipalities that have several varieties of design depending on the location. Typical examples of TSSs are shown in Fig. 5.4–6. In all cases, an impermeable base and surface cover are used, and soil backfill is utilized to provide shielding. Since it is not possible to make such structures completely watertight, drainage is incorporated in most cases either by means of gravity flow or a pump. The drainage water is monitored and captured in a sump. If necessary, the drainage is treated to ensure that clearance levels prescribed by the national Government are met for any releases. A venting system is also implemented to avoid heat buildup and over-pressurization by gas resulting, predominantly, from the biodegradation of organic materials. A collection of information on good practices, based on experience gained, has also been compiled by the Fukushima Office of the MOE. As of the end of December 2014, TSSs for waste from remediation had been commissioned in 1050 locations by public operators in accordance with plans designed by the national Government and municipalities in Fukushima Prefecture. Contaminated materials generated during decontamination are collected and stored in these facilities in different types of large flexible bags.

Designated waste generated in specific facilities (ash from incineration facilities, sludge from the use of drinking water treatment facilities for separation processes, sludge from sewage treatment facilities, contaminated agricultural products, etc.) is stored temporarily at each facility site under the responsibility of the waste generators (Fig. 5.4–7). In the case of waste in the SDA, dedicated TSSs are being developed, and waste is sorted according to the type of material for further processing (material recycling, incineration, or other special treatments). Since the MOE is responsible for retrieving the designated waste (with activity concentrations exceeding 8000 Bq/kg), the MOE will have to commission existing controlled waste disposal facilities or new facilities where it is difficult to utilize existing facilities. Designated waste generated in Fukushima Prefecture with contamination levels exceeding 100 000 Bq/kg will be stored in the ISF prior to subsequent disposal, whereas in other prefectures it is transferred to a leachate controlled landfill [202].

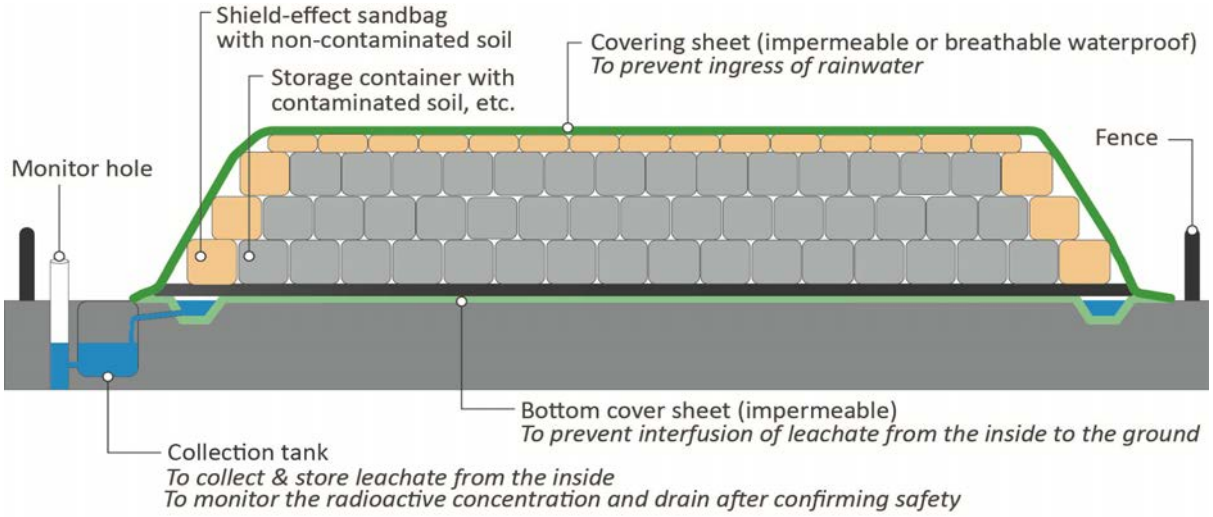




FIG. 5.4–6. Examples of TSS designs [201] (Photograph on the left courtesy of the Ministry of the Environment).



FIG. 5.4–7. Examples of TSSs for designated waste [203].



FIG. 5.4–7. Examples of TSSs for designated waste [203] (cont.).

Interim storage

The main objective of an ISF is to ensure safety and provide complete control over the contaminated materials (soil and waste) until a disposal site is available. An ISF will consist of facilities for emplacement and segregation, volume reduction, storage, and R&D, and monitoring equipment. Three concepts for such a facility, appropriate for different wastes and types of land, are illustrated in Fig. 5.4–8 [193, 204].

The key radionuclides considered in the design are ^{134}Cs and ^{137}Cs. Currently, no limits have been determined on the total amount of activity that can be managed in any one facility. The design will ensure that the level of radiation in the vicinity of the facility does not exceed 1 mSv/y.

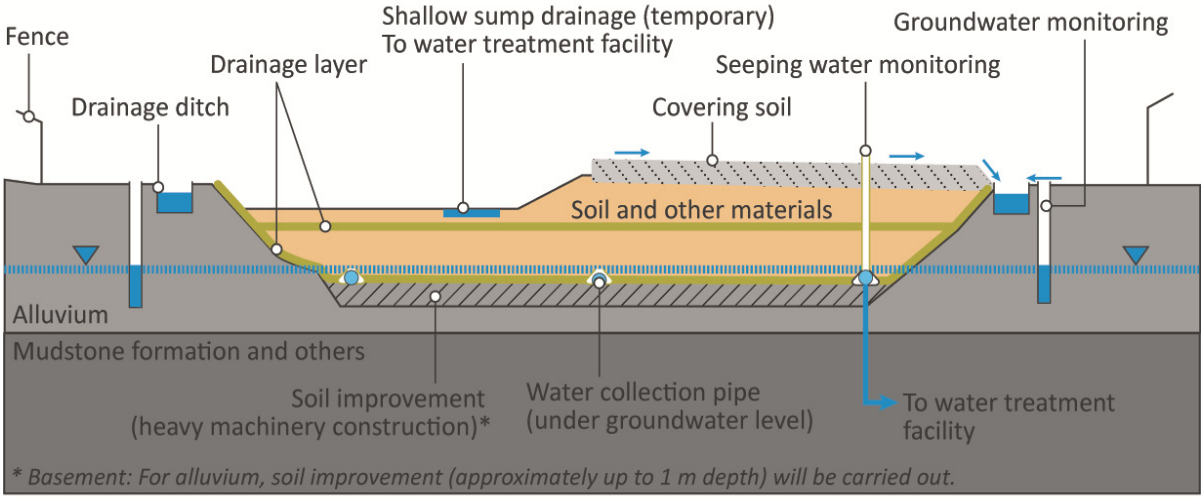
By April 2013, MOE had commenced on-site surveys, for example surveys on drilling and boring, to collect data to develop detailed plans for the ISF. Potential sites were based upon:

— The ability to secure the necessary site area;
— Proximity to areas that generate a large amount of removed soil and waste;
— Access to major roads.

Identification of sites for the location of ISFs is of high priority, and considerable efforts have been made to secure such facilities [182, 202]. In February 2014, the Governor of Fukushima Prefecture requested the MOE to review a plan to consolidate the ISFs in Okuma Town and Futaba Town. The MOE accepted the consolidation plan in March 2014, and both towns accepted the plan in May 2014. In September 2014, the Governor formally accepted the siting of ISFs Okuma Town and Futaba Town. Figure 5.4–9 shows the conceptual structure of such a storage facility for contaminated soil and waste.

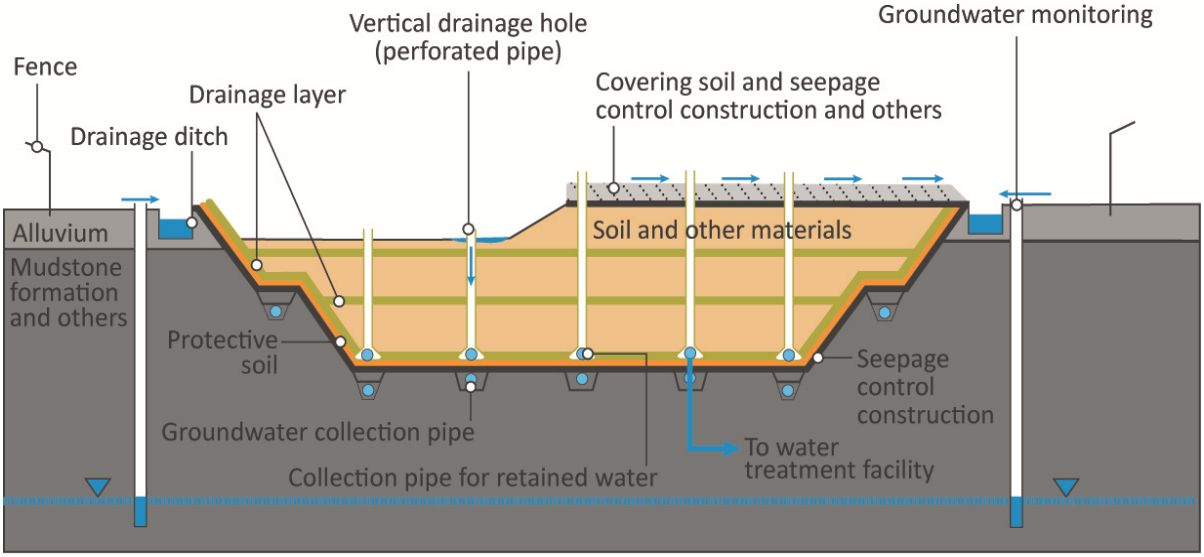
Type-I soil storage facility

(for lowlands and activity concentrations of caesium in soil of up to 8000 Bq/kg)



Type-II soil storage facility

(for hills/tableland and activity concentrations of caesium in soil of more than 8000 Bq/kg)



Waste storage facility

(for hills/tableland and activity concentrations of caesium in waste of more than 100 000 Bq/kg)

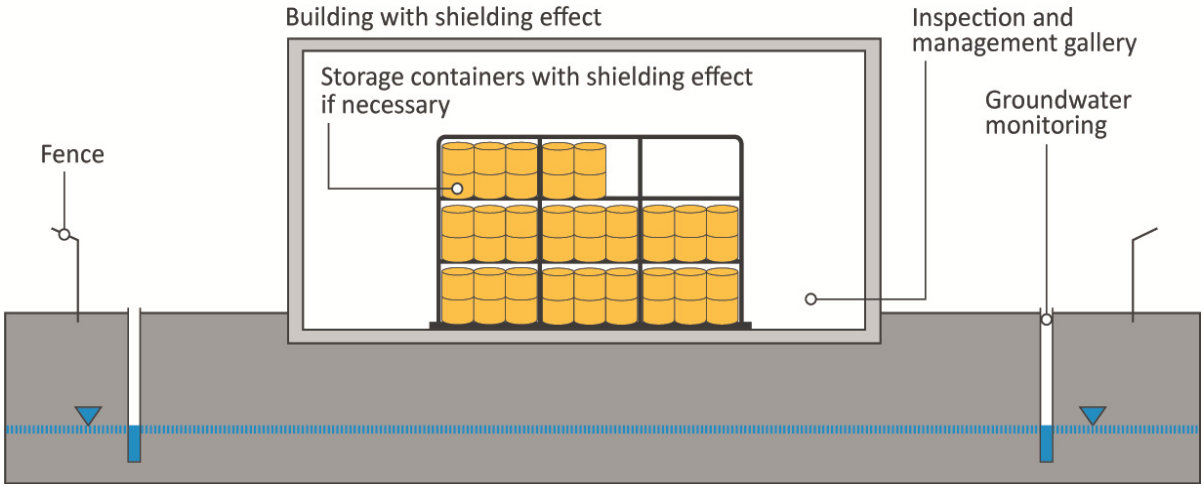


FIG. 5.4–8. Concepts of an ISF for different wastes and types of land [55, 185].

Disposal

The national Government is responsible for the disposal of waste from decontamination operations. Material that cannot be disposed of in conventional or special landfills will require the establishment of new disposal facilities [205, 206].

Outside Fukushima Prefecture, contaminated waste of radioactive content under 100 000 Bq/kg will be disposed in leachate controlled landfill sites according to the Act on Special Measures Concerning the Handling of Radioactive Pollution [27] (see Fig. 5.4–2). These landfills are facilities to dispose of domestic and standard industrial waste and are regulated by the Waste Management Law [7].

Faced with the difficulty of transporting designated waste to the existing leachate controlled landfill sites, MOE has proposed building new designated waste landfill sites to dispose of designated waste. Such facilities would be underground concrete structures covered with bentonite and soil and designed to prevent the migration of radionuclides out of the facility. An example of the structure of such a landfill disposal site is shown in Fig. 5.4–9.

Landfill sites should be located in areas characterized by low population density, infertile and unprofitable land, should have a favourable geological setting, and lie well above water bearing formations. In combination with a multibarrier design, this will exclude, to the maximum possible extent, the possibility of any adverse impacts on the public [184, 202].

Under Japanese law, there is no limit on the total activity that can be disposed of in such a facility. A dose limit of 1 mSv/y is applied for members of the public living in the vicinity of the facility.

Designated waste in Fukushima Prefecture with a caesium concentration greater than 8000 Bq/kg and less than 100 000 Bq/kg is to be transported to an existing leachate controlled landfill site. Waste exceeding 100 000 Bq/kg is to be transported to the ISF. In the other five prefectures with limited storage capacity for a larger amount of waste (Miyagi, Ibaraki, Tochigi, Gunma and Chiba), it was necessary to treat designated waste promptly based on the local conditions in each prefecture (Figs 5.4–2, 5.4–3 and 5.4–4).

Public involvement and information

In January 2012, the Decontamination Information Plaza was established in Fukushima City, as a joint programme of Fukushima Prefecture and the MOE to provide decontamination expertise to municipalities, and to provide a focus for collecting and disseminating information on volunteer requests for decontamination, and so on. In order to facilitate the implementation of remediation and associated waste management outside the Fukushima Daiichi NPP, it has been beneficial to involve stakeholders in various aspects, such as consultation with local communities for decision making processes, siting of storage and treatment facilities and other waste management activities. Also, in order to obtain understanding of local community expectations for remediation activities, transparency and communication have become more important (see Section 5.5).

In order to improve communication with the local community, the Plaza has been used to promote the cooperation of the national Government, Fukushima Prefecture, related agencies and organizations. In order to inform the public and the municipalities, the following information has been provided on a web site:

- The legal structure, current status and issues, and descriptions of waste processing and disposal proposals;
- Release of the results of monitoring, such as ambient dose rates, and information on decontamination activities and the safety of temporary storage sites

Thematic brochures have been prepared by MOE and distributed to provide a description of the processing of designated waste [81].

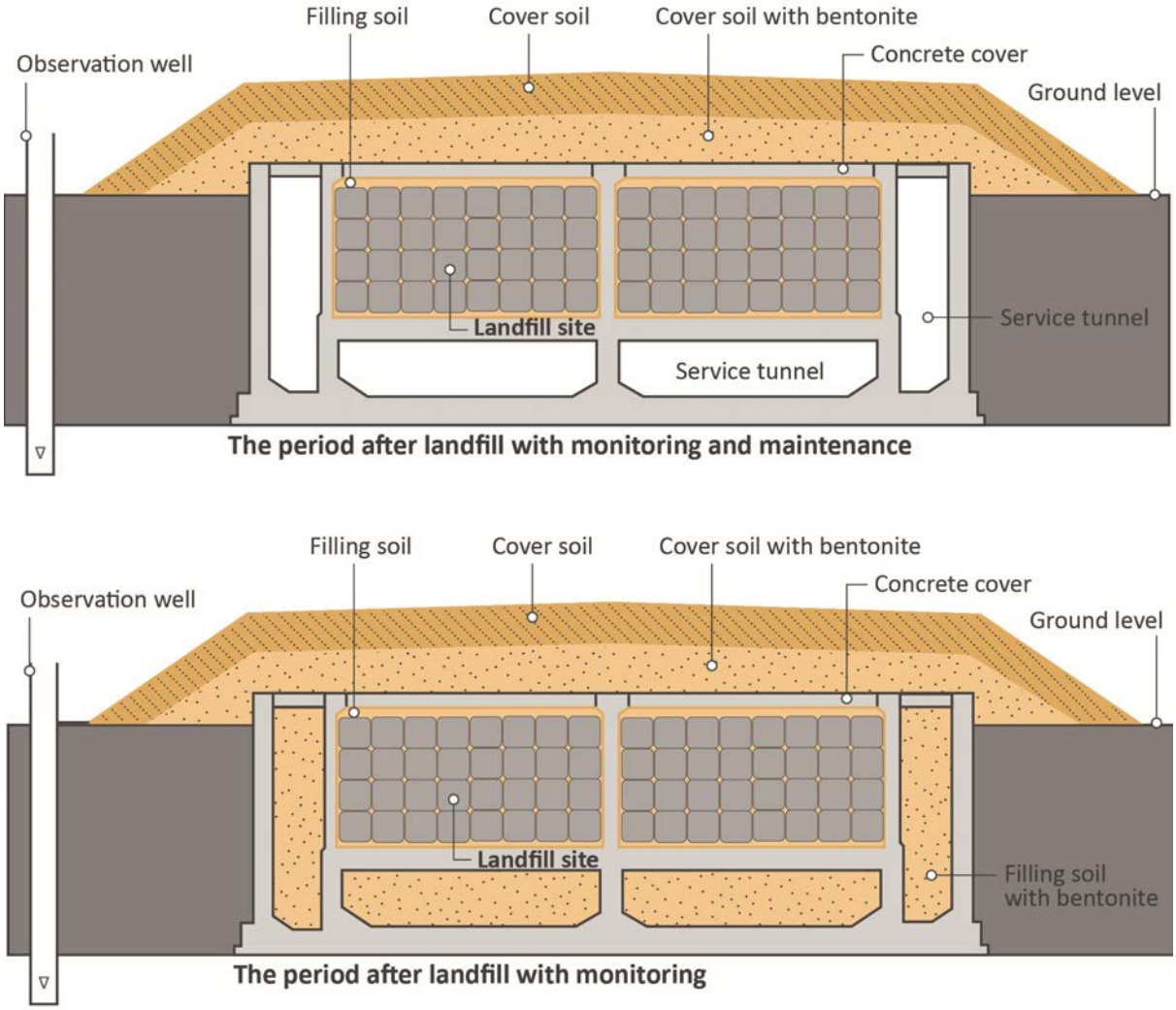


FIG. 5.4–9. Design of landfill disposal for designated waste [192].

5.4.4. On-site management of waste and contaminated material

The combination of earthquake, tsunami and the accident at the Fukushima Daiichi NPP generated a variety of different types of waste that has to be managed on the site. The waste includes:

- Contaminated debris and rubble consisting of concrete bricks, metal, broken ducts, etc.;
- Large volumes of relatively low contamination solids, such as soil and wood;
- Water (currently 400 m^3 is generated every day from the specific procedures for cooling the damaged reactors), which has to be stored and treated to remove the radionuclides to the extent practicable (details on reactor cooling and the associated generation of water are described in Section 5.3.4.1);
- Contaminated ion exchange resins used for treatment of the contaminated cooling water that contains high levels of radionuclides;
- Absorption material from filtration of contaminated gases;

— Contaminated trees that were felled to create space for the storage of solid waste and contaminated water;
— Material contaminated during the work on the reactor site, such as protective clothing, cleaning equipment and material;
— Damaged nuclear fuel and debris.

On-site waste management activities have, to date, focused largely on dose reduction at the boundary, as well as on consolidation and safe storage of contaminated material and radioactive waste. The early priority for on-site activities focused on concerns associated with clearing debris to enable post-accident recovery and restoration of power to the site, stabilization of the damaged reactors and controlling dose rates to workers. As stabilization was achieved, controlling the additional ambient dose rate for a member of the public at the site boundary to less than 1 mSv/y was a key consideration for on-site activities [119, 207]. In order to meet this requirement, it was necessary, inter alia, to locate some on-site storage facilities away from the boundary and to provide soil cover for stored waste (see Section 5.3.4.2 and also Ref. [207]).

The management of very large amounts of waste with varying physical and chemical compositions and characteristics, including large volumes of water, is a complex undertaking. The presence of organic matter, biodegradable material and soil in solid waste is an additional complication.

5.4.4.1. On-site waste management strategy

The initial on-site waste management strategy focused on providing safe, temporary storage for the wastes associated with stabilization and dose reduction efforts. Key actions included the:

— Construction of temporary storage facilities (with soil coverage of debris);
— Construction of soil covered temporary storage for cut down trees;
— Relocation of temporary storage facilities to reduce dose rates at the site boundary;
— Construction of a temporary cask storage facility to support removal of nuclear fuel;
— Construction of storage facilities for secondary waste from water treatment (e.g. absorption media).

TEPCO developed and maintains the Roadmap for decommissioning of the facility which includes the management of on-site waste [119] (see Section 5.3.3). An illustration of part of the strategy for on-site waste management is provided in Fig. 5.4–10 [168]. The main elements of the overall on-site waste management strategy are:

— Packaging and storage of the fuel removed from the reactor cores and the spent fuel pools (see also Section 5.3);
— Management of contaminated water;
— Control of releases of gaseous effluents;
— Processing of solid waste;
— Plans for disposal of solid waste.

Figure 5.4–11 provides an overview of the boundary of the on-site area (red dashed line) and the locations of the on-site facilities in April 2014. A brief summary of the primary types of contaminated material and radioactive waste, including storage approaches (trees, debris, water/secondary waste, nuclear fuel) is provided in the following sections.

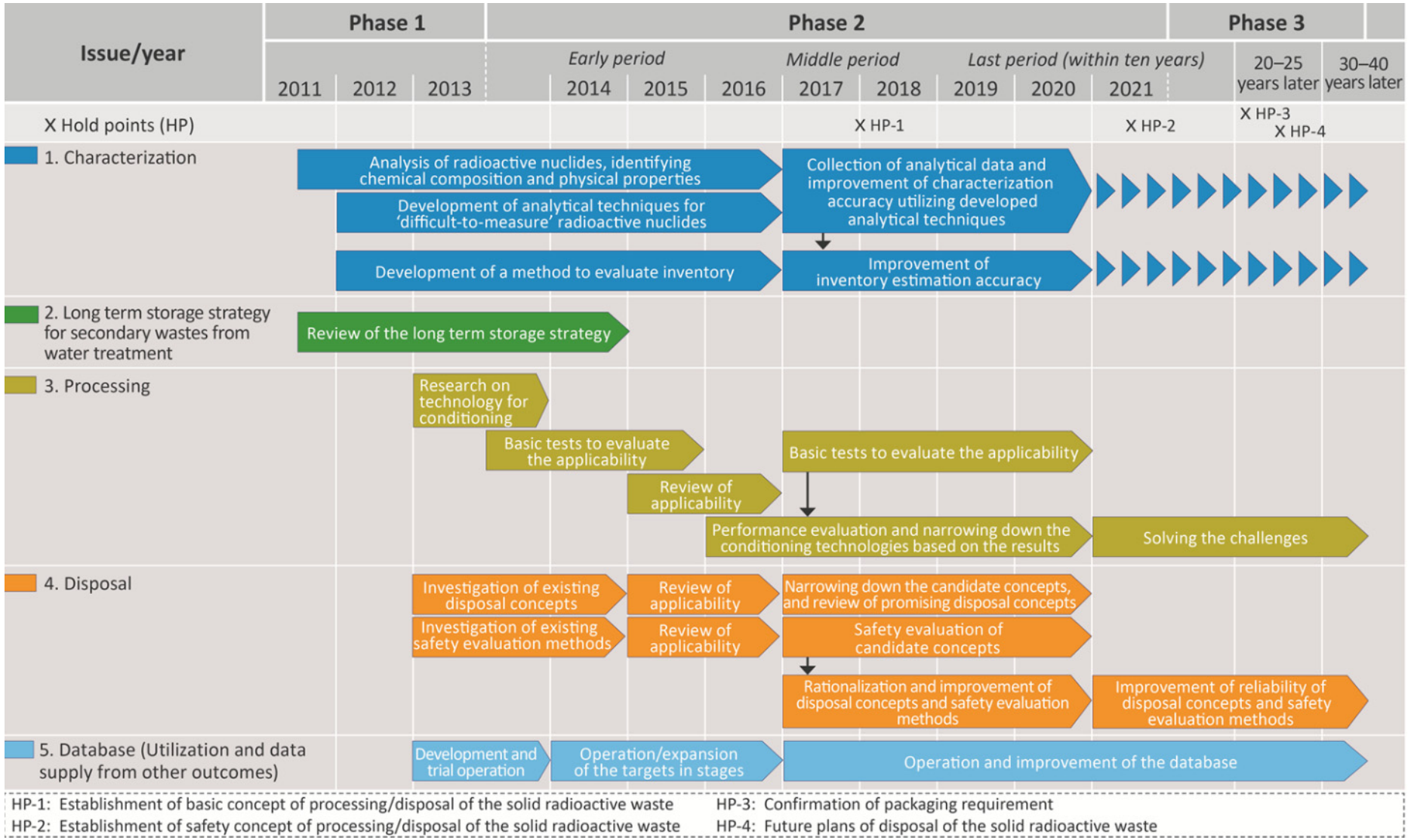


FIG. 5.4–10. Part of the strategy for on-site waste management [169].

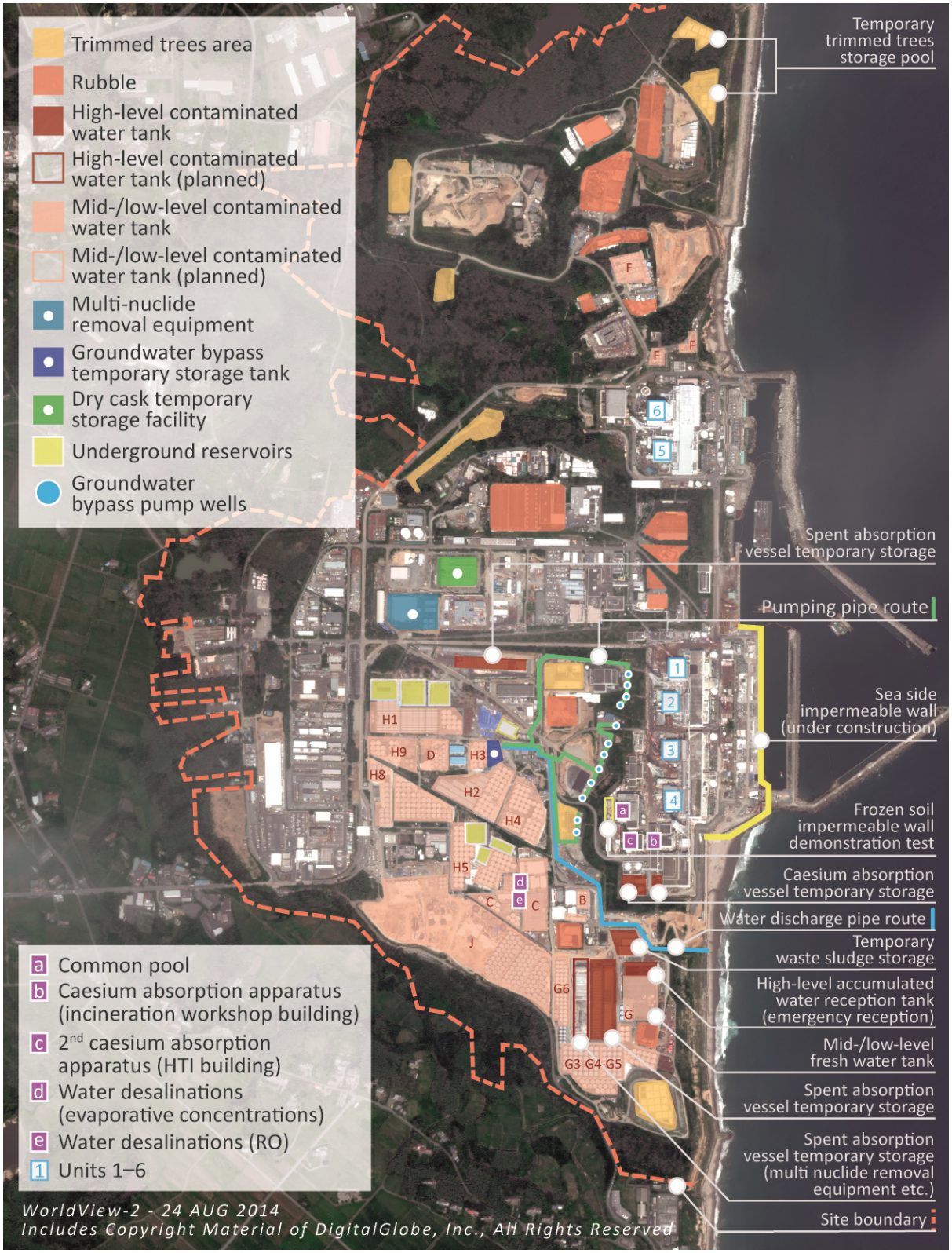


FIG. 5.4–11. Overview of the on-site area and current waste management facilities [55, 134].

5.4.4.2. Types, quantities, and characteristics of waste and contaminated material

A variety of different types of waste and contaminated material must be managed in the on-site areas. Much of the material (e.g. trees, debris) is similar to off-site waste, but with higher radionuclide

concentrations, reflecting the location relative to the release. There are also large amounts of waste requiring special handling that are specific to the on-site area. These wastes include: fuel debris and very large amounts of contaminated water/secondary water treatment waste. The contaminated water/secondary waste, trees and debris are all managed independently. Debris and felled trees have been further segregated and stored with barriers using a graded approach based on dose rates and contamination levels. A brief summary of the primary types of waste (trees, debris, water/secondary waste) is provided in the following sections.

Trees and debris

As of 30 November 2014, 131 900 m^3 of debris and 79 700 m^3 of trees were being stored on-site [208, 209]. The amounts of trees and debris being stored on-site in temporary storage facilities are provided in Table 5.4–5 [208, 210], together with the fraction of the quantity of waste in storage relative to the current estimated capacity for each of the storage facilities. It is conservatively estimated that a total of 560 000 m^3 of contaminated material will be generated by the end of the fuel debris removal, which is planned for 2027. A new centralized storage facility is being planned with a capacity of approximately 160 000 m^3. The difference between the expected amount of waste and the planned capacity of the storage facility highlights the expectation that waste segregation, volume reduction, and recycling will reduce the volume of waste requiring long term management (storage) as radioactive waste [212].

TABLE 5.4–5. QUANTITIES OF DEBRIS AND TREES STORED ON-SITE AS OF 30 NOVEMBER 2014 [208, 210]

Place of storage	Area boundary ambient dose (mSv/h)	Type	Storage method	Amount of storage (m^3)	Occupancy of area (%)
Solid waste storage facility	0.03	Rubble	Container	5 100	43
A: North part of site	0.45	Rubble	Temporary storage facility	2 900	41
C: North part of site	>0.01	Rubble	Storage outdoor	48 800	86
D: North part of site	0.01	Rubble	Sheet curing	2 600	88
E: North part of site	0.02	Rubble	Sheet curing	4 200	27
F: North part of site	0.01	Rubble	Container	600	99
			Storage outdoor	2 000	27
J: South part of site	0.03	Rubble	Storage outdoor	4 700	98
L: North part of site	>0.01	Rubble	Underground temporary storage facility	8 000	100
O: South-west part of site	0.03	Rubble	Storage outdoor	26 200	95
Q: West part of site	0.12	Rubble	Container	5 700	93
U: South part of site	>0.01	Rubble	Storage outdoor	700	100
W: West part of site	0.03	Rubble	Sheet curing	20 300	69
Total (rubble)				131 900	74

TABLE 5.4–5. QUANTITIES OF DEBRIS AND TREES STORED ON-SITE AS OF 30 NOVEMBER 2014 [208, 210] (cont.)

Place of storage	Area boundary ambient dose (mSv/h)	Type	Storage method	Amount of storage (m^3)	Occupancy of area (%)
G: North part of site	>0.01	Felled tree	Felled tree temporary storage	7 300	27
H: North part of site	0.01	Felled tree	Storage outdoor	14 300	81
I: North part of site	0.02	Felled tree	Storage outdoor	10 500	100
M: West part of site	>0.01	Felled tree	Storage outdoor	37 600	83
T: South part of site	0.01	Felled tree	Felled tree temporary storage	10 100	44
V: South part of site	—	Felled tree	Storage outdoor	0	0
Total (felled tree)				79 700	58

Trees

The trunks, and the branches, leaves and roots of trees are managed separately, recognizing that higher activity levels are present on the branches, leaves and roots than on the trunks. It is estimated that the distribution of activity is roughly 30% trunks, 40% branches and leaves, and 30% roots. Further segregation of bark from the trunks could be effective in leaving minimal contamination on the trunks [210, 212].

The tree trunks are temporarily stored in stacks with limitations on the height and separation and ventilation to ensure airflow in the stacks to reduce the fire hazard. Temperatures are also monitored to further protect against fire. The branches, leaves and roots are placed in covered temporary storage facilities that include multiple barriers with retaining walls and soil along the sides, and soil and impermeable high density polyethylene (HDPE) sheets above the waste for shielding and to control the infiltration of water. Figure 5.4–12 is a diagram of a covered storage facility for branches, leaves and roots.

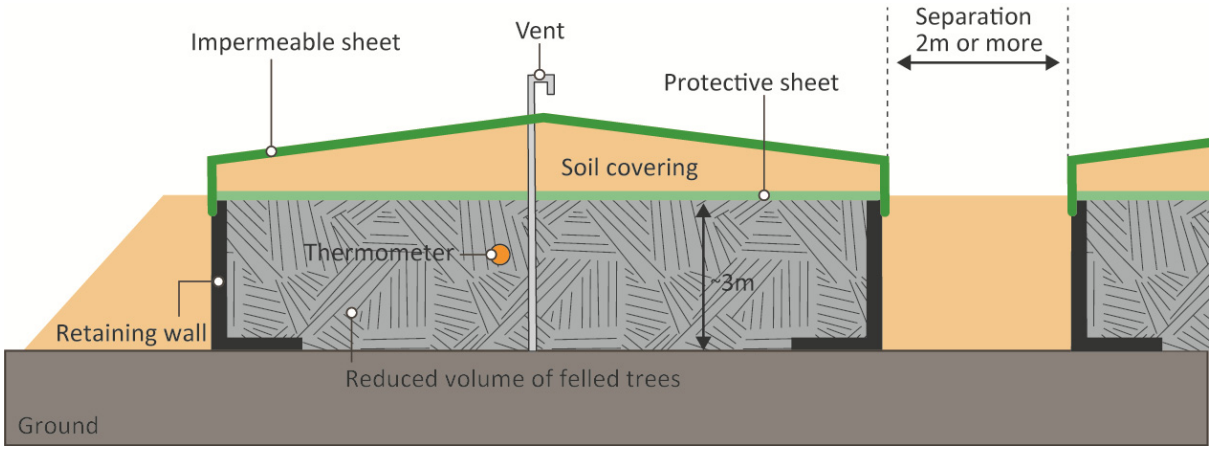


FIG. 5.4–12. Diagram of a soil covered storage facility for branches, leaves and roots [207].

Debris

Initial activities to stabilize and to reduce dose rates from the damaged reactors resulted in the collection of large amounts of debris (Fig. 5.4–13). Debris also continues to be produced as a result of ongoing recovery activities. Some of the debris has high levels of contamination and its management requires additional radiation protection measures for workers. This poses challenges from the perspective of accessing, characterizing and removing the debris. Debris has been transported by means of heavy equipment. The waste is transported to collection areas and then stored in different types of facilities based on the measured dose rates. The storage types in use include storage buildings, soil covered temporary storage facilities, storage tents, and outdoor storage covered by sheets to limit water infiltration. For soil covered temporary storage, the soil and HDPE sheets provide shielding and reduce the amount of infiltration of water into the stored waste.



21 February 2012 *22 July 2013*

FIG. 5.4–13. Example of debris removal from Unit 3 reactor building [207].

Containers and storage areas for debris were needed immediately to support accident mitigation activities. Three hundred transport containers with dimensions of 3.2 m (L) × 1.6 m (W) × 1.1 m (H) happened to be available on-site at the time of the accident and were used to store debris to support the immediate response efforts. Additional commercially available containers were purchased to meet the continuing urgent storage needs. Initially, a temporary tent type facility that had been constructed for a different purpose was used for waste consolidation prior to the development of the dedicated storage facilities.

Debris is segregated based on the surface dose rates and types of material, e.g. concrete or steel. Guidelines were established to ensure that debris with surface dose rates greater than 1 mSv/h is stored in storage tents, soil covered temporary storage facilities or solid waste storage buildings. These guidelines were developed for the protection of workers and to support the maintenance of an additional ambient dose rate of 1 mSv/y at the site boundary (Table 5.4–6). Several thousand cubic metres of contaminated soil have been generated and are being stored separately from other debris. The small amounts of operational waste (e.g. HEPA filters) are managed similarly to debris [212].

TABLE 5.4–6. GUIDELINES FOR SEGREGATION AND STORAGE OF DEBRIS [207]

Action to be taken during storage	Surface dose rate of debris (guide value*)			
	More than 30 mSv/h**	30 mSv/h to 1 mSv/h	1 mSv/h to 0.1 mSv/h	0.1 mSv/h or less
Shielding	Containers and building	Concrete wall, soil, containers	None	None
Prevent dispersion	Containers	Tent, soil, containers	Sheet cover	None
Temporary storage method	Container storage, Solid waste storage building	Container storage, temporary storage facility, soil covered temporary storage facility	Sheet cover	Outdoor collection

* Review guide value as appropriate considering on-site air dose rate.
** For those over 1 mSv/h, temporarily store in containers, solid waste storage building or shielded area.

Water and secondary waste

Management of the water required to cool the reactors has become a significant problem on-site. The reactors of the damaged Units 1–3 are each cooled in a partially closed water circuit with a capacity of about 400 m^3 per day (Fig. 5.3–1), as described in more detail in Section 5.3. Cooling water that leaks into the reactor buildings from the damaged reactor systems is collected by pumping equipment, processed through the treatment facilities and reused for cooling. An additional problem is the daily inflow of about 400 m^3 of groundwater into the buildings. This volume is contaminated by the plant leaks and, therefore, must also be processed and stored. Thus, management of contaminated water from cooling and groundwater inflow and the contaminated absorption media from water treatment activities are the sources of the largest volumes of on-site waste requiring processing and storage (Fig. 5.3–1).

Since the normal waste processing facility had been inundated by the tsunami, it was not available at the time immediately following the accident. Hence, there was an urgent need to develop a capacity to treat the large amounts of water that were used during stabilization of the reactors and the spent fuel pools (measures for cooling are described in Section 5.3.4.1). Measures were also implemented to limit the inflow of groundwater into the damaged facility [140], including the construction of 12 wells for pumping groundwater from locations upstream of the reactors to lower the water table and reduce the volume of contaminated water that must be processed and stored (Sections 5.3.3 and 5.3.4) [119, 213]. It was also necessary to reduce the inflow and provide treatment capacity to maintain water levels in the facilities and thus prevent overflow and additional releases to the environment.

A special Task Force for Contaminated Water and Tanks was established to accelerate decision making, and the Fukushima Daiichi Decontamination and Decommissioning Engineering Company was established in April 2014 to focus the decontamination and decommissioning (D&D) efforts [214, 215].

The storage and processing of large amounts of water that continue to accumulate have posed a major challenge. The initial waste water was a mixture of sea water used for cooling and highly contaminated cooling water from the damaged reactors containing a variety of radionuclides, which were mainly fission products. It also contained oil and silt that were deposited in the facilities as a result of the tsunami. This posed a number of unique challenges, because water treatment plants in nuclear facilities are not usually designed for such mixtures.

Fresh water was substituted for sea water for cooling purposes after one month and, after four months, fresh water was replaced by recycled water from the treatment process to create the partially-closed system that is currently operating (Fig. 5.3–1). All water from the system must be processed and

controlled. Currently, all water from these processes is stored on-site. The international peer review mission [127] recommended that the option of resuming controlled discharges to the sea be considered to help reduce the risks associated with continued storage of very large amounts of water with low levels of contamination. It was also recognized that final decision making would require engaging all stakeholders, including TEPCO, the NRA, the national Government, the Fukushima Prefecture government, local communities and others, and that there was a need to consider socioeconomic conditions in the consultation process and to implement a comprehensive monitoring programme to ensure that there was no detrimental impact on human health and the environment.

Shortly after the accident, TEPCO implemented proposals from domestic and overseas companies, including AREVA (France) for water decontamination systems, KURION (USA) for a caesium adsorption system and Toshiba (Japan) for a second caesium adsorption system [216].

On 30 April 2011, TEPCO started construction of the water treatment facilities, with oil separation, caesium adsorption (KURION), decontamination (AREVA) and water desalination with a reverse osmosis apparatus. The water treatment facilities started operation on 17 June 2011. During the early operations, some problems occurred with the KURION and AREVA systems. While the AREVA decontamination system could be implemented quickly to support the immediate need for water treatment, its operation resulted in the generation of sludge with relatively high activity levels that required additional measures to reduce occupational exposures and assist with waste management. After being deployed immediately following the accident, the use of the AREVA decontamination system was discontinued in September 2011 [216]; however, it is available as a backup if there are problems with the other systems.

TEPCO installed a second caesium adsorption system called SARRY (Simplified Active Water Retrieve and Recovery System), which started operation on 19 August 2011. In parallel, TEPCO implemented the distillation apparatus for desalination in series with the reverse osmosis membrane apparatus. Since then, the KURION and SARRY systems have been operated in parallel. There are also mobile caesium removal systems in use. As a result of design and operating improvements, based on experience with the KURION and AREVA systems, the SARRY system has proven easier to maintain. It has been highly effective in removing caesium and addressing other non-radioactive contaminants, with the result that the water is acceptable for use in cooling the reactors.

An additional process is being applied for the removal of other radionuclides. The multi-nuclide removal facility (ALPS) was designed and constructed to further reduce the activity concentrations of a range of radionuclides in processed water. TEPCO started construction of this facility in June 2011 and completed it in October 2012. Trial runs commenced in March 2013, and full capacity was achieved in 2014. ALPS provides focused removal of radionuclides that are not removed through the current treatment systems (Fig. 5.4–14). This facility includes iron co-precipitation, carbonate co-precipitation, 14 adsorption towers and 2 additional treatment columns, where specific media are included to address the radionuclides in the water to be treated. The iron co-precipitation step targets removal of α emitting radionuclides, ^{54}Mn, and ^{60}Co; the carbonate co-precipitation step targets removal of elements that would reduce the efficiency of the adsorption process (e.g. Ca and Mg). The adsorption and treatment towers use different media to target a range of radionuclides (see Table 5.4–7). The current system is designed to process approximately 750 m^3 of contaminated water per day. A second ALPS system, with the same capacity, was installed in September 2014. An improved system with a capacity of 500 m^3/d started operation in October 2014 [217]. The international peer review [127] recommended that TEPCO continue, and even accelerate, its efforts to improve the performance and enhance the capacity of ALPS, given its importance for management of the water that continues to be generated on-site.

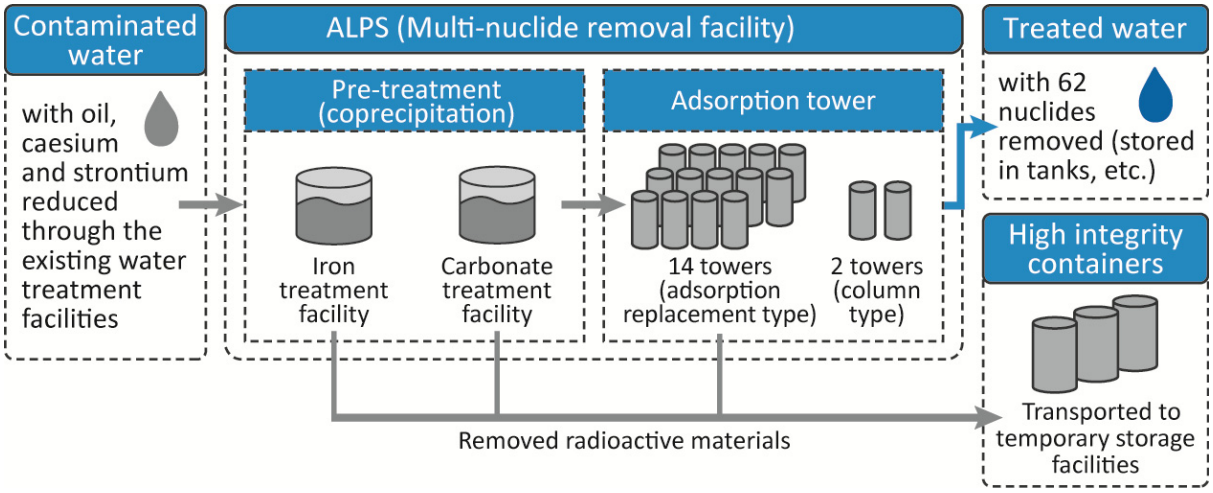


FIG. 5.4–14. The Advanced Liquid Processing System (ALPS) [207].

TABLE 5.4–7. MEDIA AND KEY RADIONUCLIDES TARGETED IN DIFFERENT PARTS OF THE TREATMENT SYSTEM [207]

No.	Containing	Composition of absorbent	Main elements and materials removed	No. of vessels
1	Absorption vessel	Activated carbon	Colloid	1
2		Titanate	Sr (M2+)	3
3		Ferrocyanide compound	Cs	2
4		Silver impregnated activated carbon	I	2
5		Titanium oxide	Sb	2
6		Chelating resin	Co (M2+, M3+)	4
7	Treatment column	Resin absorbent	Ru, negatively charged colloid	1 (1)*

* One of the two treatment columns uses an auxiliary colloid.

The commissioning tests for the first ALPS commenced in May 2013 [216]. Initial results from tests using contaminated sea water and outlet water from the caesium removal process have demonstrated that 62 radionuclides can be removed to achieve levels that satisfy the regulatory limits for discharge [207]. The radionuclides removed are summarized in Table 5.4–8. However, tritium is not removed by the process. In March 2014, while ALPS was still in test operation, some minor unplanned events have occurred related to unexpected β radiation levels at an outlet and cloudy water at an inlet for one of the adsorption towers [218]. By May 2015, three ALPs facilities were in operation [133].

The ALPS facility results in the production of a slurry and adsorption media as secondary waste. Two types of sludge are produced from the pretreatment processes and adsorption media will be generated in the separate adsorption vessels and treatment columns. This waste is stored in high integrity containers made of radiation resistant polyethylene that are reinforced in a stainless steel container. The containers have a planned lifetime in excess of 20 years.

TABLE 5.4–8. LIST OF RADIONUCLIDES TARGETED IN THE ALPS PROCESSES [208]

No.	Nuclide	No.	Nuclide	No.	Nuclide	No.	Nuclide
1	Rb-86	17	Sn-126	33	Ce-141	49	Pu-240
2	Sr-89	18	Sb-124	34	Ce-144	50	Pu-241
3	Sr-90	19	Sb-125	35	Pr-144	51	Am-241
4	Y-90	20	Te-123m	36	Pr-144m	52	Am-242m
5	Y-91	21	Te-125m	37	Pm-146	53	Am-243
6	Nb-95	22	Te-127	38	Pm-147	54	Cm-242
7	Tc-99	23	Te-127m	39	Pm-148	55	Cm-243
8	Ru-103	24	Te-129	40	Pm-148m	56	Cm-244
9	Ru-106	25	Te-129m	41	Sm-151	57	Mn-54
10	Rh-103m	26	I-129	42	Eu-152	58	Fe-59
11	Rh-106	27	Cs-134	43	Eu-154	59	Co-58
12	Ag-110m	28	Cs-135	44	Eu-155	60	Co-60
13	Cd-113m	29	Cs-136	45	Gd-153	61	Ni-63
14	Cd-115m	30	Cs-137	46	Tb-160	62	Zn-65
15	Sn-119m	31	Ba-137m	47	Pu-238		
16	Sn-123	32	Ba-140	48	Pu-239		

The water management system includes approximately 4 km of polyethylene pipes. The flow of water is illustrated in Fig. 5.3–1. As of 25 December 2014, approximately 62 600 m^3 of water was accumulated in the reactor buildings for Units 1–4, 17 040 m^3 was stored in the centralized radioactive waste treatment building, and 1 128 010 m^3 of water had been processed through the processing facilities [219]. Water management considerations were an urgent priority and having predetermined designs and plans for storage tanks and processing facilities may be valuable aspects for accident planning in the future.

In addition to the water that must be stored and managed, the AREVA, KURION and SARRY processes result in the generation of secondary wastes. Two primary types of waste are generated: sludge, and used vessels from the caesium removal processes. Currently, two adsorption processes, KURION and SARRY, are used prior to water being sent to the desalination process (the AREVA decontamination process is not currently operating). The adsorption processes result in the accumulation of shielded steel vessels containing spent zeolite that can remove caesium and, to some extent, other contaminants such as oil, technetium and iodine. The vessels are stored in concrete box culverts (Fig. 5.4–15). As of 25 December 2014, 597 m^3 of waste sludge (700 m^3 capacity) from the AREVA process and 1443 used vessels from the KURION and SARRY processes were being stored [219]. The international peer review acknowledged the effectiveness of the current efforts for characterization and safe storage of these wastes and the plans to develop options for processing in preparation for future disposal [127].

Water and liquid wastes are stored in a system of tanks. Concentrated salt water from reverse osmosis is stored in vertical cylindrical steel tanks with a total capacity of 400 000 m^3 (diameter approximately 12 m; height approximately 11 m; capacity 1000 t). Smaller square shape steel tanks (2 m × 2 m × 9 m, capacity 40 t) are used for desalinated water. Furthermore, horizontal steel tanks are available for evaporative concentrate (cylindrical forms, 100 t). This type of storage requires only a relatively small area to accommodate 295 tanks with a total capacity of 30 000 t.

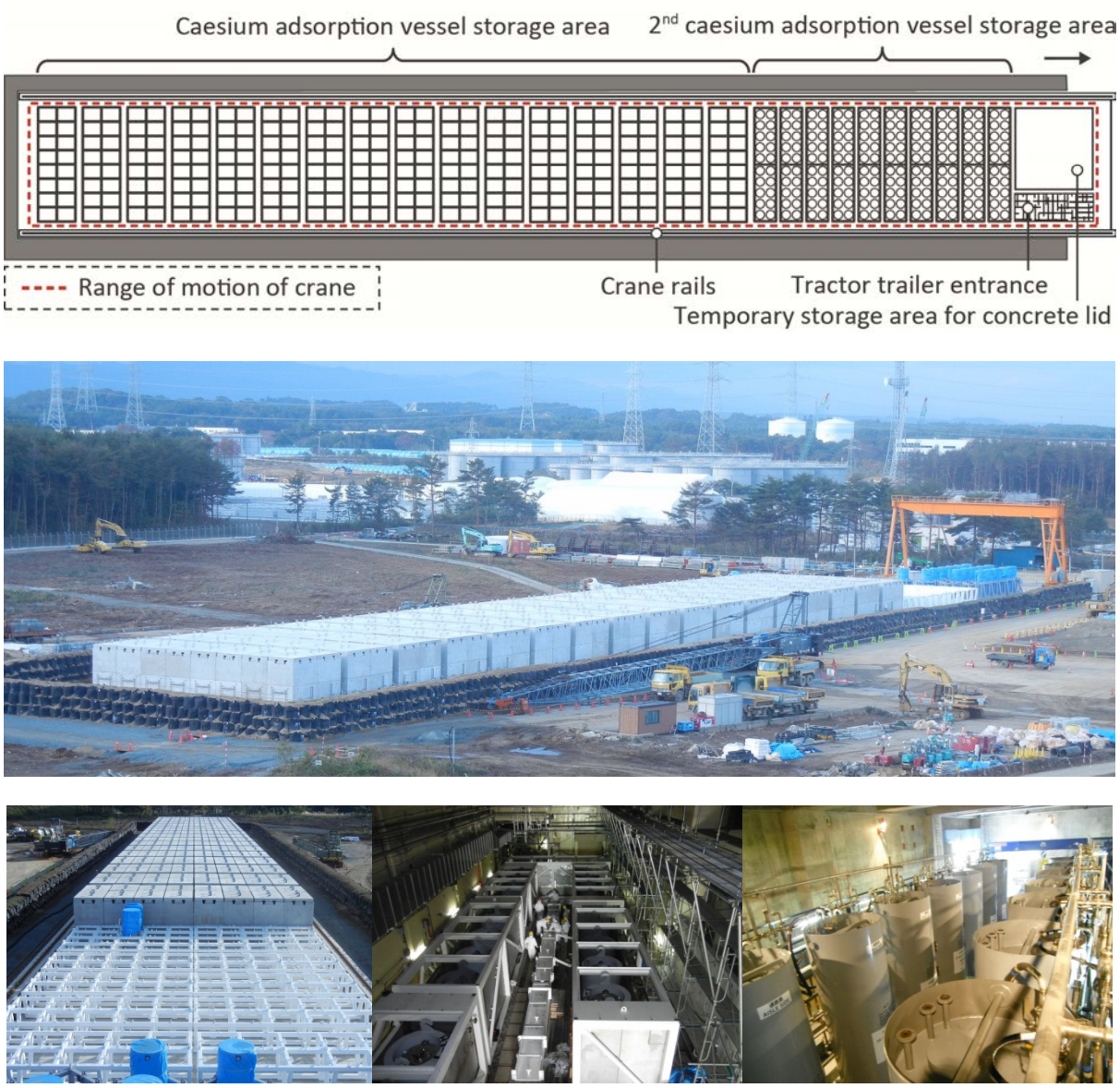


FIG. 5.4–15. Temporary storage facility for caesium adsorption vessels (top); caesium adsorption vessels (lower left), KURION vessels (middle) and SARRY vessels in the operating facilities (lower right) [207].

Plans are proceeding to increase the number of tanks available, so that treated water, the volume of which is continuing to grow, can be stored. The plan was to complete 15 new tanks (15 000 m^3) per month in FY 2013 and to increase the construction in the following years. A location for such an installation has been prepared in the southern area of the site. By the end of FY 2015, the tank capacity is projected to increase to 800 000 m^3 [220]. The number of current storage tanks are illustrated in Fig. 5.4–14. Some leakage from the tanks has been reported (Section 1.10.4). Immediately following the accident, tanks were quickly constructed to avoid the need to discharge contaminated water. These tanks used bolt and flange joints. Welded tanks are now being used, and the bolted tanks are being taken out of service and will be decontaminated [221].

As a result of the leaks, METI directed that several mitigative measures be implemented [222]. These included:

— Enhanced management of the tanks and surrounding area;
— Increased frequency of inspections to determine integrity of the tanks;

— Accelerated replacement of bolted joint tanks with welded joint tanks;
— Accelerated implementation of the ALPS (see Section 5.4.4.3) and collection of contaminated soil from the leaks;
— Identification of the risks of storing highly contaminated water and taking actions to obviate the risks.

TEPCO has implemented specific measures in response to the direction of METI and has provided extensive information to the public regarding the level of risk arising from the releases of radioactivity that have occurred. Nevertheless, as yet, no decision has been taken on the further management of the stored water.

The large quantities of contaminated water on the site present a variety of risks. Owing to malfunctions of tanks, pipes and valves, or during heavy rainfall, leaks of radioactively contaminated water from components were observed. In some cases, the leaks have led to releases of radionuclides to the sea. The identification of such leaks triggered more intensive monitoring, both on-site as well as in the marine environment [222]. Although measures were being implemented to stop or reduce the leakage, more sustainable solutions are needed, considering all options, including the possible resumption of controlled discharges to the sea. As a result of the IAEA Review Missions [117, 223], TEPCO was advised to perform an assessment of the potential radiological impact of the release of water containing tritium and any other residual radionuclides to the sea. It was also recognized that final decision making would require engaging all stakeholders, including TEPCO, the NRA, the national Government, the Fukushima Prefecture government, local communities and others, and that there was a need to consider socioeconomic conditions in the consultation process and to implement a comprehensive monitoring programme to ensure that there was no detrimental impact on human health and the environment [117, 223].

In parallel with the ongoing water treatment activities, R&D activities focusing on technical solutions for the treatment of waste water containing salt are being undertaken. The objective is to produce waste forms that are suitable for long term storage on-site. Several techniques — such as direct cementation, drying and storage, and drying and subsequent cementation — have been investigated. This includes various practical tests with the aim of increasing the salt content in the cement matrix as much as possible, while still meeting the required mechanical strength and homogeneity.

Storage of reactor fuel

This section summarizes the approach to developing storage capacity for the fuel being removed from the reactor buildings and the general plans and status of on-site storage of the reactor fuel. Removal of fuel from the reactor pools is discussed in Section 5.3.

Prior to the accident, reactor fuel was stored in the reactor pools, then moved to a common pool located on-site. From the common pool, some fuel was transferred off-site for reprocessing and some fuel was transferred to dry storage casks and placed in the cask storage building. At the time of the accident, approximately 93% of the capacity of the common pool (of 6840 fuel assemblies) was occupied. A total of 1573 fuel assemblies remained in the reactor storage pools on 22 December 2014. Thus, it was necessary to make space available in the common pool. The temporary cask storage facility has a capacity of 50 casks stored in individual concrete modules with plans to add space for 15 more casks in the future [224].

Nine dry casks were being stored in the cask storage building when it was inundated with sea water, sand and debris as a result of the tsunami. One of the casks has been opened and a representative spent fuel assembly was inspected. There were no abnormalities in the cask or the fuel inside. All nine casks have been removed, inspected, parts replaced as necessary, and placed in the new temporary dry storage area (see Section 5.3.4).

5.4.4.3. Future plans

In the short term, future activities on-site will concentrate on improvements to the working environment and the cleaning and safe storage of all contaminated water that is processed through the treatment system. A Committee on Countermeasures for Contaminated Water Treatment was established by METI in April 2013 and is evaluating its options [225]. In its report in 2013, the Committee reviewed options and analysed the characteristics and storage conditions of the contaminated water on the site as a baseline for appraising options for the future management of this waste stream, including potential controlled discharges (Fig. 5.4–16) [225]. The decontamination and adsorption facilities that were constructed just after the accident were designed with an emphasis on removing caesium to reduce external dose rates associated with stored water and to clean the water sufficiently for reuse in the reactor cooling process. The next phase is to consider removal of other radionuclides to reduce the risks associated with the continuing management of the water.

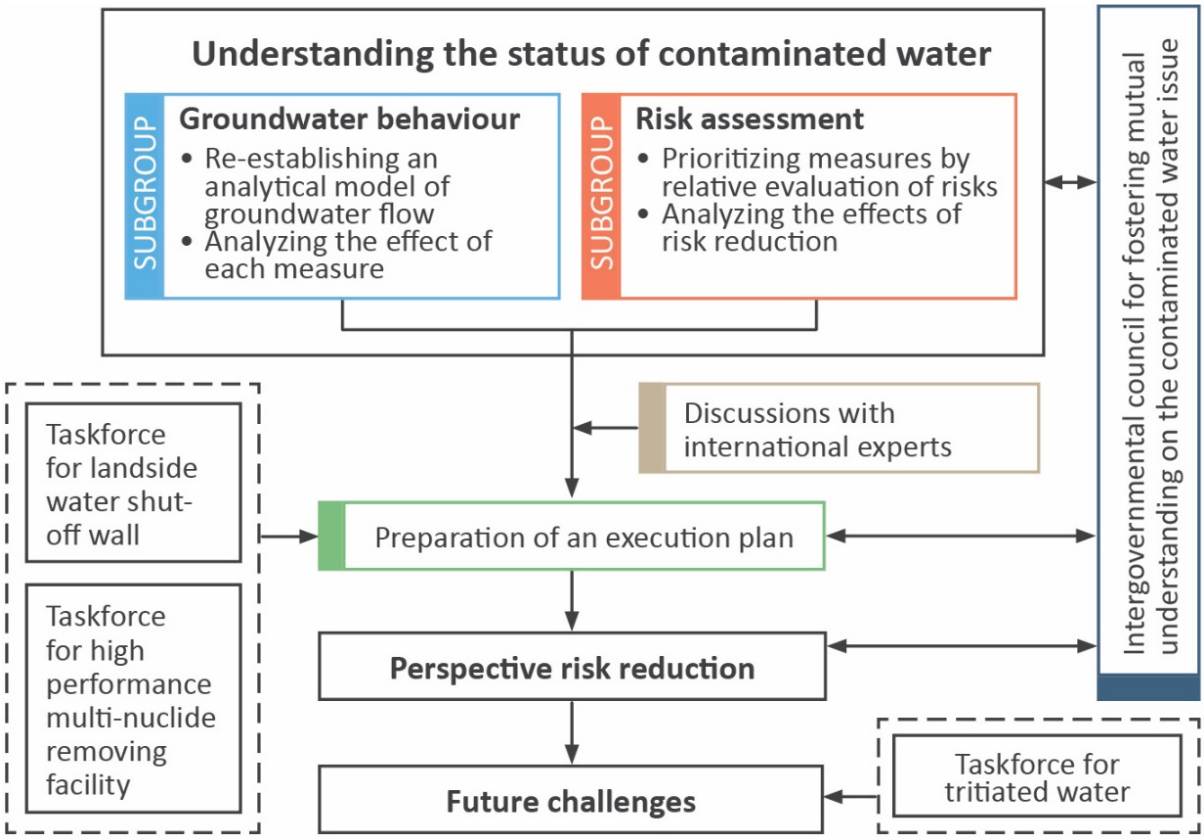


FIG. 5.4–16. Risk review approach for contaminated water [225].

Two significant activities are planned to further reduce the amount of groundwater that flows into the damaged reactor facilities (see Section 5.3): (1) a groundwater diversion that will provide a path for groundwater to pass around the reactor area; and (2) a landside impervious wall system that is being developed around the reactor. These features will be an important contribution to reducing the amounts of additional water that are introduced into the treatment system, which will help to reduce the rate at which new storage capacity is needed.

Work is also under way to address potential concerns regarding leaks by improving the reliability of the piping system for the circulation of water for reactor cooling. Operation of the reactor water injection system with the CST from Unit 3 as a water source started in July 2013. This helped reduce

the length of piping required and also increased the storage available. A new reverse osmosis system will be installed in a turbine building, which will result in a significant reduction in the length of pipe required for the water circulation system (from about 3 km of pipe to about 0.8 km of pipe) in 2015 [226]. The total length of pipe will be reduced to approximately 2.1 km from the original 4 km. This includes the approximately 1.3 km of pipe required for the transfer line for surplus water to the upper heights.

There are also plans [211] for the transition from temporary storage facilities of debris to more robust facilities designed to provide safe interim storage for the period prior to disposal. During the transition to the ISF, there is a plan to cover very low activity waste that is currently stored uncovered on the ground surface with HDPE sheets, pending plans for potential recycling and reuse. Incineration of combustible debris and miscellaneous job control waste (e.g. protective clothing) was planned to begin in the FY 2014. An additional incinerator that will be used for felled trees is planned to begin operation in FY 2018 [147]. Ash from incinerated trees will be stored in the ISF.

The management of on-site waste following the Fukushima Daiichi accident poses many complex R&D issues, many of which are unprecedented and challenging. There is cooperation among domestic and overseas organizations, and relevant experience and knowledge from all over the world is being compiled. On 1 August 2013, the Minister of Economy, Trade and Industry established the IRID to manage R&D related to the Fukushima Daiichi accident. IRID was established under the authority granted by the Research Association for Technology Act, and was inaugurated in August 2013. It is pursuing a number of R&D activities [227] in accordance with the mid to long term Roadmap, including:

— Characterization of the radioactive waste;
— Investigation of the safety and stability of long term storage;
— Investigation of processing technologies;
— Investigation and development of safe disposal systems.

Concerning the on-site work, TEPCO maintains relationships with approximately 400 partner companies, and established the Fukushima Daiichi Countermeasure Project Team in February 2012. The Fukushima Daiichi Decontamination and Decommissioning Engineering Company was established in April 2014 to provide a focus to the D&D efforts. Improvements to the work environment and systematic staff training will help to maintain an appropriate organization and qualified staff. The number of workers registered at the Fukushima Daiichi NPP, as of November 2014, was about 40 000. Therefore, it is foreseen that there will be no shortage of workers [228].

Further plans for decommissioning work are documented in the mid to long term Roadmap [119] and decommissioning efforts are discussed in Section 5.3. The removal of nuclear fuel debris represents the most ambitious challenge and may be started by 2020[38]. Assessment of the radiological and environmental impacts of the storage of solid and liquid waste and the potential discharge of treated waste water by use of realistic assumptions for potential exposures have been recommended by international peer reviews. Such assessments can provide the scientific basis to support a reduction in the amount of waste to be stored.

The type and amount of waste resulting from the eventual decommissioning of the reactors will depend on the approach that is adopted. Development of processing facilities and further refinement of disposal plans will also be addressed over the longer term. Research activities are under way to explore potential options.

[38] Revised to 2021 in the revised Roadmap, published in June 2015 [121].

Disposal of on-site waste is an important issue during the planning and implementation of current on-site waste management activities. The final form of the waste will be important when exploring disposal options. The management of fuel debris and the reactor vessels needs to specifically address occupational exposure. The transport of waste with high activity levels requires specific attention. It will be essential to consider interdependences between decisions made during the next few years and their implications for future disposal.

5.4.6 Summary

The stabilization, decontamination and recovery efforts that followed the Fukushima Daiichi accident have resulted in very large quantities of contaminated material and radioactive waste. The main contaminant radionuclides are ^{134}Cs and ^{137}Cs. The management of large quantities of on-site and off-site waste with varying physical, chemical and radiological properties in an urgent manner under difficult conditions has necessitated extraordinary efforts with respect to handling, segregation, treatment, conditioning, transportation, storage and future disposal. The following activities have been accomplished under challenging conditions resulting from high radiation levels and loss of infrastructure resulting from the tsunami:

- Renovation of equipment to handle and to transport contaminated material and radioactive waste;
- The management (including treatment and storage) of large volumes of contaminated water/sea water being used for reactor cooling purposes;
- The preparation and provision of temporary waste storage sites and interim waste storage facilities.

The execution of these measures has required amendments to legislation and to the national approach to waste management.

Immediately following the accident, the most important challenge for off-site waste management was the need to allocate relevant responsibilities, and for this purpose, the government established new legislation. The MOE was appointed as the body responsible for implementing off-site remediation activities. In cooperation with relevant interested parties, the MOE has developed and provided specific guidelines to address these needs.

With regard to off-site waste management, there have been difficulties in reaching agreement on locations to store contaminated material. The need for waste volume reduction efforts and effective waste segregation became apparent early in the recovery process. To address this need, the existing infrastructure for municipal solid waste (e.g. municipal incinerator facilities and waste landfills) was assessed as a potential option for the volume reduction of off-site contaminated material. However, obtaining the agreement of municipalities to employ conventional incinerators to incinerate contaminated material and radioactive waste from decontamination has been a challenge.

Considering on-site waste management, the contaminated solid and liquid material generated by the various recovery activities has required the establishment of effective strategies for waste management, including waste segregation, characterization, storage and future disposal. The management of large amounts of contaminated water associated with the continued cooling of the reactors remains one of the major challenges. This problem has been exacerbated by the inflow of large volumes of groundwater into the facilities, requiring additional measures for waste water management. Debris also continues to be generated by ongoing recovery activities. As a result, there is a continuing need for increased storage capacities for various types of solid and liquid waste streams. Consequently, volume reduction has also become an important factor in on-site waste management, e.g. by waste avoidance, installation of incinerators, reuse and recycling of materials.

Currently, the emphasis is on securing sufficient storage facilities to support ongoing recovery efforts and on dose reduction to workers and the public at the site boundary. Holistic planning for the management of radioactive waste, including reuse and recycling as well as considerations of disposal, has started and will become the primary focus in the future.

5.4.7 Observations and lessons

- **National strategies and measures for post-accident recovery need to include the development of a generic strategy for managing contaminated liquid and solid material and radioactive waste, supported by generic safety assessments for discharge, storage and disposal.**
  Such a strategy would assist in the implementation of pre-disposal management (for example, handling, treatment, conditioning and storage) of accident generated contaminated material and radioactive waste. It could also suggest appropriate routes for the disposal of materials. Waste management strategies may involve the use of existing processing, storage and disposal facilities, such as incinerators or leachate controlled landfills, but other approaches may be necessary, depending on the volumes and characteristics of the wastes involved. The development of such strategies could be supported by the development of a generic safety case.
- **An appropriate regulatory regime is needed for the management of post-accident contaminated material and radioactive waste that clearly defines the roles and responsibilities of the various institutions involved.**
  Advance planning, prior to any accident, and preparedness for regulating the management of contaminated material and radioactive waste arising from protective actions implemented during an emergency phase or remedial measures would be an advantage.
- **Control of the amount of contaminated material generated as a result of implementing the remediation strategy is important**.
  Having established criteria for acceptable residual contamination, it is essential to carefully control the amount of contaminated material generated during the implementation of the remediation strategy to minimize the amount of waste that must be managed.
- **The availability of generic storage and disposal facility concepts would be beneficial.** Should the use of storage facilities for extended periods of time be anticipated, the ageing management of these facilities needs to be considered.

5.5. COMMUNITY REVITALIZATION AND STAKEHOLDER ENGAGEMENT

5.5.1. Introduction

The nuclear accident and the radiation protection measures introduced in both the emergency and post-accident (existing exposure situation*)* phases have had far-reaching consequences on the way of life for affected communities. The consequences associated with evacuation, relocation, and agricultural restrictions are of particular note. The Reconstruction Agency[39] recognizes the importance of the societal aspects of the tsunami, earthquake and nuclear accident, and includes physical and socioeconomic reconstruction as part of the recovery [229]. Revitalization plans address a number of issues, such as the reconstruction of infrastructure, community support and compensation [230]. MOE and the Reconstruction Agency also note the importance of communication and stakeholder engagement as essential parts of the recovery process [29].

[39] The Reconstruction Agency was established in 2012 with the mission of accelerating the process of reconstruction following the earthquake and tsunami.

Surveys of the evacuated populations indicate that, in addition to the radiation exposure and resulting remediation, restoration of community infrastructure, as well as the safety of the Fukushima Daiichi NPP and waste management issues, are important in influencing decisions on whether to return [231]. The need in post-accident recovery to address non-radiological aspects[40], including stakeholder engagement and communication, is also highlighted in a number of international requirements and guidance on accident remediation (e.g. the IAEA's Basic Safety Standards and ICRP recommendations) [1, 8].

The tsunami and earthquake had direct impacts on infrastructure. The subsequent accident at the Fukushima Daiichi NPP and the associated radioactive contamination also affected infrastructure. The effects on infrastructure include: loss of schools, hospitals and commercial enterprises, impact on trade and economy, and demographic changes brought about by population movement. All these factors have an influence on the post-accident remediation and recovery phase. Although the consequences of any accident or disaster can bring about social upheaval and disruption of the way of life, such consequences were amplified following the Fukushima Daiichi accident by a number of issues. These include: the circumstances for long term evacuees, especially those remaining in temporary housing; challenges arising from the lack of public trust in authorities and radiological reference levels; loss of employment and livelihoods; damage to consumer trust in products from both within and outside contaminated areas; and concerns about stigmatization and discrimination arising from radiation exposure or association with the accident site.

This section addresses the societal and socioeconomic issues of the Fukushima Daiichi accident within the post-accident recovery phase, and the measures taken to address those issues. The objective of the section is to provide an overview of issues that are relevant to a broader understanding of the challenges of post-accident recovery and decision making; it does not represent an extensive analysis of the socioeconomic situation. The section focuses predominantly on the nuclear accident. The numerous societal and economic consequences of the earthquake and tsunami are outside the scope of this section. Section 5.5.2 introduces the legal framework for reconstruction and revitalization, with a focus on stakeholder engagement and communication/consultation in remediation. Section 5.5.3 presents a broad overview of the societal consequences of the accident, the emergency response and the post-accident remediation. Section 5.5.4 focuses on the various revitalization measures, such as human resources and infrastructure, health and community support, and compensation. Section 5.5.5 reviews the status and actions linked to stakeholder engagement and communication, including self-help actions and the involvement of affected communities in remediation activities. Section 5.5.6 deals with media reporting and consequences. Section 5.5.7 presents a discussion of 'what is safe' and its relevance for the affected community and recovery criteria. Sections 5.5.8 and 5.5.9 conclude with a summary and observations and lessons for the international community.

5.5.2. The legal framework

5.5.2.1. Reconstruction and revitalization

In response to the earthquake, tsunami, and nuclear accident on 11 March 2011, the Japanese Cabinet announced on 11 April the formation of the Reconstruction Design Council to assist in the formulation of a roadmap for reconstruction that "will provide residents of the disaster areas with courage and hope for the future, and will lead to the rebirth of a prosperous and dynamic Japan shared by all its people" [232]. The council was composed of members with expert knowledge of post-earthquake reconstruction, and was convened by the Prime Minister.

[40] Non-radiological aspects are defined as any societal, economic or environmental detriment (or benefit) of the nuclear accident itself or responses to the accident. They include psychological health and well-being, but not the direct health impacts of exposure to radiation.

There was a body of experience, from both international sources (e.g. Hurricane Katrina, the Haiti earthquake, the Chernobyl nuclear accident) and Japanese sources (e.g. the Great Kanto earthquake and the Great Hanshin-Awaji earthquake) for the Reconstruction Design Council to draw upon. The Reconstruction Design Council reported back to the Prime Minister on 25 June 2011 [233]. The Council's report addressed all societal aspects relevant to recovery from the earthquake, tsunami, and nuclear accident and included a number of recommendations for the physical and socioeconomic reconstruction of both the affected areas and Japan as a whole.

The Basic Act on Reconstruction in response to the Great East Japan Earthquake was enacted on 24 June 2011 [234]. This Act established the authority of the Reconstruction Design Council, established a reconstruction headquarters and anticipated the formation of a Reconstruction Agency under separate legislation.

The Reconstruction Agency was established in February 2012, with the mission of accelerating the process of reconstruction following the earthquake and tsunami.

The Basic Guidelines for Reconstruction [229] provide the Reconstruction Agency with a blueprint to tackle the numerous challenges in the reconstruction process in response to the earthquake. Included are the following:

- The creation of a Special Zone for Reconstruction [234] to promptly implement reconstruction proposals from the affected communities;
- Modifications to regulations and procedures to assist reconstruction efforts;
- Financial instruments to promote the revival of local economic activities;
- Special arrangements for land use restructuring and building codes.

The Fukushima Daiichi accident created challenges for reconstruction in addition to those associated with the earthquake and tsunami, notably arising from the prolonged evacuation, uncertainties over radiation exposures and reference levels, and a variety of socioeconomic consequences. The basic principles governing societal and economic revitalization are shared by a number of the revitalization efforts in Fukushima Prefecture. These typically cover decontamination, economic recovery and compensation, as well as communication and stakeholder engagement [230, 235]. Examples of plans and approaches to revitalization are given in Section 5.5.4.

5.5.2.2. Stakeholder engagement and communication for remediation

The Act on Special Measures Concerning the Handling of Radioactive Pollution [27] includes the legal framework for stakeholder involvement and communication in remediation and waste management activities by clarifying the responsibilities of the relevant stakeholders, such as the national and local governments, nuclear power producers and citizens. The Act also imposes obligations on national and local governments to notify and consult with other stakeholders including the public Articles 3 to 6 of the Act, which place responsibilities on national and local governments and on the nuclear power producers and citizens, to implement and cooperate with measures taken to deal with the environmental pollution from radioactive materials released by the accident. On the basis of these responsibilities, the following division of activities have been established among the various stakeholders:

- The national Government provides policies and standards, conducts remediation and waste management activities in areas which are affected by the Fukushima Daiichi accident (i.e. SDA and ICSA), and promotes the efforts of local governments by taking technical and financial measures.
- In the ICSA, the local governments (i.e. prefecture and municipalities) formulate and implement remediation and waste management plans.
- The nuclear power company (TEPCO) implements any necessary measures in good faith, while assisting the national and local governments to conduct remediation and waste management

activities. Other utilities make efforts to cooperate with the national and local governments in managing the remediation activities. TEPCO covers the costs of the measures under the Act for the remediation.

— The relevant stakeholders (e.g. citizens, landowners) endeavour to cooperate with the national and local governments in managing the radioactively contaminated material.

Further details and examples of revitalization measures and stakeholder engagement activities are provided in Sections 5.5.4 and 5.5.5.

5.5.3. The affected population and infrastructure

5.5.3.1. Evacuees and returning residents in affected areas

The status and prospects of evacuated populations are major features of the societal consequences of the Fukushima Daiichi accident. One of the main objectives of remediation includes measures that will allow people to return to their homes and lead normal lives. The reasons for evacuation, overall numbers and the areas from which people have been evacuated, and remedial actions being undertaken in each type of area have been presented in Section 5.2. Many of the residents had experienced multiple relocations and revisions of evacuation zones [236]. At the peak, in June 2012, over 164 000 people were categorized as evacuees [237, 238].

The different evacuation areas and the number of evacuees in the SDA (see Section 5.2) and surrounding areas in October 2014 are shown in Figs 5.5–1 and 5.5–2. The main reduction in the number of evacuees occurred as a consequence of the return of residents within the 20–30 km zone and other areas in the ICSA (see Section 5.2). This has reduced the number of evacuees from a peak of more than 70 000 to an estimated 21 000 from the 20–30 km zone (the 'Evacuation Prepared Area') and 30 000 from outside the 30 km zone.

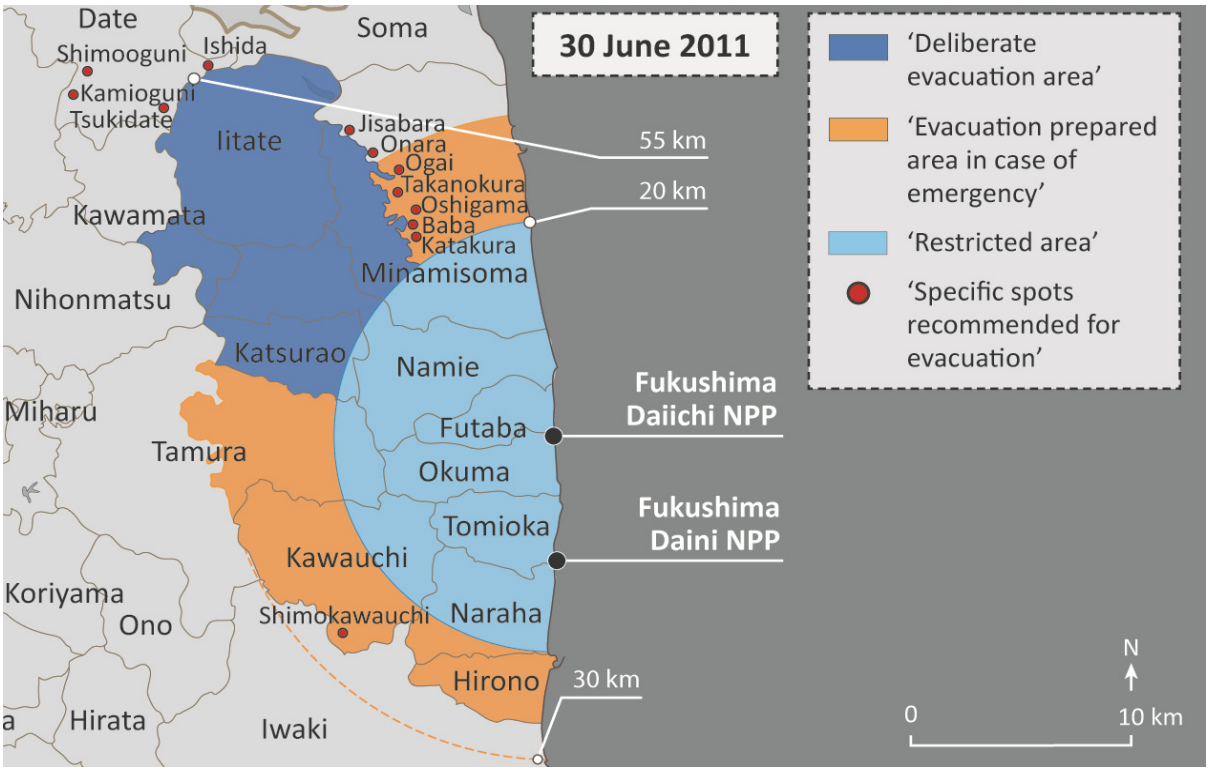
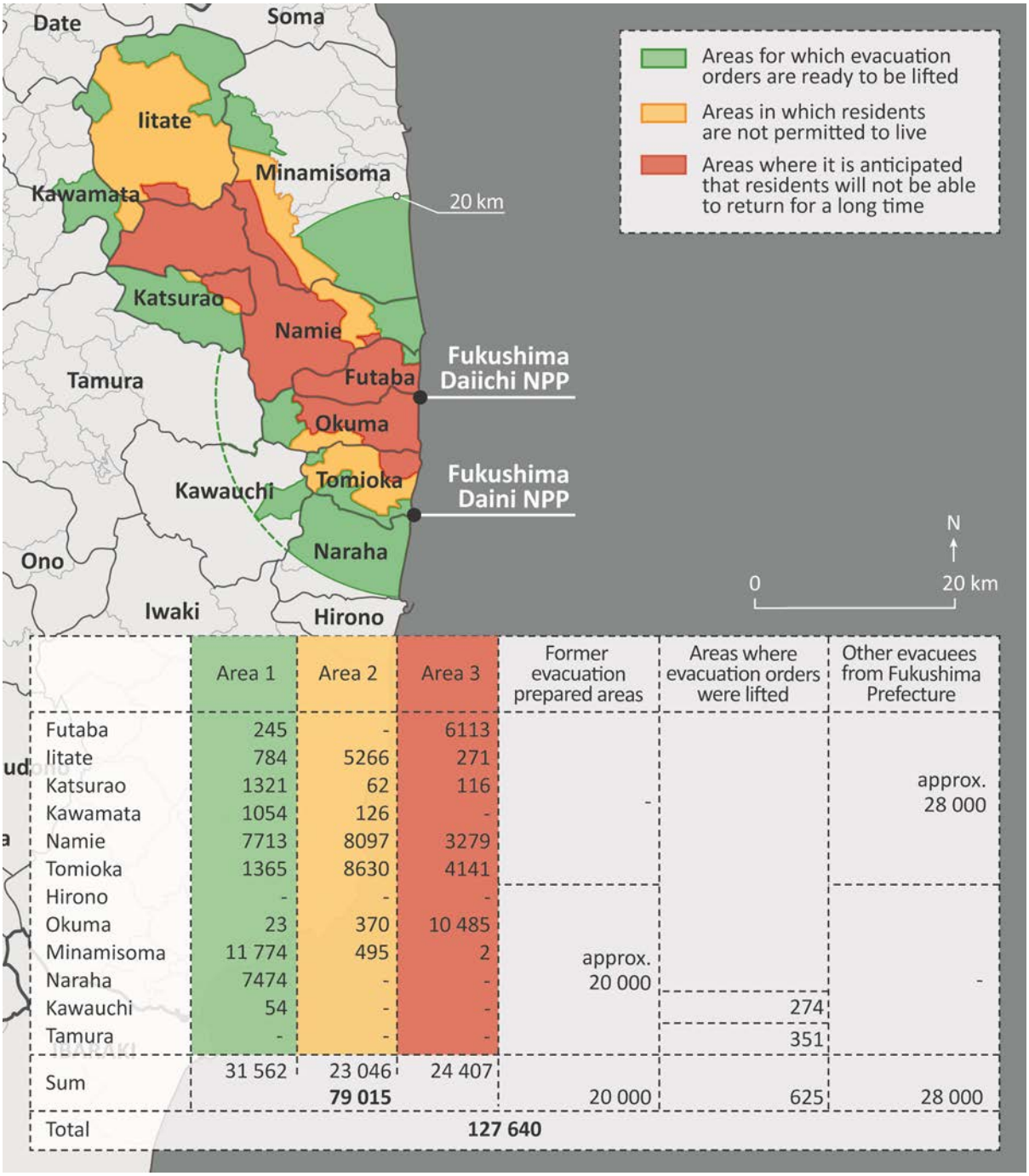


FIG. 5.5–1. Restricted area, Deliberate Evacuation Area, area prepared for evacuation in case of emergency and regions including specific spots recommended for evacuation (as of 30 June 2011) [239].



	Area 1	Area 2	Area 3	Former evacuation prepared areas	Areas where evacuation orders were lifted	Other evacuees from Fukushima Prefecture
Futaba	245	-	6113	-		approx. 28 000
Iitate	784	5266	271			
Katsurao	1321	62	116			
Kawamata	1054	126	-			
Namie	7713	8097	3279			
Tomioka	1365	8630	4141			
Hirono	-	-	-	approx. 20 000		-
Okuma	23	370	10 485			
Minamisoma	11 774	495	2			
Naraha	7474	-	-		274	
Kawauchi	54	-	-		351	
Tamura	-	-	-			
Sum	31 562	23 046	24 407	20 000	625	28 000
		79 015				
Total	**127 640**					

FIG. 5.5–2. Number of evacuees in Fukushima Prefecture in October 2014 [240].

The overall trends in total evacuee numbers and population changes are shown in Table 5.5–1 and Fig. 5.5–3. Just over 7000 people had returned between June and December 2012, and about 12 500 between December 2012 and February 2013 [230]. These are gross population numbers that should be considered along with the number of persons moving out of the area during this time. However, it is clear that at the present time, only a small fraction of the population has returned, although the trend shows that this is increasing with time.

TABLE 5.5–1. POPULATION CHANGES IN FUKUSHIMA PREFECTURE [241]

Population in Fukushima Prefecture	1 March 2011	1 March 2015	Change
Number of households	721 535	729 978	8 443
Population	2 024 401	1 932 392	-92 009
Aged 0 to 14	274 322	239 517	-34 805
Aged 15 to 64	1 235 833	1 141 051	-94 782
Aged 65 or older	502 160	539 738	37 578
Aged 75 or older	275 465	285 088	9 623
Age unknown	12 086	12 086	0

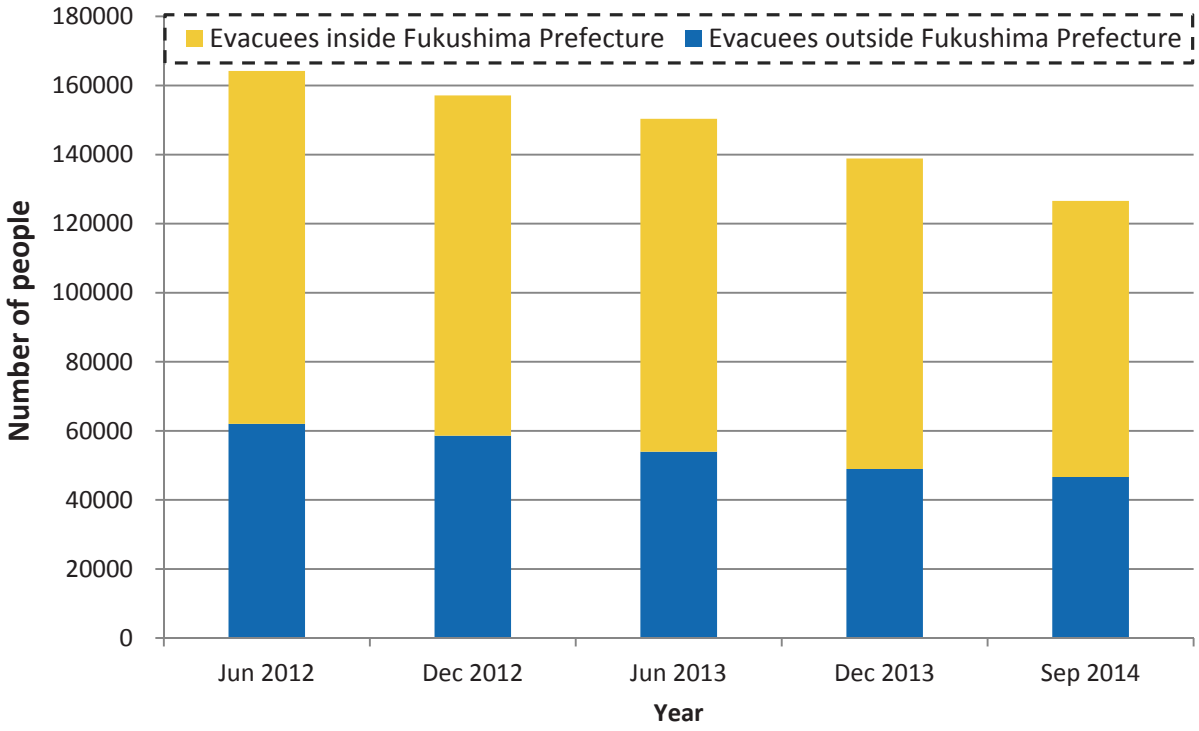


FIG. 5.5–3. Changes in the number of evacuees in Fukushima Prefecture [241].

Prolonged evacuation

The age distribution of the population between March 2011 and September 2013 over the whole of Fukushima Prefecture shows a decrease in the younger population (10% for people aged 0–14 years), and an increase of about 3% for populations older than 65 [230]. The number of households remained effectively constant (a decrease of only 0.02%). These numbers reflect the entire prefecture, and more significant demographic changes can be seen at the local level.

The ageing of populations was a phenomenon that existed before the Fukushima Daiichi accident [230]. However, this effect has been accelerated by the accident and the tsunami has also had an effect, especially among fishing communities [230]. The demographical changes illustrate the social disruption brought about by the separation of families, typically resulting from one parent leaving the area with their children while the other parent remains for work reasons [242, 243]. Demographical changes are more pronounced at locations outside the SDA and in temporary housing communities. In

those areas, it is more likely that younger families have moved away from the area, while elderly populations are more likely to return [244, 245]. For many residents in areas outside the 20 km SDA — designated the Evacuation Prepared Areas — the decision to evacuate was not only driven by concerns about radiation exposure, but also by the affected infrastructure [67]. As discussed below, many of the municipalities in these areas are including revitalization of infrastructure as part of their recovery plans to encourage people to return.

Information about the number of children in kindergartens and schools gives another perspective on demographic changes. In Japan, the school year starts in April, after the spring vacation, which means that especially for families with young children, the decision whether or not to return in the first months after the accident was heavily influenced by the schooling situation. In 2010, there were 117 668 children registered at elementary schools and 61 866 children registered at junior high schools in Fukushima Prefecture. These numbers dropped between 2011 and 2013 by around 1800 [246]. As an indication of the overall order of magnitude of these changes, it may also be seen from Table 5.5–1 that, between 1 March 2011 and 1 March 2015, the number of children under 15 years of age in Fukushima Prefecture dropped by almost 35 000.

A number of surveys on evacuees have been carried out between 2012 and 2013 [231, 246, 247]. Surveys carried out by the Reconstruction Agency on residents from the SDA and Deliberate Evacuation Areas (see Fig. 5.5–1) indicate that the ambient radiation dose is only one factor (and in some instances not the major concern) in evacuees' considerations about whether or not to return. The population surveys indicate that issues such as infrastructure (e.g. schools, hospitals, commerce and transportation) and way of life in the affected areas are also important factors [231]. The situation for children is a major factor impacting on decisions by families about whether to move away from the area or to return. The intention not to return varied widely between the different towns and villages, but ranged from 10–46% for all households and 15–54% for households with children [231]. Issues influencing these decisions include the radiation exposure of children, but also factors such as whether the children can walk to school and play outside [67, 236, 244, 248].

In addition to the wide variation in the residents' intentions to return between the different locations, the surveys show a dependency on age, with the elderly more likely to want to return [231, 244]. Other factors influencing the intention to return include general concerns in the affected populations over stigmatization and discrimination. For example, surveys of TEPCO workers highlighted that they had experienced discrimination [243]. There have been reports of discrimination against children evacuated as a result of the Fukushima Daiichi accident after moving to new schools [242]. Evacuees have also expressed concerns that their children would not be able to find partners or marry in the future [244].

The particular challenges for people living in temporary accommodation have been highlighted in previous chapters, and include a range of mental health and general well-being issues associated with high levels of unemployment and lifestyle factors [249]. The total number of evacuees living in temporary accommodation is not available, but by June 2013, 16 800 temporary housing units had been constructed and nearly 24 000 families were living in accommodation rented by the prefecture government [230]. In addition, there are plans for building about 2570 units of permanent public housing by FY 2015 for people affected by the earthquake and tsunami. The development plan of building 4890 units of permanent public housing for those evacuated in the response to the accident is in progress.

The success of remediation in the SDA is closely related to residents' intentions to return. However, residents' opinions about what level of radiation exposure is acceptable, and which areas should be prioritized for remediation, tend to be divided both between and within different communities [1, 8, 67, 232, 236].

5.5.3.2. Agriculture and other enterprises

The socioeconomic consequences linked to the impacts of the accident on agriculture and other enterprises go beyond the SDA and the ICSA. In addition to the loss of employment and livelihood for those affected, they include the socioeconomic disruptions caused by bans on food production, export losses from food and other consumer goods, costs of monitoring to demonstrate compliance with radiological criteria and compensation to affected citizens. Agricultural activities have essentially stopped in the evacuated areas, but also in other areas where restrictions in land use have been imposed. Indirect socioeconomic consequences include those arising from consumer trust, not only in food products, but also with other commodities and businesses. Even for products or areas in Fukushima that were not directly affected by the accident, lack of consumer trust in produce or avoidance of the area as a tourist destination have had knock-on commercial effects [230].

Evacuation resulted in the loss of farms and businesses. In the 1170 km^2 of the SDA, 72% of the area is forest, 20% agricultural (paddy field and other agriculture), 4% residential and 4% other [250, 251]. In addition, fishing ceased within 30 km of the Fukushima Daiichi NPP (returning to 20 km at the end of September 2011), following the establishment of the evacuation prepared area, and a further 700 km^2 outside the SDA has either been evacuated or has experienced cessation of agricultural or other commercial production.

The loss of agricultural and fishery industries has life changing impacts on those farmers and fishermen who have lost their livelihoods. Particularly in regions where restrictions are still in place, these impacts are exacerbated by uncertainties as to when, and if, producers will be able to resume activities.

In economic terms, producers in Fukushima Prefecture also suffered hardship due to the loss of consumer confidence in produce from the area, including commodities for which monitoring results were below the reference limits [67, 230]. On a wider scale, the accident had impacts on trade and export within and outside Japan [252, 253]. While most of the focus was on foods, impacts extended to other consumer goods, such as exported cars, and the requirement by many countries for measurements for any radioactive contamination. However, as detailed below, this did not have a lasting impact on exports, but this effect does highlight the potential sensitivity of markets to consumer opinion.

All fishing activities in Fukushima Prefecture were suspended following the accident in March 2011, except for some trial fishing outside the 20 km exclusion zone, targeting 39 specific species [254].

Tourism is another important source of income in Fukushima Prefecture. Important tourist and cultural enterprises in the region include spas, Tsuruga Castle, Oze and Nanko National Parks, the Iwaki aquarium, as well as cultural activities such as the Soma-Nomaoi festival [230, 237, 238, 242]. There was a drop in the total number of visitors to the region of more than 50% between 2011 and 2012 following the earthquake and tsunami. However, a similar effect was observed throughout Japan; Fukushima Prefecture was not the only area affected. The number of visitors has risen with time [255], and in 2013 the value was only about 20% less than that for 2010. In addition, many coastal facilities such as beaches were severely impacted by the tsunami, and the aquarium at Iwaki lost the majority of its stock (although it reopened in 2013). The accident also has had an impact on local cultural and leisure activities.

Import and export

From a global point of view, the combination of earthquake, tsunami and nuclear accident in Japan in March 2011 had a direct effect on the Japanese economy. Exports fell by 2.4% in April 2011, compared to the corresponding level for April 2010. In fact, many industrial activities suffered

immediately following the accident, and the export of manufactured goods declined, particularly for electronic components and semiconductors (Table 5.5–2 and Fig. 5.5–4 [256]) At the same time, imports increased, especially those of fuels, chemicals and foods, resulting in a deficit in the trade balance in April and May 2011. Indeed, Tohoku is a region where many materials and components intended for use all over Japan, as well as internationally, are produced. Breaks in production of these industries therefore have had a direct impact on the economic activities around the world [252]. Imports of fossil fuel remained at a higher level at the time of writing. [257].

TABLE 5.5–2 TRADE BALANCE IN THE TOHOKU AREA (IN UNITS OF HUNDRED MILLION YEN) [256]

Year	Export			Import			Trade balance	Change per year
	Amount	Change per year (%)		Amount	Change per year (%)			
		Tohoku area	Japan		Tohoku area	Japan		
2002	4 562	7.3	0,9	7 238	-0.1	1.7	-2 676	-10.5
2003	5 067	11.1	0.9	7 896	9.1	1.8	-2 829	5.7
2004	5 610	10.7	0.9	8 907	12.8	1.8	-3 298	16.6
2005	5 810	3.6	0.9	11 246	26.3	2.0	-5 436	64.8
2006	7 131	22.7	0.9	14 107	25.4	2.1	-6 976	28.3
2007	8 284	16.2	1.0	15 548	10.2	2.1	-7 264	4.1
2008	7 655	-7.6	0.9	16 467	5.9	2.1	-8 812	21.3
2009	5 003	-34.7	0.9	10 668	-35.2	2.1	-5 665	-35.7
2010	6 484	29.6	1.0	13 021	22.1	2.1	-6 537	15.4
2011	3 886	-40.1	0.6	7 949	-39.0	1.2	-4 063	-37.9
2012	4 425	13.9	0.7	14 309	80.0	2.0	-9 833	143.3

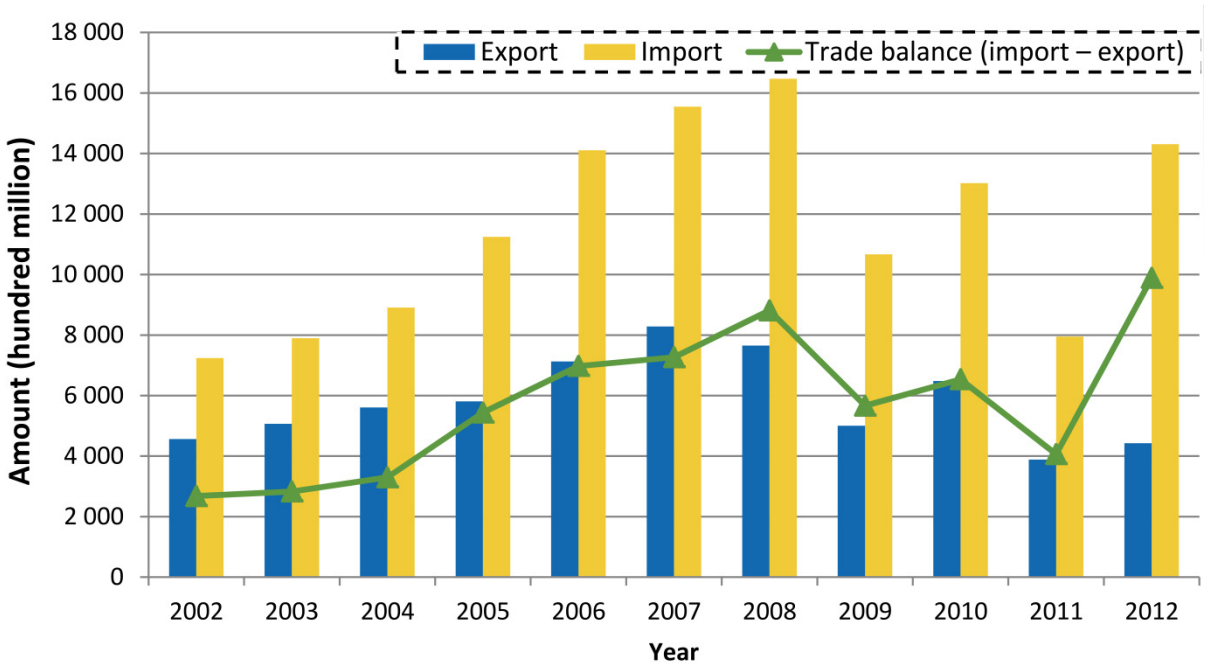


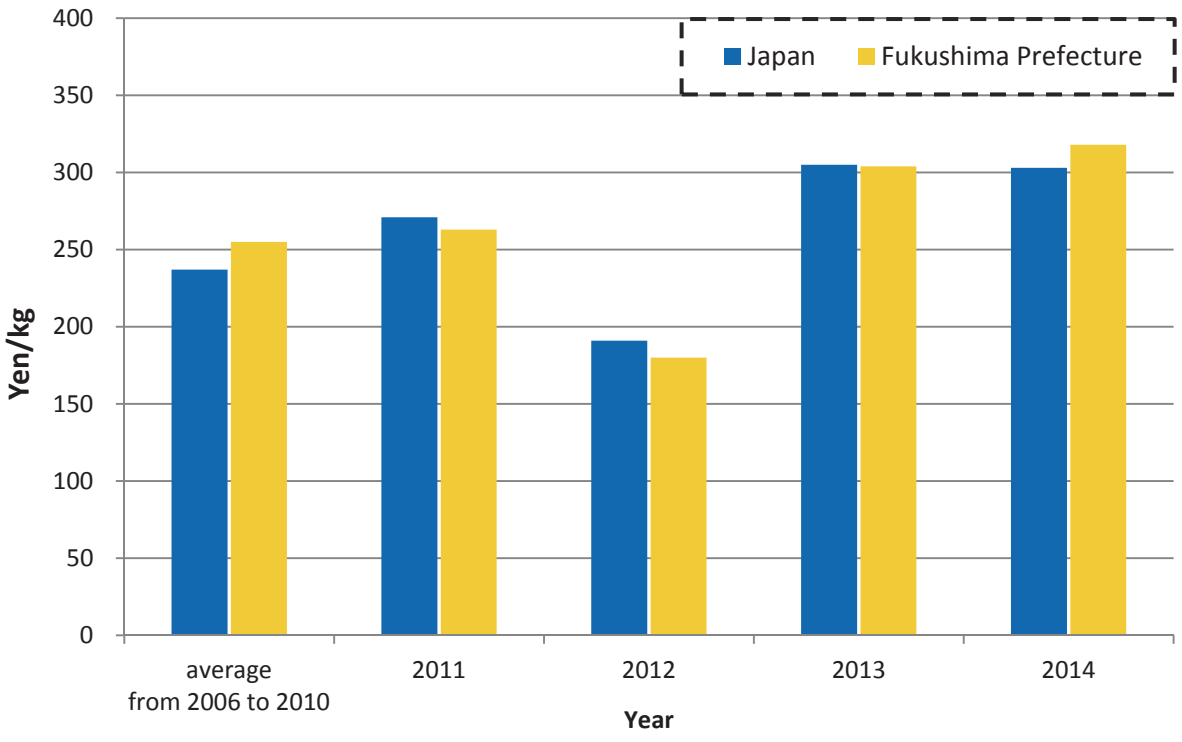
FIG. 5.5–4. Trade balance in the Tohoku area (units in hundred million) [256].

With regard to foods, exports fell by more than 20% in April 2011. The decrease in exports continued in May, with an additional drop of more than 20%. However, as of June 2011, the exports of foods returned to approximately the same level as the previous year (a decline of only 3.6%). The decline in exports was due to disruptions in production and the anxiety among consumers concerning radioactivity, as well as to the restrictive measures implemented by some countries regarding Japanese food. However, these reactions started to grow more moderate as of June 2011 [252], possibly as the result of restored confidence due to the monitoring efforts implemented in Japan and the communication with stakeholders (see Section 5.5.4).

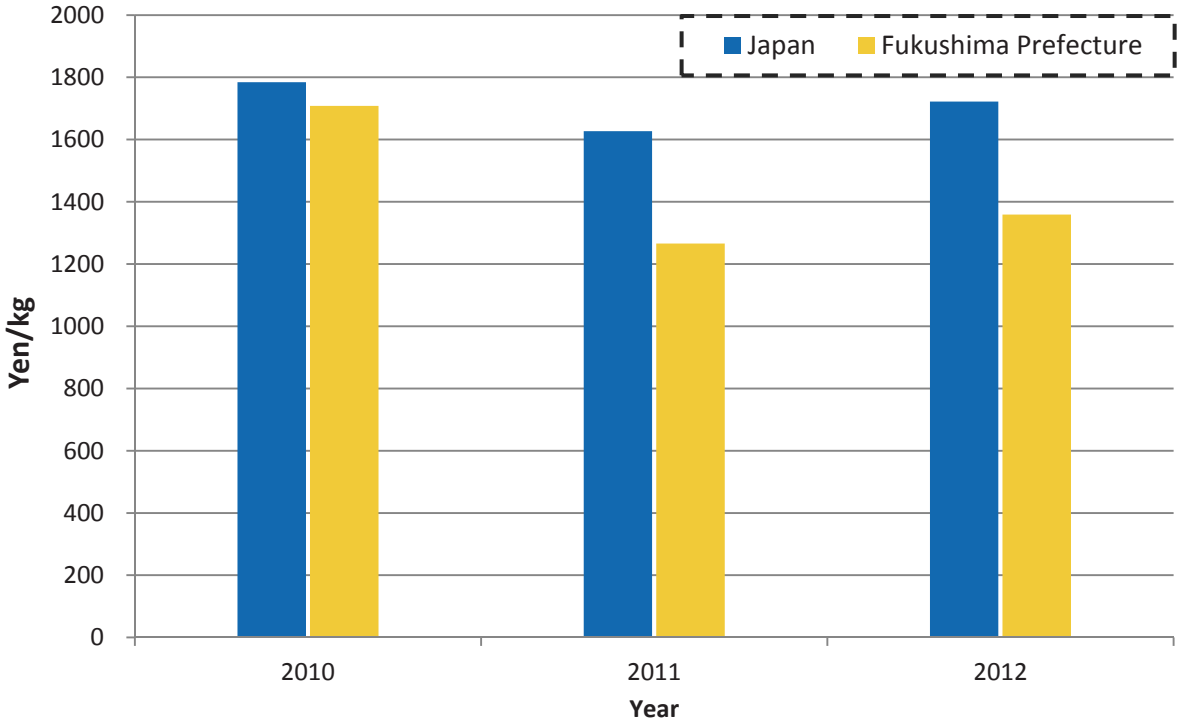
In 2011, exports of Japanese agricultural, forestry and marine products decreased significantly (by over 10%), especially to Asian countries. However, some products remained in high demand for export, including sake and green tea [252].

Within Japan, a number of products from the Fukushima area showed a significant drop in price as compared to those from the rest of Japan (Fig. 5.5–5), including peaches, beef and brown rice. Prices for these products were about 20%–30% lower than before the accident. By 2013, some recovery in these prices was observed [41].

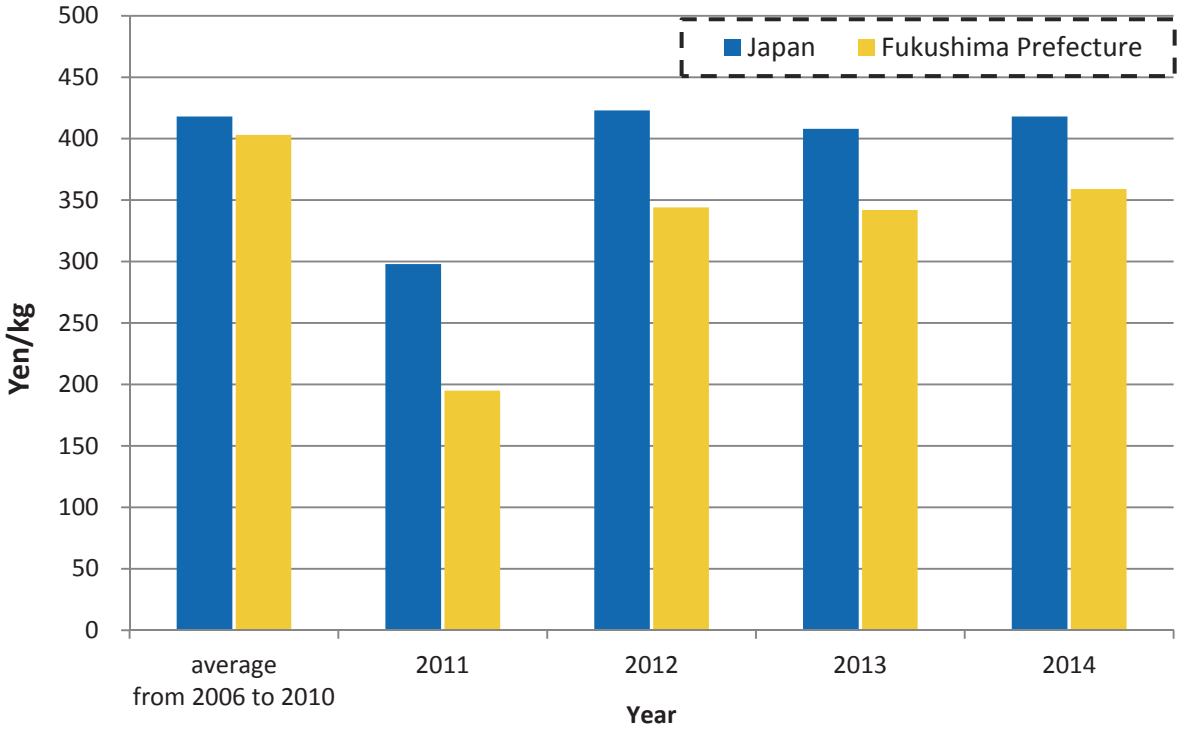
There is no direct evidence that links the price recovery to the change of the reference level for radiocaesium in food; other factors may have played a role. In fact, the prices of food, especially for fresh products, fluctuate greatly each year depending on the production quantity and the quality. In addition, Japanese authorities have also launched information campaigns, aimed at both Japanese and international consumers, highlighting the actions taken in Japan with regard to the radiation control of foods [260, 261]. However, the prices of food also reflect the demand. For example, peaches, which are a characteristic product of Fukushima Prefecture that are also exported outside Japan, experienced a significant decrease in price in the year of the accident that may be linked to a strong decline in the demand from neighbouring countries. However, in 2012, prices had almost returned to their previous level.



(a)



(b)



(c)

FIG. 5.5–5. Change in prices for agricultural products from Fukushima Prefecture; (a) cucumber, (b) beef; (c) peaches [239, 256, 257]

5.5.3.3. Services and infrastructure affected

The importance of infrastructure on the population's decisions to evacuate or return has already been highlighted. Infrastructure issues include the availability of schools, medical services, commercial enterprises (supermarkets, shops), transportation and government offices.

After the evacuation order was imposed, nine municipalities decided to move their administrative functions from their original town/village offices to temporary offices outside their municipalities. As of February 2014, seven municipalities were operating from temporary offices (Table 5.5–3). Hirono Town and Kawauchi Village resumed their services in their original offices in March 2012 to prepare for full scale return of the residents who evacuated after the accident. Hirono Town is located in the 20–30 km zone and outside the evacuation order area, but as a coastal municipality was also affected by the tsunami. Most of the Kawauchi Village municipality is located outside the 20–30 km zone.

TABLE 5.5–3. MOVEMENT OF MUNICIPAL ADMINISTRATIVE OFFICES[a]

	Locations of temporary administrative offices
Hirono Town	⇒ Ono Town ⇒ Iwaki City ⇒ Hirono Town (1 March 2012)
Naraha Town	⇒ Iwaki City ⇒ Aizumisato Town ⇒ Iwaki City (17 January 2012)
Tomioka Town	⇒ Koriyama City (19 December 2011)
Kawauchi Village	⇒ Koriyama City ⇒ Kawauchi Village (26 March 2012)
Okuma Town	⇒ Tamura City ⇒ Aizuwakamatsu City (5 April 2011)
Futaba Town	⇒ Kawamata Town ⇒ Saitama City ⇒ Kazo City ⇒ Iwaki City (17 June 2013)
Namie Town	⇒ Nihonmatsu City (1 October 2012)
Katsurao Village	⇒ Aizubange Town ⇒ Miharu Town (1 July 2011)
Iitate Village	⇒ Fukushima City (1 June 2011)

[a] Source: Fukushima Prefectural Government, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Namie Town, Katsurao Village, Iitate Village.

In the areas outside the SDA and Deliberate Evacuation Areas, it is difficult to discern the degree to which the shops and supermarkets closed because the residents left, or the residents left because there were no longer any shops. While the latter is referred to as a contributing factor by the residents themselves, it has also been reported that delivery companies stopped delivering to supermarkets after the accident.

The status of schools, hospitals and other social and welfare facilities is dependent upon a combination both of material damage by the tsunami and earthquake, and abandonment after evacuation. In December 2012, there were a total of 137 hospitals[41] in operation in Fukushima Prefecture. As a result of the tsunami and the nuclear accident, seven of the larger hospitals were taken out of operation within the SDA and remain closed. Of these, three hospitals are located in the 'difficult to return' zone, one in the area where residents are not yet permitted to live and three in the areas where evacuation orders are ready to be lifted [230, 262]. In addition to hospitals, the Fukushima Prefecture government reported that the earthquake, tsunami and nuclear accident resulted in the loss of 35 social welfare facilities, 29 child welfare facilities and 92 schools. Of these, 9 social welfare facilities (elderly and social care), 6 child welfare facilities and 8 schools are located in the SDA [230, 262].

[41] A hospital is defined here as any medical facility with more than ten beds for patients.



FIG. 5.5–6. Extract from a leaflet issued by the authorities in Fukushima Prefecture illustrating priority projects and their objectives [241].

The eight schools in the SDA have been relocated to alternative facilities and operate as satellite schools, with a corresponding movement of children and teachers. Hospitals and medical care are more complicated, and the effects vary across the different types of medical services. For example, greater impacts have been observed in public health and psychiatric support than in larger hospitals [244, 263]. Between March 2011 and December 2012, the number of doctors and nurses in the South Soma coastal region decreased by 50% and 40%, respectively, from 120 doctors and 1188 nurses in the 16 hospitals of the region, to 60 and 724, respectively. By August 2013, this number had risen slightly to 78 doctors and 747 nurses, but was still well below the levels before the tsunami and nuclear accident. This reflects, in part, the decrease in population, but the percentage of the reduction is greater than that in the reduction in the population. In terms of physical damage, the main impacts on transportation in the region were due to the tsunami, which particularly affected the coastal roads and railways. However, the restricted area bisects the main coastal road and railway line (JR Joban line) arteries, significantly increasing the travel time between Tokyo and the areas to the north of the zone, such as Futaba Town, Soma City and Minamisoma City.

5.5.4. Recovery and revitalization strategies

Revitalization initiatives and reconstruction activities linked to recovery range from those at national Government level to initiatives by non-governmental organizations and local communities. The Government of Japan established a Reconstruction Agency; Fukushima Prefecture has initiated various activities (Fig. 5.5–6) including the establishment of the Centre for Environmental Creation; and the Fukushima Revitalization Headquarters was set up by TEPCO in 2013. All projects combine radiation protection actions with broader societal aspects, such as infrastructure revitalization, public engagement and involvement and (in the case of the Revitalization Headquarters) compensation. This section presents an overview of the main strategies.

5.5.4.1. Human resources and infrastructure

In addition to the decontamination and remediation actions for reducing doses, efforts also address the reconstruction of infrastructure, housing and transportation. Such actions focus on regaining consumer trust in produce, stimulation of local pride and promotion of tourism. Examples include food fairs, advertising projects to promote the quality of local produce and tourist campaigns to attract visitors to the region. National survey and information campaigns have been set up by the Consumer Affairs Agency, and prefecture level initiatives include 'Ethos for Fukushima' [264], as well as specific regional initiatives such as the establishment of focus groups, science cafes and community centre groups.

The actions vary across the prefecture, often depending on the engagement of local politicians and the different challenges within the region. Specific success stories include the cooperation between peach fruit growers, distributors and industry, both in remediation activities and in a number of initiatives aimed at regaining public trust in Fukushima peaches [230].

Provision of information and communication with the public is a central part of revitalization. A Decontamination Information Plaza was opened in Fukushima City in January 2012 as a joint project of Fukushima Prefecture and the MOE. It represents an information hub for the area. Other actions at the local level cover a wide range of communication activities, including dialogues between experts and the public and specific advice for self-help actions. Research and information centres have been planned for local municipalities (e.g. Minamisoma City, Miharu Town) [230]. The Fukushima Revitalization Headquarters has been carrying out the '100 000 People Project', which sends TEPCO employees to many parts of Fukushima, on a daily basis, for various activities, including cleaning contaminated houses and assisting with local events [265]. These actions are helping to establish two way communication with Fukushima residents and restore their trust. Information and communication activities are discussed in greater detail in Section 5.5.5.

Recognizing that the availability of employment is also a driving factor for the return of residents (or in-migration of people who had not previously lived in the area), other initiatives focus on the rebuilding of businesses as well as the creation of new commercial opportunities. A business investment subsidy was introduced for new enterprises with the planned establishment of 380 new companies, including businesses in the transportation, information technology (IT), medical and renewable energy sectors. Specific examples include IT projects in Soma City, medical materials manufacturing in Hirono Town and a R&D centre for renewable energy established by the National Institute of Advanced Industrial Science and Technology (AIST) in Koriyama City [230, 266]. In this respect, it is accepted that revitalization does not necessarily mean restoration or return of all previous commercial activities. New businesses may replace the old enterprises, and hence the returning workforce need may not be the same people who left.

5.5.4.2. Consumer trust

A number of initiatives focus on re-establishing consumer trust in the products of Fukushima Prefecture. The Japanese authorities launched information campaigns, making use also of social media, aimed at both Japanese and international consumers [260, 261]. The Japanese Consumer Affairs Agency conducted surveys on consumer opinion and interviews with producers and distributors, and carried out promotional activities and explanations of relevant reference levels for foods [261]. Consumers requested access to monitoring and measurement devices, and it was recognized by the Consumer Affairs Agency that this requires both training and the availability of suitable experts [261].

A consumer survey [260, 261] provides additional information on the perception of Japanese people toward foods, including those from Fukushima Prefecture. This internet survey contacted 5176 people throughout Japan on three occasions (in February 2013, August 2013 and February 2014). Of the people surveyed, 66% reported that they paid attention to where the food came from, but of those, only about 15% did so because of a perceived radiation risk associated with produce from Fukushima Prefecture. The percentage of people concerned with a perceived radiation risk has declined during the period covered by the three surveys. The majority replied that factors such as taste and quality were more important. These results suggest that, although there is a continuing impact of the accident on consumer choices, and uncertainties about the reference levels remain, worries about radiocaesium levels in foods are not a major concern of the majority of consumers [260].

5.5.4.3. Health and well-being

The accident and remediation measures impacted on the mental health and social well-being of the affected population on a number of levels. These include the disruption of the general social well-being of the public (evacuees, populations living in contaminated areas, young families, etc.), the impact on the psychological health of workers and the impact on the condition of psychiatric patients [249, 263]. The overarching factors influencing psychological well-being are described in Technical Volume 4, Section 4.4. This section considers some of the support actions and recovery programmes that were initiated to help the affected population.

With regard to the general public, the MHLW has been engaged in efforts to dispatch mental health care teams [266, 267]. These efforts include providing access to telephone counselling for persons who were found by the Fukushima Health Management Survey to have high risk (see Technical Volume 4, Section 4.4), or those who indicated a wish to talk about their concerns [266, 267]. Public health officials (district nurses, midwives, etc.) have set up a number of initiatives on a local basis, including focus group discussions and counselling for pregnant women and young mothers.

TEPCO workers have also been receiving access to mental health support, in response to the combination of stress factors to which this group has been subjected. The majority of workers were living in areas close to the Fukushima Daiichi NPP at the time of the accident and thus suffered the loss of family and friends owing to the tsunami. Many workers also lived in areas subject to long term evacuation owing to radiation levels, and their work at the NPP has resulted in separation from their family. While those factors are experienced by many other people from within the 30 km coastal region, the TEPCO workers have, in addition, been subject to discrimination and social stigmatization by other members of the public. This has been identified by the workers themselves as one of the main factors behind mental stress [244].

Since prior history of psychological stress is one of the major risk factors for post-traumatic stress, the accident also has had an impact on existing psychiatric patients. The restricted and Deliberate Evacuation Areas contained more than 800 hospital places and 11 out-patient support centres

dedicated to psychiatric care. The long term recovery of the situation has included a number of efforts to ensure the proper care of these patients [263].

With regard to workers, the MHLW developed ministerial guidelines based on Article 70-2 of the Industrial Safety and Health Act of 11 October 2011, which prescribes the following [268]:

- Establishment of a scheme of health management in each work place, including conduct of a medical examination;
- An eye examination for cataracts for those people with an effective exposure dose in excess of 50 mSv during the emergency, as well as cancer screening and thyroid tests once a year for those who received an effective dose in excess of 100 mSv during the emergency (see Technical Volume 4).

Provision of health guidance

The MHLW established a database to store exposure dose data and the results of the medical examinations of emergency workers. In addition, the MHLW issued registration cards to all emergency workers, so they can receive health counselling and health guidance. After the cessation of radiation work, the workers can receive screening tests in designated medical facilities at the expense of the MHLW [269, 270].

5.5.4.4. Compensation framework

At the time of the nuclear accident, Japan was not Party to any of the conventions on civil liability for nuclear damage[42] [271–274] containing the basic principles on nuclear liability[43] [275] (Japan ratified the Convention on Supplementary Compensation for Nuclear Damage (CSC) [274] on 15 January 2015). Rather, in 1961 Japan enacted national legislation addressing nuclear liability — the Act on Compensation for Nuclear Damage [276] (Act No. 147 of 1961, as amended), referred to as the Compensation Act, and the Act on Indemnity Agreements for Compensation for Nuclear Damage (Act No. 148 of 1961, as amended) [277], referred to as the Indemnity Agreements Act. This legislation was consistent with the basic principles of nuclear liability embodied in the conventions. Under this legislation, TEPCO was exclusively liable for nuclear damage caused by the Fukushima Daiichi accident. Its liability was unlimited in amount. Following the accident, TEPCO was not granted exemption from liability by the Government and Diet on the assumption that the exemption

[42] There are currently two international regimes for civil liability for nuclear damage. The first is the so-called 'Paris regime', which consists of the 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy (the Paris Convention) [271], concluded under the auspices of the Organisation for Economic Co-operation and Development (OECD). It is open to OECD Member States and to other States only if all Parties give their consent. The Paris Convention is supplemented by the 1963 Brussels Convention Supplementary to the Paris Convention (the Brussels Supplementary Convention). Both conventions were amended by protocols adopted in 1964 and 1982, and were further amended by protocols adopted on 12 February 2004, which, however, as of August 2012, are not yet in force.
The second regime is the so-called 'Vienna regime', which consists of the 1963 Vienna Convention on Civil Liability for Nuclear Damage (the 1963 Vienna Convention) [272] and the 1997 Protocol to Amend the Vienna Convention (the 1997 Vienna Convention), both concluded under the auspices of the IAEA and open to all Member States of the United Nations, its specialized agencies or the IAEA, or to all States, respectively. In order to create a treaty link between the different regimes, two instruments were adopted. The first one is the 1988 Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention (the Joint Protocol) [273], adopted under the auspices of the IAEA and the OECD. The second instrument is the 1997 Convention on Supplementary Compensation for Nuclear Damage (CSC) [274], concluded under the auspices of the IAEA.

[43] These are: the channelling of liability, absolute liability; minimum liability amount; liability limited in time; mandatory financial security; channelling of jurisdiction; and non-discrimination. These principles are summarized in the Overview of the Modernized IAEA Nuclear Liability Law, which effectively forms the introduction to the 'Explanatory Texts to the 1997 Vienna Convention on Civil Liability for Nuclear Damage and the 1997 Convention on Supplementary Compensation for Nuclear Damage', approved by the IAEA International Expert Group on Nuclear Liability (INLEX) and published in 2007 as IAEA International Law Series No. 3 [275].

clause related to a grave natural disaster, as specified in the Act on Compensation for Nuclear Damage, was inapplicable in this case.

With regard to the Fukushima Daiichi NPP, TEPCO is obliged to financially secure its liability up to Yen 120 billion. On the concept of nuclear damage, the Compensation Act does not list what is deemed to be nuclear damage, rather a so-called 'reasonable causation test' is applied in order to determine what damages are to be compensated. Potential victims may refer their claims directly to the operator concerned, to a local court or to the Dispute Reconciliation Committee for Nuclear Damage Compensation, which, in the case of the Fukushima Daiichi accident, was set up in April 2011.

According to Section 3 of the Compensation Act, the operator is exonerated from liability for damage caused by a "grave natural disaster of an exceptional character or by an insurrection" [276]. With regard to the Fukushima Daiichi accident, the Japanese Government and Diet acted on the assumption that the earthquake and tsunami on 11 March 2011 did not constitute a grave natural disaster within the meaning of Section 3 and as a result, TEPCO should not be exempted from liability for nuclear damage. Pursuant to the Compensation and Indemnity Acts, TEPCO signed an indemnity agreement with the Government of Japan by which the latter agrees to cover those risks that are not insurable in the private sector, such as earthquakes and tsunamis. Further, Section 16 of the Compensation Act provides for the possibility of government aid, where the cost of nuclear damage exceeds the amount of the operator's financial capacity, under certain conditions and subject to the decision by the National Diet.

The enactment on 5 August 2011 of the Act on Emergency Measures Related to Damage Caused by the 2011 Nuclear Accident (Act No. 91 of 2011) [278], inter alia, enabled the Government of Japan to start making provisional compensation payments in place of TEPCO as an emergency measure. The government also implemented other means to allow the operator to cope with its obligations towards the victims of the accident. In September 2011, the government pursuant to the Nuclear Damage Compensation Facilitation Corporation Act (Act No. 94, 10 August 2011) [279] set-up the Nuclear Damage Compensation Facilitation Corporation (currently the Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF)). The Act envisages a procedure whereby the liable operator may request financial support from NDF in cases where the actual amount of damage to be compensated is expected to exceed the financial security amount envisaged in the Compensation Act. Additionally, in July 2012, NDF paid Yen 1 trillion for preferred shares and became the controlling shareholder of TEPCO with a little over 50% voting rights [280].

To meet the damage suffered by Japanese citizens following the accident, a special committee, the Dispute Reconciliation Committee for Nuclear Damage Compensation, was set up to provide guidelines defining the scope and amount of compensation falling under the responsibility of the operator (TEPCO). The guidelines were based on the Act on Compensation for Nuclear Damage [276], and followed several steps that have evolved since 2011 according to the situation in Japan. The Japanese compensation policy reflects the socioeconomic aspects of the Fukushima Daiichi accident. Compensation is given not only to those ordered to evacuate, but also for impacts on livelihood and way of life, loss of profits due to restrictions and loss of consumer trust and, for those remaining, infrastructure changes. In addition, there are specific provisions for young families and pregnant women.

The Dispute Reconciliation Committee prepared and published its first Interim Guidelines on 5 August 2011 [281] as a response to the most urgent needs of the people affected. Numerous hearings have been conducted with public and private actors at national, regional and local levels in order to clarify the nature and extent of the damage. The Interim Guidelines provide a comprehensive picture of the scope of compensation. They indicate that any damage other than those categorized in the guidelines with a sufficient causal relationship to the accident should also be taken into account.

Annex III provides a comprehensive picture of the scope of the Interim Guidelines [281] related to compensation, and damage associated with: evacuation; the establishment of marine exclusion zones and no-fly zones; restrictions on shipping agricultural products; other government orders; 'rumour related' damage; radiation exposure, decontamination, and other indirect damage. The types of damage not covered by the Interim Guidelines are not automatically disqualified, and it is possible for other types of damage to be officially recognized if there is a sufficiently strong relationship between the damage and the Fukushima Daiichi accident.

It was recognized that consumers are particularly likely to reject agricultural, forestry and fisheries products, because it is relatively easy to replace food from the affected areas with food produced outside these areas. Tourism was also addressed by the Interim Guidelines.

TEPCO made provisional payments to residents and commercial operators beginning in April 2011, both in areas subject to the government instructions and also to commercial operators subject to shipping restrictions. These provisional payments were important since at that time the scope and extent of nuclear damage had not yet been categorized. Nevertheless, the conditions of payment were complex, since the affected people were required to provide supporting documents such as certificate of residence, receipts for expenses or documents attesting past income from commercial activities. This documentation was very difficult to produce, especially for those who had been evacuated. At the request of the Government, TEPCO then revised its procedure for compensation. From September 2011, TEPCO processed applications for compensation according to the Interim Guidelines.

On 6 December 2011, a supplement to the Interim Guidelines was published which broadened the scope of compensation to include damage associated with voluntary evacuation, beyond the perimeters set by the Japanese authorities [282]. The supplement recognized the absence of clear information about the risks to the local populations and acknowledged that voluntary evacuations, especially by pregnant women and children, should be taken into account in the compensation scheme.

Finally, to take into account the evolution of the areas affected by evacuation instructions, the Dispute Reconciliation Committee published the second supplement to the Interim Guidelines on 16 March 2012 related to the review of evacuation areas by the Government following stabilization of the damaged NPP reactors (announced on 16 December 2011) and the subsequent declaration that the perimeters of areas under evacuation could evolve (on 26 December 2011). The second supplement defined more precisely the amounts of compensation related to evacuation and relocation, and the resulting disruption in lifestyle, in all three areas: the primary evacuation area, the evacuation prepared areas, and the areas recommended for evacuation. At that time, the amount was about Yen 100 000 per person and per month under the following conditions of eligibility:

- In the evacuation areas, as defined on 1 April 2012, there was no predefined period of eligibility for compensation to be provided.
- In the evacuation prepared areas during the emergency phase, as designated until 30 September 2011, the period of eligibility was until August 2012, with compensation being provided even if people had returned home.
- For the evacuation recommendation regions, the period for eligibility was a three month period following the lifting of evacuation instructions, with compensation being provided even if people had returned home.

The loss or reduction of the value of property was defined, taking into account the possibility of residents returning or not returning:

- In areas where the return of populations was not considered possible, property loss was estimated at 100%.
- In the areas subject to living restrictions and in areas preparing for the lifting of evacuation instructions, the value of the property lost was estimated taking into account the duration of the evacuation, and also the evolution of market prices.

The guidelines also advised TEPCO that, regarding compensation, a rational and flexible approach was required such that any damage showing a clear connection with the accident should be compensated, even if the form of damage had not been identified in the guidelines.

For remediation, the Act on Special Measures Concerning the Handling of Radioactive Pollution specified that remediation costs must be supported by the operator, including damage to property or business that may occur during the remediation operations. This included expenses related to necessary testing prior to the implementation of remediation measures on a larger scale.

After the publication of the Interim Guidelines in August 2011, the areas and items subject to restriction of food marketing expanded, based on the new standards for food and provisional regulatory values for materials used in agriculture and forestry. This resulted in a situation where the general public declined to buy many items of food and agricultural produce. Therefore, the third supplement to the Interim Guidelines, published on 30 January 2013, broadened the scope of compensation to include "rumour related damage" [283].

On 26 December 2013, the fourth supplement to the Interim Guidelines was published to cover the damage associated with prolonging the evacuation orders [283]. This supplement covers the compensation for the mental suffering of people from Area 3 of the SDA, where it is expected that residents will face difficulties in returning for a long time, and compensation for new housing after returning home or acquiring housing at new locations. Under this supplement, people who had left an area where the evacuation order was lifted would continue to receive compensation for a period of one year (from the lifting of the evacuation order).

Further, to prepare for the return of people to evacuated areas, initially planned to occur from spring 2014, the Japanese Government announced that the compensation system would evolve under its Cabinet Decision for Accelerating the Reconstruction of Fukushima from the Nuclear Disaster on 20 December 2013 [284]. Based on the Cabinet Decision, TEPCO will provide additional compensation of about Yen 900 000 per person returning to live in the affected areas within a year after the lifting of the evacuation order [285]. This additional compensation covers the reduced availability of many services, such as public transport or shops, compared to the situation before the accident.

Further information on the framework on civil liability for nuclear damage is provided in Ref. [280].

5.5.4.5. Remediation operations and priorities

Outside the SDA and evacuation areas, people are generally continuing to live in the affected areas during the remediation work. In both the SDA and ICSA, the communities are consulted and involved in the planning, decision making and implementation of the remediation strategy. Accordingly, the degree to which this has been implemented and the methods used vary between the different municipalities by taking account of each situation [286]. There is an increasing consensus that recovery and revitalization cannot be achieved without the involvement of affected populations. There is also an increasing number of examples of the development of initiatives involving the local

population, across a range of remediation and recovery activities, and their effect on the acceptability, efficiency and success of recovery strategies. These are closely related to the issues of stakeholder engagement and communication.

5.5.5. Stakeholder engagement and communication

In addition to the general provisions in the Act on Special Measures Concerning the Handling of Radioactive Pollution [27] presented in Section 5.5.2, there are a number of initiatives to support stakeholder engagement in Japan in post-accidental remediation and recovery. These cover a wide range of stakeholders, including institutional and governmental bodies, as well as affected citizens, and a range of issues connected to the accident and its consequences. The issue of communication is closely related to stakeholder engagement, as is risk perception and the particular challenges related to communication about reference levels and the important question of 'what is safe?' The following subsection presents the legal and institutional frameworks related to stakeholders' engagement and their development after the Fukushima Daiichi accident, the responsibilities of different parties and initiatives that have been adopted and carried out in practice. Subsequent subsections present examples of national and international initiatives in stakeholder engagement, cases from self-help activities and stakeholder issues around site selection for waste facilities, community considerations of 'what is safe?' and general developments in dissemination and information channels.

5.5.5.1. Stakeholder engagement and communication in the Japanese institutional framework

According to the Act on Special Measures Concerning the Handling of Radioactive Pollution [27], the MOE was required to prepare Basic Principles [29] for the management of the environmental contamination caused by the accident. In accordance with the Act, before the final publication of the basic principles in November 2011, MOE published the draft and requested comments from the public. About 15 000 comments were provided and, as appropriate, were reflected in the revision to the draft [287]. This showed the considerable public interest in these principles and also the openness of government to improve them based on the public's comments. According to the Basic Principles, the national and local governments must request the support and participation of local residents in the remediation activities. Governments are obliged to promptly and accurately inform the public about remediation plans and activities, including information on related risks to the public. This can be done by dispatching experts to meetings held by local governments to provide adequate explanations to the local residents.

Furthermore, the Act on Special Measures Concerning the Handling of Radioactive Pollution requires the national Government — involving local governments — to establish a unified system for monitoring and measurements of doses, and to disseminate the results to the public.

To smoothly implement the remediation programme, the MOE designates specific areas for the collection, transfer, storage and disposal of waste generated during remediation activities (ICSA and SDA). Prior to the designation of the ICSA, the MOE is required to consult the heads of the relevant local governments. The MOE is also required to designate a proposed ICSA, if the relevant criteria are met. After such designations or changes, the MOE immediately makes a public announcement and notifies the heads of the relevant local governments. This is also the case for developments or modifications to waste treatment plans within these areas.

When the national Government develops a remediation plan in the SDA, the MOE is obliged to consult in advance with the relevant administrative bodies to obtain their views. After approval or modification, plans are made publicly available.

Before remediation in the ICSA, the prefectural governor may set up and consult a council composed of representatives of the national Government, prefectures, municipalities and the implementers. The MOE is also consulted. After approval or modification, plans are made publicly available.

Before starting remediation work in the SDA and ICSA, measurements of radiation levels of the lands and the buildings are required. Prior to undertaking the monitoring activities, landowners and other relevant stakeholders are informed about planned activities to give them an opportunity to comment. All monitoring results conducted within the SDA or ICSA are made publicly available. The landowners and other relevant stakeholders are expected to comply and to allow entry and measurement activities.

The flow chart of the implementation process for remediation and interactions with the stakeholders is given in Fig. 5.5–7. It can be seen that all steps in the development of plans and their implementation include stakeholder participation and consultation. For example, agreement is required from the landowners before starting any remediation activities. In cases where it is not possible to identify the landowner, the decontamination plans are published in the official gazette and a certain period of time is given for the recording of objections.

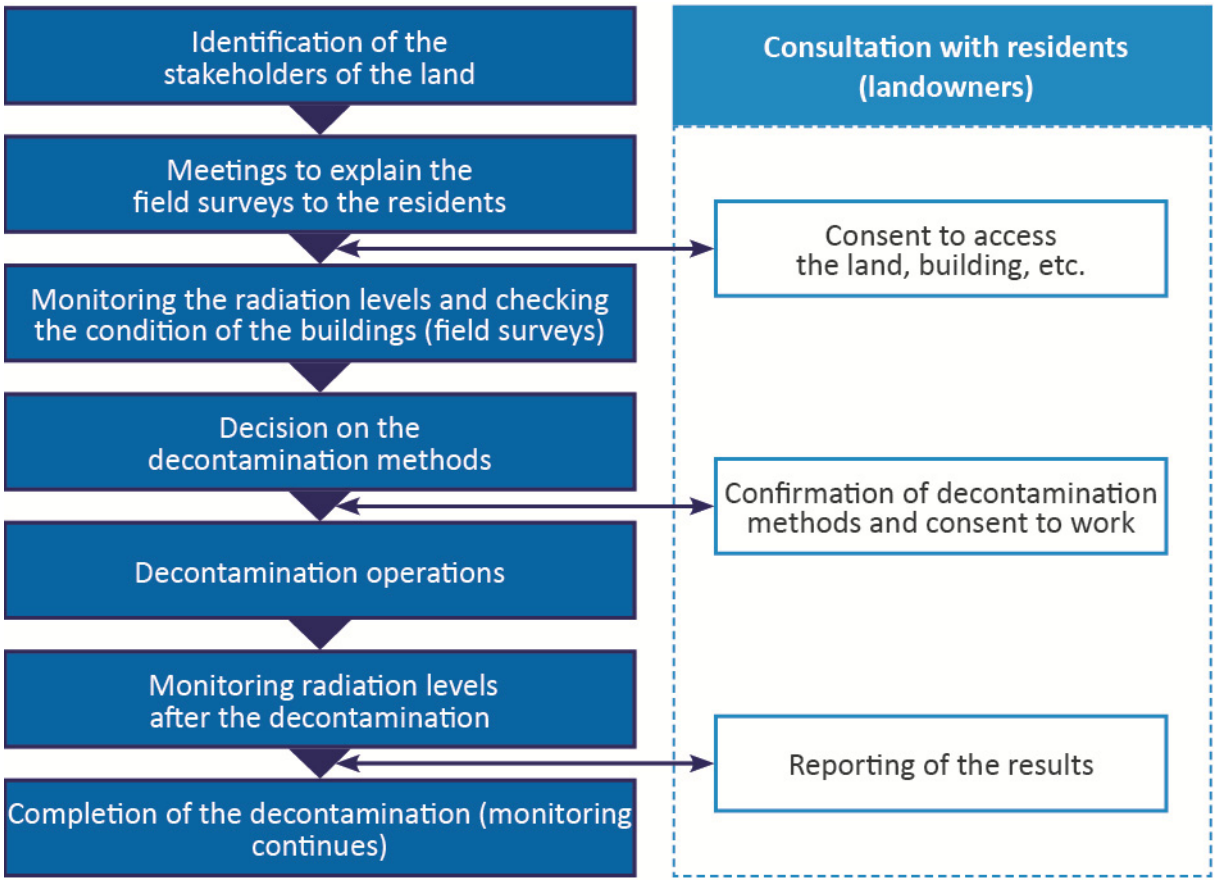


FIG. 5.5–7. Flow chart of the implementation process for remediation and consultations with residents [287].

After the adoption of the Act on Special Measures Concerning the Handling of Radioactive Pollution, time schedules for the implementation of recovery activities proceeded along two parallel pathways from 2011, both involving different stakeholders and communication activities:

(1) Extensive remediation activities were undertaken within the SDA and ICSA with the formulation of decontamination plans up until April 2012, and implementation of the plans by the government or by municipalities during 2012, 2013 and 2014. There are many examples of communication and public engagement, which are presented below.
(2) Activities for identifying and developing suitable sites for waste management have proceeded in parallel with remediation activities. The plans for treatment of all specified waste, removed soil and waste generated as a result of decontamination were prepared by January 2012, and those for temporary and landfill sites were intended to be in place by the end of 2013. However, the implementation activities, especially with the site selection for temporary storage sites and interim storage facilities have been delayed [288]. This is largely due to problems with public trust, especially with neighbouring populations, and the difficulties in providing relevant information to people [192]. The specific challenges regarding the siting of different waste management facilities are presented in Section 5.5.5.3.

The Act also foresees a broad exchange of information and communication with the public. Both national and local governments are responsible for disseminating knowledge and providing information about the impacts of radioactivity on human health and the living environment, and about the measures that can be taken to reduce such impacts.

These provisions for communication and stakeholder engagement, established in the legal framework following the Fukushima Daiichi accident, are in line with the International Basic Safety Standards [1] for an existing exposure situation. This requires that mechanisms for public information are in place and that interested parties affected by the existing exposure situation are involved in the planning, implementation and verification of the remedial actions, including any monitoring and surveillance following remediation. IAEA guidance on communication and stakeholder engagement exists for some other areas such as emergency preparedness, environmental remediation projects and site selection for different facilities; further consideration of communication and stakeholder engagement for the recovery phase after a nuclear accident would be useful.

5.5.5.2. Self-help recovery options and participation of the affected populations in remediation activities

The involvement of the affected communities in the recovery and remediation activities is a specific example of stakeholder engagement, and helps in addressing communication issues. Self-help actions that increase personal control over the radiological situation can make an important contribution to the success of remediation, as well as helping to restore the emotional well-being of the affected individuals. There are a number of approaches that can help promote this, including:

— Development of situation specific strategies for providing information on how people can control or reduce their own exposures;
— Providing access to personal dosimeters or monitoring equipment;
— Including the public in decision making and remediation actions.

The importance of such initiatives was widely recognized after the Chernobyl accident and other situations involving radioactive contamination [289–291], and there are a number of examples of such initiatives following the accident at the Fukushima Daiichi NPP, which are presented below.

Access to dosimeters and individual dose measurements

Increased personal control can be achieved through access to individual dose measurements:

— External exposures can be derived by carrying personal dosimeters;

— Internal exposures can be assessed via whole body monitoring, analysis of the components of the diet and food monitoring.

Both authorities and volunteers have set up a number of monitoring initiatives, ranging from the loan of dosimeters and monitoring equipment, school dinner and food basket measurements [292, 293], to the provision of personal dosimeters, some of which are linked to GPS positioning and data logging facilities that enable individuals to gain information on where, and when, their exposures are received [294, 295]. Such measurement and monitoring actions have the added benefits of providing individuals with personal information about their own situation — allowing them to make decisions about their behaviour that are based on personal rather than generic information (e.g. average doses based on measurements of environmental media such as soil, water and food).

The individual monitoring programme also provides an opportunity for those affected to communicate directly with professionals about the results, for example during whole body monitoring or measurements of collected foods. Technological developments have allowed for the production of relatively cheap personal dosimeters, and exchange of information on monitoring results within social media.

The SAFECAST initiative carried out in Minamisoma City, Tamura City, and Koriyama is an example of local and volunteer participation in radiation monitoring exercises [295]. This initiative is supported by a network of Japanese and international volunteers. Various portable devices for radiological measurement have been developed that can be coupled with GPS data, leading to a 'street by street' programme to meet the request of local stakeholders to have a precise radiological mapping of their cities. This, in turn, has fed into the development of appropriate decontamination plans. While the SAFECAST data are not subject to the same exacting technical and quality assurance programme of data collection by national regulatory bodies, such non-government bodies can disseminate the data with greater immediacy.

Participation in remediation activities

The participation of affected populations in remediation decision making and activities means that measures can be adapted to the local context and issues, and promotes dialogue with experts in radiation protection and other areas (e.g. food production or forestry). This, in turn, can enable the affected populations to apply both the tools and concepts of radiation protection in their everyday life, and select actions that are appropriate to their lifestyle.

Most of the examples of citizen participation in remediation following the Fukushima Daiichi accident have been outside the SDA, although there is an ongoing and increasing activity in areas where restrictions are about to be lifted (see Section 5.2). Initiatives include:

— In Fukushima City, citizens set the priorities and defined the communal spaces and facilities where the decontamination activities were to be implemented [296];
— Fukushima City also established the official structure within the prefecture for communication and training to support the decontamination work;
— Date City performed decontamination very early, in 2011 [297, 298], largely owing to a strong position of the municipality and the mayor. Initially, there was some distrust of the national Government and public administration within the community and strong opposition against the siting of temporary storage sites. After intensive communication with citizens (involving more than 100 briefings) on the approaches, on the decontamination techniques, on the risks and health effects, distribution of all relevant information, familiarization with the results of pilot decontamination experiments, and active participation of residents in the decontamination works, the attitude towards the plans changed.

By the end of 2011, when the decontamination guidelines were published by the MOE, 40 houses had already been decontaminated in Date, mainly by volunteers. Experiments were also conducted on peach orchards (e.g. removal of soils) and forests (e.g. removal of soils and collection of leaves).

Early involvement of citizens also aided in the selection of temporary storage sites. The first site was chosen in October 2011, which helped to accelerate the site selection process and decontamination. Promotion of public understanding of decontamination and the nature of radiation, through explanatory meetings, and the voluntary approach to propose candidate places for temporary storage sites has resulted in almost 100 such sites being identified for the area [297, 298].

Implications for communication and community support

The engagement of affected populations in remediation requires substantial levels of public information and consultation, as well as the support of radiation protection experts. The benefits of this approach are that it enables people to become better informed about decontamination and waste management and highlights important issues (e.g. protection of children's health, characteristic local agricultural production). It also helps to ensure that local constraints (land use, meteorology) can be taken into account in rehabilitation strategies. This type of interaction with stakeholders also indicates that communication channels in the recovery phase have evolved in Japan, and are much more than a simple presentation of facts and generic numbers. Practical information on what people can do to reduce their exposure can be conveyed, for example, through information centres such as the Decontamination Plaza at Fukushima City, web sites, and the telephone help and advice lines described above.

The self-help actions also need coordination, human resource support and the availability of experts to help people understand the measurements. It is also necessary to provide suitable training and information about protection to ensure that self-help activities do not unnecessarily increase individual doses to participants.

Of course, not all people wish to be involved in measurement and remediation activities. Many simply want to be informed and reassured that everything is under control. This highlights the need for multiple channels and levels of communication.

5.5.5.3. Siting of waste management facilities

In regions where decontamination is being implemented, large amounts of waste have been and continue to be produced. Therefore, one of the most significant challenges is securing temporary and other storage sites for contaminated soil and other material. There are some areas where temporary storage sites have been successfully established as a result of the close consultation between municipalities and residents. A large portion of the decontamination waste in Fukushima Prefecture is in temporary storage sites [70]. However, many municipalities are facing difficulties in gaining public acceptance for securing additional sites.

National and prefectural government experts have provided information on storage facility designs. However, residents are reluctant to accept storage sites in their neighbourhoods. There are concerns that TSSs could be needed for an extended period. The lack of operating TSSs means that the waste produced by community led decontamination work is simply stored at the sites where it is generated, including schools, private homes, parks and agricultural fields.

In addition, in Fukushima Prefecture, the national Government is in consultation with stakeholders to develop an ISF to store and manage safely a large amount of removed soil, pending final disposal.

There is an immediate need to develop more effective processes for public involvement in decisions on remediation systems (e.g. site selection for treatment and storage facilities, repopulation strategies for evacuated areas). Improvements in this area are necessary to support the very difficult challenges of restoring the evacuated areas. Public involvement practices and consensus building effectiveness, including the acceptance of TSSs, have varied significantly across the communities undergoing decontamination. It would be useful to review the variations in these practices and identify the factors that lead to success and that could be applied more broadly within the affected areas.

Relevant international activities

The Japanese Government and related Japanese institutions and municipalities established many international connections and collaborations in order to share the latest technology and information, and to utilize these for decontamination activities. Some of those collaborations also address stakeholder engagement and communication issues. Some examples of relevant activities are given here.

The IAEA has provided significant assistance to the Government of Japan to stabilize the situation, to provide the best available information on approaches to decommissioning, remediation and revitalization, and to ensure stakeholder involvement. It organized a number of International Experts Meetings as a direct result of the IAEA Action Plan on Nuclear Safety[44], the results of which are published elsewhere [299, 300].

Several expert missions to Fukushima Prefecture and to the Fukushima Daiichi NPP have taken place [41, 117, 301] which looked at stakeholder involvement and communication activities. These missions supported the ongoing activities of the central and local governments and provided practical advice, including the proposal to include more independent stakeholders (universities and/or academia) in the process of developing a stakeholder involvement strategy and implementation methods, based on stakeholder needs and domestic cultural settings. TEPCO and the Government of Japan were encouraged to collaborate to promote stakeholder involvement and communication in a more transparent and systematic manner.

The ICRP established a dialogue [244] in autumn 2011 with Fukushima Prefecture, several cities and villages in Japan, civil society organizations, universities in Japan, and other international (in Belarus, France and Norway) and national institutions related to radiation protection. The aim was to organize a forum to stimulate a dialogue with all concerned parties in the Fukushima Prefecture, and to identify the problems and the challenges of the rehabilitation of living conditions in the long term contaminated territories.

By the end of 2013, seven dialogue meetings had taken place in Japan involving the affected population and local professionals in the management of the situation. The topics discussed at the meetings included:

- The situation in the affected areas and stakeholder concerns;
- The problems perceived by the local citizens;
- The progress made in understanding the situation, together with the value in sharing experience on the rehabilitation of living conditions in the affected areas;

[44] The Action Plan, unanimously endorsed by the 55th IAEA General Conference in 2011, defined a programme of work to strengthen the global nuclear safety framework. It consists of 12 main actions related to: safety assessments; IAEA peer reviews; emergency preparedness and response; national regulatory bodies; operating organizations; IAEA safety standards; the international legal framework; Member States planning to embark on a nuclear power programme; capacity building; protection of people and the environment from ionizing radiation; communication and information dissemination; and research and development. For a detailed information about the Action Plan, see Technical Volume 1, Section 1.6.

— Sharing experience related to the complex problem of contaminated foods;
— Questions related to the education of children;
— Discussions on the delicate issue of returning or staying in the affected areas;
— The challenges being faced by the citizens of Iitate Village, who have been evacuated and are living in exile for more than two years;
— Rehabilitation of living conditions after the Fukushima Daiichi accident: self-help actions in Iwaki and Hamadori; working together in the affected areas in Minamisoma City.

Common issues raised at many meetings focused on the impacts of the accident on community, the situation for children, concerns over discrimination and the importance of actions that increase understanding and personal control over the situation. The ICRP's Seventh Dialogue [302] was devoted to testimonies about how people and communities had mobilized themselves with the support of experts (self-help actions) to understand the situation in their immediate environment and to implement actions to mitigate or master this situation. It is planned that the dialogues will continue and improve public understanding on radioactive waste management and remediation activities, and ensure the active engagement of stakeholders.

Based on collaboration between the USA and Japan, US Embassy Science Fellows [303] reported their observations and recommendations regarding radiation protection, decontamination, waste management, environmental monitoring, and also stakeholder engagement. According to this report, there are several aspects of the Fukushima remediation efforts that still require effective stakeholder involvement and engagement. These topics are presented in Table 5.5–4 and vary, from the provision of information on the strategies, plans, priorities, technical issues and their characteristics, to communication activities where the exchange of data and information take place.

TABLE 5.5–4. ASPECTS OF FUKUSHIMA REMEDIATION EFFORTS REQUIRING EFFECTIVE STAKEHOLDER INVOLVEMENT [303]

Remediation system element	Stakeholder involvement issues
Radiation protection	Development of radiation protection strategies for populated areas Development of repopulation guidelines for currently evacuated areas Development of radiation protection strategies for areas to be repopulated
Waste management	Selection of sites for temporary storage facilities in ICSA Selection of sites for temporary storage facilities in SDA Selection of sites for interim storage facilities Incineration for treatment of radioactive waste Reuse or recycle of decontaminated materials
Remediation strategy	Development of priorities for remediation of evacuation areas, including high dose areas. Definition of remediation and reconstruction efforts for evacuated areas.
Environmental monitoring	Understanding variations in dose rates and approaches for managing radiation exposure.

5.5.5.4. Dissemination and communication channels

The Fukushima Daiichi accident was characterized by multiple issues; the tsunami and earthquake destroyed much of the existing infrastructure, and the nuclear accident contaminated large areas. As discussed in Section 3.3., the information provided to the public and local people during the emergency situation was delayed, inconsistent, unclear and conflicting. Some of the information was disseminated through several different official sources in an uncoordinated manner or not communicated. This immediately raised a number of safety concerns, and contributed to a loss of public confidence in governmental institutions and authorities [236].

Much more attention was given to communication once the situation had been stabilized. One month after the accident, the Cabinet Office's Japan Support Team for Residents Affected by Nuclear Incidents provided information to the affected people on: the status of environmental remediation; decisions on lifting the evacuation orders; radiation monitoring of people, food and the surrounding environment; progress on compensation for nuclear accident related damages; and measures being taken for supporting affected people, events and activities [304]. In particular, the Government of Japan published newsletters starting in September 2011. Also, immediately following the accident, the government created a radio programme to respond to questions from affected people. This programme started in April 2011 and ended in March 2012.

Municipalities are also making use of a number of information channels. In order to provide information to affected people, the Fukushima Prefecture government has made use of local newspapers, radio stations and TV programmes. The officials and experts dispatched by the prefecture government organize explanatory and consultation meetings for the people who were evacuated from the prefecture. Through its own web site, the Fukushima Prefecture government also periodically publishes leaflets loosely translated as 'Newspaper on Current Events in Fukushima' [305] to share information on the status of remediation, reconstruction and rehabilitation in Fukushima, new standards to be applied for compensation, supporting measures for a safe and healthy life (temporary housing, child raising, radiation monitoring, health management, etc.). The prefecture also established a blog to support the affected people[45] and created a web portal[46] to provide information on consultation, information exchange and other meetings. Similar activities are conducted by the municipal governments as well, for example, the web site of Iitate Village[47].

Activities of the MOE

For the implementation of remediation activities and development of different storage sites, the MOE and municipalities established several different channels of communications with the local public in the area. The following activities have been developed and implemented with the aim of improving understanding and cooperation on remediation measures:

- The Decontamination Information Plaza [306] was established in Fukushima City. This hosts a variety of exhibitions containing information and documents, such as models of decontamination operations and a storage site, as well as a community consulting corner where workshops, meetings, and consultation with stakeholders take place. Experts are dispatched to local communities to hold seminars and lectures to raise awareness of radiation risks and remediation activities, including the explanation of concepts for temporary storage.
- The MOE [287] has developed a web site to provide information regarding remediation, such as decontamination plans, guidelines, current status and the effects and risks of radiation, in a comprehensive and timely manner. This provides information for other stakeholders, such as the media, general public, interested associations and organizations, and the international community.
- The MOE has distributed pamphlets and booklets to explain to the public the basic concepts and relevant knowledge and information on decontamination and radiation exposure and supports local municipalities when they hold explanatory meetings for landowners by the provision of experts.
- The MOE broadcasts programmes to enhance knowledge and understanding of remediation and related issues through the mass media such as TV and radio, and local newspapers. These include articles in periodicals and videos of the general public to report the status of decontamination activities and plans towards restoration in various areas of Fukushima Prefecture.

[45] http://plaza.rakuten.co.jp/fukushimahinan

[46] http://fukushima.jpn-civil.net/

[47] http://www.vill.iitate.fukushima.jp/saigai/

- A special video, entitled Living in Fukushima: Stories of Decontamination and Reconstruction [307], has been produced that, in addition to providing technical information about decontamination activities, offers views on how different groups of the population have been organized to improve the daily life of children and people in the area. Examples are the initiatives of parents groups at schools, community members, and farmers.
- The MOE also conducts Fukushima Restoration Supporter Activities to support the efforts and activities of local communities, including such initiatives as the Minister of the Environment visiting and working in Fukushima.

Activities of TEPCO

Although there is no legal requirement for the involvement of stakeholders in decommissioning and radioactive waste management activities at the Fukushima Daiichi NPP, TEPCO and the Government of Japan have established approaches and practices for communication and the involvement of stakeholders. Basic principles for stakeholder communications include providing prompt, open, and comprehensive information, development of a strategic and proactive approach to communications and to establish channels for dialogue with stakeholders [308].

TEPCO has developed many communication activities to provide information on ongoing activities at the Fukushima Daiichi NPP. Since 2013, these communication activities have established channels for discussions with interested stakeholders and provided information on decommissioning activities, on-site incidents, potential risks and possible countermeasures to mitigate the risks [308]. The revised Roadmap (see also Section 5.3.3) for the Decommissioning of the Fukushima Daiichi NPP [128] emphasized the importance of developing and maintaining transparent communication with local and national citizens to gain their understanding and respect.[48] This is one of the basic principles underlying the implementation of the Roadmap.

The Government of Japan has set up the Fukushima Advisory Board on Decommissioning and Contaminated Water Management. The Board involves the Fukushima Prefecture government, municipalities, and relevant local organizations such as the associations of commerce and industry, fishermen's associations, local media, universities, non-profit organizations and experts [309]. The discussions of the Board are intended to strengthen public relations and to stimulate public communication.

TEPCO recognized that there was a gap between the information provided and the public's perception of developments at the Fukushima Daiichi site. Therefore, TEPCO created a new position of Risk Communicator and established the Social Communication Office with the objective of promoting public relations and risk communication. The TEPCO web pages provide regularly updated news on the development of decontamination and restoration on-site, as well as other related information for a variety of stakeholders in a transparent and comprehensive manner [310].

In August 2013, the flow of radioactively contaminated water into the Pacific Ocean attracted much attention. There was a delay in providing information on this event. As a consequence, TEPCO placed a priority on issuing "rapid and honest announcements concerning the risks and negative situations, without fear of repercussions, even when the results of evaluation do not adequately establish clear grounds" [308]. However, the abrupt announcement without proper explanation and reference created a serious misunderstanding of the events and raised unnecessary concerns among the stakeholders

[48] It is anticipated that there will be further revisions to the Roadmap as plans are adapted in response to changing conditions and new information. The third revision of the Roadmap was issued during the final preparation of this Technical Volume (June 2015). This modified the schedule and the approach for fuel and debris removal and refined approaches for risk reduction, communication with local stakeholders, reduction in workers' exposures, and management of research and development [121].

about the credibility of the information. TEPCO has recognized the importance of developing a more appropriate form of risk communication through a more strategic and proactive approach and providing sufficient opportunities for two-way communication.

5.5.6. Media reporting and consequences

In a nuclear accident situation, the media, both traditional and new forms, play an extremely important role in communicating with the public (see also Section 3.3). The Fukushima Daiichi accident was characterized by a high level of media coverage, through the internet, social media and, during the initial phase, continuous broadcasting on news channels. The coverage of the accident lasted for several months, focusing on mainly the problems linked to the safety of the accident site, but also on the protective actions applied by Japanese authorities. The growth of social media facilitated reporting on the event, as well as the consequences, by individuals and non-governmental organizations with a range of perspectives.

A critical review of the way information about the Fukushima Daiichi accident was transmitted in the mass media [311] identified some basic characteristics and some lessons. New media effectively accelerated, decentralized and diversified the provision of information while offering platforms for direct citizen participation, expression and feedback. The growing presence of the new media and their interaction with the traditional media result in potentially greater challenges for institutions, which need to communicate with the public about risks. The review indicated that this dynamic situation also offers opportunities for moving closer to a citizen centred approach to risk communication using a variety of types and channels for dissemination [311].

As described above, the Government of Japan has established mechanisms to respond to media reporting with the aim of ensuring objectivity and improving trust in institutions. One example was the establishment of the Taskforce for Securing Appropriate Decontamination Works by the MOE, following media reports alleging inappropriate decontamination works in the beginning of 2013. The Taskforce carried out an investigation, and published its findings at the end of January 2013 [312].

The reporting of the Fukushima Daiichi accident was an example of a phenomenon known as social amplification of risk (SAR) [313]. In such circumstances, information processes, institutional structures, social group behaviour and individual responses shape the social experience of risk associated with the accident, and thereby contribute to the consequences for society. A simplified representation of SAR is given in Fig. 5.5–8. It demonstrates the connections between the event (in this case the Fukushima Daiichi accident), its characteristics (e.g. potential health consequences and future risks, relocation of population contamination of environment) and its interpretation (intensive coverage by all forms of media with prevailing negative reporting). This process may give rise to multiple indirect effects of the accident on society, with a ripple effect, leading to impacts on the economy, production and tourism, and also leading to a reassessment of communication of nuclear issues within the companies involved and, eventually, the nuclear industry worldwide.

5.5.7. Addressing the question of what is safe

A major goal of the post-accident recovery programme in the Fukushima region is that people will again feel safe living there. It is therefore important to find a way to answer the question that the community invariably asks, ‘what is safe?’.

The difficulty in all objective definitions of what is safe is that they fail to acknowledge and address the additional subjective element that feeds public anxiety, especially in an accident situation involving radiation exposure, which is little understood, unseen and hence feared.

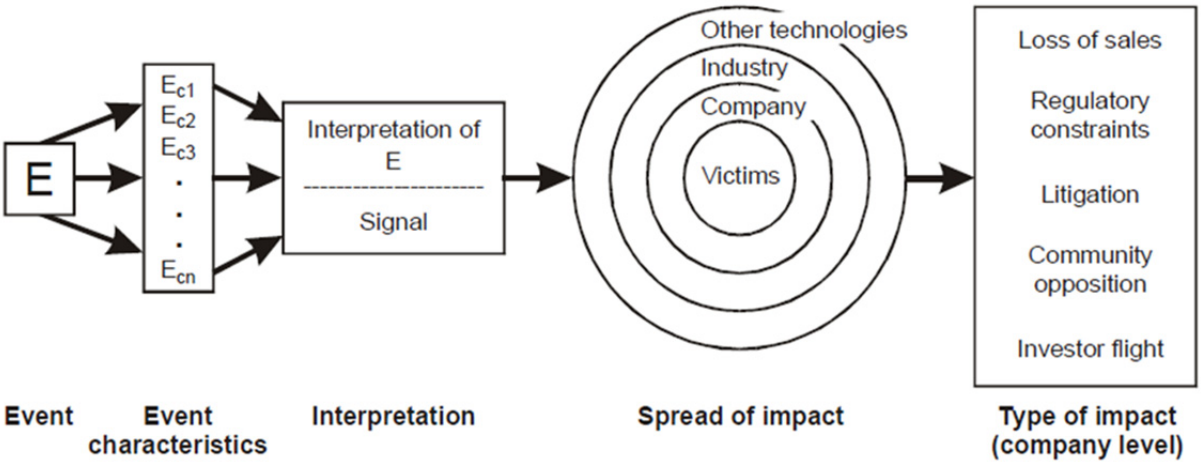


FIG. 5.5–8. Simplified representation of social amplification of risk and its potential impact on society [313].

For present purposes in a post-accident situation, a definition of safe for an informed community may include 'no sense of hazard'.

The accident at the Fukushima Daiichi NPP has highlighted the concern of people to be reassured of their safety. In view of this, it is important to develop a practical definition of safe to assist in communicating with stakeholders [299]. Within the context of post-accident recovery, the questions confronting the community are:

— What is the appropriate reference level for off-site remediation?
— What are the appropriate action levels for food?
— What actions should be undertaken at the site of the damaged NPPs to render them safe?
— What are the most appropriate options for safe storage and disposal of the contaminated accident waste?

However, the perception of risks and potential hazards depends on a number of dimensions that go beyond the probability of harm, including a sense of personal benefit, consent and control. Perceived risk is often very different from objective assessments. A good example is air travel, where there can be a discrepancy between subjective individual anxieties about flying, and the objectively very low levels of risk when compared with most other modes of transport.

In addressing the concerns of the affected community, it is acknowledged that it is not sufficient to rely solely on measurements or compliance with particular standards. More than that, especially with today's prevalence of social media, the public must be able to form their own understanding and to exercise choice in what they believe, and who and what they place their trust in, in forming those beliefs. Informed understanding and beliefs are the goal. And in a climate of factual information and open canvassing of all issues, it is not unreasonable for a community, given the time and opportunity, to reach its own understanding and beliefs, to embrace solutions that properly fall between the equally unhelpful extremes of too little and too much protection.

It is necessary to consider the needs of the communities affected by the Fukushima Daiichi accident and the problems they face. The challenge is not just about trust and acceptance of particular strongly asserted numbers and standards, but about interacting with a community that is disposed to be questioning, critical and sceptical. The objective for the Fukushima community is to not be unduly anxious about minor radiation risks that are understood by an informed and challenging community to be at the very low end of the risk scale. The goal is that after such a careful assessment of all the objective and subjective drivers of community anxiety, the stakeholders themselves form an

understanding of those issues that are most critical to community health and well-being, and those that are simply insignificant.

In this respect, practices that can increase the feeling of personal control and understanding over the situation can often go far in reducing anxiety, at least in parts of the community. Examples are requests for personal dosimeters and access to monitoring, and the participation of affected populations in decision making and implementation of remediation.

Reacting to a sense of public anxiety by setting unduly conservative standards is a short term solution that may, in the long term, enhance the unnecessary fear of low doses of radiation. Methods that promote a common understanding and a sense of personal control, through participation and dialogue with affected communities, can be a better long term investment.

5.5.8 Summary

The nuclear accident and radiation protection measures introduced in both the emergency and post-accident recovery phases have far-reaching consequences on the way of life for affected populations. Recognition that the nuclear accident has had socioeconomic consequences that go beyond direct radiological issues is a central feature of the revitalization and reconstruction projects introduced in Fukushima Prefecture, which address a number of issues such as infrastructure reconstruction, community support and compensation. Communication with the public remains a challenge but is paramount to rebuilding trust. The involvement of the affected populations in decision making and recovery has been given more focus, and there is an increased awareness of the importance of stakeholder involvement.

Community and infrastructure revitalization

The earthquake, tsunami and the accident at the Fukushima Daiichi NPP resulted in loss of infrastructure (schools, hospitals and commercial enterprises), impacts on trade and the economy, and demographic changes brought about by the movement of the population. Families were separated by one parent leaving the area with their children while the other parent stayed in evacuated areas for work. Moreover, young families were reluctant to return compared with the elderly generation. Other major challenges include the lifestyle circumstances for long term evacuees, especially those remaining in temporary housing, the combined damaging effects of the tsunami and earthquake, challenges from a lack of trust in consumer products and radiological reference levels, and concerns about stigmatization and discrimination.

Local economic development is closely linked with consumer trust. Important economic activities in Fukushima Prefecture, such as agriculture and tourism, are vulnerable to changes in public confidence because consumers can easily choose alternative products or activities. Efforts have been made to promote the economy of Fukushima Prefecture, with early success.

The framework for compensation established in Japan, implemented gradually and taking into account the expectations of the affected population, has certainly helped to improve the daily life of these people. However, partly because of the complexity of the assessment of damages, the implementation of the framework carries the risk of generating a feeling of inequality between different groups of affected people.

The nuclear accident has demonstrated that residents' decisions to return go beyond radiological issues, including the situation resulting from the remediation programme. Recovery does not mean a return to the previous state, but rather a new normality. Indicators of a revitalized infrastructure and community include: a place to call home; a sense of safety; community structures and jobs; provision

of health care and aged care facilities; educational and leisure facilities; economic well-being; opportunities for farming and local food production; and participation in decision making.

Stakeholder engagement and communication

The accident highlighted the diversity of stakeholders and challenges connected to their respective roles and responsibilities. These diverse stakeholders have different information needs, and the communication approach taken needs to be adapted accordingly. The Fukushima Daiichi accident has provided a number of examples showing the benefits of involving affected populations in recovery, from consultation and dialogue to actual implementation of remediation actions. Access to personal dosimeters and monitoring has been an effective strategy. This has the advantage of providing individuals with the means to understand their specific situation and allows them to take a degree of control of the situation. It also provides an opportunity for dialogue with experts, thus facilitating recovery. However, this needs to be supported with human resources.

The initial response to the accident was hampered by the lack of a clear strategy for the engagement of stakeholders and communication, and particularly related to poor preparedness for accident recovery. There has been an increased engagement of stakeholders at various stages of remediation and recovery, but the strategy for stakeholder involvement and implementation methods needs further development.

Dissemination and information channels

The type of information provided to the public by the Government of Japan, by TEPCO and by local authorities has evolved during the post-accident period. There is a greater degree of coordination and responsible bodies have developed routines and a variety of dissemination routes and materials, including the use of social media. The strategy has also extended from simple provision of information to procedures that include mechanisms for community feedback and dialogue. This has been particularly important for the return of residents to evacuated areas and the selection of sites for waste management facilities.

Stakeholders require information on the question of what is safe, in order to allow critical evaluation by the community of the recovery efforts. This has been a continuing challenge after the Fukushima Daiichi accident, and especially in relation to reference levels for remediation. The accident illustrated the multiple dimensions to this question, and that it is not only a scientific issue. Multiple sources of information exist and are available; the challenge is how to help people understand the different points of view, and also for experts to understand what kind of information the public is requesting. Reliable information must be made available rapidly as the need arises, or the information vacuum will be quickly filled with potentially less reliable information.

The involvement of the affected communities in acquiring the needed information is a specific example of stakeholder engagement. Self-help actions that increase personal control over the radiological situation can make an important contribution to the success of remediation. However, appropriate guidance is needed to ensure that self-help activities do not unnecessarily increase individual doses of participants.

5.5.9 Observations and lessons

— **It is necessary to recognize the socioeconomic consequences of any nuclear accident and of the subsequent protective actions, and to develop revitalization and reconstruction projects that address issues such as reconstruction of infrastructure, community revitalization and compensation.**

Nuclear accidents and the protective and remedial actions introduced in both the emergency phase and the post-accident recovery phase, with the objective of reducing doses, have far reaching consequences on the way of life of the affected population. Engagement of stakeholders at various stages of remediation and recovery is essential.

— **The payment of compensation to individuals for losses, injuries and harm is an important tool for recovery but is challenging to implement.**
The compensation framework needs to be transparent and include mechanisms that stimulate the return of residents to their homes or enable them to establish a new life elsewhere. This needs to be implemented, as much as possible, in an equitable way that does not lead to divisions within or between communities. The continued exploration of different compensation models and their impacts on remediation decision making could contribute to the development of international guidance on recovery mechanisms.

— **Involvement of the affected populations in decision making and implementation of remediation is essential for the success, acceptability and efficiency of recovery.**
There is a need for international guidance on communication and stakeholder engagement during accident recovery and remediation.

— **A generic national framework for public communication and stakeholder involvement related to accident recovery and remediation is needed to establish effective mechanisms for dialogue with a clear allocation of roles and responsibilities.**
Engaging with stakeholders is a long term process, requiring the use of appropriate procedures for all aspects and participants. Engagement can take place at different levels and may include representatives from all parts of society. Regular engagement in advance of any accident can help to build trust and a common understanding. It is important that recovery strategies and activities such as site selection for waste management facilities and remedial actions are included in this dialogue.

— **Self-help activities by local residents, such as monitoring and participation in remediation actions, are important mechanisms for fostering an understanding of remedial measures and providing the public with a degree of control over their situation.**
The provision of monitoring stations for the public at local centres and the dissemination of monitoring data help to provide reassurance and promote confidence in the food production system, in particular, and in the success of the remediation actions, in general. However, sufficient resources need to be allocated to support and coordinate the self-help activities and to promote dialogue with experts.

— **Support by stakeholders is essential for all aspects of post-accident recovery. In particular, engagement of the affected population in the decision making processes is necessary for the success, acceptability and effectiveness of the recovery and for the revitalization of communities. An effective recovery programme requires the trust and the involvement of the affected population. Confidence in the implementation of recovery measures has to be built through processes of dialogue, the provision of consistent, clear and timely information, and support to the affected population.**
Governments need to provide a realistic description of a recovery programme to the public that is consistent, clear and timely. A variety of information channels, including social media, need to be used to reach all interested groups.
Perceptions of radiation risks and answers to questions about ‘safe’ radiation levels have many dimensions, including scientific, societal and ethical. These answers need to be clearly communicated to relevant communities through educational programmes — ideally before an accident has occurred.
It is important that the affected population receives support for local recovery efforts. Support for self-help actions related to remediation and for rebuilding businesses can increase involvement in the recovery programme, and build the trust of the affected population.

APPENDIX I
PILOT DEMONSTRATION PROJECTS FOR REMEDIATION IN JAPAN

In this appendix, the testing of remediation measures carried out for residential areas, agricultural land, aquatic ecosystems and forests is described. The pilot demonstration projects were experimental or field based projects carried out (in 2011) to identify the remediation measures that are most effective and suitable for implementation in Japanese conditions. A variety of factors led to the decision to test the measures in Japan, including: (1) the need to access the effectiveness and applicability of remediation solutions to the site specific conditions prevailing in Japan; (2) the lack of experience in Japan in dealing with the remediation of large areas affected by the accident, including inhabited areas; (3) the need to collect information on site specific data on effectiveness in dose rate reduction associated with individual remediation measures; and (4) the need to test and train the work force on the use of different equipment to be used in remedial work, with a focus on ensuring worker safety.

The Japanese authorities were also aware, and made a critical assessment of, the wide range of remedial measures that have been developed, tested and implemented in the remediation of legacy sites and areas contaminated by nuclear and radiological accidents, notably the accidents in Kyshtym, Chernobyl and Goiânia [42–45]. Aspects related to the effectiveness of remediation measures in terms of dose reduction, technical feasibility, cost, public acceptance, worker safety, operational safety and long term environmental protection were particularly scrutinized.

The results from the pilot projects were assessed in relation to the information collected from the above mentioned previous experience, and they were then used to help in the selection of the remedial measures that would be used in the large scale remediation of the contaminated areas. The pilot projects also provided a set of recommendations on how to ensure decontamination efficiency and worker safety while reducing time, cost and environmental impacts and optimizing the management of the generated waste [314].

Several suitable decontamination target areas were selected in which to apply the pilot demonstration projects. These areas were chosen based on the type of land use (e.g. cities and villages and their surrounding roads, farmlands, and forests) and topography.

I.1. DEMONSTRATION PROJECTS IN RESIDENTIAL AREAS

The Japan Atomic Energy Agency (JAEA) was requested by the Japanese Cabinet Office to examine the applicability of decontamination technologies within the evacuated area[1] and to implement pilot decontamination measures in late 2011 in areas with an estimated additional annual effective dose exceeding 20 mSv, mostly before the enactment of the Act on Special Measures Concerning the Handling of Radioactive Pollution. The aim was to identify effective decontamination technologies that could then be implemented to reduce external dose rates to allow evacuees to return to re-establish their normal lifestyles as quickly as possible, while simultaneously maintaining worker safety [16, 17].

The strategy pursued with JAEA projects involved three steps, as described below:

— Step 1. Initial testing that involved the preliminary evaluation of decontamination technologies at a limited number of test sites outside the evacuated zones. The choice to start the tests in these

[1] With the exception of one site south of the evacuation zone.

areas was due to the lower dose rates present and the available logistics. Date City and Minamisoma City hosted the initial testing activities.

— Step 2. Larger scale decontamination projects, involving potentially feasible decontamination technologies, were implemented for large scale application in areas with dose rates that were higher than those prevailing during the initial testing. These activities were developed within the evacuated zones and were performed by contractors.
— Step 3. Decontamination model evaluation projects, based on the results of the larger scale decontamination projects and decontamination model projects, were implemented in the areas termed as 'difficult to return' zones, where dose rates were higher.

Based on the experience gained in steps 1 and 2, plans for regional decontamination were developed and are now being implemented. The objective of the overall strategy was to conduct the first two steps as rapidly as possible so that remediation work could commence in 2012.

There are other decontamination projects, such as the Decontamination Model Evaluation Projects for the highly contaminated Namie Town and Futaba Town, both carried out by the Ministry of the Environment (MOE).

Table I.1 summarizes the effectiveness of decontamination for different types of technologies that were applied for several kinds of decontamination targets in residential areas [17, 315].

The effectiveness of decontamination was quantified by means of the decontamination factor (DF)[2]. [2] Two measurements that allow the determination of the effectiveness of surface decontamination were taken in two different ways, before and after decontamination. The first approach involves the measurement of the counts per minute (counts/min), or dose rate (μSv/h) at the surface of the object being decontaminated. These measurements are taken 1 cm above the given surface. The results of this approach are referred to as DF_s in this volume. The second approach involves similar measurements, but taken at a selected point within the decontaminated area at 1 m above the ground[3] to give the DF_a in this text. The DF_a depends on site specific factors, such as the size and topography of the decontaminated area, and the location of structures. The DF_a may give a better guide to the dose rate reduction for people than the DF_s.

To achieve a DF_a of 5, thorough decontamination of a soil circle with a radius of about 10 m is typically required [316]. However, high levels of background gamma radiation from unremediated areas close to the test site can lead to an underestimation of the effectiveness of a given procedure. To minimize the influence of background radiation, data from sites with surface decontamination densities of less than 2000 counts/min were excluded from Table I.1.

Taking all the decontamination methods into consideration, it is evident that the most effective measures (with the highest DF_s values) are topsoil stripping and removal of the surface level through deep cutting. The median DF_s values achieved in school athletic grounds (unpaved soil and asphalt paved surfaces) were, respectively, 8.3 and 20. The other methods (or combinations of methods) produced similar DF_s values that varied in a relatively narrow range of 1.4–4.0 for all the surfaces being decontaminated.

Following the initial testing, JAEA decontamination pilot projects (step 2) were carried out within a short period of time in late 2011. Sixteen sites in 11 municipalities, including low and highly contaminated locations within the evacuated zone, hosted these projects. Areas where the pilot

[2] The IAEA Safety Glossary defines the decontamination factor (DF) as "the ratio of the activity per unit area (or per unit mass or volume) before a particular decontamination technique is applied to the activity per unit area (or per unit mass or volume) after application of the technique" [2].

[3] This measurement is referred to as the 'ambient dose rate'

projects were implemented were located in what was later defined as the SDA. Their sizes were, on average, 0.20 km^2 per municipality, totalling 2.12 km^2.

TABLE I.1. DECONTAMINATION EFFECTIVENESS (AS REPRESENTED BY THE SURFACE DECONTAMINATION FACTOR, DF_S) IN RESIDENTIAL AREAS FOR DIFFERENT REMEDIATION MEASURES APPLIED TO VARIOUS SURFACES[a] (DATA MOSTLY FROM 2011) [315][4]

Decontamination target(s)	Decontamination technology	No. of measurements	Decontamination factor (DF_s) (dimensionless, median and range)[b]
Eaves, roof, gutters	Wiping off after removal of deposits that have accumulated in the rainwater troughs; high pressure washing after removal of deposits	343	3.5 (2–5)
Storm water catch basins	High pressure washing after removal of deposits	85	3.8 (2.5–10)
Street gutters	Removal of deposits; high pressure washing after removal of deposits	132	4.0 (2.5–10)
Roofs	Wiping off; washing with brushes; high pressure washing, often with brushing or wiping off	464	2.0 (1.3–10)
Outer walls	Wiping off; washing with brushes; high pressure washing, often with brushing or wiping off	64	2.4 (1.1–10)
Gardens and other ground	Mowing; topsoil stripping (3–5 cm or more); soil replacement; lawn stripping; replacement with quarried stone following removal	446	2.4 (1–>10)
Parking lots and other paved surfaces around buildings and structures	Washing, sometimes with sweeping; high pressure washing, often with brushing; grinding (shot blasting, vacuum blasting, dust collection sanders and grinders)	601	2.4 (1.4–10)
School athletic grounds, etc. (unpaved soil)	Topsoil stripping	271	8.3 (5–10)
Roads (asphalt paved surfaces)	Washing, with some sweeping; high pressure washing, with removal of sand and soil or brushing; grinding (shot blasting)	506	1.4 (1–3)

[a] For data of 2000 counts/min or higher surface decontamination density before decontamination.
[b] The decontamination factor (DF) was calculated using the per cent reduction rate in counts/min from the IAEA 2013 Mission Report [41] (also called the decontamination effectiveness, DE). The DF was calculated based on the definition provided in the IAEA Safety Glossary [2], where: $DF = 100/(100 - DE)$. The median DF_s 50% histogram frequency for the per cent reduction rate, for a given type of decontamination target.

The JAEA decontamination pilot projects were performed on farmland, forest, fruit trees, residential areas, schools, offices and an industrial area. These sites were located in various types of terrain (e.g. mountainous, hilly and level ground). Projects were implemented following a common protocol, where possible, and the results represent a coherent data set to compare the relative decontamination effectiveness of different measures. A wide range of decontamination measures and volume reduction measures for the contaminated material generated were examined and their advantages and disadvantages reported in a standardized manner [16, 17, 317]. An important criterion in the selection

[4] DF_s values have been calculated from the median and range per cent reduction rate of counts/min data provided in Ref [315].

of a target area for the implementation of the decontamination tests was the existence of adequate space nearby to temporarily store the waste generated. In some areas, it took time to agree on these sites with the local land owners.

JAEA provided a detailed report of the Decontamination Pilot Project [16, 17]. It identified a number of challenges associated with these pilot projects, including the need to ensure that potential errors and uncertainties were associated with the measurements and the DF_s. The challenges arose due to the need to carry out the early studies under great time pressure and on an unprecedentedly large scale, in a situation where the required number of technical personnel and the appropriate equipment were not available.

As explained above, measurement of the effectiveness of decontamination included the measurement of the ambient dose rate at a defined point before and after the decontamination work. The dose rate values at each site were measured at intervals after the decontamination had taken place. The analysis of these results made it possible to quantify the variations of ambient dose rates with time in 14 test sites; the results obtained are shown in Fig. I.1 [55].

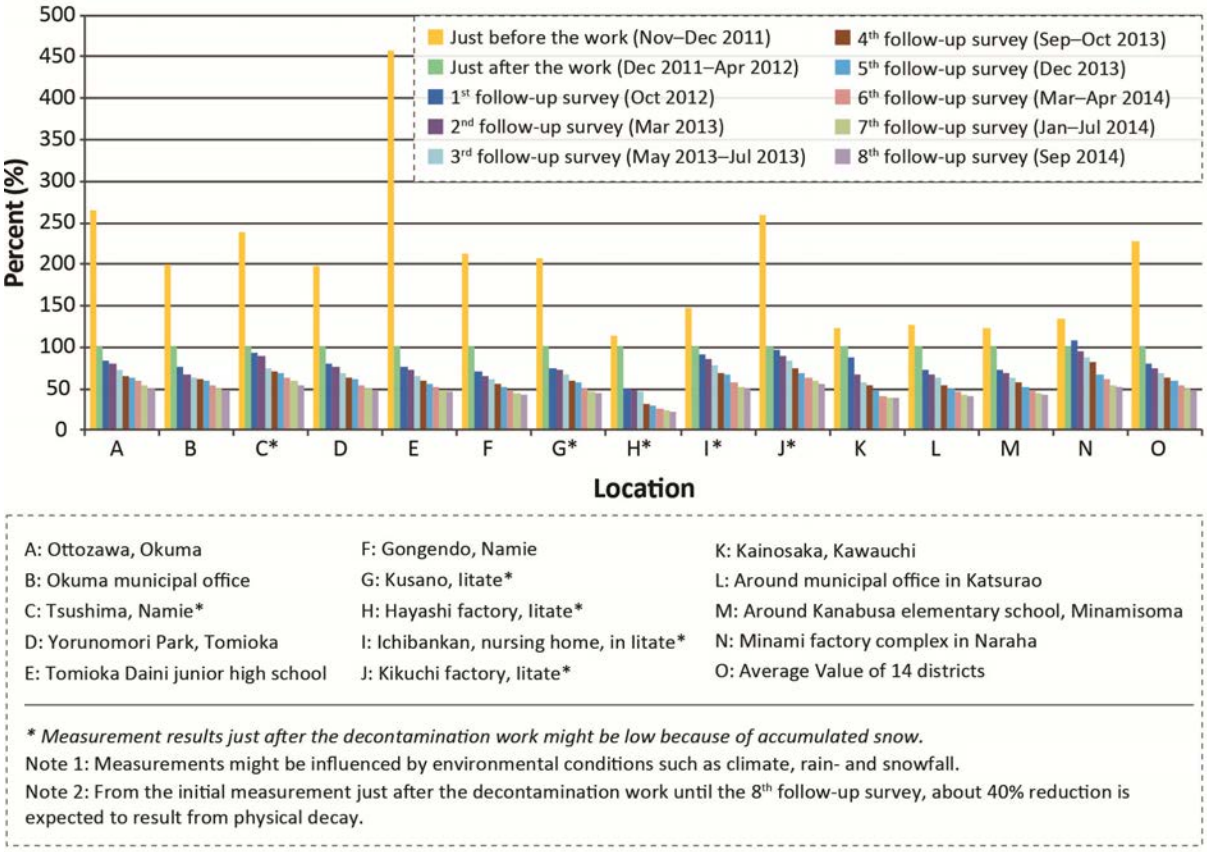


FIG. I.1. Changes with time in the ambient dose rate before and after demonstration projects in the evacuation area. The dose rate (μSv/h) is the averaged value measured in each of the sites. The value immediately after decontamination (green column) is normalized to be 100% [55].

Figure I.1 shows the averaged dose reduction from many measurement points across the entire study site (see comparison between orange and green columns). The input of additional radiocaesium was not significant over the measurement periods after decontamination.

The reduction was generally higher for highly contaminated sites, such as Okuma Town and Tomioka Town, and lower for less contaminated sites, such as Naraha Town and Minamisoma City. However, caution should be used when interpreting the data, as there were some differences between sites in the application of the decontamination procedures, especially if there were time or other resource constraints.

The most contaminated area included in the pilot projects was Ottozawa in Okuma Town, where the average ambient dose rates measured before and directly after decontamination were 67 and 25 μSv/h, respectively, corresponding to a DF_a for the average dose rates of 2.65. Naraha Town had the lowest contamination levels, with average dose rates of 0.39 and 0.29 μSv/h before and after decontamination, respectively, and a DF_a for the average dose rates of 1.34. The highest DF_a was for Tomioka Town Junior High School, with a DF_a of 4.6.

The JAEA project generated experience on large scale decontamination of a populated area relevant to Japanese conditions. Planning procedures were developed that were consistent with local conditions, and efforts were made to communicate plans and progress to local communities and to involve them, whenever possible, in decision making.

The experience gained during the decontamination pilot projects played a key role in the drafting of guidelines and manuals that are currently being used to guide implementation. They constitute a source of reference for the national Government, local municipalities and the contractors performing regional decontamination (Section 5.2.5). The ease of measurement of radiocaesium, its relatively low radiotoxicity and high association with inorganic surfaces, all contributed to the selection of the tested methods. The extent to which the accumulated experience and data can be transferred to other radionuclides or situations would need to be assessed on a case by case basis.

Decontamination model evaluation projects by the MOE (step 3) have been implemented in the 'difficult to return' SDA 3 to provide a basis for the discussion of efforts to simultaneously remediate and reconstruct areas that have been evacuated for an extended period of time. The tests evaluated to what extent radiation doses can be reduced by the use of the standard decontamination measures being used elsewhere. These tests were conducted from October 2013 to January 2014 and were designed to ensure that good quality data were acquired in highly contaminated areas. The MOE has carried out tests at six sites in Namie Town and Futaba Town, which included parkland, farmland, residential areas, forests, kindergartens and hospitals [318]. The remediation measures carried out are given in Table I.2.

TABLE I.2. DECONTAMINATION MEASURES USED IN THE DECONTAMINATION MODEL EVALUATION PROJECTS CARRIED OUT BY MOE AT SDA 3 SITES BETWEEN OCTOBER 2013 AND JANUARY 2014 [318].

Target	Remediation measures
Residential areas	Wiping exterior walls, removal of plants from gardens, removal of topsoil (5 cm), soil treatment
Farmland	Removal of plants from gardens, removal of topsoil (5 cm), soil treatment[a], ploughing[a] (15 cm)
Roads	Removal of deposited radioactive material, washing with very high pressure water
Forests	Removal of litter and understorey plants, pruning trees

[a] Not performed at one site.

A large number of measurements were made at each site on a 5 m grid for residential areas and a 10 m grid elsewhere, avoiding edge effects. The data for all six sites are compiled for different types of targets as DF_a in Fig. I.2 for three different ambient dose rate ranges before remediation. The DF_a

values were highest for farmland and lowest for forest. Most median values for each target, excluding forest, were between 2 and 3.

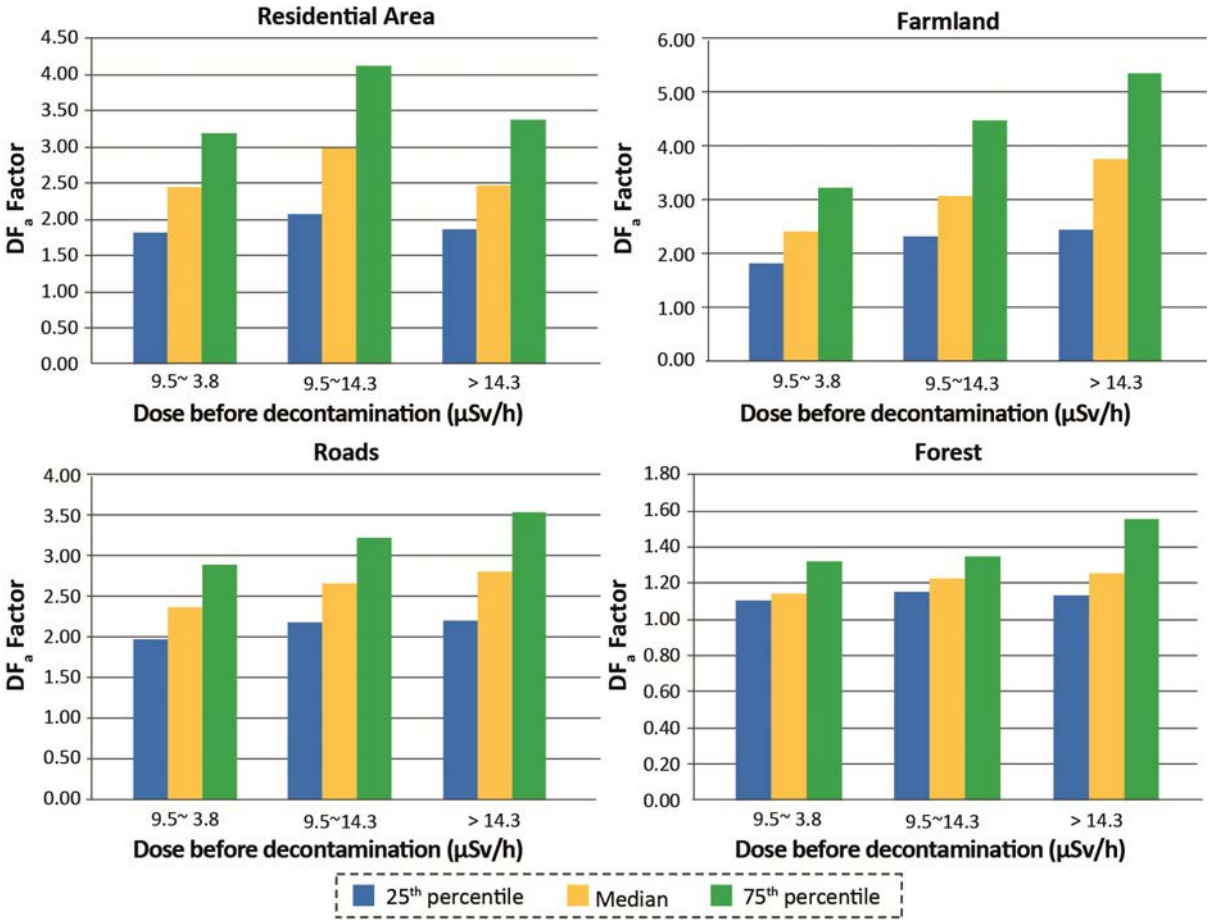


FIG. I.2. Decontamination factors (DF_a) for different targets achieved in the MOE decontamination model evaluation project in six SDA 3 sites [318].

I.2. MEASURES OF SUCCESS OF REMEDIAL ACTIONS

Research performed in residential areas of Tamura City, where gamma dose rates were determined both before and after remediation actions, showed that average gamma dose rates were reduced by between 36% and 46% in residential areas. Average dose rate reductions in the two municipalities following remedial actions in farmlands, forests and roads were 21% and 44%, respectively. The data indicate that reduction of ambient gamma dose rates is more pronounced in areas with higher initial dose rates. After remediation, the decline of the gamma dose rates continues owing to the natural processes of weathering and radioactive decay [319].

The external dose rates to workers involved in the decontamination operations are shown for the six sites in Fig. I.3. The maximum observed value was 92.4 μSv/d registered in the Ide district. If a worker carried out decontamination activities under these conditions over a period of 240 days, the accumulated individual effective dose would be 22.2 mSv. If the same calculation was applied to the average individual effective dose rate — of about 71.5 μSv/d — the accumulated individual effective dose in the same period would be 17.2 mSv, which would not exceed the values set in the regulatory requirements. Nevertheless, measures were taken to reduce the exposures of workers to radiation in the pilot projects, primarily by the rotation of the workers who had worked in areas with higher dose rates to areas with lower values.

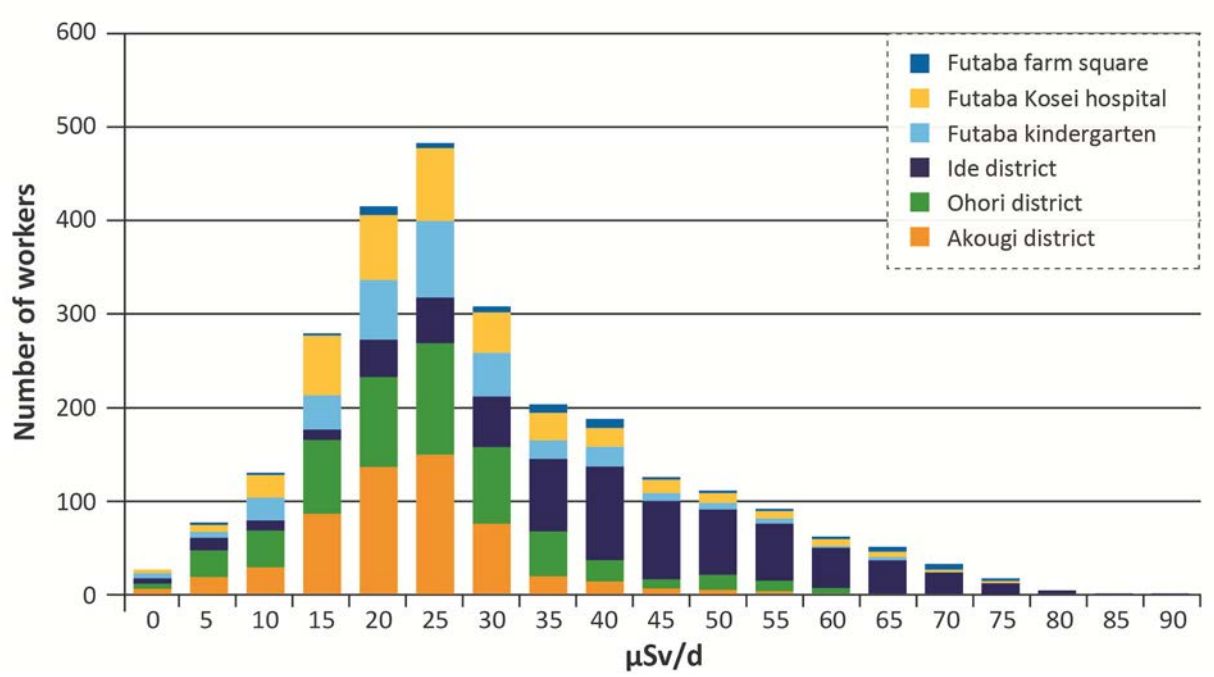


FIG. I.3. Frequency distribution of dose rates to decontamination workers in the six demonstration sites in SDA 3 [320].

I.3. DEMONSTRATION PROJECTS IN AGRICULTURAL PRODUCTION AREAS

The Fukushima Daiichi accident had a severe impact on rural activities, resulting in a need to develop and implement large scale agricultural remediation. Suitable remediation measures to be tested were selected based on prior experience of remediation in areas affected by other accidents, notably the Chernobyl accident. The effectiveness of individual techniques for the contaminated Japanese land was evaluated by testing and validating agricultural remedial measures to identify sustainable remediation strategies for farmlands [321, 322]. Many of the tested measures also considered disposal of residues after soil removal. To quantify the effectiveness of soil treatments, the reduction factor is used, which is the ratio of the activity concentration in the crop before and after the application of the remedial action [47].

During the initial months/years after deposition, when only the soil surface is contaminated, some soil treatments can result in a considerable reduction in both external and internal doses. Such treatments include topsoil removal (field decontamination), burying of top soil and dilution of radionuclides in topsoil by ploughing. Topsoil removal in farmland areas adopted by the National Agricultural Research Organization (NARO) for Japanese farming conditions involved:

(1) Measurement of the vertical distribution of radionuclides in soil;
(2) Crushing of surface soil by use of a power harrow;
(3) Scraping surface soil using a rear blade;
(4) Soil collection and removal by use of a front loader and dump track;
(5) Bagging with a power shovel.

The reduction factor for this procedure (a measure of the amount of radiocaesium removed from the rooting zone of plants) was an average of 75% for dry rice paddies and slightly more (80%) for other dry fields.

Ploughing dilutes radioactive contamination located in the upper soil layers from which most plant roots absorb their nutrients. In undisturbed soil in 2011, the radiocaesium was mainly concentrated in the top 0–1 cm layer. After normal ploughing, radiocaesium was redistributed within the 0–20 cm top layer. In the case of deep ploughing, radiocaesium was placed at a depth of 20–30 cm [323]. The observed DF_a values in the above situations were 1.4, 1.7 and 2.0 after shallow, conventional and deep ploughing, respectively [323].

Topsoil removal was also carried out after spraying a solidification agent to harden the soil, which was then mechanically removed. This process led to a reduction of 80% of the radiocaesium initially present in the soil.

For paddy fields, suspension of the upper soil by agitation on water and subsequent collection of the soil in suspension removed about 40% of radiocaesium originally present.

In 2011, data on the relationship between the radiocaesium activity concentration in rice (with caesium activity concentration above 500 Bq/kg) and the content of exchangeable potassium oxide (K_2O) in the soil in which the rice was cultivated showed an inverse correlation, i.e. the content of caesium was higher in rice in those soils in which the concentration of K_2O was lower (Fig. I.4). A low concentration of exchangeable K_2O in soil was associated with an increase in the uptake of radiocaesium by rice. This behaviour has been extensively reported previously for a large number of crops cultivated in soil contaminated with isotopes of caesium after the Chernobyl accident [324]. Such data prompted Japanese farmers to apply additional amounts of potassium fertilizer to the soils of their farms. The amount applied was dictated by the measured activity concentrations of radiocaesium in the harvested crops. The application of potassium is based on a preliminary agrochemical evaluation of the soil properties and may not be effective in soils with naturally high exchangeable potassium concentrations, i.e. higher than 25 mg K_2O/100g [325]. As a remedial measure, NARO recommended increasing exchangeable potassium in soil up to 25 mg K_2O/100g in those cases where the content of exchangeable potassium was below that level.

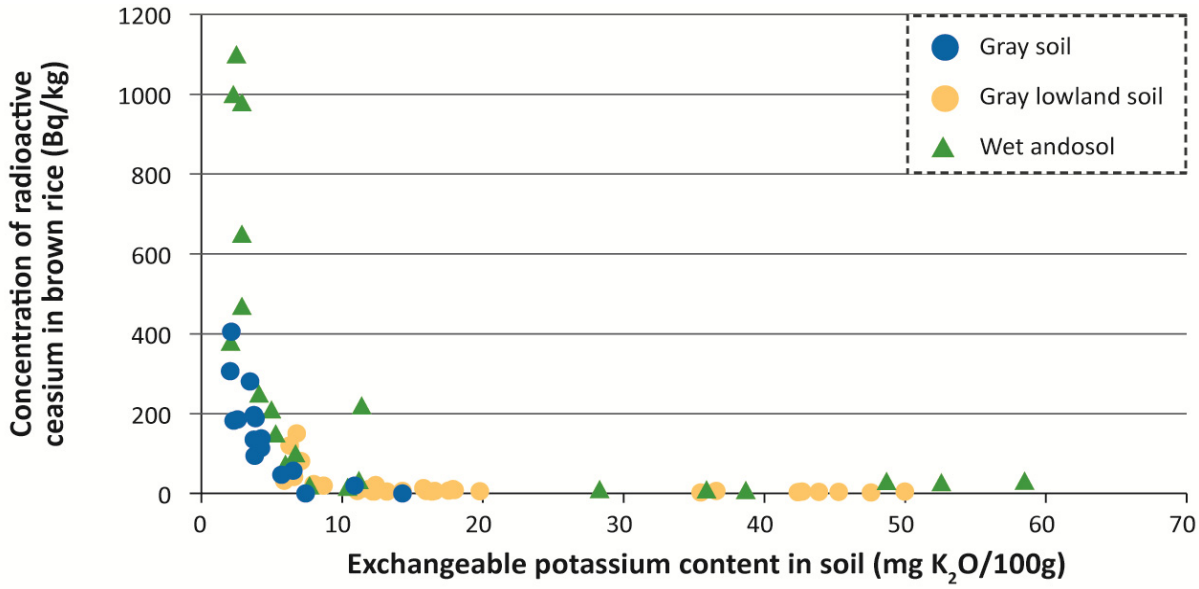


FIG. I.4. The relationship between exchangeable potassium in soil and radiocaesium activity concentration in husked rice, which can be used to determine the need for additional potassium in soil [82].

Application of cattle manure compost to contaminated soil at elevated rates of more than 75 t/km^2 reduced radiocaesium transfer to plants by 40% compared with similar sites where manure was not applied [75].

Some soil treatments that used natural minerals such as zeolite or bentonite, polymer adsorbents and Prussian blue were also tested for efficacy in reducing radiocaesium uptake into crops. Application of 500 t/km^2 of vermiculite from South Africa or 1000 t/km^2 of pumice tuff powder containing a clinoptilite (zeolite) reduced the transfer factor substantially [75]. However, no effect was observed after application of local zeolite produced in Fukushima Prefecture, and further research is required to identify suitable local sorbents [75].

On forage fields, activity concentrations could be reduced considerably by a combination of measures, such as ploughing, reseeding, application of greater quantities of potassium fertilizer and the application of lime (field renovation) [323]. Radiocaesium activity concentrations in grass (*Dactylis glomerata)* were reduced by a factor in the range of 4–6 by this combination of actions.

Remediation measures tested during pilot studies are shown in Table I.3. Most of these measures achieved a significant reduction in surface dose rates, but topsoil removal generated large amounts of contaminated material, and some measures produced dust under dry conditions. The application of remediation measures in Table I.3 reduced external dose rates for agricultural workers, whereas application of potassium fertilizer alone did not.

TABLE I.3. REMEDIATION MEASURES TESTED DURING PILOT STUDIES (STEP 2) IMPLEMENTED IN FARMLAND WITHIN FUKUSHIMA PREFECTURE [16]

Type of decontamination activity	Method	Decontamination factor DF_a (dimensionless)	Volume of soil removed (contaminated material)	Decontamination speed
Reversal tillage	Reversal tillage (tractor and ploughing)	1–3	None	1340 m^2/d (with 1.2 persons)
	Interchanging topsoil with subsoil (mechanical digger; ploughing)	3	None	120 m^2/d (with 1.2 persons)
Topsoil removal	Thin layer topsoil stripping equipment, hammer knife (to 1 cm soil depth)	2	0.03 m^3/m^2	500 m^2/d (with 7 persons)
	Stripping of 5 cm soil layer with mechanical digger	1–5	0.03–0.08 m^3/m^2	1300 m^2/d (with 15 persons)
Spraying of surface hardening agent	Topsoil hardening and collection via stripping using a mechanical digger	1–5	None	290 m^2/d (with 6 persons)

I.4. DEMONSTRATION PROJECTS IN FOREST AREAS

Experience after the Chernobyl accident suggests that it is unlikely that any technologically based forest remediation measures, such as the large scale removal of surface forest soil or chemical treatments to alter the distribution or transfer of radiocaesium in the forest, will be practicable and effective on a large scale. Remediation of contaminated forests in Japan presents particular challenges, given the extent and nature of this type of ecosystem in the affected areas. Since reduction of the external radiation dose in areas inhabited by people was identified as a high priority task in Japan, considerable effort has been devoted to addressing issues associated with the substantial areas of contaminated forest, much of which is located on mountain slopes.

Three types of remediation measures have been tested, namely forest border decontamination, stabilization of forest understorey (e.g. by use of surface protection measures after floor sweeping operations) and adaptation of normal forestry processes to reduce lateral transfer of radiocaesium. At the time of writing, decontamination of forest borders was the only one of these remediation measures that had been implemented.

The outer 20 m borders of forests adjacent to settlements or agricultural land were identified and prioritized for decontamination to reduce external doses to the resident population. Forest decontamination technologies were initially tested in demonstration projects in Japan and focused on the collection and removal of fallen leaves/branches and litter under the trees in a 20 m buffer strip adjacent to residences, farmland and public spaces (Table I.4). The implementation of the 'floor sweeping activities' measure was very labour intensive.

The application of forest border decontamination resulted in the generation of contaminated material and some secondary contamination, which required implementation of special waste management measures. The data shown in Table I.4 were not specifically collected for the purpose of assessing contaminated material generation and should be treated with caution.

TABLE I.4. SUMMARY OF DECONTAMINATION SPEEDS, CONTAMINATED MATERIAL GENERATED AND SIDE EFFECTS OF THE APPLICATION OF PILOT DECONTAMINATION FORESTED AREAS IN FUKUSHIMA PREFECTURE [16]

Components	Method	Volume of contaminated material generated	Secondary contamination	Decontamination speed (in flat areas)	Decontamination Factor DF_a (dimensionless)[a]
Forest floor	Removal of fallen leaves, humus and topsoil	0.1–0.2 m^3/m^2	None	220 m^2/d (with 5 persons)	15
Trees	Trunk washing	Small amount of bark and moss	Wash water infiltration into soil	32 trees/d (with 4 persons)	1–7
	Branch trimming in the lower parts	2.2 m^3/tree (combustible)	Fine portions of twigs and sticks that cannot be collected	150 m^2/d (with 4 persons)	1–2
	Felling	Large amount of bark, branches and leaves	Contaminated chainsaw chips scattered on the ground	—	—

[a] Dose rate measured at a height of 1 m above the ground.

When a combination of underbrush clearing and removal of fallen leaves was applied in coniferous forest, the DF_s was in the region of 1.2–1.4. When the litter layer was also removed, the DF_s increased to around 3. In deciduous forest, a combination of underbrush clearing and removal of recently fallen leaves had no effect (since there were no leaves present during radiocaesium deposition), whereas a similar reduction to that for coniferous forest (approximate DF_s of 3) was achieved when most of the litter layer was removed.

For both types of forest, the removal of the litter layer considerably reduced surface dose rates, but may also lead to enhanced soil erosion, especially during rainfall and on steep slopes. The corresponding reduction in the ambient dose rate measured at the centre of the decontaminated area varied from DF_a 1.3 for evergreen forest (Japanese cedar) to DF_a 1.7 for broad leaved forest (oak)

[103], although the average reduction in external dose rate is small, with a DF_a that was only slightly greater than 1.

Various forest related restrictions have been applied in Japan to reduce the exposure of people in addition to the decontamination of the outer borders of forests. For external exposure pathways, these include restrictions on access and firewood collection and the advice on suitability of recreational activities. The risk and consequences of fires in contaminated forests have also been considered and a dose evaluation tool for assessing the impact of wildfires has been developed [325]. For internal exposure pathways, restrictions on harvesting and consuming food from forests and monitoring of collected produce will help to reduce internal dose; advice on suitability of recreational activities is provided. However, restrictions on the use of forests can result in negative ecological and social consequences in the long term, and advice from the authorities to the general public may be heeded less carefully over time. This situation can be offset by the provision of suitable educational programmes at the local level to explain the purpose of the measures applied.

Continued development of sustainable remediation strategies appropriate for the site specific conditions in Japan, especially the steep forested catchments, are being developed to better understand the long term behaviour of radiocaesium in forest areas around residential areas, farmland and public spaces. The impacts of lateral redistribution of contaminated soil and potential remediation required for these processes are being evaluated by the use of forest models.

I.5. DEMONSTRATION PROJECTS IN AQUATIC ECOSYSTEMS

Remediation of freshwater and marine ecosystems is challenging, and can yield ambiguous and often poor results due to the size and complex nature of these systems. The complexities in manipulating aquatic ecosystems, and the lack of success of remediation approaches that were tested in freshwater systems after the Chernobyl accident, strongly indicate that large scale remediation focused on the water bodies would be unlikely to yield significant and lasting reductions in doses to people and may result in detrimental side effects [326, 327]. The disadvantages include low and temporary remediation effectiveness, generation of large volumes of contaminated material, resuspension and redistribution of contaminated particulates during remediation work and destruction of benthic habitats. Owing to concerns about the erosion of soil from contaminated catchments, and subsequent redistribution of particulates into downstream receiving environments such as rice paddy fields, localized sediment removal has been undertaken in Japan to reduce external dose and radiocaesium uptake by crop species.

Overall, there are no remediation technologies for natural freshwater or marine ecosystems which do not cause significant disruption to the environment and habitat. Even if remediation were practical, owing to the highly spatially localized distribution of contamination downstream of the Fukushima Daiichi NPP [328], reduction in doses to people would be limited.

Overall, there is limited potential for effective and practical remediation of aquatic systems. In such circumstances, prohibition of fishing and recreation based on monitoring the natural reduction in activity concentrations in aquatic organisms, sediment and water is appropriate and effectively protects the public.

REFERENCES

[1] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection: 2007 Edition, IAEA, Vienna (2007).

[3] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, Publication 103, Pergamon Press, Oxford (2007).

[4] HEDEMANN-JENSEN, P., McEWAN, A.C., Is ICRP guidance on the use of reference levels consistent? J. Radiol. Prot. **31** 4 (2011) 431–444.

[5] GOVERNMENT OF JAPAN, Act on Special Measures Concerning Nuclear Emergency Preparedness, Act No. 156, 17 December 1999, http://www.cas.go.jp/jp/seisaku/hourei/data/ASMCNEP.pdf

[6] Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material and Reactors, Act No. 166, 10 June 1957, as last ammended by Act No. 84 of 2007 (Japan), http://www.nsr.go.jp/archive/nisa/english/resources/legislativeframework/files/ReactorRegulation.pdf

[7] Waste Management and Public Cleansing Law, Law No. 137, 1970, as last amended by Act No. 34 of 2010 (Japan).

[8] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency, Publication 111, Pergamon Press, Oxford (2009).

[9] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Scope of Radiological Protection Control Measures, Publication 104, Pergamon Press, Oxford (2007).

[10] MINISTRY OF THE ENVIRONMENT, Outline of the Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District –Off the Pacific Ocean Earthquake that Occurred on March 11, 2011 (2011), http://josen.env.go.jp/en/pdf/annex_01.pdf

[11] TAKAHARA, S., IIJIMA, M., SHIMADA, K., KIMURA, M., HOMMA, T., Probabilistic Assessment of Doses to the Public Living in Areas Contaminated by the Fukushima Daiichi Nuclear Power Plant Accident, Radiation Monitoring and Dose Estimation of the Fukushima Nuclear Accident (TAKAHASHI, S., Ed.), Springer Japan (2014) 197–214.

[12] STATISTICS JAPAN, 2010 Census (2011) (in Japanese), http://www.stat.go.jp/data/kokusei/2010/index2.htm#kekkagai

[13] UNITED NATIONS, Sources, Effects and Risks of Ionizing Radiation (Report to the General Assembly), UNSCEAR 2013 Report, Volume I, Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident after the 2011 Great East-Japan Earthquake and Tsunami, Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2014).

[14] TAKAHARA, S., IIJIMA, M., SHIMADA, K., KIMURA, M., HOMMA, T., "Assessment of radiation doses to the public in areas contaminated by the Fukushima Daiichi Nuclear Power Station accident", Int. Symp. on Environmental Monitoring and Dose Estimation of Residents after Accident of TEPCO's Fukushima Daiichi Nuclear Power Station, Kyoto, 2012

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Generic Procedures for Assessment and Response during a Radiological Emergency, IAEA-TECDOC-1162, IAEA, Vienna (2000).

[16] JAPAN ATOMIC ENERGY AGENCY, Remediation of Contaminated Areas in the Aftermath of the Accident at the Fukushima Daiichi Nuclear Power Station: Overview, Analysis and Lessons Learned Part 1: A Report on the "Decontamination Pilot Project", JAEA-Review 2014-051, JAEA, Tokyo (2015).

[17] JAPAN ATOMIC ENERGY AGENCY, Development of Method to Understand Long-term Influences of Radionuclides from TEPCO Fukushima Daiichi Nuclear Power Plant Accident, JAEA, Tokyo (2014) (in Japanese),
http://fukushima.jaea.go.jp/initiatives/cat03/entry06.html
[18] UNITED STATES DEPARTMENT OF ENERGY, DOE EM Project Experience & Lessons Learned for In Situ Decommissioning, DOE, Washington, DC (2013).
[19] SAITO, K., An Overview of the Current Distribution of Radionuclides Released to the Environment Following the Fukushima accident (2014),
http://www-pub.iaea.org/iaeameetings/cn224p/Session1/Saito.pdf
[20] SAITO, K., et al., Detailed deposition density maps constructed by large-scale soil sampling for gamma-ray emitting radioactive nuclides from the Fukushima Dai-ichi nuclear power plant accident, J. Environ. Radioact. **139** (2015) 308–319.
[21] GOVERNMENT OF JAPAN, Map and numerical data, official communication (2015).
[22] KINASE, S., TAKAHASHI, T., SATO, S., SAKAMOTO, R., SAITO, K., Development of prediction models for radioactive caesium distribution within the 80-km radius of the Fukushima Daiichi nuclear power plant, Radiat. Prot. Dosim. **160** 4 (2014) 318–321.
[23] KINASE, S., TAKAHASHI, T., SATO, S., SAKAMOTO, R., SAITO, K., "Ecological half-life of radioactive caesium within 80 km-radius of the Fukushima Daiichi nuclear power plant", Proc. 4th Europ. IRPA Congress, Geneva, 2014 (abstract).
[24] NUCLEAR REGULATION AUTHORITY, Study on Distribution and Migration of Radioactive Substances around the Fukushima Daiichi Nuclear Power Plant (2014) (in Japanese),
http://fukushima.jaea.go.jp/initiatives/cat03/pdf06/1-1.pdf
[25] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009).
[26] INTERNATIONAL ATOMIC ENERGY AGENCY, Policy and Strategies for Environmental Remediation, IAEA Nuclear Energy Series No. NW-G-3.1, IAEA, Vienna (2015).
[27] MINISTRY OF THE ENVIRONMENT, Act on Special Measures Concerning the Handling of Environmental Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake That Occurred on March 11, 2011, Act No. 110, 2011 (Japan).
[28] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Basic Policy for Emergency Response on Decontamination Work (2011),
http://www.meti.go.jp/english/press/2011/pdf/0826_03b.pdf
[29] MINISTRY OF THE ENVIRONMENT, Basic Principles of the Act on Special Measures Concerning the Handling of Environment Pollution by Radioactive Materials Discharged from the Nuclear Power Station Accident Associated with the Tohoku District — Off the Pacific Ocean Earthquake That Occurred on March 11, 2011 (2011),
http://josen.env.go.jp/en/framework/pdf/basic_principles.pdf
[30] NEMOTO, T., Prime Minister of Japan and His Cabinet, Acceleration of Reconstruction Efforts from the Great East Japan Earthquake (2014),
http://www.reconstruction.go.jp/rap/2014/02/20140224_fpc.pdf
[31] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Efforts for the Reconstruction Assistance of Agriculture, Forestry and Fisheries after the Great East Japan Earthquake (2014) (in Japanese),
http://www.maff.go.jp/j/kanbo/kihyo02/fukkou/pdf/2612_zen.pdf
[32] RECONSTRUCTION AGENCY, Discussion Note: 1st Task Force Meeting to Accelerate and Integrate Decontamination and Reconstruction (2013) (in Japanese),
http://www.reconstruction.go.jp/topics/20130119_3_siryou1.pdf
[33] MINISTRY OF THE ENVIRONMENT, National budget related to decontamination and contaminated waste management, official communication (2015).
[34] NUCLEAR SAFETY COMMISSION OF JAPAN, Basic Policy of the Nuclear Safety Commission of Japan on Radiation Protection for Termination of Evacuation and Reconstruction (2011),
http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110719suggest_4.pdf

[35] CABINET SECRETARIAT OF THE GOVERNMENT OF JAPAN, Report of the Working Group on Risk Management of Low-dose Radiation Exposure (2011), http://www.cas.go.jp/jp/genpatsujiko/info/twg/Working_Group_Report.pdf
[36] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Assessing Dose of the Representative Person for the Purpose of the Radiation Protection of the Public, Publication 101, Pergamon Press, Oxford and New York (2006) 114.
[37] Ordinance on Prevention of Ionizing Radiation Hazards at Work to Decontaminate Soil and Wastes Contaminated by Radioactive Materials Resulting from the Great East Japan Earthquake and Related Works, Ordinance of the Ministry of Health Labour and Welfare No. 152, 2011 (Japan), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_111222_a04.pdf
[38] YASUI, S., Establishment of new regulations for radiological protection for decontamination work involving radioactive fallout emitted by the Fukushima Daiichi APP accident, J. Occup. Environ. Hyg. **10** 9 (2013) D119–D124.
[39] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Areas to Which Evacuation Orders Have Been Issued (2013), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20130807_01.pdf
[40] GOLIKOV, V.Y., BALONOV, M.I., JACOB, P., External exposure of the population living in areas of Russia contaminated due to the Chernobyl accident, Radiat. Environ. Biophys. **41** 3 (2002) 185–193.
[41] INTERNATIONAL ATOMIC ENERGY AGENCY, The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site of the Fukushima Daiichi Nuclear Power Plant (2014), https://www.iaea.org/sites/default/files/final_report230114.pdf
[42] ÁLVAREZ-FARIZO, B., GIL, J.M., HOWARD, B.J., Impacts from restoration strategies: Assessment through valuation workshops, Ecol. Econ. **68** 3 (2009) 787–797.
[43] COX, G., et al., Identifying optimal agricultural countermeasure strategies for a hypothetical contamination scenario using the strategy model, J. Environ. Radioact. **83** 3 (2005) 383–397.
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine, IAEA, Vienna (2006), https://www.iaea.org/sites/default/files/chernobyl.pdf
[45] RASKOB, W., European approach to nuclear and radiological emergency management and rehabilitation strategies (EURANOS), Kerntech. **72** 4 (2007) 179–182.
[46] HOWARD, B.J., et al., A critical evaluation of the STRATEGY project, Radiat.Protect. Dosim. **109** 1–2 (2004) 63–67.
[47] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidelines for Remediation Strategies to Reduce the Radiological Consequences of Environmental Contamination, Technical Reports Series No. 475, IAEA, Vienna (2012).
[48] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No. 472, IAEA, Vienna (2010).
[49] MINISTRY OF THE ENVIRONMENT, Decontamination Guidelines (2013), http://josen.env.go.jp/en/framework/pdf/decontamination_guidelines_2nd.pdf
[50] MINISTRY OF THE ENVIRONMENT, Unit prices for decontamination in the SDAs directly controlled by the national government, official communication (2015).
[51] MINISTRY OF THE ENVIRONMENT, Decontamination Technology Options eXploration [xDTOX] (2011) (in Japanese), https://www2.env.go.jp/dtox/
[52] AGRICULTURE, FORESTRY AND FISHERIES RESEARCH COUNCIL, Handbook on Technologies to Remove Radioactive Material from Farmland Soil (Decontamination Technology), 1st edn (2012) (in Japanese), http://www.s.affrc.go.jp/docs/press/pdf/120302-01.pdf
[53] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Technical Guidelines on Farmland Decontamination: Monitoring, Planning and Implementation (2012) (in Japanese), http://www.maff.go.jp/j/press/nousin/noukan/pdf/120831-08.pdf

[54] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Technical Guidelines for Removing and Preventing Spread of Radioactive Material in Forests (2012) (in Japanese), http://www.rinya.maff.go.jp/j/press/kenho/pdf/120427-02.pdf
[55] MINISTRY OF THE ENVIRONMENT, Progress on Off-Site Clean-up Efforts in Japan (2015), http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf?150113
[56] MINISTRY OF HEALTH, LABOUR AND WELFARE, Revision of Guideline on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/ri_1226_21.html
[57] MINISTRY OF HEALTH, LABOUR AND WELFARE, A Ministerial Ordinance for Preventing Radiation Hazards of Workers Engaged in the Disposal of Accident-derived Waste, etc. Was Published, and its Guidelines Were Formulated(2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/wd/pr_130412.html
[58] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Prevention of Radiation Hazards for Workers Engaged in Decontamination Works (2011). http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/dr/pr_120615_a03.pdf
[59] MINISTRY OF HEALTH, LABOUR AND WELFARE, Organization for Registration Control of Radiation Exposure Doses for Decontamination and Related Works (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/ort/ri_1226_17.html
[60] MINISTRY OF HEALTH, LABOUR AND WELFARE, Systematic Control of Radiation Exposure Doses for Decontamination and Related Works (2015), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/ort/pr_131115_a01.pdf
[61] RADIATION EFFECTS ASSOCIATION, MINISTRY OF HEALTH, LABOUR AND WELFARE, MINISTRY OF THE ENVIRONMENT, The Launch of the Organization for Systematic Control of Radiation Exposure Doses, etc. for Decontamination and Related Works (2013), http://www.mhlw.go.jp/english/topics/2011eq/workers/dr/ort/pr_131115.html
[62] RADIATION EFFECTS ASSOCIATION, MINISTRY OF HEALTH, LABOUR AND WELFARE, MINISTRY OF ENVIRONMENT, Statistics on Radiation Exposure Doses of Decontamination Workers and Other Items Have Been Announced (2015), http://www.mhlw.go.jp/english/topics/2011eq/workers/ors/oi/pr_150415.html
[63] MINISTRY OF THE ENVIRONMENT, Answer to question 1 — 4th submission, official communication (2014).
[64] FUKUSHIMA OFFICE FOR ENVIRONMENTAL RESTORATION, Collection of good practices in decontamination (2013) (in Japanese), http://tohoku.env.go.jp/fukushima/pre_2013/data/0520ab.pdf
[65] MINISTRY OF THE ENVIRONMENT, Measures for Decontamination of Radioactive Materials Discharged by TEPCO's Fukushima Daiichi NPS Accident (2013), http://josen.env.go.jp/en/
[66] MINISTRY OF THE ENVIRONMENT, Number of planned and completed remediation activities in Fukushima and other prefectures, official communication (2015).
[67] NUCLEAR REGULATION AUTHORITY, Practical Measures for Evacuees to Return to their Homes, (2013), https://www.nsr.go.jp/data/000067234.pdf
[68] MINISTRY OF THE ENVIRONMENT, "Decontamination Roadmap" for the Special Decontamination Areas, Tokyo (2012), http://josen.env.go.jp/en/roadmap/pdf/outline_of_the_roadmap.pdf
[69] MINISTRY OF THE ENVIRONMENT, Short-term Decontamination Roadmap for Special Decontamination Areas, (2013), http://josen.env.go.jp/en/roadmap/pdf/roadmap_appendix1_3.pdf
[70] MINISTRY OF THE ENVIRONMENT, Progress on Off-site Cleanup and Interim Storage in Japan, (2014), http://josen.env.go.jp/en/pdf/progressseet_progress_on_cleanup_efforts.pdf?140827
[71] OHMURA, T., "Progress of off-site decontamination of Fukushima Daiichi NPP in Japan", paper presented at IAEA Cons. Mtg on Decommissioning and Environmental Remediation after an Accident: Approaches, Techniques, Tools and Equipment, Vienna, 2014.

[72] CABINET OFFICE, TEAM IN CHARGE OF ASSISTING THE LIVES OF DISASTER VICTIMS, Regarding the Difficult-to-Return Area (2013) (in Japanese), http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/shiryo/__icsFiles/afieldfile/2013/10/02/1340046_4_2.pdf
[73] MINISTRY OF THE ENVIRONMENT, Results of Decontamination (Naraha) (2014) (in Japanese), http://josen.env.go.jp/area/details/naraha.html
[74] JAPAN ATOMIC ENERGY AGENCY, Methods for Decontamination in Agricultural Farm (2013) (in Japanese), http://c-navi.jaea.go.jp/ja/remediation-work/2013-04-10-03-58-46/agricultural-land-02.html
[75] YOSHIOKA, K., "Research and development of radioactive substance removal/reduction technology in Fukushima Prefecture (agricultural lands and crops)", International Science Symp. on Combating Radionuclide Contamination in Agro-soil Environment, MAFF, Tokyo (2012) 329–338, http://www.s.affrc.go.jp/docs/anzenka/symposium/pdf/yoshioka_e4011.pdf
[76] MINISTRY OF THE ENVIRONMENT, Progress in the special decontamination area, official communication (2015).
[77] MINISTRY OF THE ENVIRONMENT, Decontamination Demonstration Project in the Area Where It Is Expected That Residents Will Face Difficulties in Returning for a Long Time (2014) (in Japanese), http://josen.env.go.jp/material/pdf/model_140529a.pdf?140610
[78] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, The Policy for Accelerating Fukushima's Reconstruction after the Nuclear Disaster (2013) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/pdf/131220_hontai.pdf
[79] MINISTRY OF HEALTH, LABOUR AND WELFARE, New Standard Limits for Radionuclides in Foods (2012), http://www.mhlw.go.jp/english/topics/2011eq/dl/new_standard.pdf.
[80] MINISTRY OF HEALTH, LABOUR AND WELFARE, Revision of the "Concepts of Inspection Planning and the Establishment and Cancellation of Items and Areas to Which Restriction of Distribution and/or Consumption of Foods Concerned Applies" (2013), http://www.mhlw.go.jp/english/topics/2011eq/dl/food-130319_2.pdf
[81] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report of the International Mission on Remediation of Large Contaminated Areas Off-site the Fukushima Dai-ichi NPP, Japan 7–15 October 2011, NE/NEFW/2011, IAEA, Vienna (2011).
[82] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Cause of High Radioactive Caesium Concentration in Rice and Remediation Measures — Summary Report on the Results of Cause Analysis and Test Rice Planting, Fukushima Prefecture (2013) (in Japanese), http://www.pref.fukushima.lg.jp/download/1/youinkaiseki-kome130124.pdf
[83] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, On the Setting of Provisional Tolerance for Radioactive Caesium in Fertilizer, Soil Conditioner, Compost and Feed (2011) (in Japanese), http://www.maff.go.jp/j/syouan/soumu/saigai/shizai.html
[84] GOVERNMENT OF JAPAN, Measures Against Beef Which Exceeds the Provisional Regulation Values of Radioactive Caesium by the Government to Ensure Safety of Beef (2011), http://japan.kantei.go.jp/kan/topics/201107/measures_beef.pdf
[85] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Cattle Identification and Traceability Systems (2007), http://www.maff.go.jp/j/syouan/tikusui/trace/pdf/usino_kotai_sikibetu_eiyaku.pdf
[86] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, The Revision of the Provisional Tolerance of Radioactive Caesium on Feed (Cattle) (2012) (in Japanese), http://www.maff.go.jp/j/syouan/soumu/saigai/shizai_2.html
[87] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, The Revision of the Provisional Tolerance of Radioactive Caesium on Feed (Pig, Poultry, Cultured Fish) (2012) (in Japanese), http://www.maff.go.jp/j/syouan/soumu/saigai/pdf/120323_tsuchi.pdf
[88] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Q&A about the Provisional Tolerance Setting for Livestock Feed March (2012) (in Japanese), http://www.maff.go.jp/j/syouan/soumu/saigai/siryou_faq.html

[89] HOWARD, B.J., BERESFORD, N.A., HOVE, K., Transfer of radiocesium to ruminants in natural and semi-natural ecosystems and appropriate countermeasures, Health Phys. **61** 6 (1991) 715–725.
[90] HOWARD, B.J., The concept of radioecological sensitivity, Radiation Protection Dosimetry **92** 1–3 (2000) 29–34.
[91] PRÖHL, G., et al., Ecological half-lives of 90Sr and 137Cs in terrestrial and aquatic ecosystems, J, Environ. Radioact. **91** 1–2 (2006) 41–72.
[92] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Instructions Associated with Food by Director-General of the Nuclear Emergency Response Headquarters (Restriction of distribution in Fukushima Prefecture) (2015), http://www.mhlw.go.jp/english/topics/2011eq/dl/food_instruction_05June_2015.pdf
[93] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Planting restriction areas for rice production maps, official communication (2015).
[94] AGRICULTURE, FORESTRY AND FISHERIES RESEARCH COUNCIL, Agricultural Soil Survey Summary (2013) (in Japanese), http://www.s.affrc.go.jp/docs/press/pdf/130809-01.pdf
[95] KOBAYASHI, T., et al., "Transfer factors of radiocesium to vegetables cultivated on soils collected in Fukushima", Gakushuin Proc. 13th Workshop on Environmental Radioactivity, Tsukuba, 2012 (KATARO BESSHO, K., TAGAMI, K., KOICHI TAKAMIYA, K., MIURA, T., Eds) Proceedings of the 13th Workshop on Environmental Radioactivity, KEK, Tsukuba, Japan (2012)., KEK (2012) (in Japanese).
[96] SHIOZAWA, S., Vertical Migration of Radiocesium Fallout in Soil in Fukushima, Agricultural Implications of the Fukushima Nuclear Accident, (NAKANISHI, T.M., TANOI, K., Eds), Springer (2013) 49–60.
[97] ODA, K., MURAMATSU, Y., OHNO, T., FUJIMURA, S., YOSHIOKA, K., "Distribution of radiocaesium in rice paddy fields and its transfer into rice plants", Gakushuin Proc. 13th Workshop on Environmental Radioactivity, KEK, Tsukuba, 2012 (KATARO BESSHO, K., TAGAMI, K., KOICHI TAKAMIYA, K., MIURA, T., Eds), KEK (2012) (in Japanese).
[98] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Answer to question 14 — 4th Submission, official communication (2014).
[99] FUJIMURA, S., et al., Accumulation of (137)Cs by rice grown in four types of soil contaminated by the Fukushima Dai-ichi nuclear power plant accident in 2011 and 2012, J. Environ. Radioact. **140** (2015) 59–64.
[100] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Response to Radionuclide Contamination in Foods after the Nuclear Power Plant Accident (2014), http://www.maff.go.jp/e/quake/pdf/140812_response_to_emergenc.pdf.
[101] ISHIDA, K., "Contamination of wild animals: effects on wildlife in high radioactivity areas of the agricultural and forest landscape", Agricultural Implications of the Fukushima Nuclear Accident (NAKANISHI, T.M., TANOI, K., Eds), Springer, Tokyo (2013) 119–129.
[102] KYODO NEWS, More boars mean more damage in Fukushima, The Japan Times (24 September 2013). http://www.japantimes.co.jp/news/2013/09/24/national/more-boars-mean-more-damage-in-fukushima/
[103] SHIBATA, S., KOGA, N., "Measures for radioactive substances concerning forests and forestry in Japan", The Second Mtg of the Japan-Ukraine Joint Committee for the Cooperation to Advance Aftermath Response to Accidents at Nuclear Power Stations, Ministry of Agriculture, Forestry and Fisheries, 2013, (2013) (in Japanese).
[104] CHARTIN, C., et al., Tracking the early dispersion of contaminated sediment along rivers draining the Fukushima radioactive pollution plume, Anthropocene **1** (2013) 23–34.
[105] NEMOTO, K., ABE, J., "Radiocesium absorption by rice in paddy field ecosystems", Agricultural Implications of the Fukushima Nuclear Accident, (NAKANISHI, T.M., TANOI, K., Eds), Springer Japan (2013) 19–27.
[106] OHTE, N., et al., "Diffusion and Transportation Dynamics of ^{137}Cs Deposited on the Forested Area in Fukushima After the Fukushima Daiichi Nuclear Power Plant Accident in March 2011", Agricultural Implications of the Fukushima Nuclear Accident (NAKANISHI, T.M., TANOI, K., Eds), Springer (2013) 177–186.

[107] TOKYO ELECTRIC POWER COMPANY, Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (2011), http://www.meti.go.jp/english/speeches/pdf/20110417_a.pdf
[108] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, TEPCO (2011), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/111221_02.pdf
[109] TOKYO ELECTRIC POWER COMPANY, Establishment of Fukushima Daiichi Decontamination & Decommissioning Engineering Company (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1235009_5892.html
[110] Act for Establishment of the Nuclear Regulation Authority, Act No. 47, 27 June, 2012, as amended by Act No. 82 of 2013 (Japan), https://www.nsr.go.jp/data/000067231.pdf.
[111] TOKYO ELECTRIC POWER COMPANY, Revision of the Implementation Plan of the Measures for the Specified Reactor Facilities at Fukushima Daiichi Nuclear Power Station (2013), http://www.tepco.co.jp/en/press/corp-com/release/2013/1229676_5130.html
[112] TOKYO ELECTRIC POWER COMPANY, Implementation Plan of the Measures for the Specified Reactor Facilities at Fukushima Daiichi Nuclear Power Station (2012) (in Japanese), http://www.tepco.co.jp/cc/press/betu13_j/images/130812j0201.pdf
[113] TOKYO ELECTRIC POWER COMPANY, Implementation Plan of the Measures to be Taken at Fukushima Daiichi Nuclear Power Station Designated as a Specified Reactor Facility (Outline) (2012), http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_12120701-e.pdf
[114] TOKYO ELECTRIC POWER COMPANY, Implementation Plan of the Measures for the Specified Reactor Facilities at Fukushima Daiichi Nuclear Power Station (2012) (In Japanese), http://www.tepco.co.jp/cc/press/betu13_j/images/130812j0201.pdf
[115] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities, IAEA Safety Standards Series No. GSR Part 6, IAEA, Vienna (2014).
[116] TOKYO ELECTRIC POWER COMPANY, Submission of a Request to Change the "Implementation Plan of the Measures for the Specified Reactor Facilities at Fukushima Daiichi Nuclear Power Station" (2013), http://www.tepco.co.jp/en/press/corp-com/release/2013/1230256_5130.html
[117] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, Japan, (25 November–4 December 2013) (2013), Vienna http://www.meti.go.jp/press/2013/02/20140213003/20140213003-2.pdf.
[118] NUCLEAR REGULATION AUTHORITY, Measures for Mid-Term Risk Reduction at TEPCO's Fukushima Daiichi NPS (2015), http://www.nsr.go.jp/data/000098679.pdf
[119] TOKYO ELECTRIC POWER COMPANY, Progress Status of Mid-and-long Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4 (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m120730-e.pdf
[120] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, COUNCIL FOR THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER STATION, Mid-and-long-term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4, (2013), http://www.meti.go.jp/english/press/2013/pdf/0627_01.pdf
[121] INTER-MINISTERIAL COUNCIL FOR CONTAMINATED WATER AND DECOMMISSIONING ISSUES, Mid-and-long-term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station (2015).
[122] CENTERS FOR DISEASE CONTROL AND PREVENTION, Heat Stress (2014), http://www.cdc.gov/niosh/topics/heatstress/
[123] INTERNATIONAL RESEARCH INSTITUTE FOR NUCLEAR DECOMISSIONING, IRID 2014 (2014), http://irid.or.jp/_pdf/pamphlet2014_eng.pdf

[124] INTERNATIONAL RESEARCH INSTITUTE FOR NUCLEAR DECOMMISSIONING, About Us — IRID (International Research Institute for Nuclear Decommissioning) (2014), http://www.irid.or.jp/en/organization
[125] INTERNATIONAL RESEARCH INSTITUTE FOR NUCLEAR DECOMISSIONING, IRID 2014 (2014), http://irid.or.jp/_pdf/pamphlet2014_eng.pdf
[126] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, International Experts Meeting, 28 January–1 February 2013, Vienna, IAEA, Vienna (2013).
[127] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 (Second Mission), IAEA, Vienna (2014).
[128] NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, COUNCIL FOR THE DECOMMISSIONING OF TEPCO'S FUKUSHIMA DAIICHI NUCLEAR POWER STATION, Revised Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Station Units 1–4, (2013), http://josen.env.go.jp/en/documents/pdf/workshop_july_17-18_2013_02.pdf
[129] GOVERNMENT OF JAPAN, TOKYO ELECTRIC POWER COMPANY, Progress Status and Future Challenges of Mid-to-Long-Term Roadmap towards the Decommissioning of Units 1–4 of TEPCO Fukushima Daiichi Nuclear Power Plant (2012), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m121203-e.pdf
[130] TOKYO ELECTRIC POWER COMPANY, 5th meeting of Working Group 5, official communication (2014).
[131] CONTAMINATED WATER TREATMENT MEASURES COMMITTEE, Measures for the Prevention of Groundwater Inflow, TEPCO, Tokyo (2012).
[132] TOKYO ELECTRIC POWER COMPANY, Status of the Fukushima Daiichi Nuclear Power Station with Focus on Countermeasures for Contaminated Water (2014), http://www.tepco.co.jp/en/decommision/planaction/images/140127_01.pdf
[133] TOKYO ELECTRIC POWER COMPANY, Contaminated Water Treatment (2015), http://www.tepco.co.jp/en/decommision/planaction/alps/index-e.html
[134] SECRETARIAT OF THE TEAM FOR COUNTERMEASURES FOR DECOMMISSIONING AND CONTAMINATED WATER TREATMENT, Summary of Decommissioning and Contaminated Water Management, Ministry of Economy, Trade and Industry (2014), http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20140529-e.pdf
[135] INTERNATIONAL ATOMIC ENERGY AGENCY, Final Report - IAEA International Peer Review Mission on Mid-and-Long Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 (Second Mission), Vienna, (25 November - 4 December 2013) (2013), https://www.iaea.org/sites/default/files/final_report120214.pdf.
[136] TOKYO ELECTRIC POWER COMPANY, Bypass of Clean Groundwater to Ocean Starts, Fukushima Daiichi NPS Prompt Report, (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1236566_5892.html
[137] GOTO, O., Countermeasures for Contaminated Water at TEPCO's Fukushima Daiichi Nuclear Power Plant, (2013), https://www.iaea.org/sites/default/files/countermeasures160913.pdf
[138] TOKYO ELECTRIC POWER COMPANY, Land-side Impermeable Wall (Frozen Soil Wall) (2015), http://www.tepco.co.jp/en/decommision/planaction/landwardwall/index-e.html
[139] TOKYO ELECTRIC POWER COMPANY, Progress Status of Groundwater Bypass Construction and Future Schedule (2013), http://www.tepco.co.jp/en/nu/fukushima-np/handouts/2013/images/handouts_ 130128_04-e.pdf
[140] TOKYO ELECTRIC POWER COMPANY, "Measures to stop or reduce ingress of groundwater into reactor and turbine buildings", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.

[141] TOKYO ELECTRIC POWER COMPANY, Present Status of Fukushima Daiichi NPS and Implemented Countermeasures — 2.4 Future Large-scale Earthquake and Tsunami Countermeasures (2014), http://www.tepco.co.jp/en/nu/fukushima-np/review/review2_4-e.html
[142] NUCLEAR SAFETY COMMISSION, Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilties (2006), http://www.nsr.go.jp/archive/nsc/NSCenglish/documents/decisions/2006/2006_59_1.pdf
[143] TOKYO ELECTRIC POWER COMPANY, Outline of "Reports about the Study Regarding Current Seismic Safety and Reinforcement of Reactor Buildings at Fukushima Daiichi Nuclear Power Station (3)" (2011), http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110826e3.pdf
[144] NUCLEAR REGULATION AUTHORITY, Outline of New Regulatory Requirements for Light Water Nuclear Power Plants (Earthquakes and Tsunamis) (2013), http://www.nsr.go.jp/data/000067118.pdf
[145] Building Standards Law, Law No. 201, 24 May, 1950, as amended in 2005 (Japan). http://www8.cao.go.jp/kisei-kaikaku/oto/otodb/english/houseido/hou/lh_06010.html
[146] NUCLEAR REGULATION AUTHORITY, An Implementation Plan for the Specified Reactor Facilities to Be Installed of Fukushima Daiichi Nuclear Power Plant (2012), https://www.nsr.go.jp/activity/earthquake/kisei/plan/plan01.html
[147] TOKYO ELECTRIC POWER COMPANY, Dose Reduction Plans of Fukushima Daiichi (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/d140424_07-j.pdf
[148] TOKYO ELECTRIC POWER COMPANY, Increases in the Concentration of Radioactive Materials in Seawater and Groundwater on the Ocean Side of the Site: Current Situation and Countermeasures (2013), http://www.tepco.co.jp/en/decommision/planaction/images/handouts_130722_07-e.pdf
[149] TOKYO ELECTRIC POWER COMPANY, Report on the Plan towards Radiation Dose Reduction at the Site Boundaries at Fukushima Daiichi Nuclear Power Station (2012) (in Japanese), http://www.tepco.co.jp/cc/press/betu12_j/images/120921j0301.pdf
[150] TOKYO ELECTRIC POWER COMPANY, "Status of efforts to remove fuel from the unit 1–4 spent fuel pools", paper presented at IAEA International Peer Review Mission on Mid-and-Long Term Roadmap towards the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[151] TOKYO ELECTRIC POWER COMPANY, Status of Efforts to Remove Fuel from the Unit 1–4 Spent Fuel Pools (2013).
[152] BUONGIORNO, J., BWR Description (2010), http://ocw.mit.edu/courses/nuclear-engineering/22-06-engineering-of-nuclear-systems-fall-2010/lectures-and-readings/MIT22_06F10_lec06b.pdf
[153] TOKYO ELECTRIC POWER COMPANY, Investigation of the Inside of Unit 3 Spent Fuel Pool Using an Underwater Camera at Fukushima Daiichi NPP (2012), http://photo.tepco.co.jp/en/date/2012/201210-e/121015-02e.html
[154] TOKYO ELECTRIC POWER COMPANY, Summary of Decommissioning and Contaminated Water Management (15 December 2014), http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/d141225_01-e.pdf
[155] TOKYO ELECTRIC POWER COMPANY, Recent Topics: Fuel Removal From Unit 4 Reactor Building Completed At Fukushima Daiichi (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1246703_5892.html
[156] TOKYO ELECTRIC POWER COMPANY, Fukushima Daiichi NPS Prompt Report 2014 (2014), http://www.tepco.co.jp/en/press/corp-com/release/2014/1246703_5892.html
[157] INTERNATIONAL ATOMIC ENERGY AGENCY, INES — The International Nuclear and Radiological Event Scale (2014), http://www-ns.iaea.org/tech-areas/emergency/ines.asp
[158] NUCLEAR REGULATORY COMMISSION, TMI-2 Core End-State Configuration (2007), http://www.nrc.gov/images/reading-rm/photo-gallery/20071114-006.jpg
[159] NEGIN, C.A., "Challenges for removal of damaged fuel and debris", IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013), http://www-pub.iaea.org/iaeameetings/IEM4/30Jan/Negin.pdf

[160] WORLD NUCLEAR ASSOCIATION, Fukushima: Background on Reactors (2012), http://www.world-nuclear.org/info/Safety-and-Security/Safety-of-Plants/Appendices/ Fukushima--Reactor-Background/
[161] HOLTON, W.C., NEGIN, C.A., OWRUTSKY, S.L., The Cleanup of Three Mile Island Unit 2 — A Technical History: 1979 to 1990 (1990), http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=NP-6931&Mode=download
[162] TOKYO ELECTRIC POWER COMPANY, Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression: Progress Report No. 1 (2013), http://www.tepco.co.jp/en/press/corp-com/release/betu13_e/images/131213e0102.pdf
[163] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013)International Experts´ Meeting on Decommissioning and Remediation after a Nuclear Accident, Vienna, (28 January - 1 February 2013), This IEM appears already Ref. 158. http://www-pub.iaea.org/iaeameetings/IEM4.aspx .
[164] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Power Reactor Information System (PRIS) (2015), http://www.iaea.org/pris/
[165] INTERNATIONAL ATOMIC ENERGY AGENCY, Decommissioning of Facilities using Radioactive Material, IAEA Safety Standards Series, No. WS-R-5, IAEA, Vienna (2006). (This publications is superseded by GSR Part 6 (2014))
[166] INTERNATIONAL ATOMIC ENERGY AGENCY, On-site Disposal as a Decommissioning Strategy, IAEA-TECDOC-1124, IAEA, Vienna (1999).
[167] TOKYO ELECTRIC POWER COMPANY, Comments received on Section 5, official communication (2015).
[168] TOKYO ELECTRIC POWER COMPANY, Fuel Removal of the Unit 4 Spent Fuel Pool of the Fukushima Daiichi NPP Completed (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/handouts/2014/images/handouts_141222_04-j.pdf
[169] Final Disposal of High-Level Radioactive Waste Act, No. 117, 31 May 2000, as amended by Act Nr. 84 of 2007 (Japan).
[170] GOVERNMENT OF JAPAN, National Report of Japan to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (2011), http://www.nsr.go.jp/english/cooperation/conventions/data/jc_4th.pdf
[171] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Main Points and Policy Package in “Japan’s Nuclear Energy National Plan” (2006), http://www.enecho.meti.go.jp/en/reports/pdf/rikkokugaiyou.pdf
[173] GOVERNMENT OF JAPAN, NUCLEAR EMERGENCY RESPONSE HEADQUARTERS, Report of the Japanese Government to IAEA Ministerial Conference on Nuclear Safety — Accident at TEPCO’s Fukushima Nuclear Power Stations (2011), http://www.iaea.org/newscenter/focus/fukushima/japan-report
[172] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Basic Policy on the Final Disposal of Designated Radioactive Wastes was Revised (2015), http://www.meti.go.jp/english/press/2015/0522_01.html
[174] CABINET SECRETARIAT OF THE GOVERNMENT OF JAPAN, Reform of Nuclear Regulation Organisation and System in Japan (2011), http://www.nsr.go.jp/archive/nisa/shingikai/700/14/240724/AT-6-1.pdf
[175] NUCLEAR REGULATION AUTHORITY, Recommendation from Advisory Committee for Prevention of Nuclear Accident (2011), http://www.nsr.go.jp/data/000068993.pdf
[176] MINISTRY OF THE ENVIRONMENT, Approaches to Ensuring Safety in the Act on Special Measures Concerning the Handling of Radioactive Pollution, (2013).
[177] INTERNATIONAL ATOMIC ENERGY AGENCY, Legal and Governmental Infrastructure for Nuclear, Radiation, Radioactive Waste and Transport Safety, IAEA Safety Standards Series No. GS-R-1, IAEA, Vienna (2000). (This publications is superseded by GSR Part 1 (2010)).

[178] NUCLEAR SAFETY COMMISSION, Near-term Policy to Ensure the Safety for Treating and Disposing Contaminated Waste around the Site of Fukushima Dai-ichi Nuclear Power Plants (2011), http://www.nsr.go.jp/archive/nsc/NSCenglish/geje/20110603suggest_2.pdf
[179] MINISTRY OF THE ENVIRONMENT, Guidelines for Treatment of Waste Contaminated with Radioactive Materials Discharged by the Accident, (2013), http://www.env.go.jp/en/focus/docs/files/20140725-87-0.pdf
[180] MINISTRY OF THE ENVIRONMENT, Countermeasures for the Great East Japan Earthquake (2012–2015), https://www.env.go.jp/en/focus/docs/01_cgeje/index.html
[181] MINISTRY OF THE ENVIRONMENT, Management of soils and solid wastes contaminated by the Fukushima NPP accident, official communication (2013).
[182] JAPAN NUS CO., LTD, Disposal of Waste from Contaminated Areas around Fukushima, RSLS Mtg Int. Working Forum on Regulatory Supervision of Legacy Sites Technical Meeting, Vienna, (2013), http://gnssn.iaea.org/RTWS/rsls-public/Shared%20Documents/Meetings/Fourth%20Meeting%20Oct%2021-24,%202013/Disposal%20of%20Waste%20%20from%20Contaminated%20Areas%20around%20Fukushima_Takashi%20Nakamura.ppt. .
[183] MINISTRY OF THE ENVIRONMENT, Re-estimation of removed soil, etc. generated in Fukushima Prefecture, Investigative Commission of Safety (2nd Session), official communication (2013).
[184] GOVERNMENT OF JAPAN, Estimation of quantity of waste within countermeasure area (December 2013), official communication (2014).
[185] MORITANI, N., Current issue on management of off-site waste contaminated with radioactive materials due to the accident at Fukushima nuclear power stations, official communication (2013).
[186] MINISTRY OF THE ENVIRONMENT, Current status of designated waste (December 2014), official communication (2015).
[187] MINISTRY OF THE ENVIRONMENT, Future plans for treatment for each municipality in countermeasure area, official communication (2013).
[188] MINISTRY OF THE ENVIRONMENT, Processing flow of waste in countermeasure area, official communication (2013).
[189] GOVERNMENT OF JAPAN, Schematic Diagram of a Temporary Storage Facility (Example) (2015), http://josen.env.go.jp/en/roadmap/pdf/chart1_5.pdf
[190] MINISTRY OF THE ENVIRONMENT, Basic Policy on Interim Storage and Other Facilities Required for the Handling of the Environmental Pollution from Radioactive Materials Associated with the Accident at Tokyo Electric Power Co.'s Fukushima Daiichi Nuclear Power Stations (2011), http://josen.env.go.jp/en/roadmap/pdf/basic_policy.pdf
[191] MINISTRY OF THE ENVIRONMENT, Management state of waste in countermeasure area, official communication (2013).
[192] MINISTRY OF THE ENVIRONMENT, Management of Off-site Waste Contaminated with Radioactive Material Due to the Accident at Fukushima Nuclear Power Station (2012), https://www.env.go.jp/en/focus/docs/files/20121128-58.pdf
[193] MINISTRY OF THE ENVIRONMENT, Guidelines on disposal methods for incinerated ash and other waste with radiation levels higher than 8,000 Bq/kg up to less than 100,000 Bq/kg, official communication (2011).
[194] YASUI, S., New regulations for radiation protection for work involving radioactive fallout emitted by the TEPCO Fukushima Daiichi APP accident — Disposal of contaminated soil and wastes, Journal of Occupational and Environmental Hygiene **11** 10 (2014) D147–D156.
[195] SHIRATORI, Y., TAGAWA, A., FY 2011 "Decontamination technology demonstration test project", paper presented at Mtg for Reporting the Results of the Decontamination Demonstration Model Project, Fukushima, 2012, http://www.jaea.go.jp/fukushima/decon04/english/3-1%20Decontamination Technology_Demonstration_Test_Project.pdf
[196] ITO, Y., "Overview of the results of the decontamination model projects — role and overview of the model projects", paper presented at Mtg for Reporting the Results of the Decontamination Demonstration Model Project, Fukushima, 2012, http://www.jaea.go.jp/fukushima/decon04/english/1%20Overview.pdf

[197] TAGAWA, A., WATANABE, M., "Demonstration test results of organic materials' volumetric reduction using bio-ethanol, thermal decomposition and burning", paper presented at 15th Int. Conf. on Environmental Remediation and Radioactive Waste Management, Brussels, 2013, http://www.asmeconferences.org/ICEM2013/pdfs/96133.pdf
[198] JAPAN ATOMIC ENERGY AGENCY, NAKAYAMA, S., KAWASE, K., IIJIMA, K., KATO, M., "Waste handling and storage in the decontamination pilot projects by JAEA for environments of Fukushima", paper presented at 15th Int. Conf. on Environmental Remediation and Radioactive Waste Management, Brussels, 2013, http://www.asmeconferences.org/ICEM2013/pdfs/96129.pdf
[199] ARITOMI, M., et al., Demonstration test on purification systems of contaminated water using liquid–solid settling technology by flocculants (decontamination technology using high-pressure water), J. Nucl. Sci. Technol. **50** 1 (2013) 35–45.
[200] KAWAKAMI, Y., "Progress on off-site cleanup effort on Fukushima nuclear power plants accident", paper presented at IAEA Technical Mtg on the Disposal of Large Volumes of Radioactive Waste, Vienna, 2013, http://gnssn.iaea.org/RTWS/general/Shared%20Documents/Waste%20Management/Waste%20Management%20after%20Emergency/Nov%202013%20NE's%20TM%20on%20the%20Disposal%20of%20large%20volume%20of%20radioactive%20waste/Tuesday/presentation%20for%20IAEA%20Rev_5_Kawakami_JAP.pdf
[201] MINISTRY OF THE ENVIRONMENT, Examples of TSS designs, official communication (2015).
[202] MINISTRY OF THE ENVIRONMENT, Guidelines for Waste from Decontamination Work (2013), http://www.env.go.jp/en/focus/docs/files/20140725-87-4.pdf
[203] MINISTRY OF THE ENVIRONMENT, Examples of TSSs for designated waste, official communication (2015).
[204] MINISTRY OF THE ENVIRONMENT, Progress on Off-site Cleanup Efforts in Japan (2013), http://www.icrp.org/docs/Tsutomu%20Sato%20Progress%20on%20Off-site%20Cleanup%20Efforts%20in%20Japan.pdf
[205] INTERNATIONAL ATOMIC ENERGY AGENCY, Predisposal Management of Radioactive Waste, IAEA Safety Standards Series No. GSR Part 5, IAEA, Vienna (2009).
[206] INTERNATIONAL ATOMIC ENERGY AGENCY, Considerations in the Development of Near Surface Repositories for Radioactive Waste, Technical Report Series No. 417, IAEA, Vienna (2003).
[207] TOKYO ELECTRIC POWER COMPANY, "Radioactive waste management — toward the decommissioning of Fukushima Daiichi nuclear power station units 1–4", paper presented at IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap Towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, 2013.
[208] TOKYO ELECTRIC POWER COMPANY, Radioactive Waste Processing and Disposal (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/d141225_12-j.pdf
[209] TOKYO ELECTRIC POWER COMPANY, Mid-and-Long-Term Plans for Solid Waste Storage of the Fukushima Daiichi Nuclear Power Station (Draft) (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/l140407_05-j.pdf
[210] GOVERNMENT OF JAPAN, Types, quantities, and characteristics of waste and contaminated material — trees and debris, official communication (2015).
[211] TOKYO ELECTRIC POWER COMPANY, A mid-and-long-term plan for storage of solid wastes in Fukushima Daiichi NPS, official communication (2014).
[212] TOKYO ELECTRIC POWER COMPANY, Answers to waste mangement questions — 2nd submission, official communication (2014).
[213] TOKYO ELECTRIC POWER COMPANY, Groundwater bypass efforts (2014) (in Japanese), http://www.tepco.co.jp/nu/fukushima-np/info/baypass-j.html
[214] TOKYO ELECTRIC POWER COMPANY, Contaminated Water Leakage from the Tank in the H4 Area, (2013), http://www.tepco.co.jp/en/nu/fukushima-np/water/13082101-e.html

[215] TOKYO ELECTRIC POWER COMPANY, TEPCO Group Decommissioning and Decontamination Action Plan (2014),
http://www.tepco.co.jp/en/decommision/team/images/FukushimaDaiichiDandD_02.pdf
[216] TOKYO ELECTRIC POWER COMPANY, "Measures for processing of accumulated water at the Fukushima Daiichi Power Station", paper presented at IAEA International Peer Review Mission on Mid-and-Long Term Roadmap towards the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture 2013.
[217] TOKYO ELECTRIC POWER COMPANY, Accumulated Water Processing Schedule (2014) (in Japanese),
http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/d141225_07-j.pdf
[218] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Progress Status and Future Challenges of the Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (2014),
http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20140327-e.pdf
[219] TOKYO ELECTRIC POWER COMPANY, Current Situation of Storage and Processing of Stagnant Water Containing a High Concentration of Radioactive Substances in the Fukushima Daiichi Nuclear Power Plant, Report No. 182 (2014) (in Japanese),
http://www.tepco.co.jp/cc/press/betu14_j/images/141226j0201.pdf
[220] TOKYO ELECTRIC POWER COMPANY, Plans for the Expansion of Stagnant Water Storage Tanks at the Units 1 to 4 in the Fukushima Daiichi Nuclear Power Plant (as of October 2014) (2014) (in Japanese),
http://www.tepco.co.jp/cc/press/betu14_j/images/141125j0201.pdf
[221] TOKYO ELECTRIC POWER COMPANY, Soundness of storage tanks secured at Fukushima Daiichi NPS (2014),
http://www.tepco.co.jp/en/press/corp-com/release/2014/1239559_5892.html
[222] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Fact Sheet: Overview of Contaminated Ground Water Leakage at TEPCO's Fukushima Daiichi NPS (2013),
http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/20130822_01.pdf
[223] INTERNATIONAL ATOMIC ENERGY AGENCY, Preliminary Summary Report: IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Third Mission), Tokyo and Fukushima Prefecture, Japan, 9–17 February 2015 (2015),
https://www.iaea.org/sites/default/files/missionreport170215.pdf
[224] TOKYO ELECTRIC POWER COMPANY, Installation of Facilities for Temporary Storage Dry Casks (2014) (in Japanese),
http://www.meti.go.jp/earthquake/nuclear/pdf/120625/120625_02cc.pdf
[225] COMMITTEE ON COUNTERMEASURES FOR CONTAMINATED WATER TREATMENT, Preventative and Multilayered Measures for Contaminated Water Treatment at the Fukushima Daiichi Nuclear Power Station of Tokyo Electric Power Company (2013),
http://www.meti.go.jp/english/earthquake/nuclear/decommissioning/pdf/131210report_E.pdf
[226] TOKYO ELECTRIC POWER COMPANY, The Current Situation of the Operation for the Circulation Loop Reduction (2014) (in Japanese),
http://www.tepco.co.jp/nu/fukushima-np/roadmap/images/d141225_06-j.pdf
[227] INTERNATIONAL RESEARCH INSTITUTE FOR DECOMISSIONING, R&D related to the processing/disposal of radioactive solid waste, IAEA International Peer Review Mission on Mid-and-Long Term Roadmap towards the decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1-4 (Second Mission), Tokyo and Fukushima Prefecture, 25 November – 4 December 2013, (2013).
[228] MINISTRY OF HEALTH, LABOUR AND WELFARE, The Status on the Exposure Dose, Health Care Management and Radiation Protection of the Workers at Fukushima Daiichi Nuclear Power Plant (2014) (in Japanese),
http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/index.html
[229] RECONSTRUCTION AGENCY, Basic Guidelines for Reconstruction in Response to the Great East Japan Earthquake (2011),
https://www.reconstruction.go.jp/topics/basic_guidelines_reconstruction.pdf

[230] FUKUSHIMA PREFECTURAL GOVERNMENT, Steps for Revitalization in Fukushima (2013), http://www.pref.fukushima.lg.jp/download/1/fukkonoayumi04.pdf
[231] RECONSTRUCTION AGENCY, 2012 Report of the Result of the Survey on Residents' Intention in the Municipalities Affected by the Nuclear Accident (2013) (in Japanese), http://www.reconstruction.go.jp/topics/20130507_ikouchousahoukokusho.pdf
[232] CABINET SECRETARIAT OF THE GOVERNMENT OF JAPAN, On the Formation of the Reconstruction Design Council in Response to the Great East Japan Earthquake (2011), http://www.cas.go.jp/jp/fukkou/english/pdf/grounds.pdf
[233] RECONSTRUCTION DESIGN COUNCIL IN RESPONSE TO THE GREAT EAST JAPAN EARTHQUAKE, Towards Reconstruction: "Hope Beyond the Disaster", Report to the Prime Minister of the Reconstruction Design Council in Response to the Great East Japan Earthquake (2011), http://www.cas.go.jp/jp/fukkou/english/pdf/report20110625.pdf
[234] Basic Act on Reconstruction from the Great East Japan Earthquake, Act 76, 24 June 2011 (Japan) , https://www.reconstruction.go.jp/english/topics/Basic_Act_on_Reconstruction.pdf.
[235] TOKYO ELECTRIC POWER COMPANY, Establishment of the Fukushima Revitalization Headquarters (2012), http://www.tepco.co.jp/en/press/corp-com/release/2012/1223417_1870.html
[236] THE NATIONAL DIET OF JAPAN FUKUSHIMA NUCLEAR ACCIDENT INDEPENDENT INVESTIGATION COMMISSION, The National Diet of Japan, Tokyo (2012), http://warp.da.ndl.go.jp/info:ndljp/pid/3751543/naiic.go.jp/en/report/
[237] CABINET OFFICE, Designating and Rearranging the Areas of Evacuation, Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, IAEA, Tokyo and Fukushima Prefecture, 14–21 October (2013), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20120723_01.pdf
[238] CABINET OFFICE, Support Team for Residents Affected By Nuclear Incidents, Designating and Rearranging the Areas of Evacuation (2014).
[239] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Restricted Area, Deliberate Evacuation Area, Evacuation-Prepared Area in Case of Emergency and Regions Including Specific Spots Recommended for Evacuation (2011), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/evacuation_map_a.pdf
[240] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Evacuation Areas and Their Population and the Number of Households (2014) (in Japanese), http://www.meti.go.jp/earthquake/nuclear/pdf/141001.pdf
[241] FUKUSHIMA PREFECTURAL GOVERNMENT, Steps for Revitalization in Fukushima (2015), http://www.pref.fukushima.lg.jp.e.od.hp.transer.com/sec/11015b/fukkoukeikaku1151.html
[242] INOUE, T., Current Issue on Remediation in Fukushima and Creation of Newborn Fukushima (2013), http://www-pub.iaea.org/iaeameetings/IEM4/30Jan/Inoue.pdf
[243] SHIGEMURA, J., TANIGAWA, T., SAITO, I., NOMURA, S., Psychological distress in workers at the Fukushima nuclear power plants, JAMA **308** 7 (2012) 667–669.
[244] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, ICRP and Fukushima (2014), www.icrp.org/page.asp?id=189
[245] RECONSTRUCTION AGENCY, Summary of the Results of Opinion Survey of Residents of Municipalities in the Areas Affected By the Fukushima Daiichi NPP accident (in Japanese), http://www.reconstruction.go.jp/topics/main-cat1/sub-cat1-4/ikoucyousa/
[246] RECONSTRUCTION AGENCY, Situation of receiving the children under school age, school children and students affected by the Great East Japan Earthquake, official communication (2013).
[247] RECONSTRUCTION AGENCY, The Result of the Survey on Namie Town Residents' Intention (Preliminary Report), Fukushima Prefecture and Namie Town, (2013).
[248] FUKUSHIMA PREFECTURAL GOVERNMENT, The Path towards the Revitalisation in Fukushima (2013), http://www-pub.iaea.org/iaeameetings/Fukushima/ws3/Uchibori.pdf
[249] BROMET, E.J., Emotional consequences of nuclear power plant disasters, Health Phys. **106** 2 (2014) 206–210.

[250] YASUTAKA, T., NAITO, W., NAKANISHI, J., Cost and effectiveness of decontamination strategies in radiation contaminated areas in Fukushima in regard to external radiation dose, PLoS ONE **8** 9 (2013).
[251] YASUTAKA, T., et al., A GIS-based evaluation of the effect of decontamination on effective doses due to long-term external exposures in Fukushima, Chemosphere **93** 6 (2013) 1222–1229.
[252] JAPAN EXTERNAL TRADE ORGANISATION, 2011 JETRO Global Trade and Investment Report (2011), https://www.jetro.go.jp/en/reports/white_paper/trade_invest_2011.pdf
[253] FOOD STANDARDS AGENCY, Import of Feed and Food Originating in or Consigned from Japan (2012), http://www.food.gov.uk/business-industry/imports/banned_restricted/japan
[254] FISHERIES AGENCY, The Leakage of Contaminated Water at TEPCO's Fukushima Daiichi Nuclear Power Station and the Safety of Fishery Products (2015), http://www.jfa.maff.go.jp/e/
[255] RECONSTRUCTION AGENCY, Situation of tourism in Fukushima, official communication (2013) (in Japanese).
[256] RECONSTRUCTION AGENCY, Outlook of the trade of Tohoku Area, official communication (2013).
[257] JAPAN EXTERNAL TRADE ORGANISATION, JETRO Global Trade and Investment Report (2014), http://www.jetro.go.jp/en/reports/white_paper/trade_invest_2014.pdf
[258] FUKUSHIMA PREFECTURAL GOVERNMENT, Steps for Revitalization in Fukushima (2014), http://www.pref.fukushima.lg.jp.e.od.hp.transer.com/sec/11015b/fukkoukeikaku1081.html
[259] TOKYO METROPOLITAN CENTRAL WHOLESALE MARKET, Market Guide (2015), http://www.shijou.metro.tokyo.jp/english/
[260] CONSUMER AFFAIRS AGENCY, Policy for measures to promote consumer understanding of food and radioactivity, official communication (2013).
[261] CONSUMER AFFAIRS AGENCY, Outline of the policy for measures to promote consumer understanding of food and radioactivity, official communication (2013).
[262] MINISTRY OF HEALTH, LABOUR AND WELFARE, The current situation of hospitals in Fukushima Prefecture, official communication (2013).
[263] YAMASHITA, J., SHIGEMURA, J., The Great East Japan Earthquake, tsunami, and Fukushima Daiichi nuclear power plant accident: A triple disaster affecting the mental health of the country, Psychiatr. Clin. North Am. **36** 3 (2013) 351–370.
[264] ETHOS IN FUKUSHIMA, Ethos in Fukushima (2014) (in Japanese), http://ethos-fukushima.blogspot.no/
[265] FUKUSHIMA PREFECTURAL GOVERNMENT, Plan for Revitalization in Fukushima Prefecture (Second Version) (2012), http://www.pref.fukushima.lg.jp/download/1/plan_for_revitalization2_outline.pdf
[266] YASUMURA, S., et al., Study protocol for the Fukushima health management survey, J. Epidemiol. **22** 5 (2012) 375–383.
[267] YASUMURA, S., Overview of the Fukushima health management survey, (2014), http://www.fmu.ac.jp/radiationhealth/workshop201402/presentation/presentation-1-2-e.pdf
[268] MINISTRY OF HEALTH, LABOUR AND WELFARE, Guidelines on Maintaining and Improving Health of Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (Overview) (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/pr_111011_a02.pdf
[269] MINISTRY OF HEALTH, LABOUR AND WELFARE, Framework for Health-care of Emergency Workers at the TEPCO Fukushima Daiichi Nuclear Power Plant (2011), http://www.mhlw.go.jp/english/topics/2011eq/workers/tepco/lhc/ors_001.html
[270] YASUI, S., Lessons learned: medical and health care management for emergency workers at the TEPCO Fukushima Daiichi APP accident, Journal of Occupational and Environmental Hygiene **11** 5 (2014) D49–58.
[271] Convention on Third Party Liability in the Field of Nuclear Energy, 29th July 1960, as amended by the Additional Protocol of 28th January 1964 and by the Protocol of 16th November 1982 (the Paris Convention).

[272] Vienna Convention on Civil Liability for Nuclear Damage (the 1963 Vienna Convention), 21 May 1963, and the 1997 Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage (the 1997 Vienna Convention), 12 September 1997.
[273] Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention (the Joint Protocol), 21 September 1988.
[274] Convention on Supplementary Compensation for Nuclear Damage, 12 September 1997.
[275] INTERNATIONAL ATOMIC ENERGY AGENCY, The 1997 Vienna Convention on Civil Liability for Nuclear Damage and the 1997 Covention on Supplementary Compensation for Nuclear Damage — Explanatory Texts, IAEA International Law Series No. 3 , IAEA, Vienna (2007).
[276] Act on Compensation for Nuclear DamageAct. No. 147 of 1961, as amended by act No. 19 of 17 April 2009 (Japan).
[277] Act on Indemnity Agreements for Compensation of Nuclear Damage, Act No. 148 of 1961, as amended by Act No. 19 of 17 April 2009 (Japan).
[278] Act on Emergency Measures on Damage Caused by Nuclear Accident in 2011, Act No. 91 of 2011 (Japan).
[279] Nuclear Damage Compensation Facilitation Corporation Act, Act No. 94 of 10 August 2011 (Japan).
[280] OECD NUCLEAR ENERGY AGENCY, Japan's Compensation System for Nuclear Damage (2012), http://www.oecd-nea.org/law/fukushima/7089-fukushima-compensation-system-pp.pdf
[281] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, DISPUTE RECONCILIATION COMMITTEE FOR NUCLEAR DAMAGE COMPENSATION, Interim Guidelines on Determination of the Scope of Nuclear Damage Resulting from the Accident at the Tokyo Electric Power Company Fukushima Daiichi and Daini Nuclear Power Plants (2011) (in Japanese), http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/houkoku/__icsFiles/afieldfile/2011/08/17/1309452_1_2.pdf
[282] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, DISPUTE RECONCILIATION COMMITTEE FOR NUCLEAR DAMAGE COMPENSATION, Supplement to the Interim Guidelines on Determination of the Scope of Nuclear Damage Resulting from the Accident at the Tokyo Electric Power Company Fukushima Daiichi and Daini Nuclear Power Plants (2011) (in Japanese), http://www.mext.go.jp/b_menu/shingi/chousa/kaihatu/016/houkoku/__icsFiles/afieldfile/2012/01/18/1315180_1.pdf
[283] MINISTRY OF EDUCATION, CULTURE, SPORTS, SCIENCE AND TECHNOLOGY, Third Supplement to the Interim Guidelines on Criteria for Determining Nuclear Damage Indemnification Coverage (Damages to the Agriculture, Forestry and Fishery Industries and the Food Industry Caused by Harmful Rumors) (2013) (in Japanese), http://www.mext.go.jp/component/a_menu/science/detail/__icsFiles/afieldfile/2013/12/27/1329116_011_1.pdf
[284] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, For Accelerating the Reconstruction of Fukushima from the Nuclear Disaster on 20 December 2013 (2013), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/pdf/20140605_01.pdf
[285] TOKYO ELECTRIC POWER COMPANY, Compensation for Additional Costs resulting from Early Return after the Evacuation Order is Lifted (2014) (in Japanese), http://www.tepco.co.jp/cc/press/2014/1235026_5851.html
[286] MORI, H., et al., Challenges of Decontamination, Community Regeneration and Livelihood Rehabilitation (2013), http://pub.iges.or.jp/modules/envirolib/upload/4718/attach/web_FAIRDO_2nd_Discussion_Paper_E_130906.pdf
[287] MINISTRY OF THE ENVIRONMENT, Stakeholder Communication Overview for Decontamination, Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 14–21 October 2013 (2013).
[288] IZUMO, A., Experience and Challenges in the Remediation of Contaminated Areas after the Fukushima NPP Accident (2012), http://www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/DISPONET/disponetfiles/TCStakeholderDialogue_Poland2012/TC-StakeholderDialogue Poland2012-ExpChallengesAfterFukushima_Izumo.pdf

[289] OUGHTON, D., FORSBERG, E.M., BAY, I., KAISER, M., HOWARD, B., An ethical dimension to sustainable restoration and long-term management of contaminated areas, J. Environ. Radioact. **74** 1–3 (2004) 171–183.
[290] UNITED NATIONS DEVELOPMENT PROGRAMME, The Human Consequences of the Chernobyl Nuclear Accident: A Strategy for Recovery (2002), http://chernobyl.undp.org/english/docs/strategy_for_recovery.pdf
[291] DUBREUIL, G.H., et al, Chernobyl post-accident management: the ETHOS project, Health Physics **77** 4 (1999) 361–372.
[292] SATO, O., NONAKA, S., TADA, J.I., Intake of radioactive materials as assessed by the duplicate diet method in Fukushima, J. Radiol. Protect. **33** 4 (2013) 823–838.
[293] HAYANO, R.S., et al., Internal radiocesium contamination of adults and children in Fukushima 7 to 20 months after the Fukushima NPP Accident as measured by extensive whole-body-counter surveys, Proc. Jpn Acad. Sci. Series B **89** 4 (2013) 157–163.
[294] NAITO, W., UESAKA, M., YAMADA, C., ISHII, H., Evaluation of dose from external irradiation for individuals living in areas affected by the Fukushima Daiichi nuclear plant accident, Radiat. Protect. Dosim. (2014).
[295] SAFECAST, Safecast Maps (2014), http://blog.safecast.org/
[296] FUKUSHIMA PREFECTURE, Decontamination measures in Fukushima Prefecture, official communication (2013).
[297] FUKUSHIMA PREFECTURE, "Decontamination in Date City", paper presented at the Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.
[298] FUKUSHIMA PREFECTURE, "Date City Implementation Plan", paper presented at the Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, 2013.
[299] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Report on Enhancing Transparency and Communication Effectiveness the Event of a Nuclear or Radiological Emergency, International Experts Meeting, 18–22 June 2012, Vienna, IAEA, Vienna (2012).,
[300] INTERNATIONAL ATOMIC ENERGY AGENCY, "Chairperson's summary", International Expert Meeting on Decommissioning and Remediation after a Nuclear Accident, International Expert Meeting on Decommissioning and Remediation after a Nuclear Accident, Vienna, (28 January – 1 February 2013).
[301] INTERNATIONAL ATOMIC ENERGY AGENCY, Mission Report: IAEA International Peer Review Mission on Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4, Tokyo and Fukushima Prefecture, Japan, 15–22 April 2013, IAEA, Vienna (2013), http://www.iaea.org/sites/default/files/missionreport220513.pdf
[302] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Conclusions and Recommendations of the Seventh ICRP Dialogue Meeting (2013), http://www.icrp.org/docs/dialogue-7-conclusions.pdf
[303] LEE, S., SINDELAR, R., TRIPLETT, M., UNITED STATES DEPARTMENT OF ENERGY, Report of the United States Embassy Science Fellows Support to the Government of Japan–Ministry of the Environment: Observations and Commentary on the Remediation of the Lands Off-site from the Fukushima Daiichi Reactors (2013), http://josen.env.go.jp/en/documents/pdf/workshop_july_17-18_2013_04.pdf
[304] MINISTRY OF ECONOMY, TRADE AND INDUSTRY, Assistance of Residents Affected by the Nuclear Incidents (2014), http://www.meti.go.jp/english/earthquake/nuclear/roadmap/
[305] FUKUSHIMA PREFECTURAL GOVERNMENT, Newspaper on Current Events in Fukushima (2014) (in Japanese), http://www.pref.fukushima.lg.jp/sec/16055b/wakarusinbun.html
[306] MINISTRY OF THE ENVIRONMENT, FUKUSHIMA PREFECTURE, Decontamination Information Plaza (2013), http://josen.env.go.jp/en/pdf/decontamination_information_plaza.pdf?0930

[307] MINISTRY OF THE ENVIRONMENT, Living in Fukushima: Stories of Decontamination and Reconstruction (2013),
http://josen-plaza.env.go.jp/materials_links/index.html#movie131007en
[308] TOKYO ELECTRIC POWER COMPANY, TEPCO's Efforts for Stakeholders Communication, IAEA International Peer Review Mission on Mid-And-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Second Mission), Tokyo and Fukushima Prefecture, (25 November–4 December 2013).
[309] TOKYO ELECTRIC POWER COMPANY, Progress Status and Future Challenges of the Mid-and-Long-Term Roadmap towards the Decommissioning of TEPCO's Fukushima Daiichi Nuclear Power Station Units 1–4 (Outline) (2014),
http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/d140228_01-e.pdf
[310] TOKYO ELECTRIC POWER COMPANY, The Current Situation at Fukushima Daiichi NPS: From 3.11 toward the Future (2015),
http://www.tepco.co.jp/en/decommision/index-e.html
[311] PERKO, T., VALUCH, J., NAGY, A., LAMMERS, P., MAYS, C., Overview of Mass and New Media Treatment of Ionizing Radiation Topics: The Case of Fukushima, (2013),
http://eagle.sckcen.be/en/Deliverables
[312] MINISTRY OF THE ENVIRONMENT, Securing Appropriate Decontamination Works (2013),
http://josen.env.go.jp/en/documents/pdf/securing_appropriate_decontamination_works.pdf
[313] KASPERSON, R.E., et al., The social amplification of risk: A conceptual framework, Risk Analysis **8** 2 (1988) 177–187.
[314] JAPAN ATOMIC ENERGY AGENCY, "Overview of the results of Fukushima decontamination pilot projects", IAEA International Experts Meeting on Decommissioning and Remediation after a Nuclear Accident, IAEA, Vienna (2013).
[315] MINISTRY OF THE ENVIRONMENT, "Decontamination effect of decontamination work", paper presented at the Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-site of the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture 2013.
[316] BALONOV, M., et al., "Theory and practice of large-scale decontamination of populated areas in the Bryansk region after the Chernobyl accident", Proc. Int. Sem. on Intervention Levels and Countermeasures for Nuclear Accidents, Cadarache, Commission of the European Communities, Luxembourg (1991) 397–415.
[317] JAPAN ATOMIC ENERGY AGENCY, Decontamination Pilot Projects Performed inside the Evacuation Zone Contaminated with Radioactive Fallout from the Fukushima Dai-ichi Nuclear Power Plant (2012) (in Japanese),
http://fukushima.jaea.go.jp/initiatives/cat01/entry02.html
[318] MINISTRY OF THE ENVIRONMENT, Report on a Decontamination Model Evaluation Project in Difficult-to-return Zones (2014) (in Japanese),
https://josen.env.go.jp/material/pdf/model_140529b.pdf
[319] MINISTRY OF THE ENVIRONMENT, The Results of Decontamination (Tamuara) (2014) (in Japanese),
http://josen.env.go.jp/area/data/tamura.html
[320] MINISTRY OF THE ENVIRONMENT, Exposure dose of workers, official communication, (2015).
[321] KIMURA, T., "Approach to countermeasures for reducing radiocaesium contamination in Agricultural soil and crops", Proc. Int. Science Symp. on Combating Radionuclide Contamination in Agro-soil Environment, Koriyama, 2012, International Science and Technology Center (2012) 312–316.
[322] MINISTRY OF AGRICULTURE, FORESTRY AND FISHERIES, Efforts for the Reconstruction Assistance of Agriculture, Forestry and Fisheries after the Great East Japan Earthquake (2014) (in Japanese),
http://www.maff.go.jp/j/kanbo/kihyo02/fukkou/pdf/2612_zen.pdf
[323] TOGAMURA, Y., "Reducing radionuclide contamination of forage crops", Proc. Int. Science Symp. on Combating Radionuclide Contamination in Agro-soil Environment, Koriyama, 2012, International Science and Technology Center (2012) 319–328.
[324] FESENKO, S.V., et al., An extended critical review of twenty years of countermeasures used in agriculture after the Chernobyl accident, Sci. Total Environ. **383** 1–3 (2007) 1–24.

[325] KATO, M., YAMADA, N., ICHIKI, T., KINOMURA, K., "Evaluation of radiation dose by wildfire in evacuation zone after the Fukushima accident", IAEA International Experts Meeting on Radiation Protection after the Fukushima Daiichi Accident: Promoting Confidence and Understanding, IAEA, Vienna (2014).
[326] SMITH, J.T., VOITSEKHOVITCH, O.V., HAKANSON, L., HILTON, J., A critical review of measures to reduce radioactive doses from drinking water and consumption of freshwater foodstuffs, J. Environ. Radioact. **56** 1–2 (2001) 11–32.
[327] VOITSEKHOVYCH, O., "Measures and restrictions applied in the areas of Ukraine affected by Chernobyl accident — lessons learned in remediation of aquatic systems", paper presented at Mtg on Cooperation Project between Fukushima Prefecture and IAEA, Fukushima, 2013.
[328] INOUE, M., et al., Spatial variations of low levels of ^{134}Cs and ^{137}Cs in seawaters within the Sea of Japan after the Fukushima Dai-ichi Nuclear Power Plant accident, Appl. Radiat. Isot. **81** (2013) 340–343.

ABBREVIATIONS

AIST	Advanced Industrial Science and Technology
ALPS	Advanced Liquid Processing System
ANRE	Agency for Natural Resources and Energy
BWR	boiling water reactor
CSC	Convention on Supplementary Compensation for Nuclear Damage
CST	condensate storage tank
D&D	decontamination and decommissioning
DE	decontamination effectiveness
DF	decontamination factor
DFa	decontamination factor (measured by the change in ambient dose rate at 1 m above the ground)
DFs	decontamination factor (measured by the change ambient dose rate at the surface, 1 cm above the ground)
DOE	United States Department of Energy
dw	dry weight
EDG	emergency diesel generator
FY	fiscal year
GSR	General Safety Requirements
HDPE	high density polyethylene
HEPA	high-efficiency particulate arrestance
HLW	high level radioactive waste
HP	hold points
ICRP	International Commission on Radiological Protection
ICSA	Intensive Contamination Survey Area
INES	International Nuclear and Radiological Event Scale
INLEX	International Expert Group on Nuclear Liability
IRID	International Research Institute for Nuclear Decommissioning
ISF	interim storage facility
IT	information technology
JAEA	Japan Atomic Energy Agency
JAEC	Japan Atomic Energy Commission
JNES	Japan Nuclear Energy Safety Organization
JNFL	Japan Nuclear Fuel Limited
LLW	low level radioactive waste
MAFF	Ministry of Agriculture, Forestry and Fisheries
METI	Ministry of Economy, Trade and Industry
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MHLW	Ministry of Health, Labour and Welfare
MOE	Ministry of the Environment
NARO	National Agricultural Research Organization
NDF	Nuclear Damage Compensation and Decommissioning Facilitation Corporation
NERHQ	Nuclear Emergency Response Headquarters
NIRS	National Institute of Radiological Sciences
NISA	Nuclear and Industrial Safety Agency
NPP	nuclear power plant
NRA	Nuclear Regulation Authority
NSC	Nuclear Safety Commission
NUMO	Nuclear Waste Management Organization of Japan
OECD	Organisation for Economic Co-operation and Development
OECD/NEA	OECD Nuclear Energy Agency
OP	Onahama Port
PCV	primary containment vessel

PWR	pressurized water reactor
R&D	research and development
RPV	reactor pressure vessel
SAR	social amplification of risk
SARRY	simplified active water retrieve and recovery system
SC	suppression chamber
SDA	Special Decontamination Area
SFP	spent fuel pool
SSCs	structures, systems and components
TEPCO	Tokyo Electric Power Company
TF	transfer factor
TMI	Three Mile Island
TRU	transuranic waste
TSS	temporary storage site
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

CONTRIBUTORS TO DRAFTING AND REVIEW

WORKING GROUP 5 (WG5): POST-ACCIDENT RECOVERY

Co-Chairs

Williams, G.
Australian Radiation Protection and Nuclear Safety Agency
Australia

Mele, I.
Department of Nuclear Energy
IAEA

Proehl, G.
Department of Nuclear Safety and Security
IAEA

Scientific Secretary

Delaunay, N.
Department of Nuclear Safety and Security
IAEA

Members

Al-Masri, M.S.
Atomic Energy Commission of Syria
Syrian Arab Republic

Balonov, M.
Institute of Radiation Hygiene
Russian Federation

Bassanelli, A.
Sogin SpA — Società Gestione Impianti Nucleari
Italy

Brennecke, P.
Senior Consultant
Germany

Darko, E.O.
Ghana Atomic Energy Commission
Ghana

Gallay, F.
Nuclear Safety Authority
France

Howard, B.J.
Centre for Ecology & Hydrology
United Kingdom

Inoue, T.
Central Research Institute of Electric Power Industry
Japan

Kifanga, L.D.
Tanzania Atomic Energy Commission
United Republic of Tanzania

Nakayama, S.
Japan Atomic Energy Agency
Japan

Oughton, D.H.
Norwegian University of Life Sciences
Norway

Rowan, D.
Atomic Energy of Canada Limited
Canada

Seitz, R.
Savannah River National Laboratory
USA

Tokarevsky, V.
Institute for Chernobyl Problems
Ukraine

Zeleznik, N.
Regional Environmental Center
Slovenia

Invited experts and contact points

Belencan, H.
Senior Consultant
USA

Negin, C.
Project Enhancement Corporation
USA

Takizawa, S.
Tokyo Electric Power Company
Japan

IAEA Secretariat staff supporting WG5

Izumo, A.
Fesenko, S.
Kumano, Y.
Monken-Fernandes, H.
Walker, J.
Sakai, K.
Yankovich, T.
Yonehara, H.

IAEA Secretariat

Project management

Project manager
Caruso, G.

Analytical project managers
Bevington, L. (Senior Safety Officer)
Boreta, B.
Massegg, V.

Graphics and data coordinator
Zimmermann, M.

Graphic designer
Kasper, M.

Implementation assistant
Gutierrez Flores, S.

Team assistant
Fitzpatrick, L.

Technical writers and editors
Boemeke, M.
Delves, D.
Harbison, S.
McDonald, A.
Ramesh, G.
Robinson, C.

Scientific Secretary of the Co-Chairs meetings
Webster, P.

External reviewers

Alonso, A., Spain
Gray, R., United Kingdom
Robinson, I., United Kingdom
Simmonds, J., United Kingdom
Webster, P., Canada

INTERNATIONAL TECHNICAL ADVISORY GROUP

Chairman

Meserve, R.
International Nuclear Safety Group (INSAG)

Scientific Secretary

Bevington, L.
Department of Nuclear Safety and Security
IAEA

Members

Asmolov, V.G.
JSC Concern Rosenergoatom

Carrière, J.M.
World Meteorological Organization

Clement, C.
International Commission on Radiological Protection

Cousins, C.
International Commission on Radiological Protection

De Boeck, B.
International Nuclear Safety Group

Echávarri, L.E. (until April 2014)
OECD Nuclear Energy Agency

Ellis, K.
World Association of Nuclear Operators

Fuketa, T.
International Nuclear Safety Group

Jamet, P.
International Nuclear Safety Group

Kim, M.
International Nuclear Safety Group

Laaksonen, J.
International Nuclear Safety Group

Le, C.D.
International Nuclear Safety Group

Liang, Q.
Food and Agriculture Organization

Mohammad Jais, A.
International Nuclear Safety Group

Magwood, W. (September 2014 onwards)
OECD Nuclear Energy Agency

Niu, S.
International Labour Organization

Sharma, S.K.†
International Nuclear Safety Group

Torgerson, D.
International Nuclear Safety Group

Weightman, M.
International Nuclear Safety Group

Weiss, W.
United Nations Scientific Committee on the Effects of Atomic Radiation

Wiroth, P.
International Nuclear Safety Group

Ziqiang, P.
International Commission on Radiological Protection

MEETINGS

Working Group (WG) meetings

18 March 2013
Initial meeting of the WG Co-Chairs, Vienna

21–22 March 2013
1st meeting of all WGs, Vienna

12–14 June 2013
2nd meeting of all WGs, Vienna

7–9 October 2013
3rd meeting of WGs 3, 4 and 5, Vienna

9–13 December 2013
4th meeting of all WGs, Vienna

10–14 February 2014
5th meeting of all WGs, Vienna

26–30 May 2014
6th meeting of WG 5, Vienna

International Technical Advisory Group (ITAG) meetings

21–22 March 2013
1st ITAG meeting, Vienna

10 June 2013
1st Joint ITAG/Co-Chairs meeting, Vienna

11 June 2013
2nd ITAG meeting, Vienna

6 December 2013
2nd Joint ITAG/Co-Chairs meeting, Vienna

7 May 2014
3rd Joint ITAG/Co-Chairs meeting, Vienna

23–24 October 2014
4th Joint ITAG/Co-Chairs meeting, Vienna

23–24 February 2015
5th Joint ITAG/Co-Chairs meeting, Vienna

Bilateral meetings in Japan

14–21 October 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Remediation

25–27 November 2013
CS to Discuss Issues Related to Radiological Consequences in Connection with the Preparation of Chapter 4 (Radiological Consequences) and Chapter 5 (Post-accident Recovery)

25 November–4 December 2013
Bilateral Discussions on Issues Related to the IAEA Report in the Area of Decommissioning

20–24 January 2014
CS to Discuss Issues Related to Regulatory Activities, Operating Experience and Waste Management Topics in Connection with the Preparation of the IAEA Report

23 January 2014
Meetings with Reconstruction Agency and Team in Charge of Assisting the Lives of Disaster Victims — Cabinet Office

IAEA
International Atomic Energy Agency

No. 24

ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

BELGIUM

Jean de Lannoy
Avenue du Roi 202, 1190 Brussels, BELGIUM
Telephone: +32 2 5384 308 • Fax: +32 2 5380 841
Email: jean.de.lannoy@euronet.be • Web site: http://www.jean-de-lannoy.be

CANADA

Renouf Publishing Co. Ltd.
22-1010 Polytek Street, Ottawa, ON K1J 9J1, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: http://www.renoufbooks.com

Bernan Associates
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

CZECH REPUBLIC

Suweco CZ, s.r.o.
SESTUPNÁ 153/11, 162 00 Prague 6, CZECH REPUBLIC
Telephone: +420 242 459 205 • Fax: +420 284 821 646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

FRANCE

Form-Edit
5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: fabien.boucard@formedit.fr • Web site: http://www.formedit.fr

Lavoisier SAS
14 rue de Provigny, 94236 Cachan CEDEX, FRANCE
Telephone: +33 1 47 40 67 00 • Fax: +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

L'Appel du livre
99 rue de Charonne, 75011 Paris, FRANCE
Telephone: +33 1 43 07 43 43 • Fax: +33 1 43 07 50 80
Email: livres@appeldulivre.fr • Web site: http://www.appeldulivre.fr

GERMANY

Goethe Buchhandlung Teubig GmbH
Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 874 015 • Fax: +49 (0) 211 49 874 28
Email: s.dehaan@schweitzer-online.de • Web site: http://www.goethebuch.de

HUNGARY

Librotrade Ltd., Book Import

Pesti ut 237. 1173 Budapest, HUNGARY
Telephone: +36 1 254-0-269 • Fax: +36 1 254-0-274
Email: books@librotrade.hu • Web site: http://www.librotrade.hu

INDIA

Allied Publishers

1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 4212 6930/31/69 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell

3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: http://www.bookwellindia.com

ITALY

Libreria Scientifica "AEIOU"

Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: http://www.libreriaaeiou.eu

JAPAN

Maruzen Co., Ltd.

1-9-18 Kaigan, Minato-ku, Tokyo 105-0022, JAPAN
Telephone: +81 3 6367 6047 • Fax: +81 3 6367 6160
Email: journal@maruzen.co.jp • Web site: http://maruzen.co.jp

RUSSIAN FEDERATION

Scientific and Engineering Centre for Nuclear and Radiation Safety

107140, Moscow, Malaya Krasnoselskaya st. 2/8, bld. 5, RUSSIAN FEDERATION
Telephone: +7 499 264 00 03 • Fax: +7 499 264 28 59
Email: secnrs@secnrs.ru • Web site: http://www.secnrs.ru

UNITED KINGDOM

The Stationery Office Ltd. (TSO)

St. Crispins House, Duke Street, Norwich, NR3 1PD, UNITED KINGDOM
Telephone: +44 (0) 333 202 5070
Email: customer.services@tso.co.uk • Web site: http://www.tso.co.uk

UNITED STATES OF AMERICA

Bernan Associates

4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Co. Ltd.

812 Proctor Avenue, Ogdensburg, NY 13669-2205, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: http://www.renoufbooks.com

Orders for both priced and unpriced publications may be addressed directly to:

IAEA Publishing Section, Marketing and Sales Unit
|International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

15-1816



IAEA
International Atomic Energy Agency

PO Box 100, Vienna International Centre
1400 Vienna, Austria

Printed in Austria
ISBN 978–92–0–107015–9 (set)