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

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

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

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.

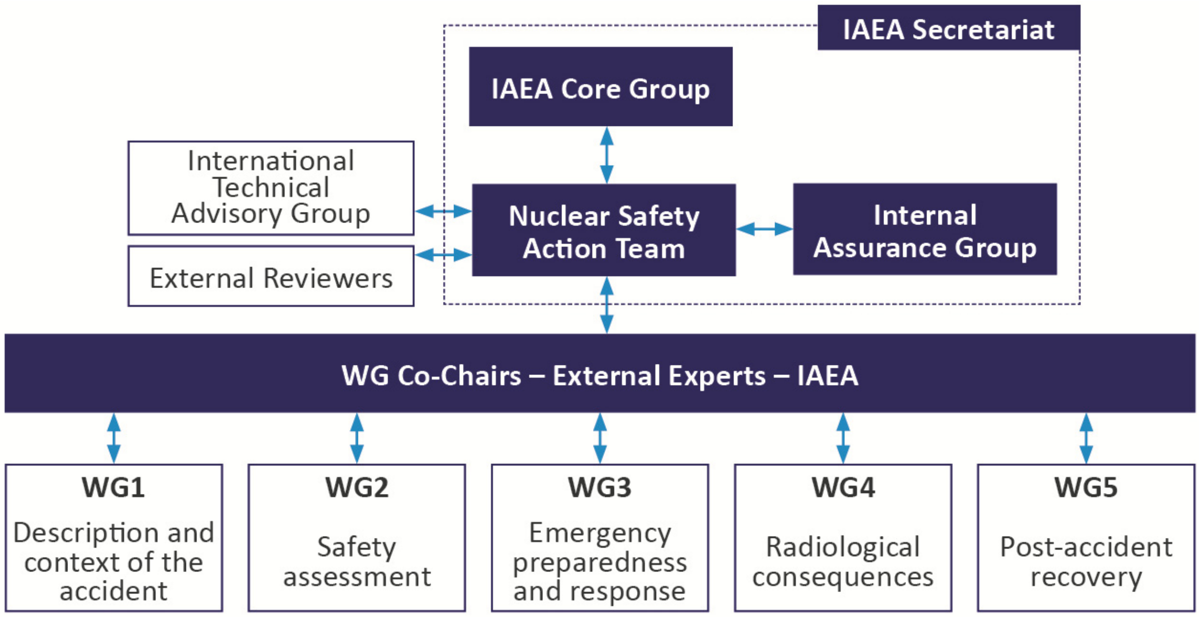


FIG. 1. IAEA organizational structure for the preparation of the report on The Fukushima Daiichi Accident.

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.

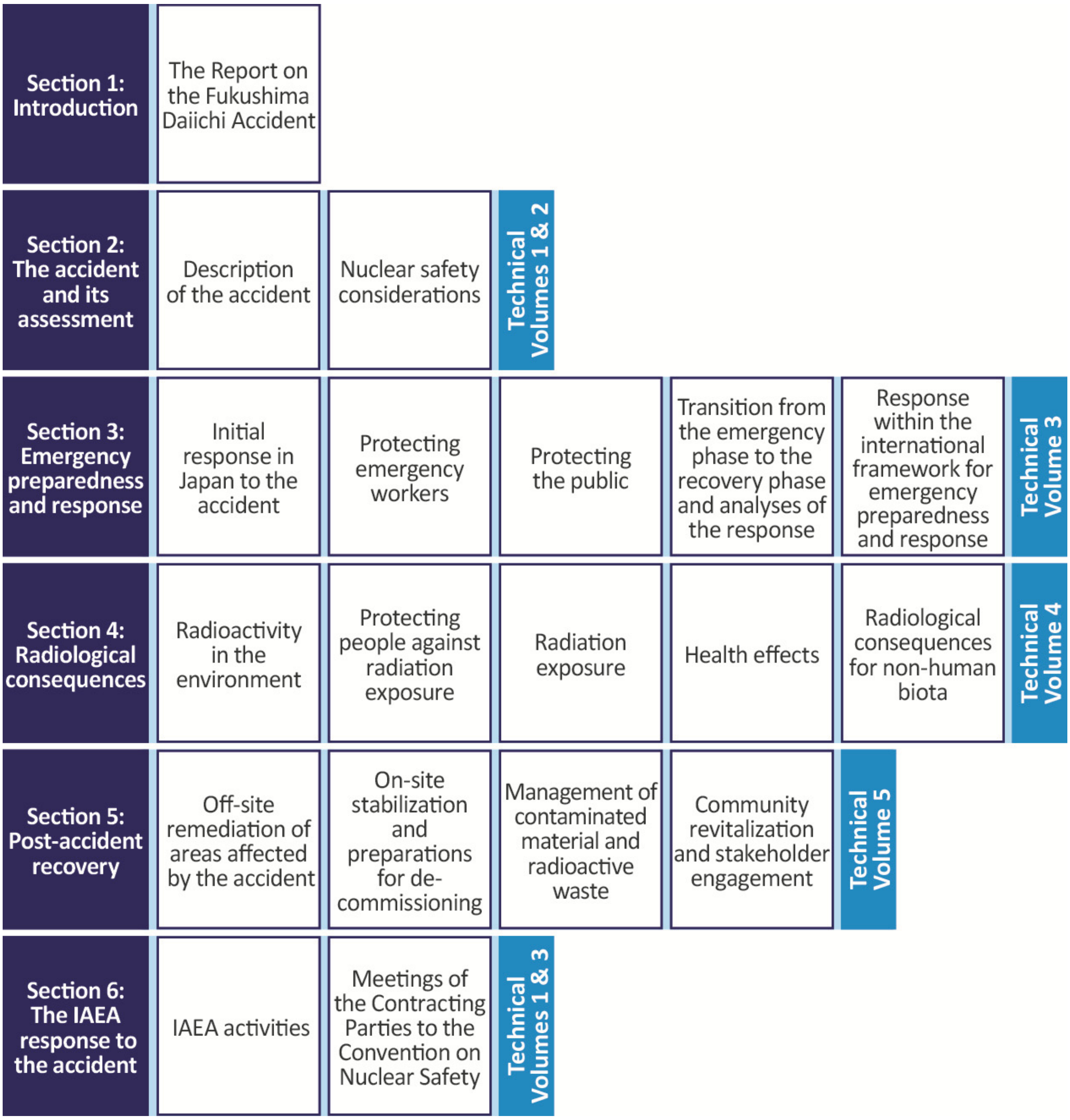


FIG. 2. Structure of the Summary Report and its relationship to the content of the technical volumes.

CONTENTS

POST-ACCIDENT RECOVERY

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.

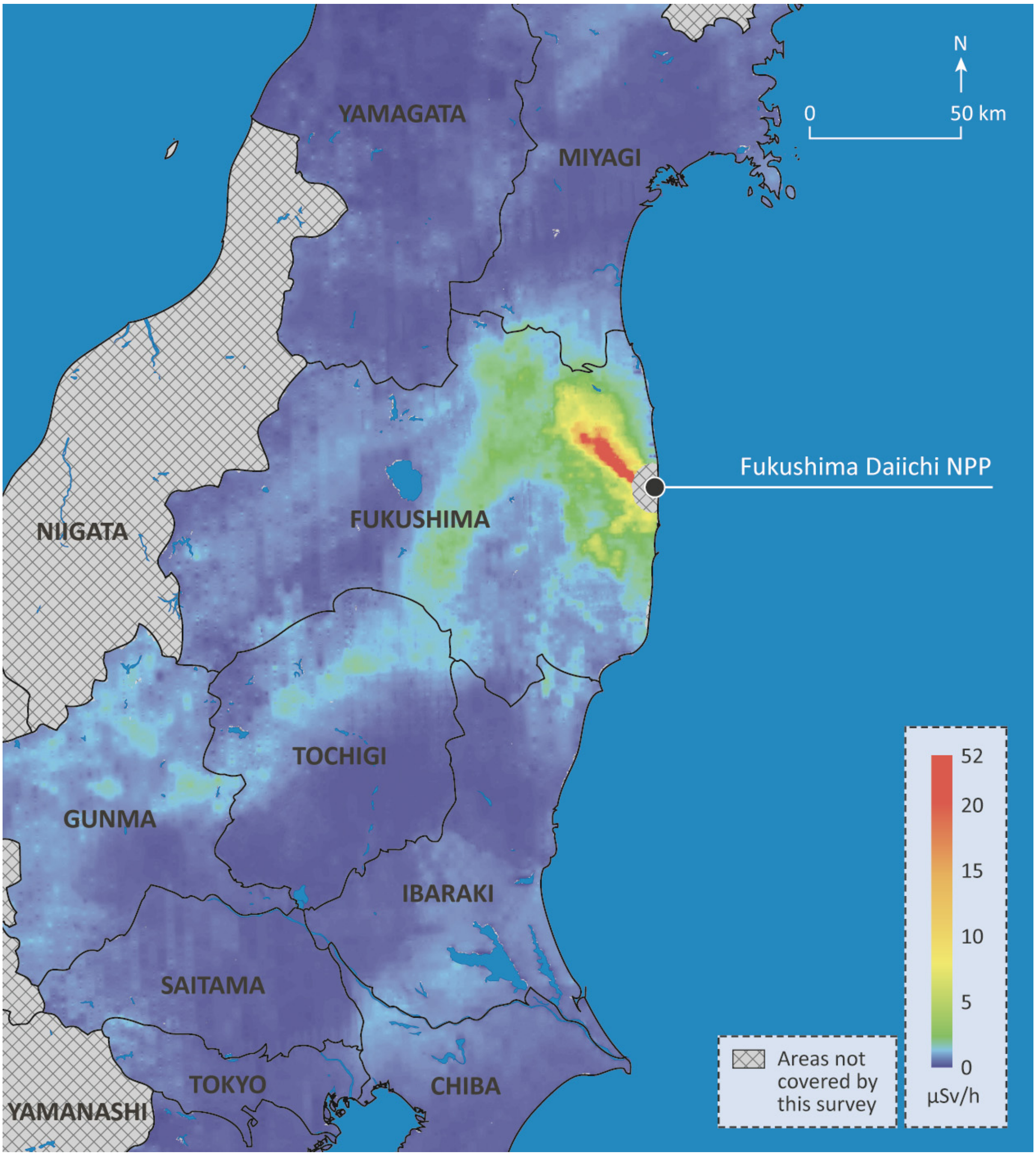


FIG. 5.2–1. Ambient dose rates 1 m above the ground surface (in µSv/h) estimated from an airborne monitoring survey (as of 18 September 2011) [21].

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.

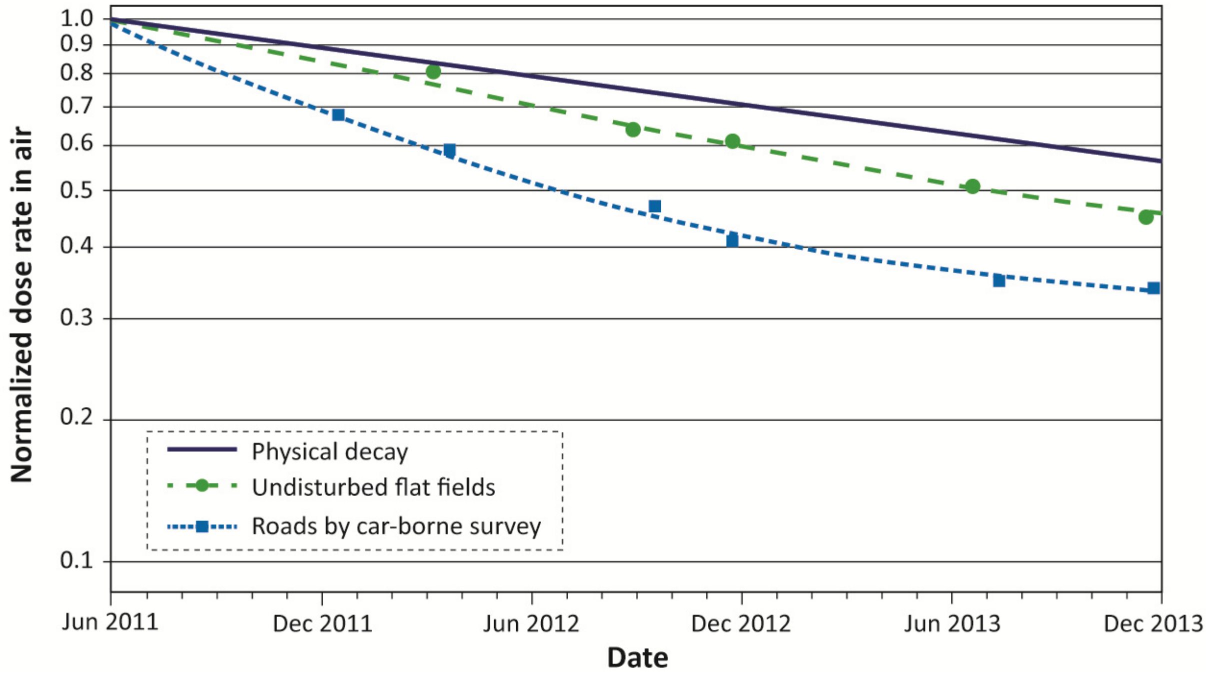


FIG. 5.2–2. Comparison of temporal change over time in the ambient dose rate of physical decay, measurements above roads and above undisturbed fields [24].

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).

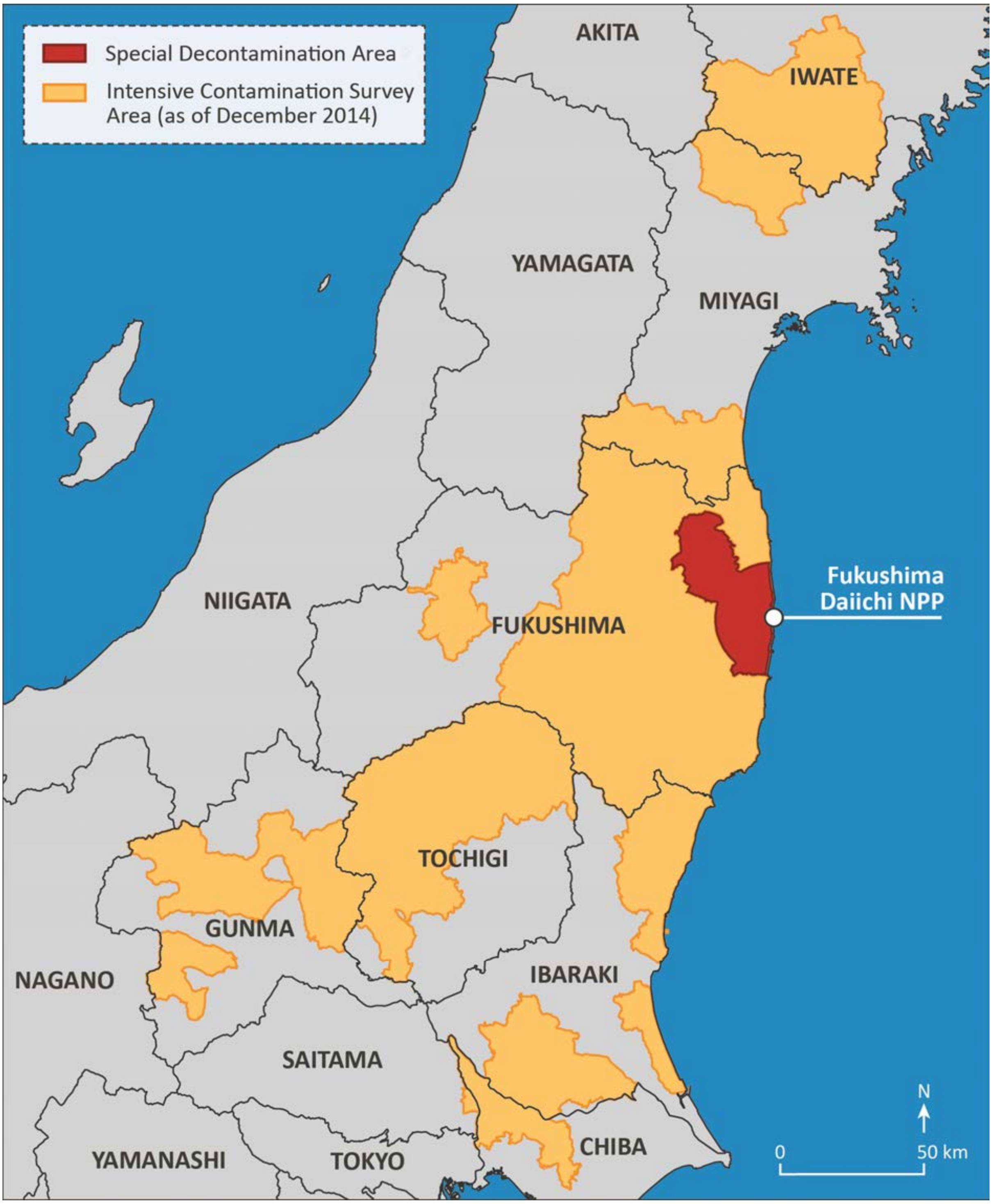


FIG. 5.2–3. The SDA and the ICSA

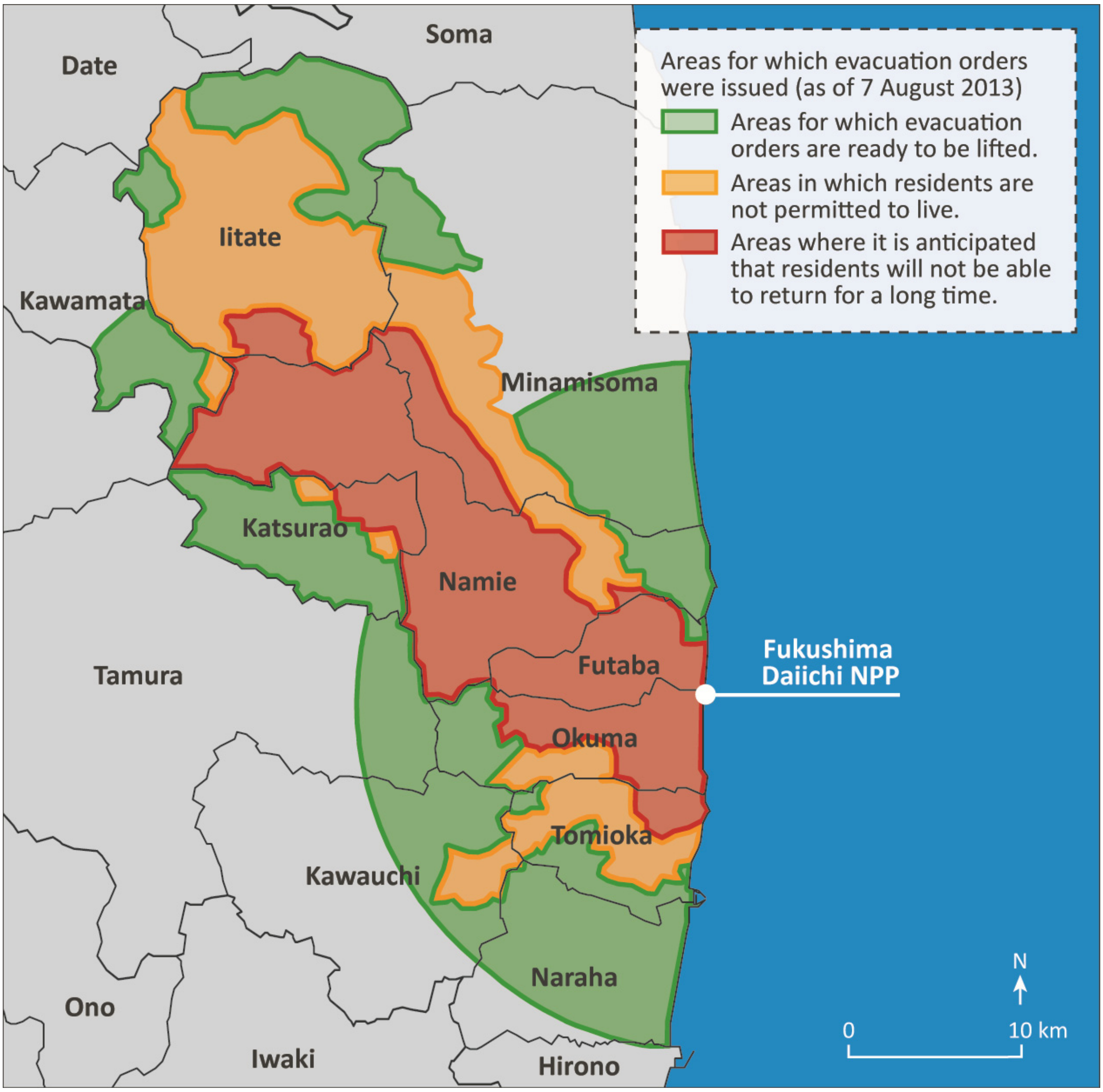


FIG. 5.2–4. The sub-division of the evacuation zone (as of 7 August 2013) [39].

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.

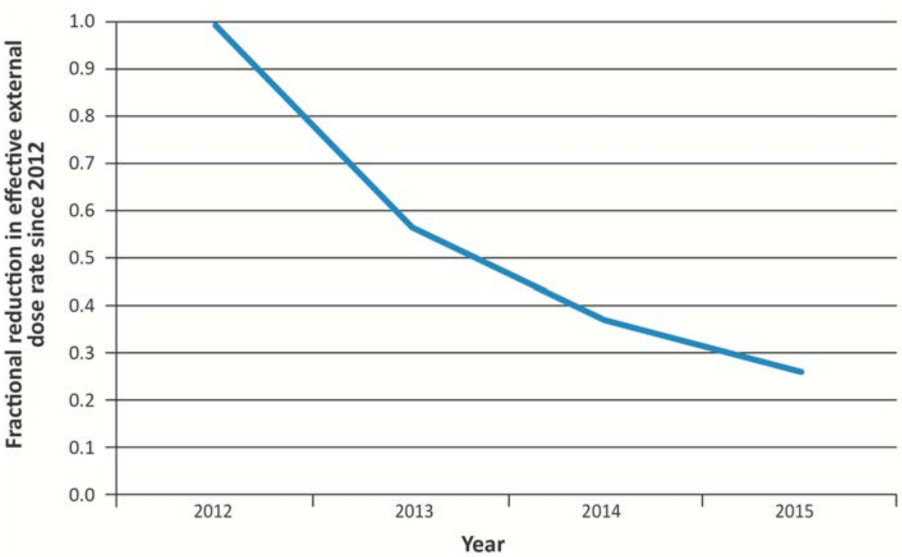


FIG. 5.2–5. Changes with time, relative to 2012, in the effective dose from external exposure to the representative person due to gamma emitting radionuclides.

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].

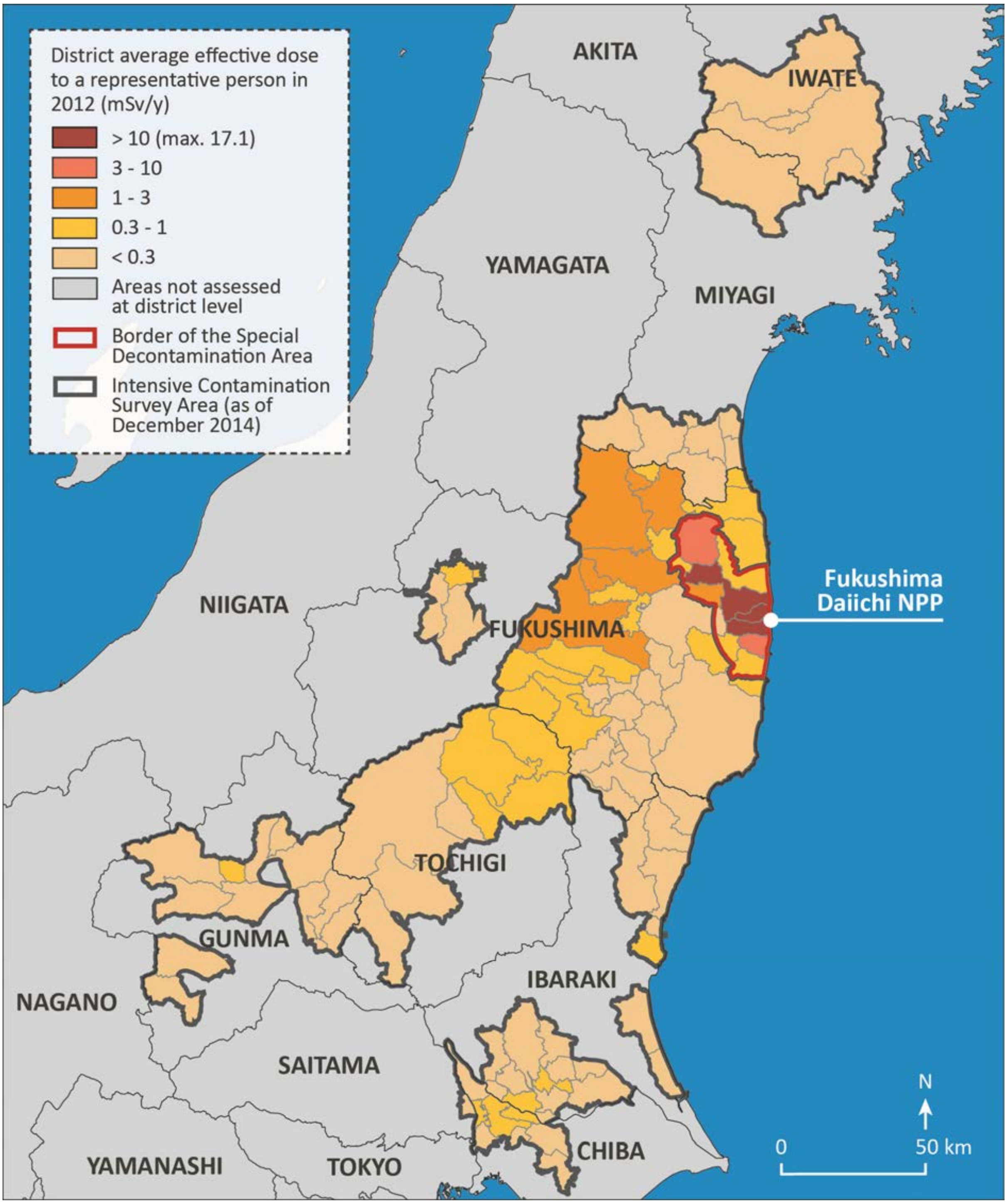


FIG. 5.2–6. Map showing the designation of the Special Decontamination Area and the ICSA (as of December 2014) [41]. Estimated district-average effective doses of a representative person in 2012 are provided based on the methodology used by UNSCEAR (See Section 5.2.6) [13, 40].

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.

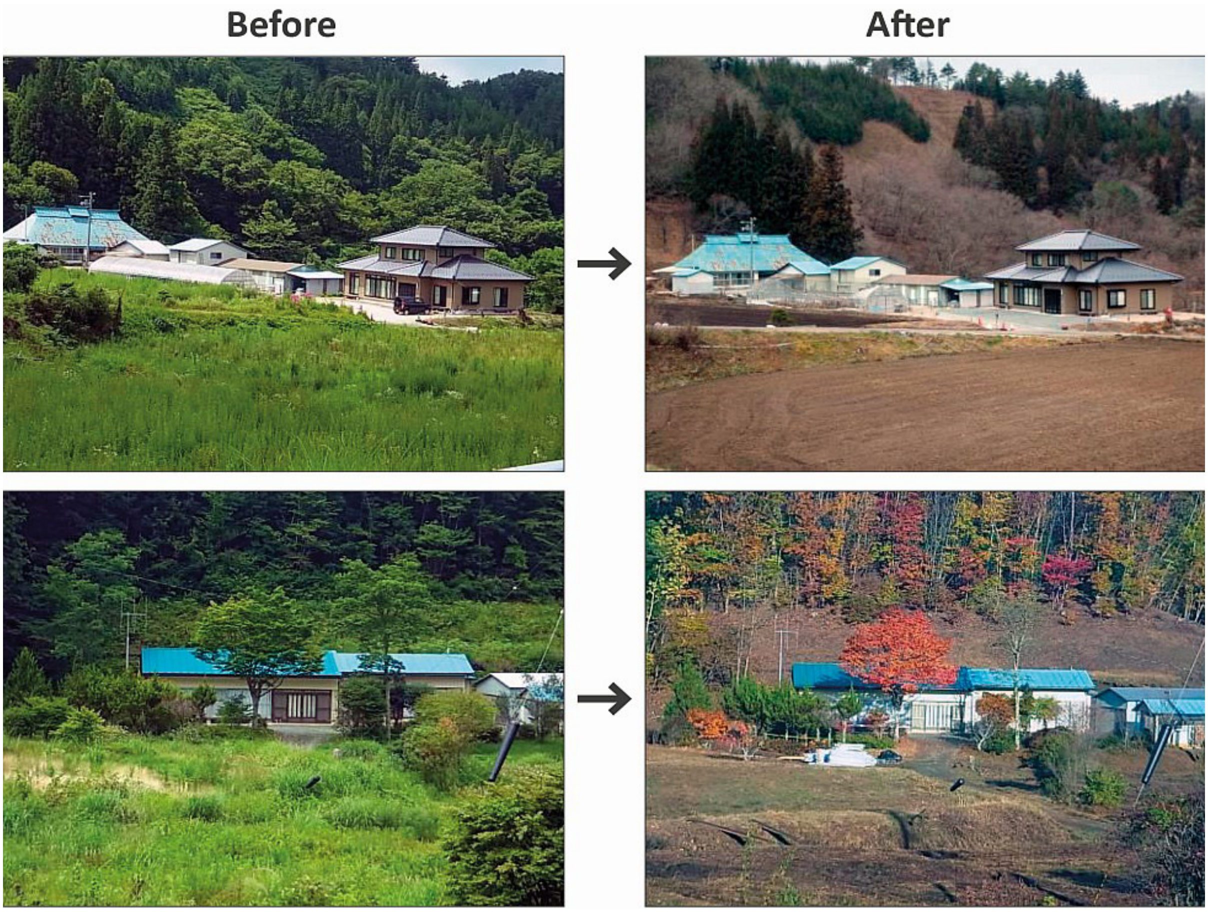


FIG. 5.2–7. Landscapes before and after remediation in Tamura City (Photographs courtesy of the Ministry of the Environment).

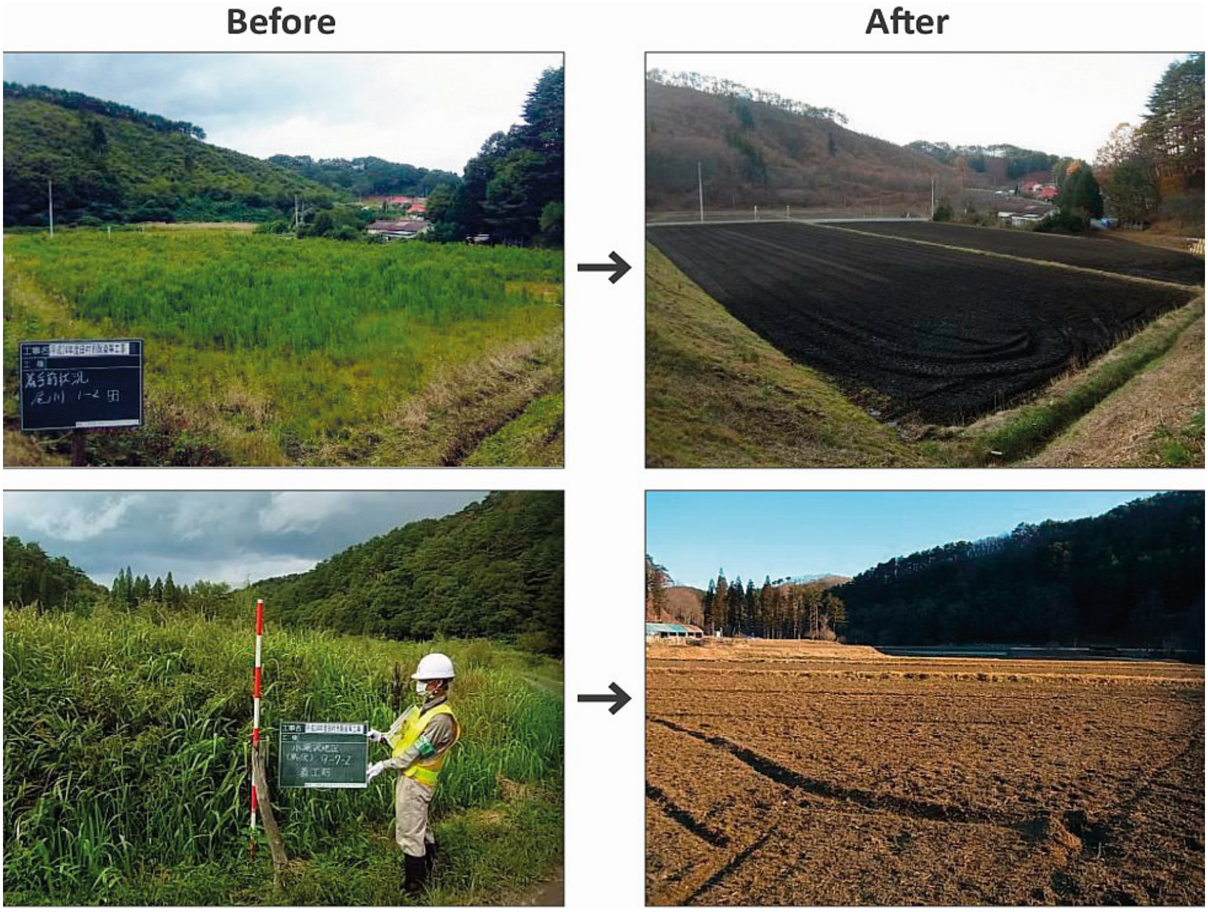


FIG. 5.2–7. Landscapes before and after remediation in Tamura City (Photographs courtesy of the Ministry of the Environment) (cont.).

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.

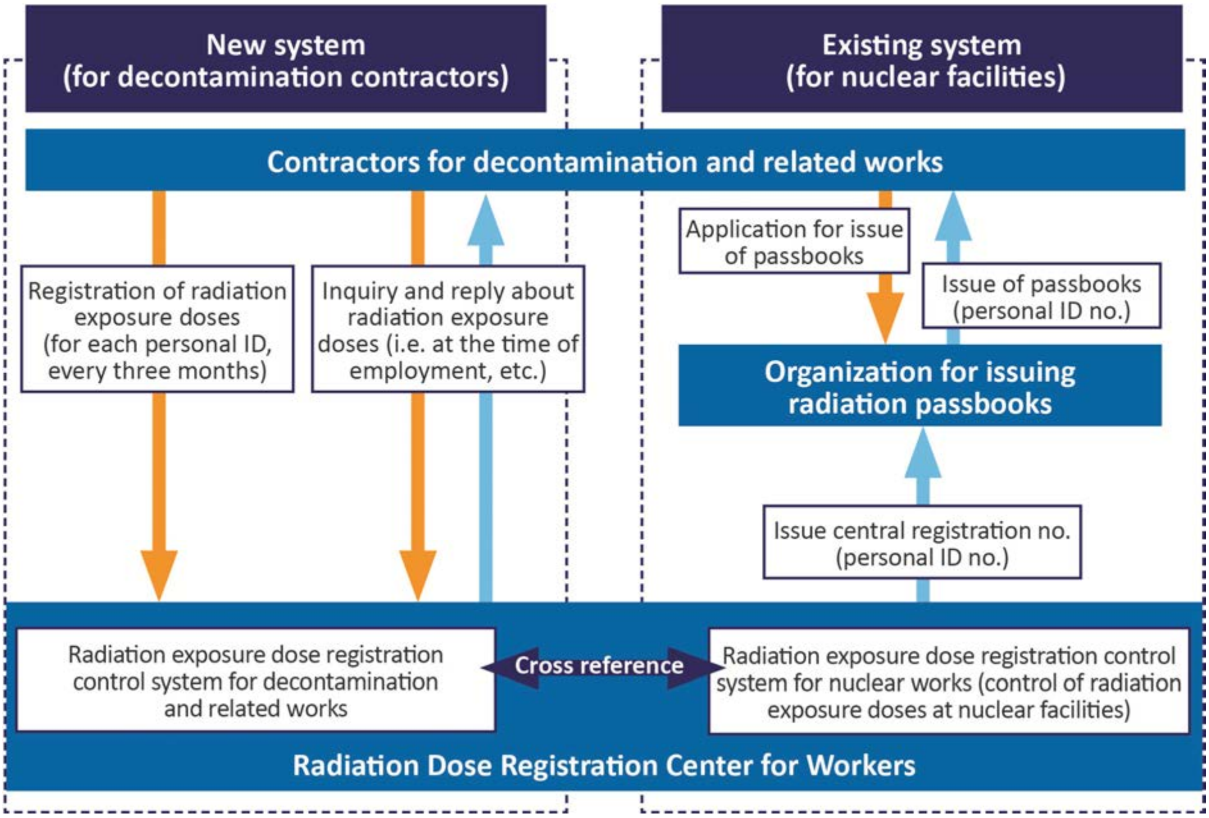


FIG. 5.2–10. System for decontamination contractors [61].

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.

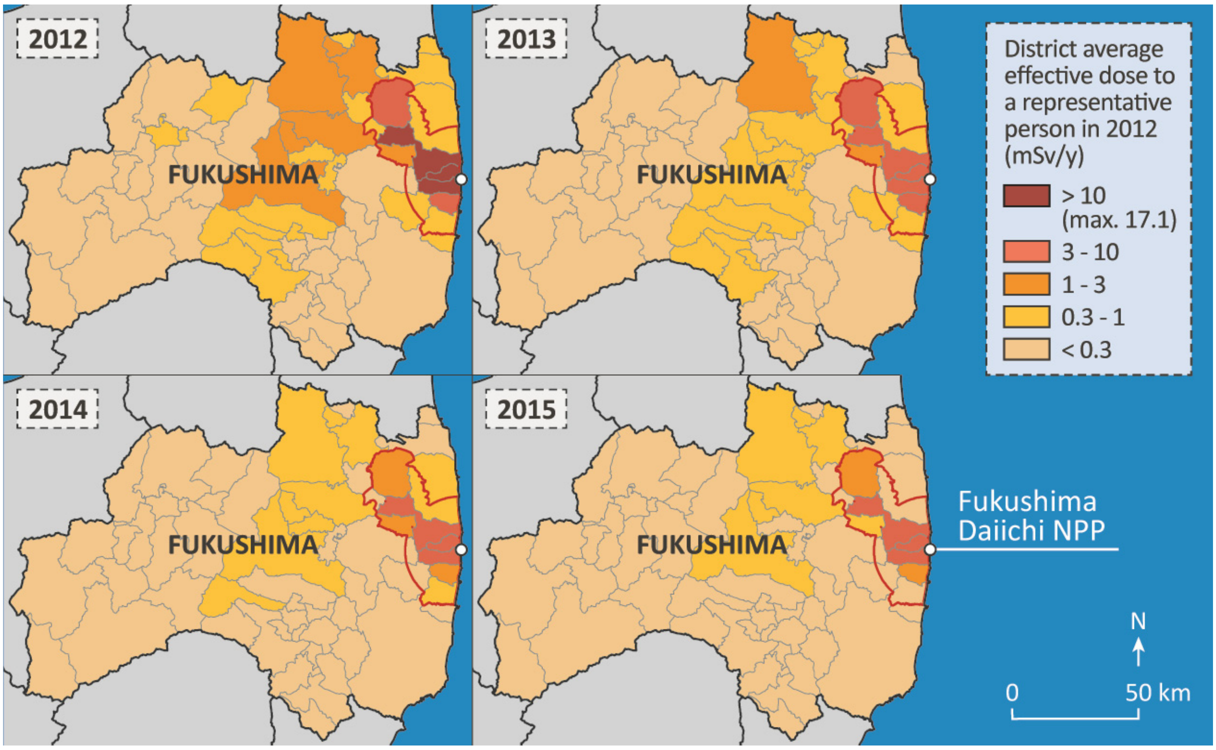


FIG. 5.2–11. Estimated district averaged annual doses to the representative person between 2012 and 2015 for ICSA districts in Fukushima Prefecture adopting the methodology used by UNSCEAR [13].

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.

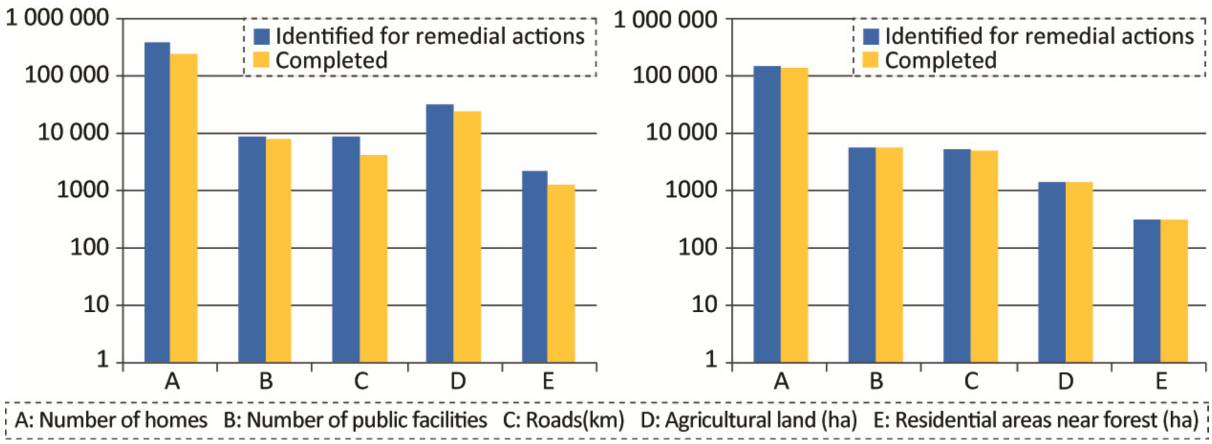


FIG. 5.2–12. Number of planned and completed remediation activities in Fukushima and other prefectures (in Fukushima Prefecture on the left and outside Fukushima Prefecture on the right) by the end March 2015 [66].

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

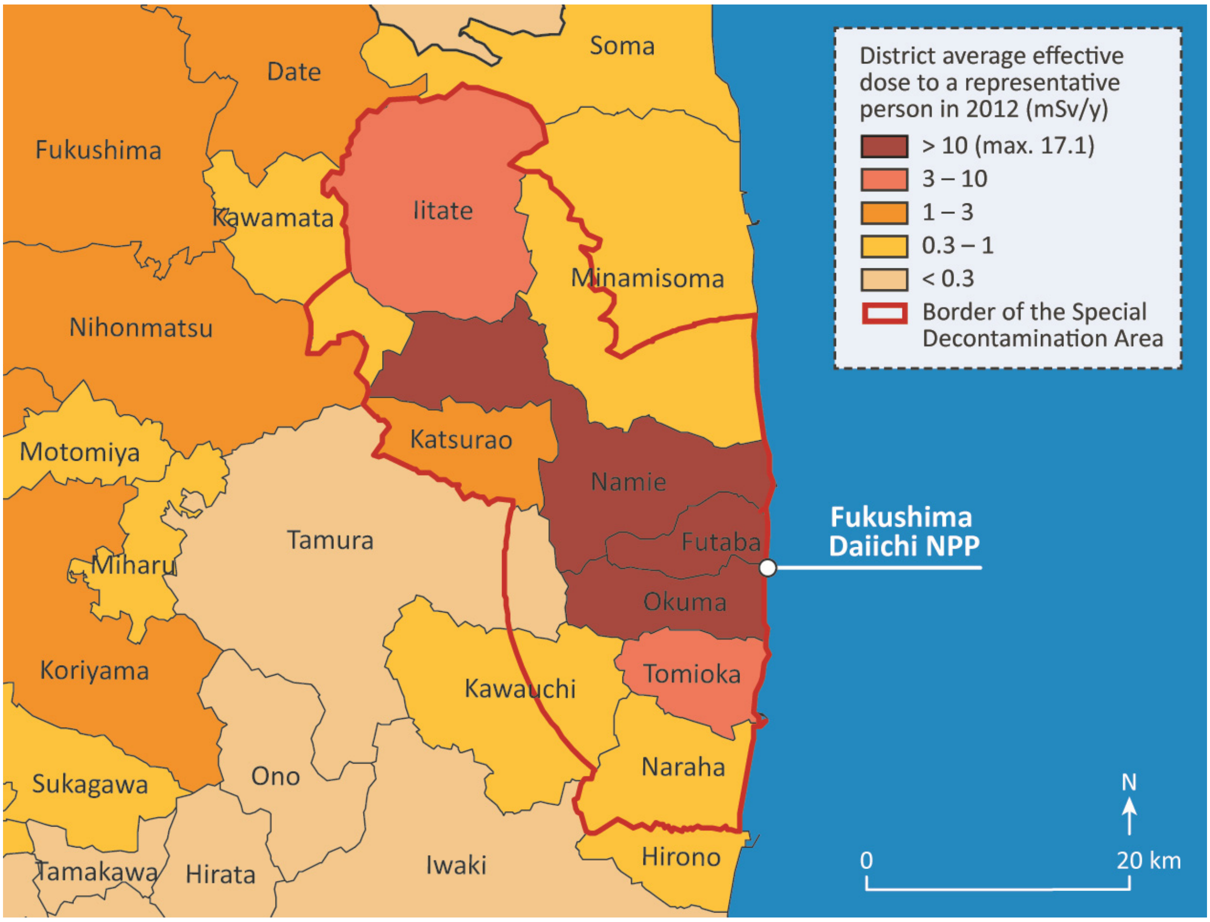


FIG. 5.2–13. Predicted district average effective dose to the representative person in 2012 in the SDA based on the UNSCEAR methodology.

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.

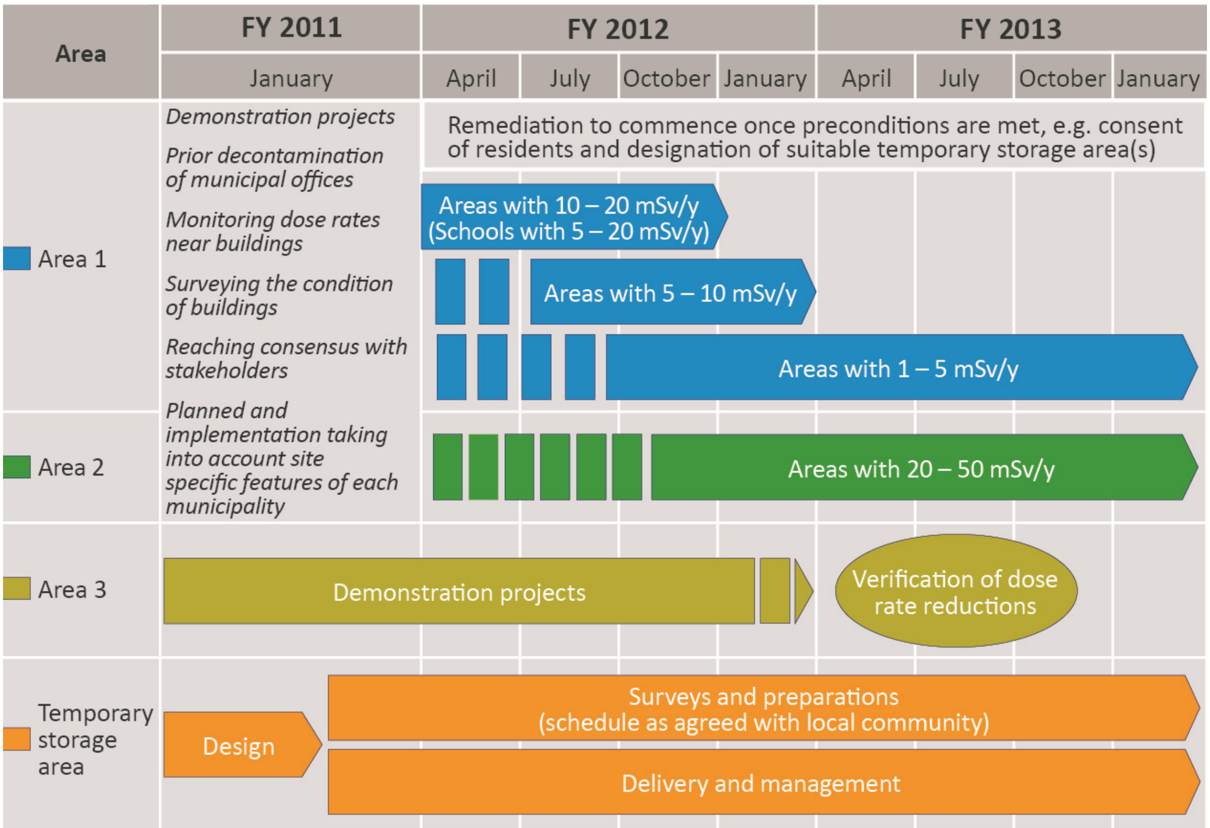


FIG. 5.2–14. Planning for remediation as of September 2013 [55, 69].

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	—	—	—	—

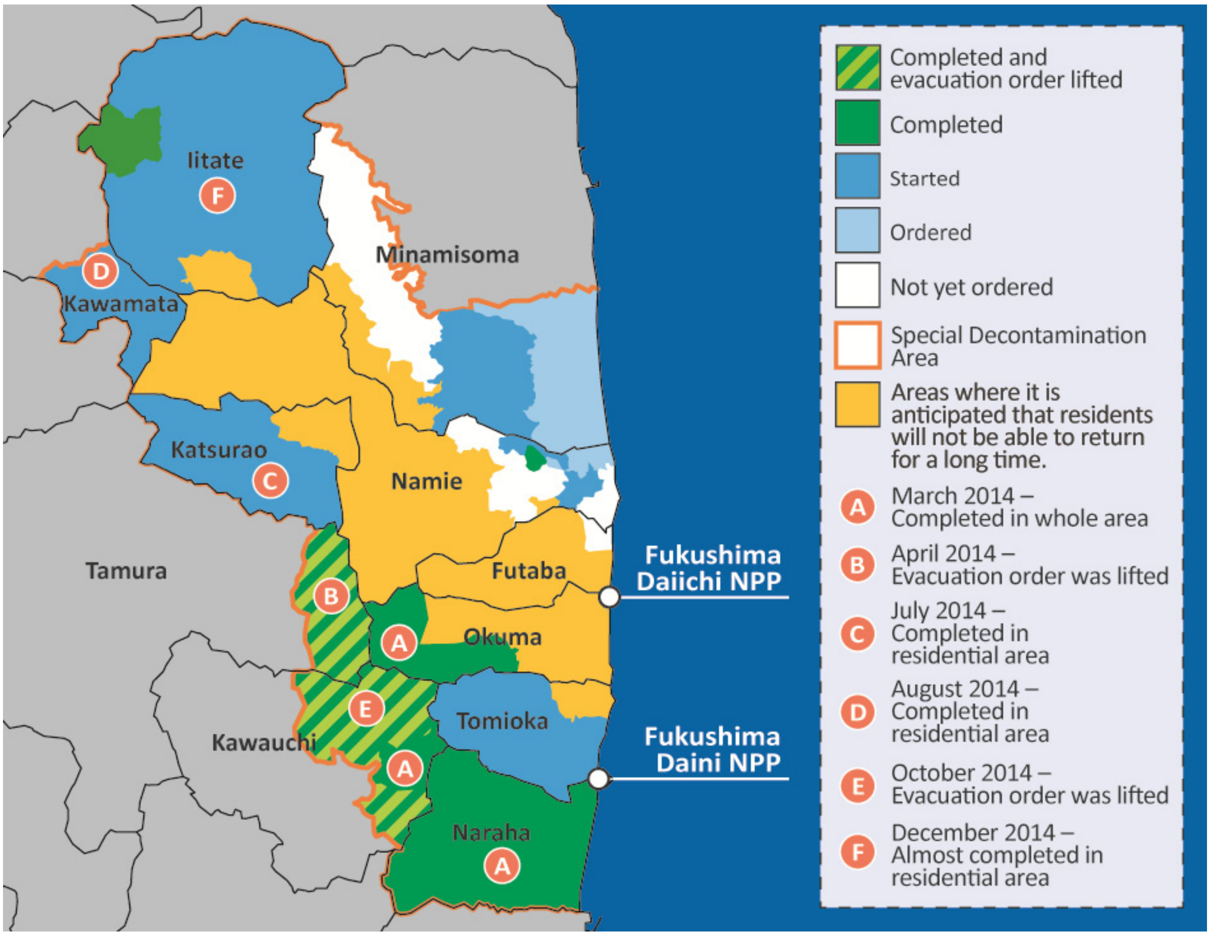


FIG. 5.2–15. Progress in remediation in SDAs up to December 2014 [55].

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.

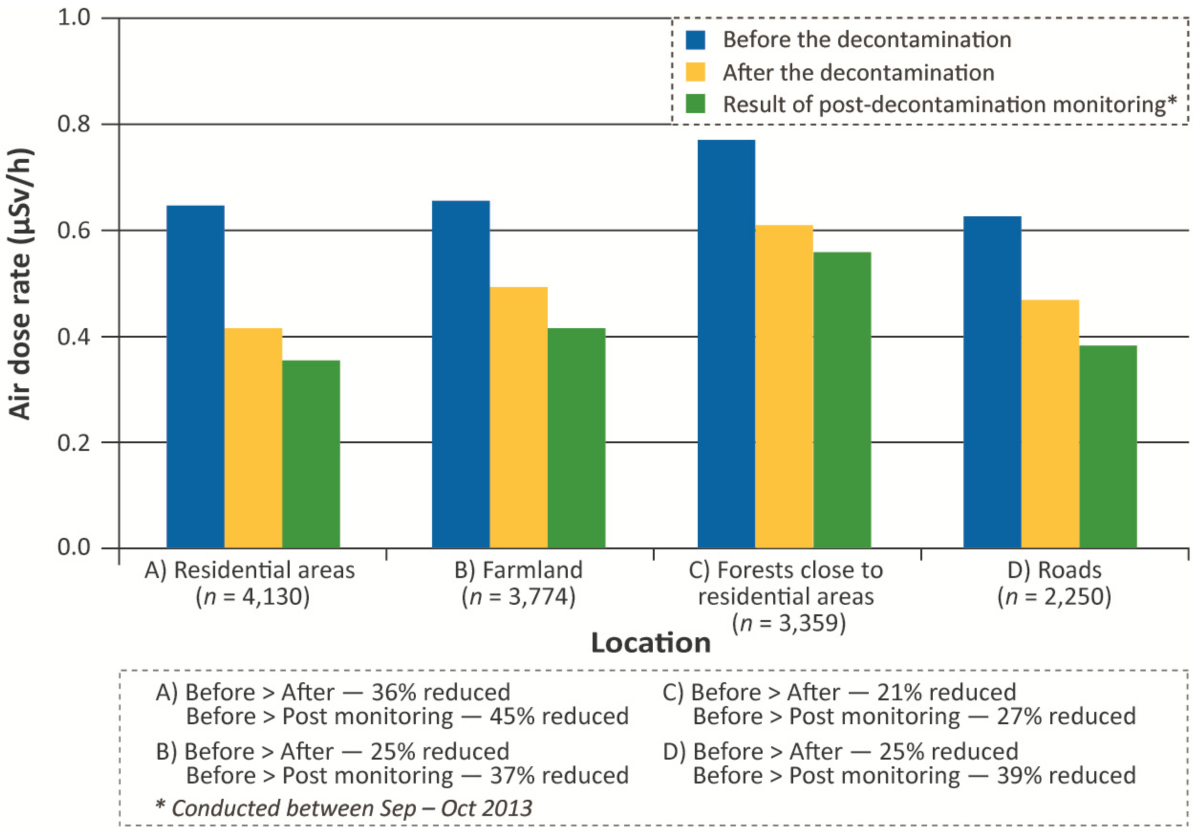


FIG. 5.2–17. Reductions in ambient dose rate achieved in Tamura City in Special Decontamination Area 1 [55].

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).

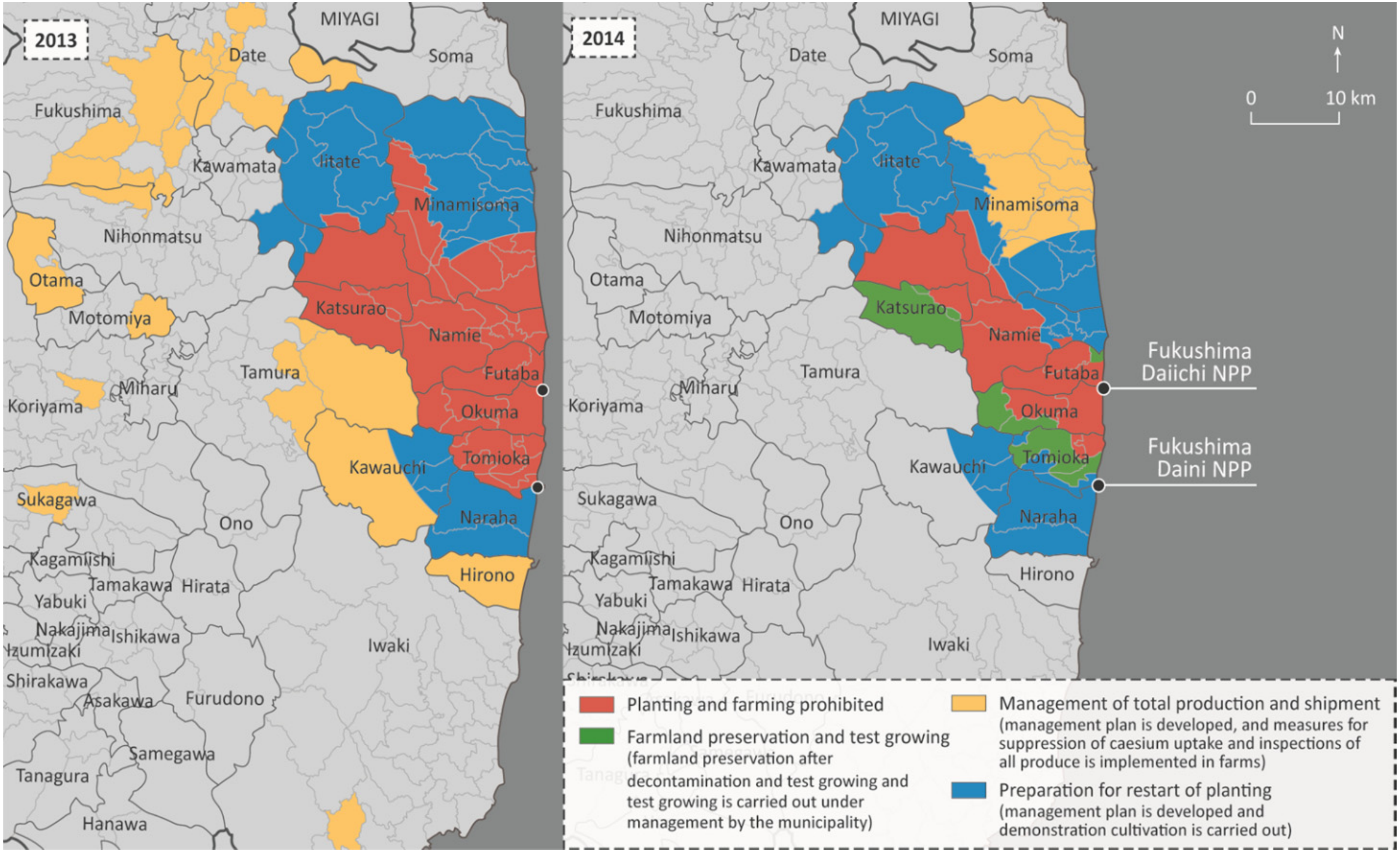


FIG. 5.2–19. Change over time in the area where rice production was restricted [93]

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^{o}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^{o}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].

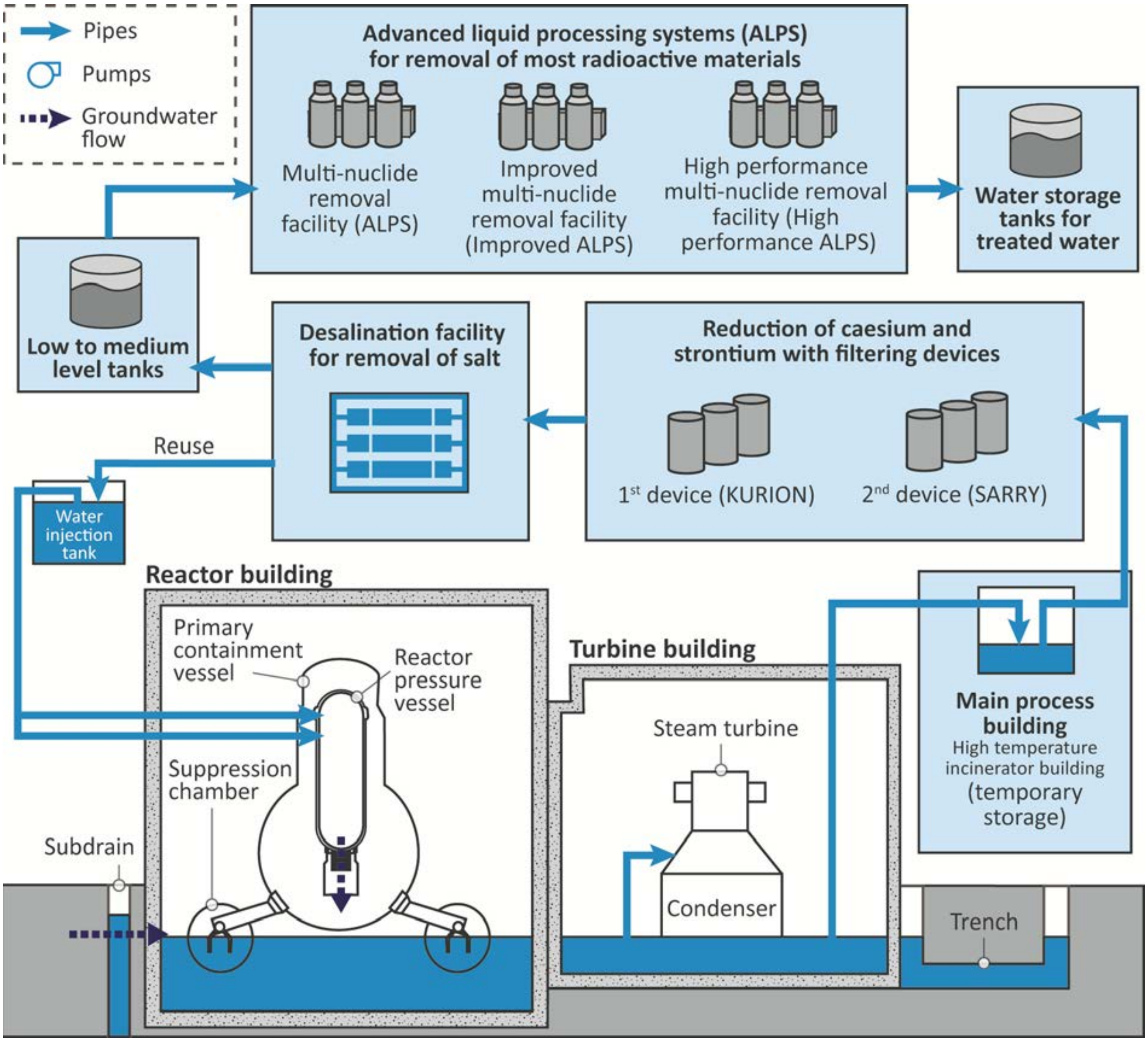


FIG. 5.3–1. Cooling loop and management of contaminated water [128].

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’.

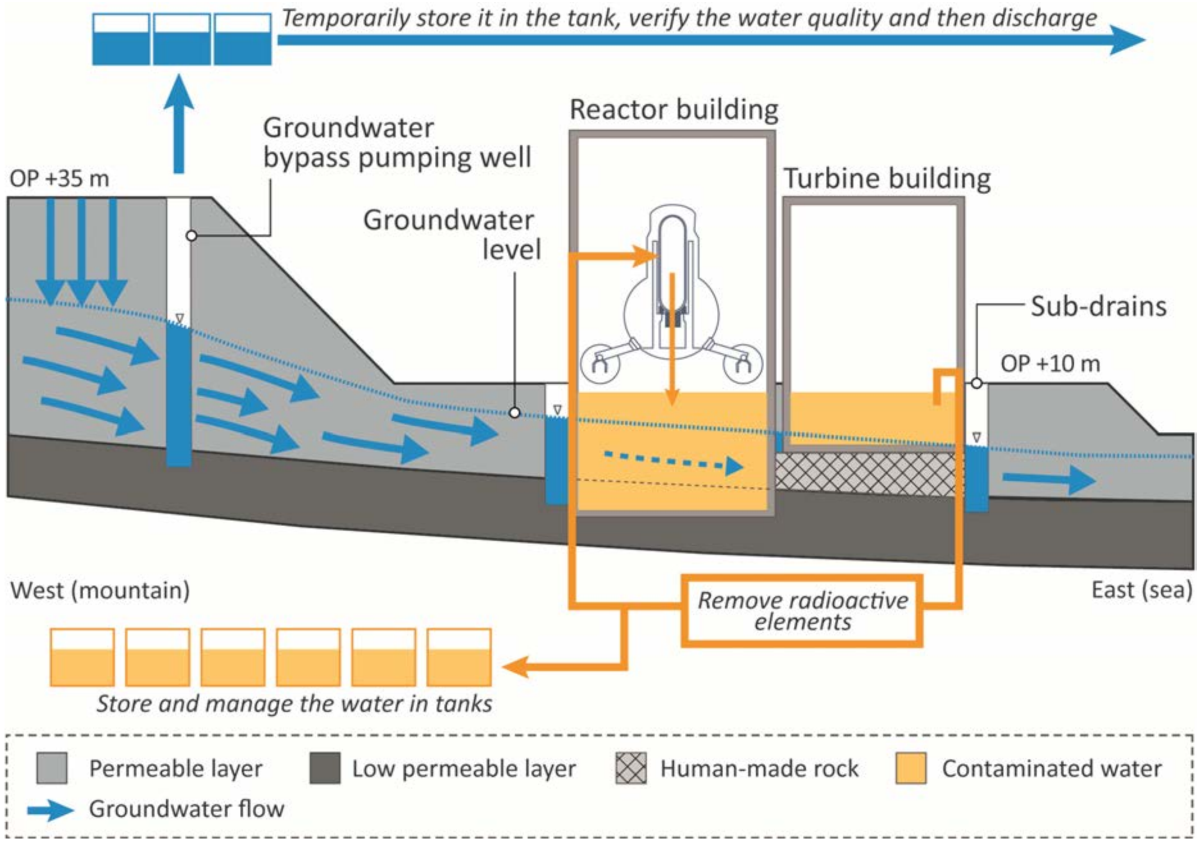


FIG. 5.3–2. Illustration of the groundwater bypass system [131].

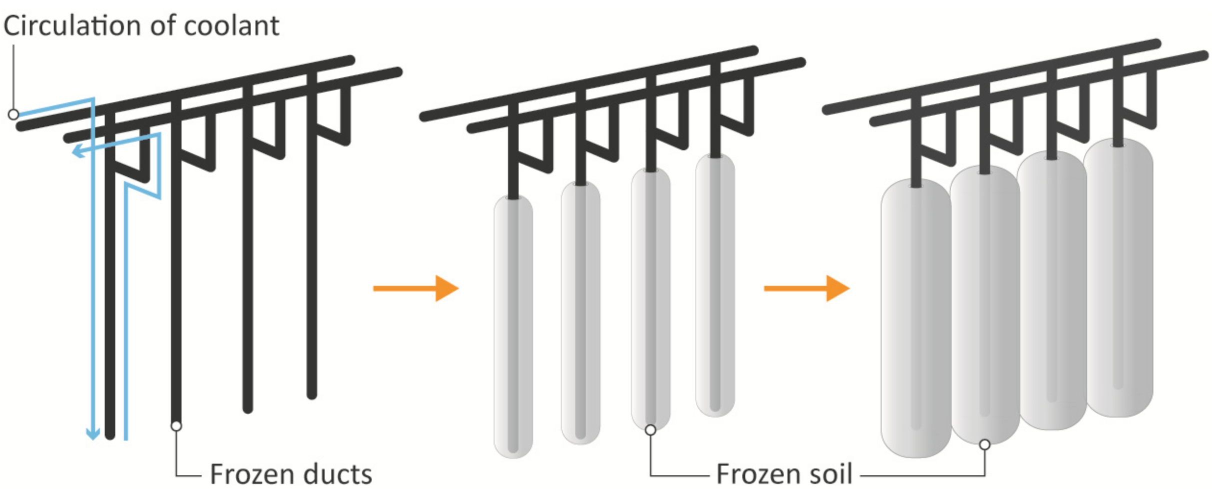


FIG. 5.3–3. Landside impervious wall [137].

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).

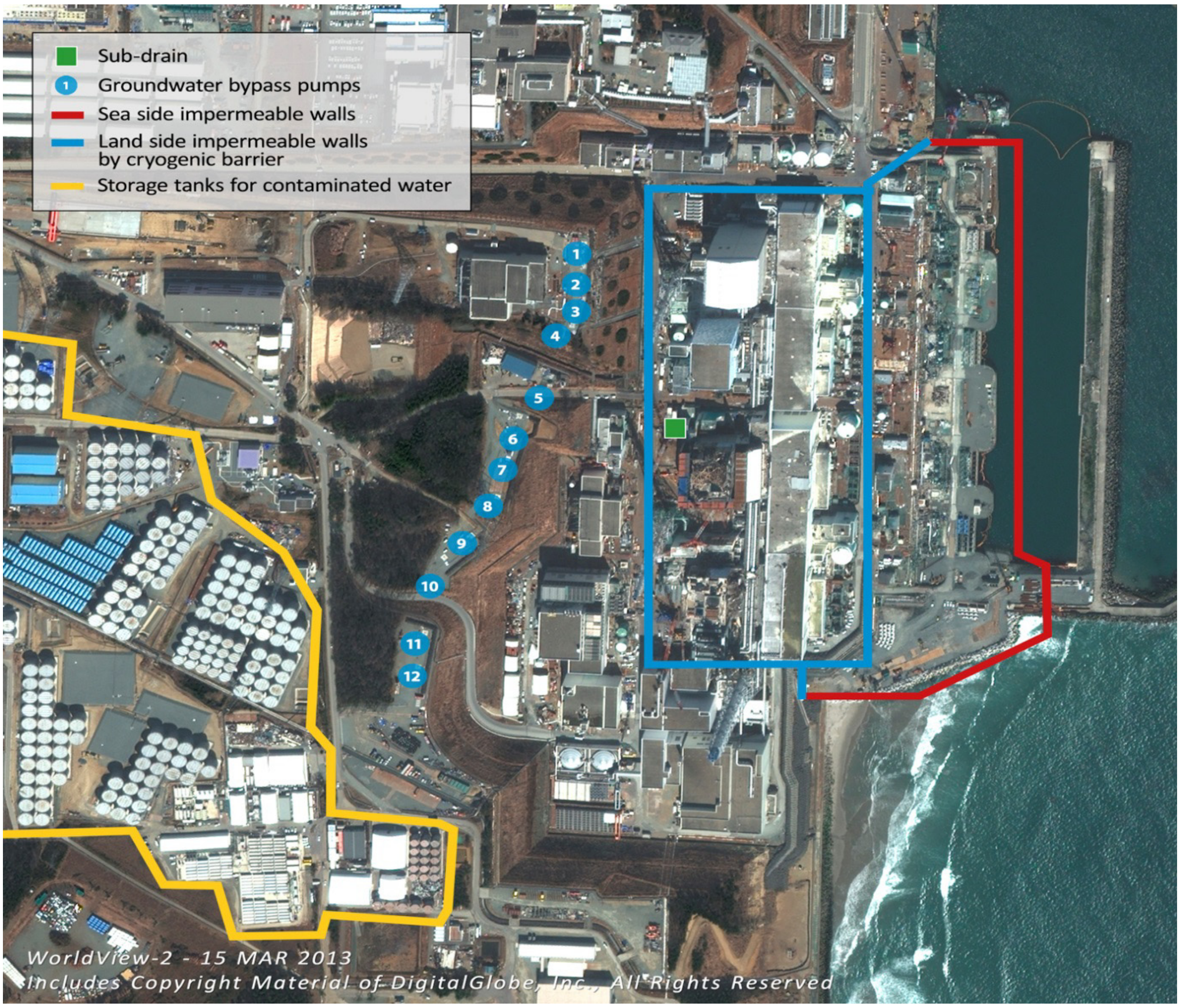


FIG. 5.3–4. Illustration of water management efforts [140].

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.

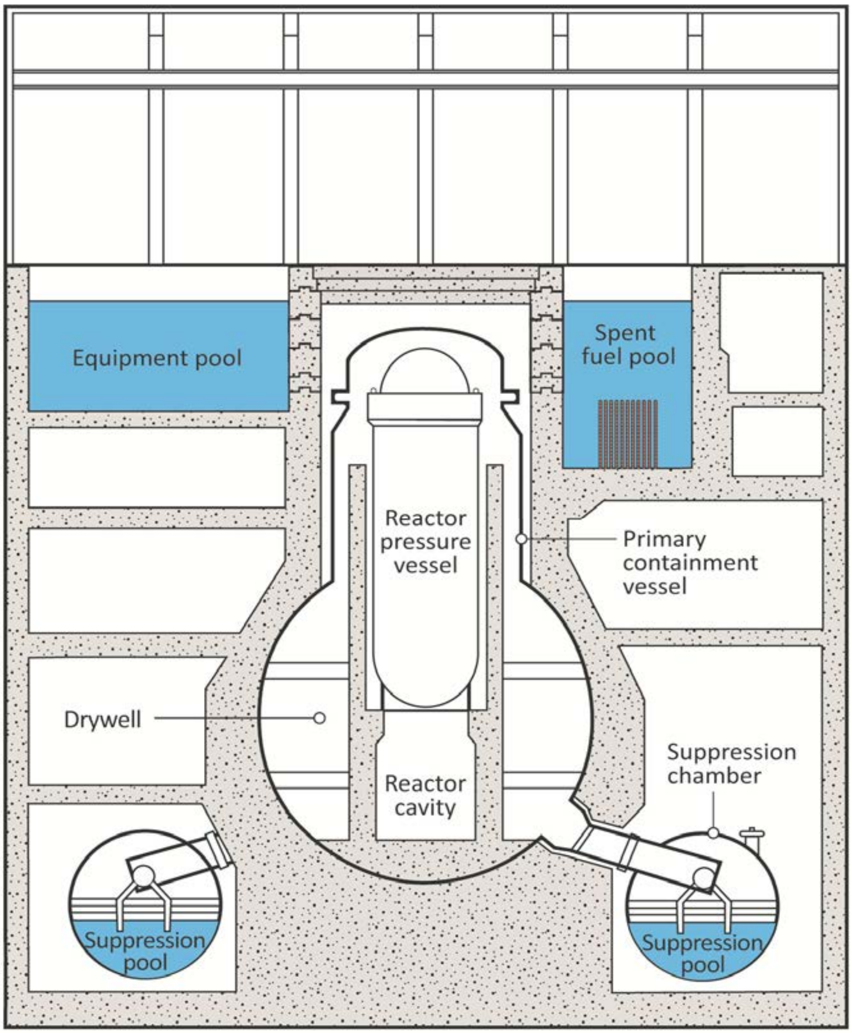


FIG. 5.3–5. Reactor vessel and fuel pool configuration.[26]

[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.

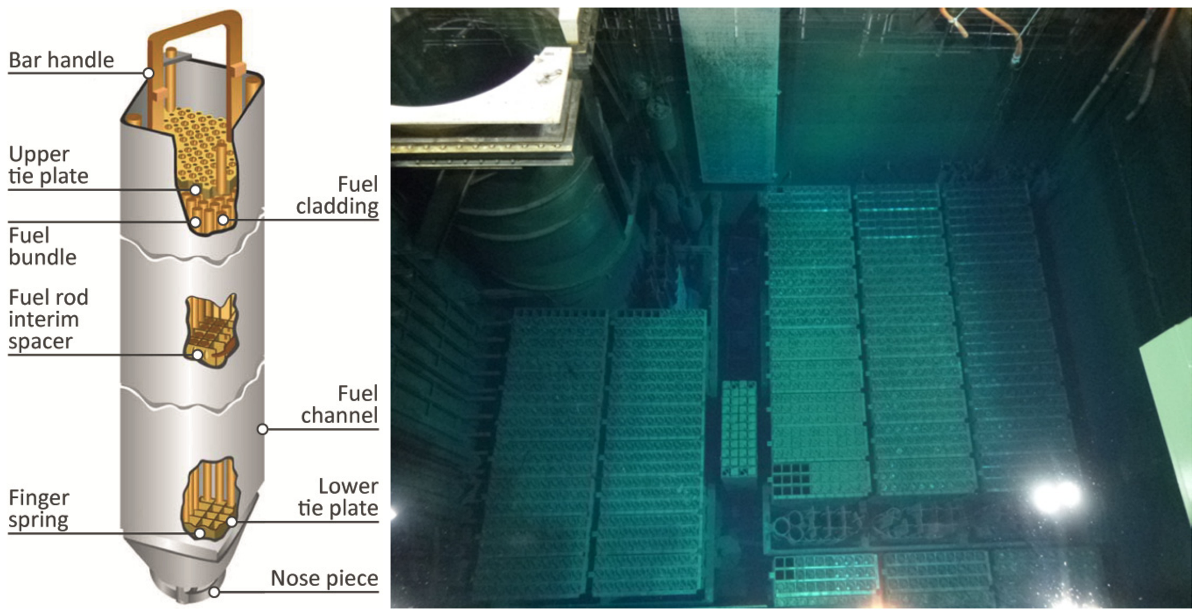


FIG. 5.3–6. BWR fuel assembly diagram and fuel assemblies in storage racks within the spent fuel pool [151].

[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].

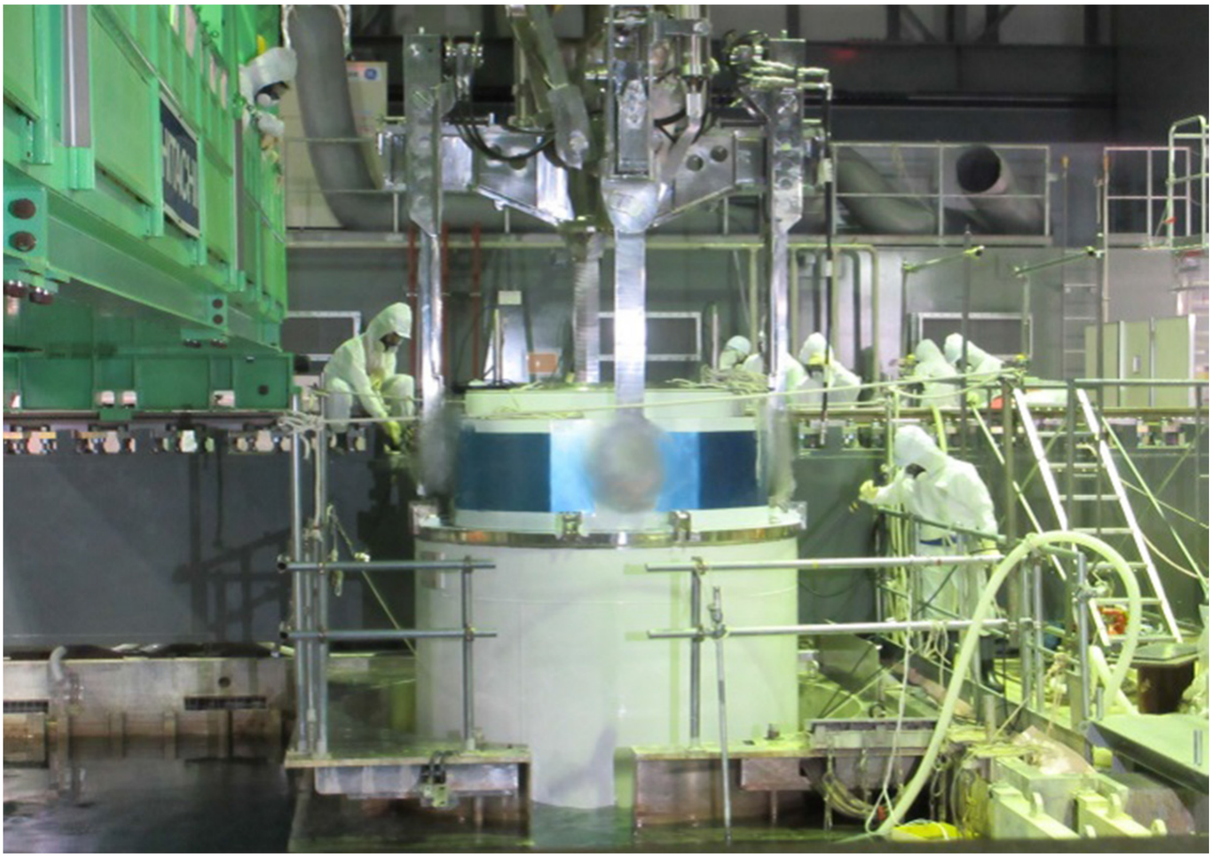


FIG. 5.3–8. Removing the transport cask from the spent fuel pool.

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].

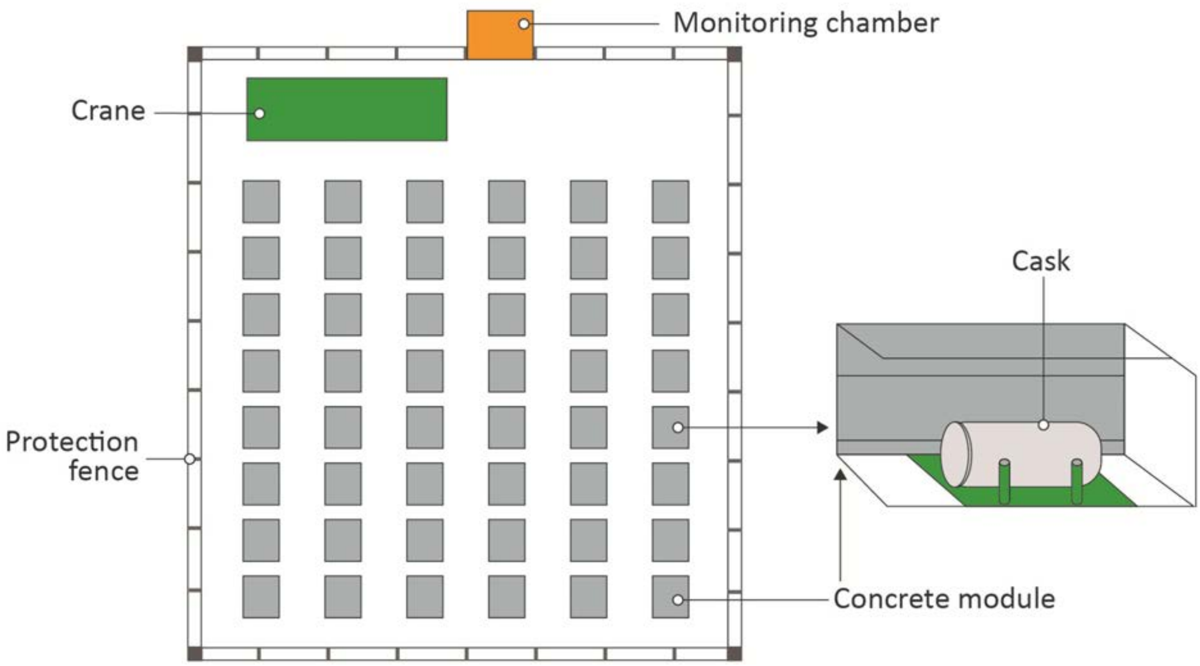


FIG. 5.3–9. Dry storage area [150].

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.

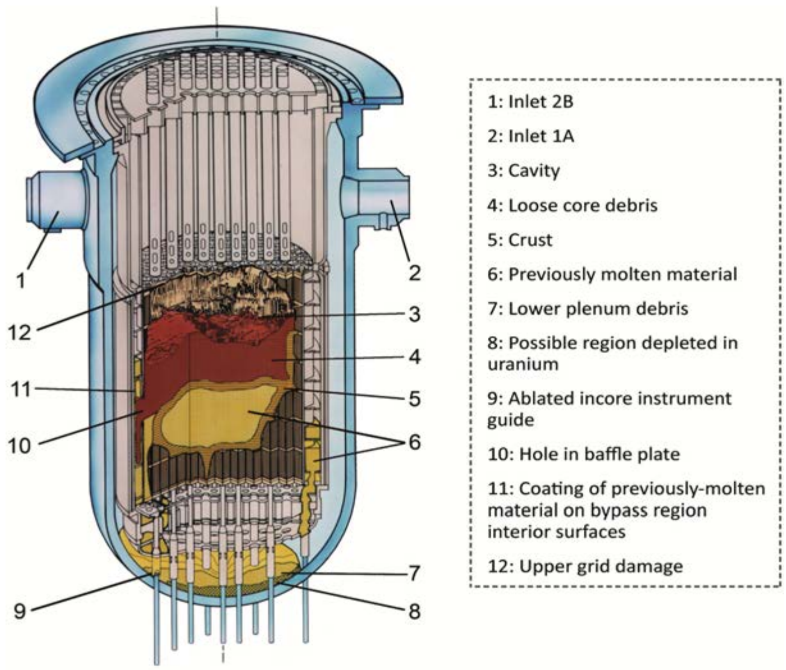


FIG. 5.3–10. TMI-2 core damage [158].

[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.

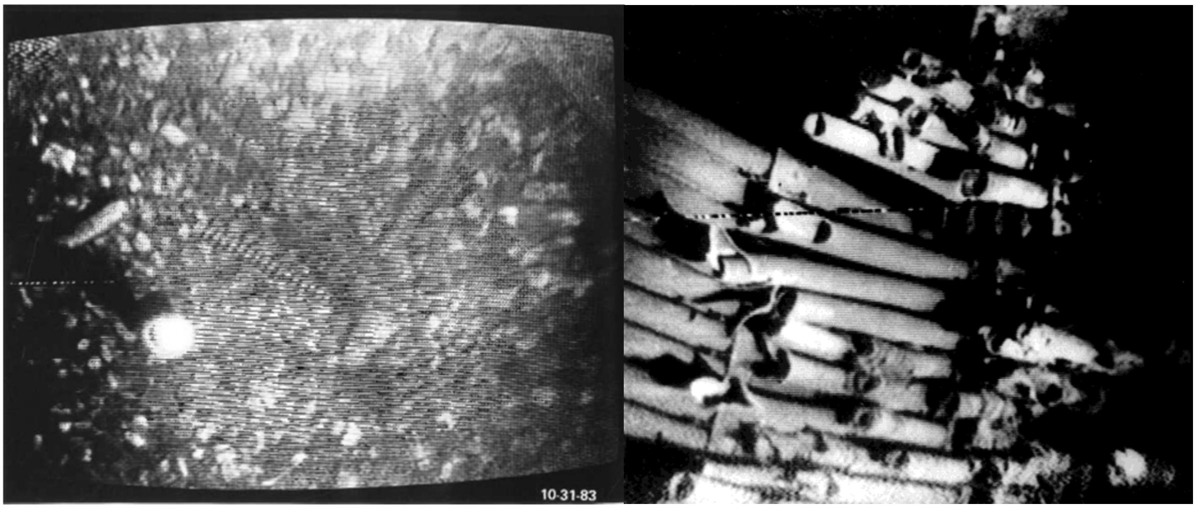


FIG. 5.3–11. TMI-2 fuel debris [159] (photograph on the left courtesy of Pennsylvania State University and that on the right of the Associated Press).

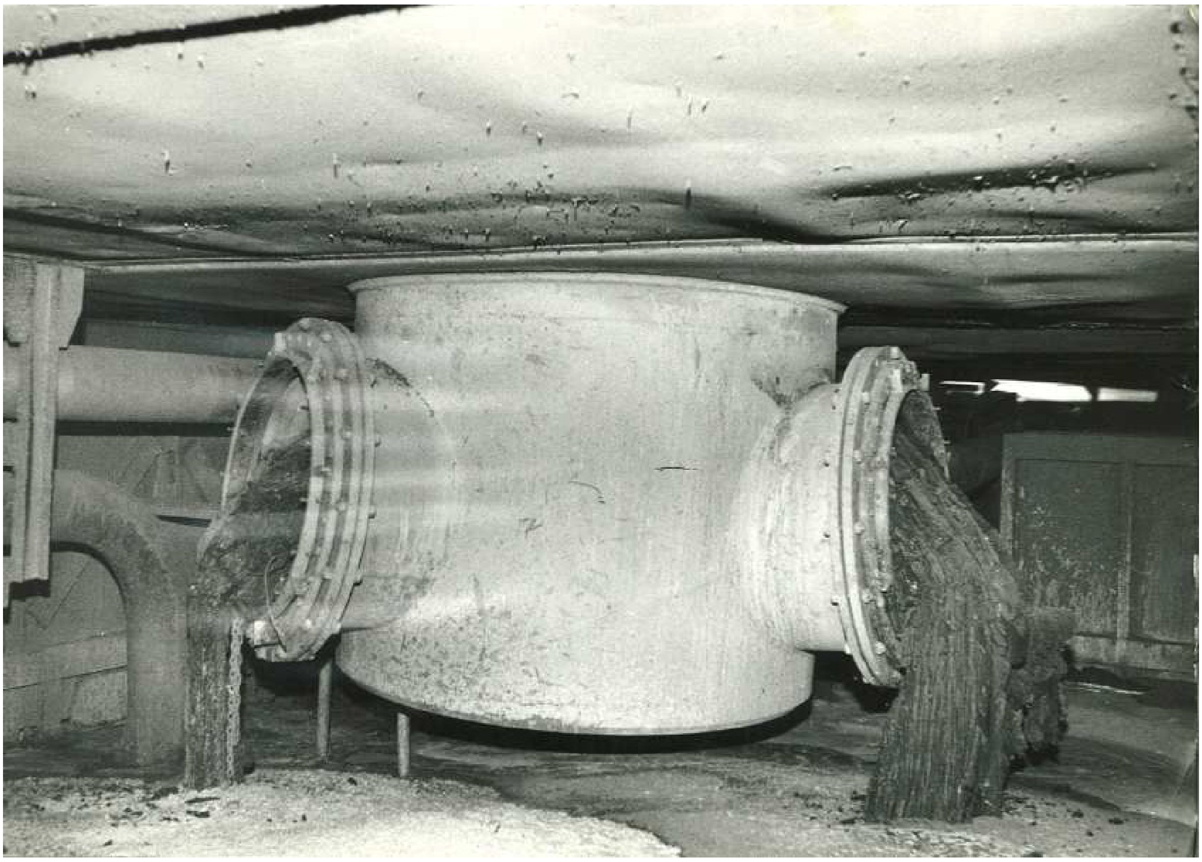


FIG. 5.3–12. Chernobyl Unit 4 core cavity and corium [159] (photograph courtesy of the International Nuclear Safety Project).

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.

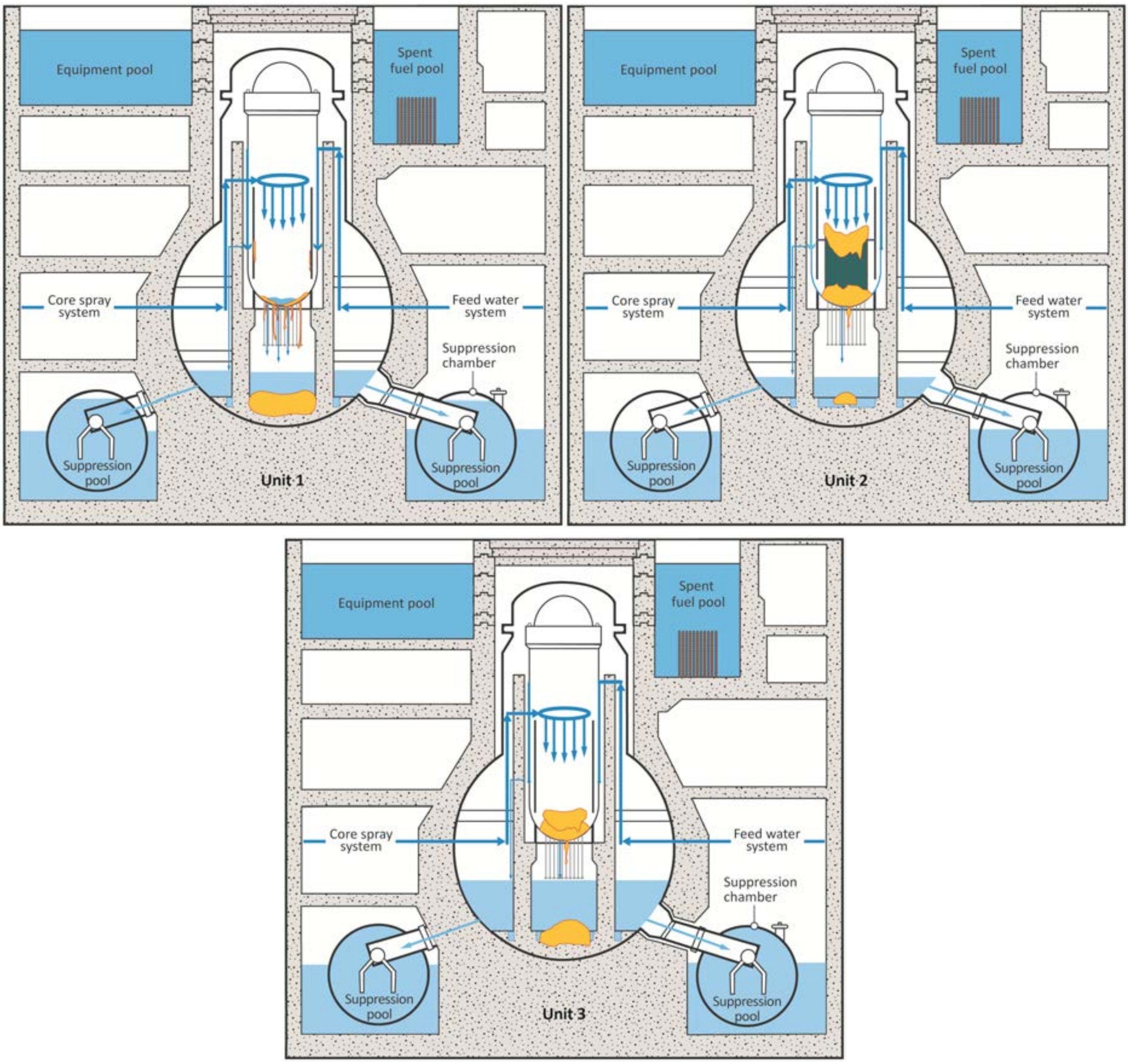


FIG. 5.3–13. Estimated conditions of the RPVs and PCVs of Units 1–3 (clockwise from top left) as of February 2014 [162].

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].

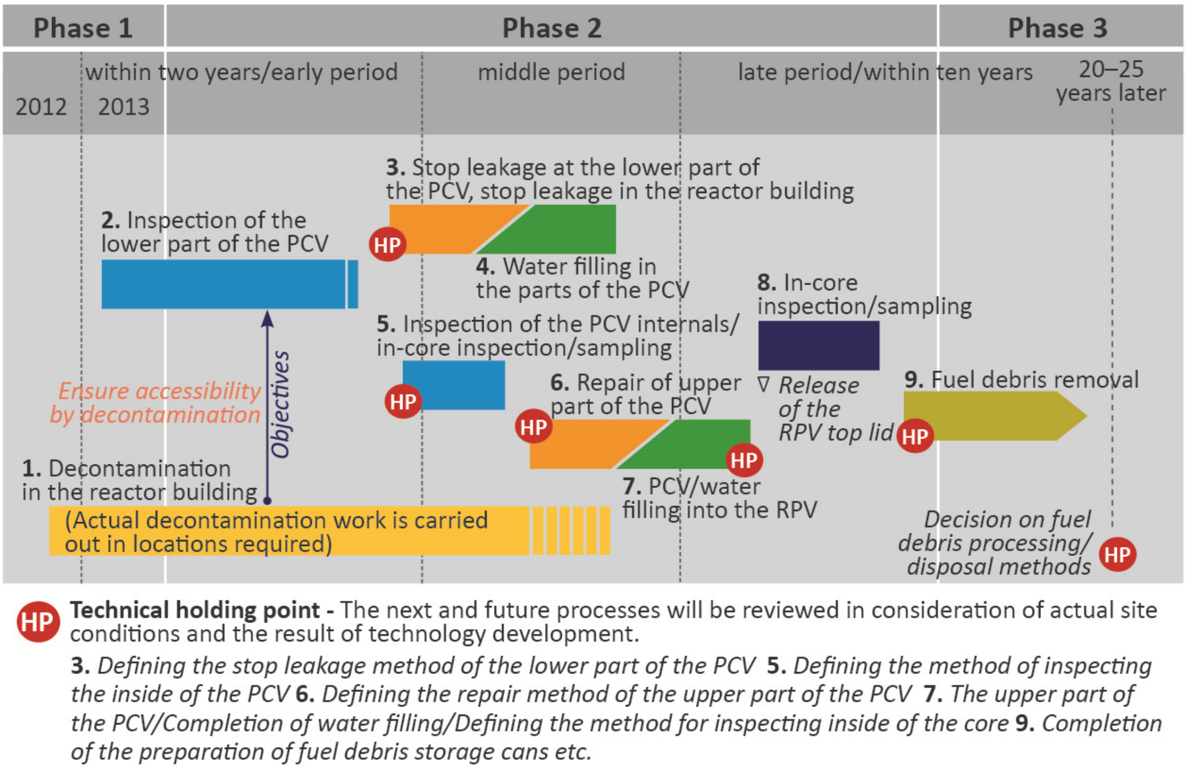


FIG. 5.3–14. Conceptual model for future debris removal activities [120].

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.

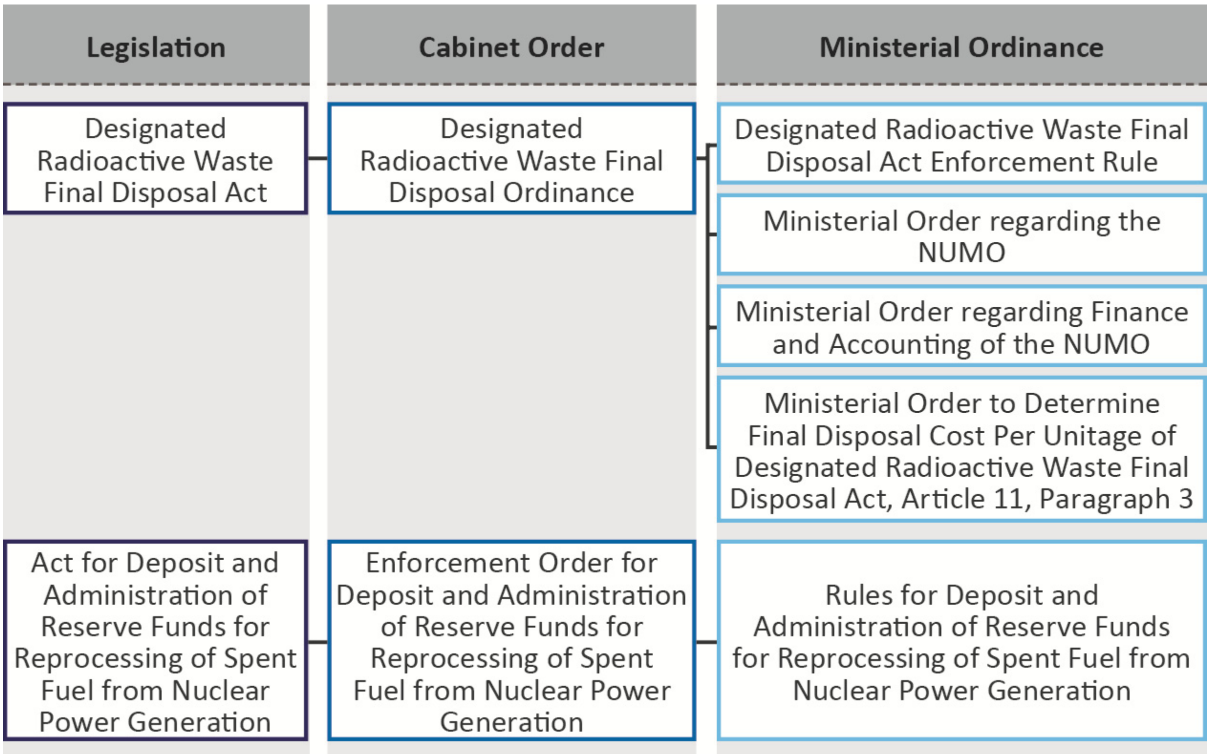


FIG. 5.4–1. Main regulatory system for the promotion of radioactive waste management and spent fuel management for normal waste streams [170].

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)	Relevant municipalities, prefectures, etc. (implementing decontamination)	Local storage, dedicated temporary storage sites	None	
		ICSAs, (other prefectures)				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)	Municipalities, prefectures, etc. (implementing decontamination)			
		ICSAs (other prefectures)				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.

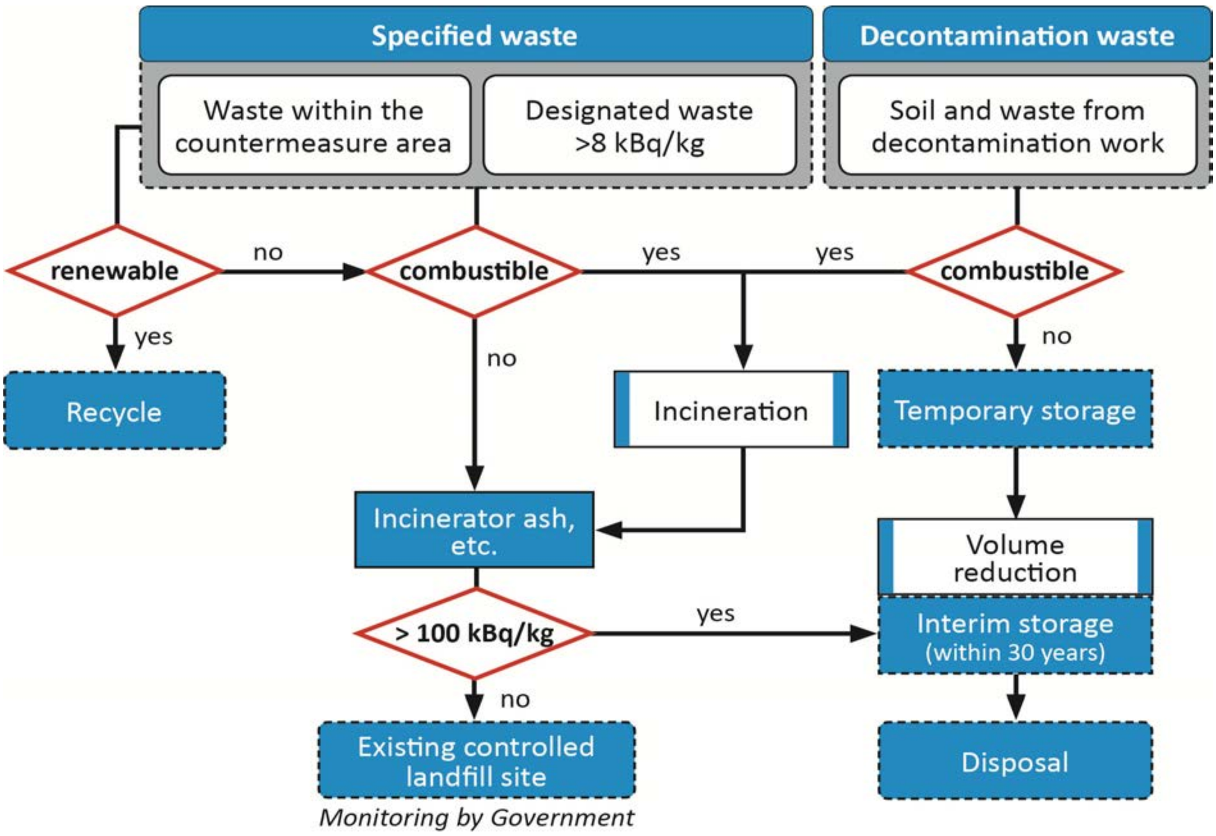


FIG. 5.4–2. Flow chart of specified waste and contaminated soil management in Fukushima Prefecture, as of December 2014 [189][37].

[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).

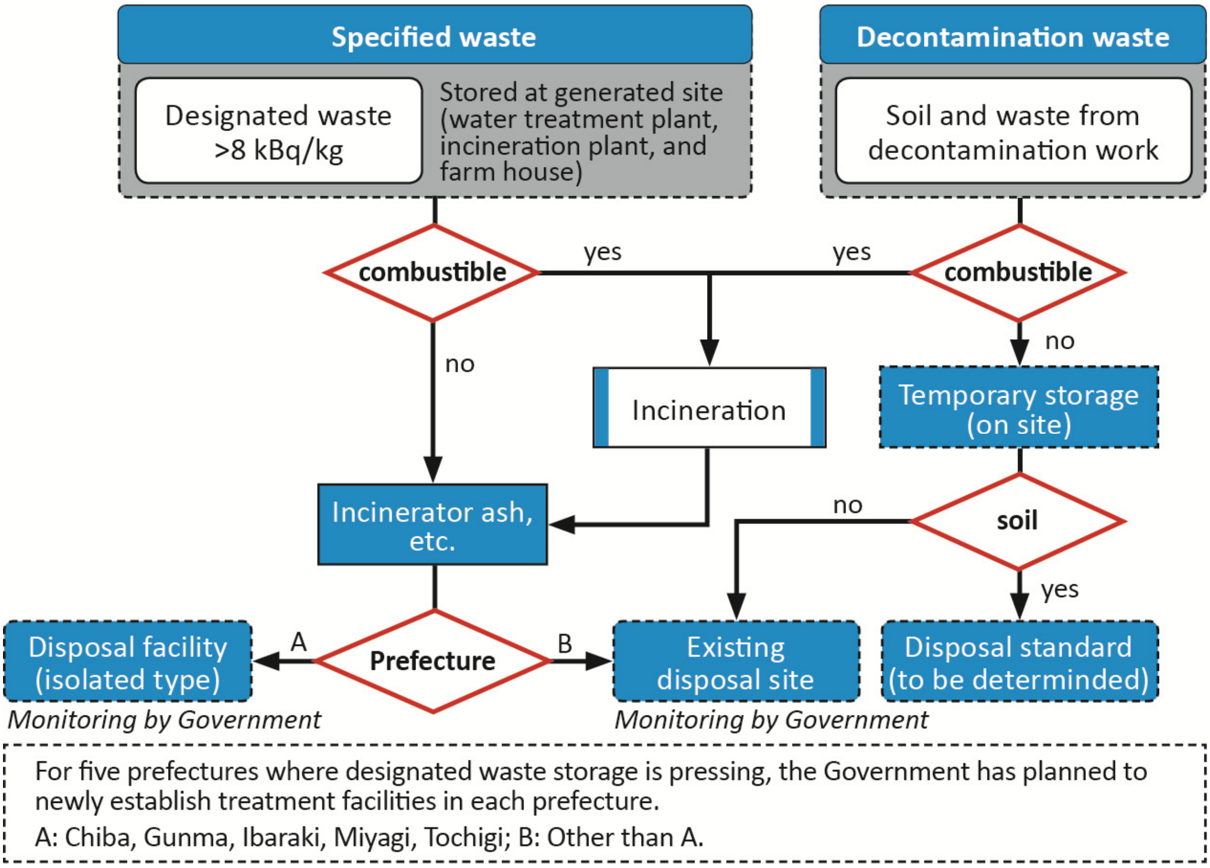


FIG. 5.4–3. Flow chart of specified waste and contaminated soil management in other prefectures [190].

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.

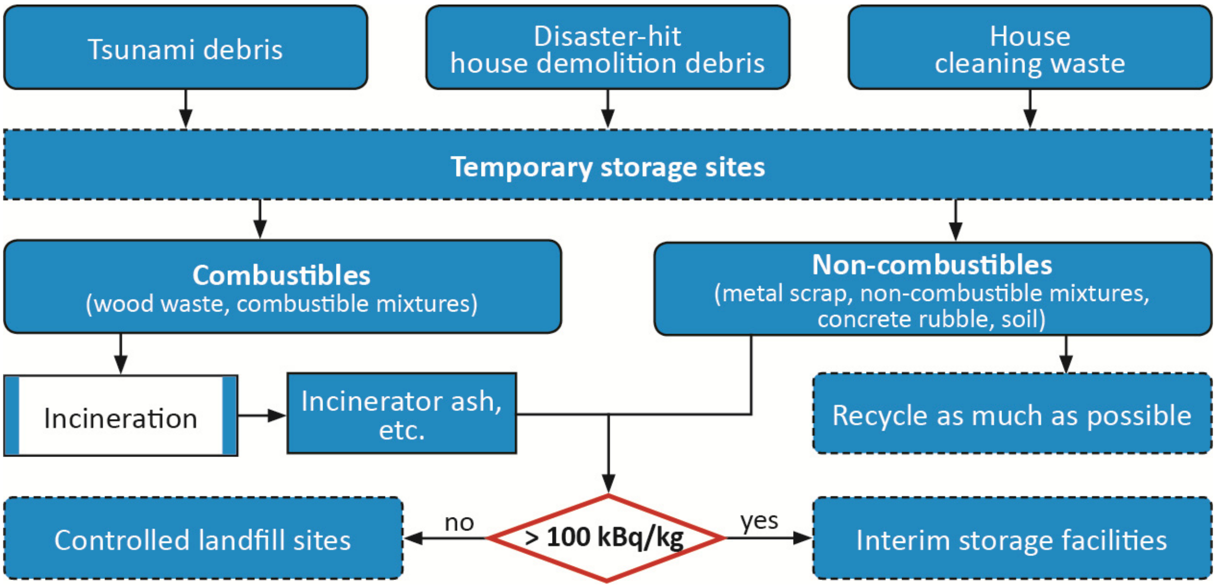


FIG 5.4–4. Processing flow of waste in the SDA [189].

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].

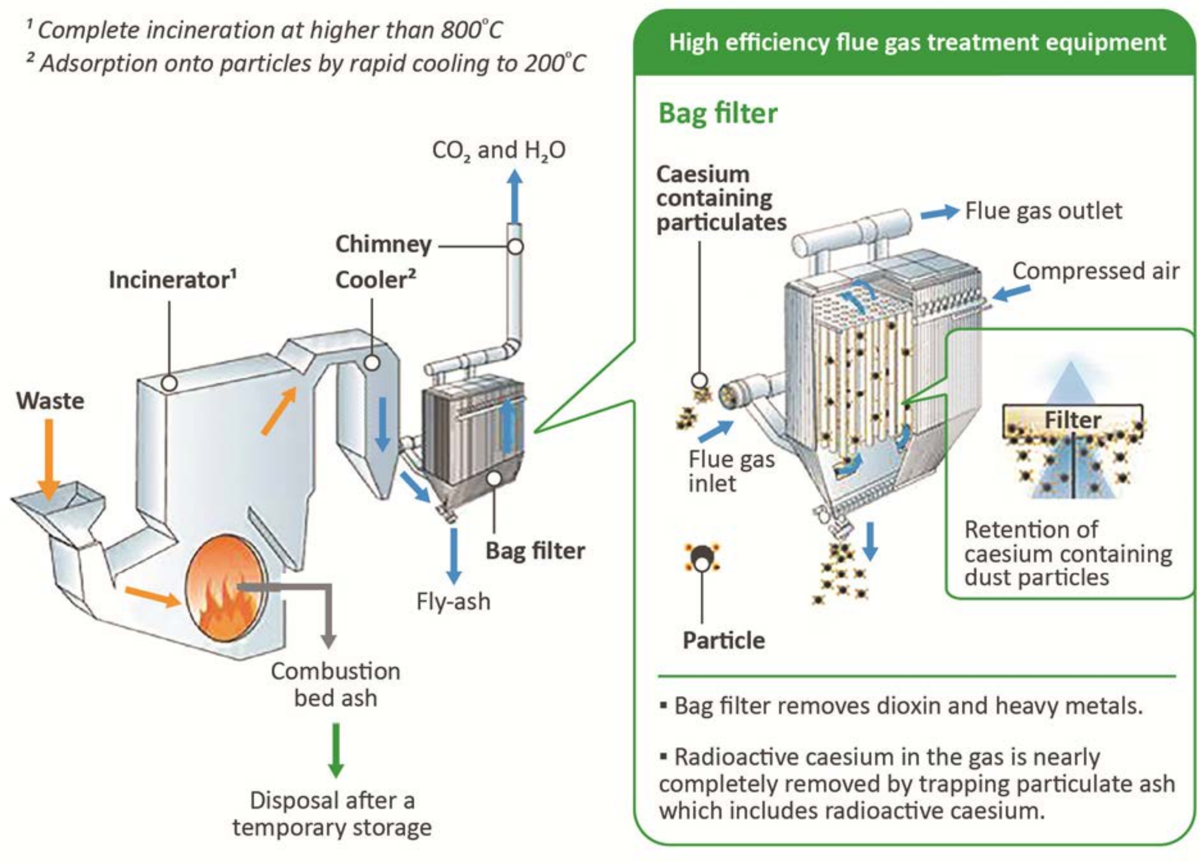


FIG 5.4–5. Schematic diagram of incinerator and off-gas cleaning systems [185].

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].

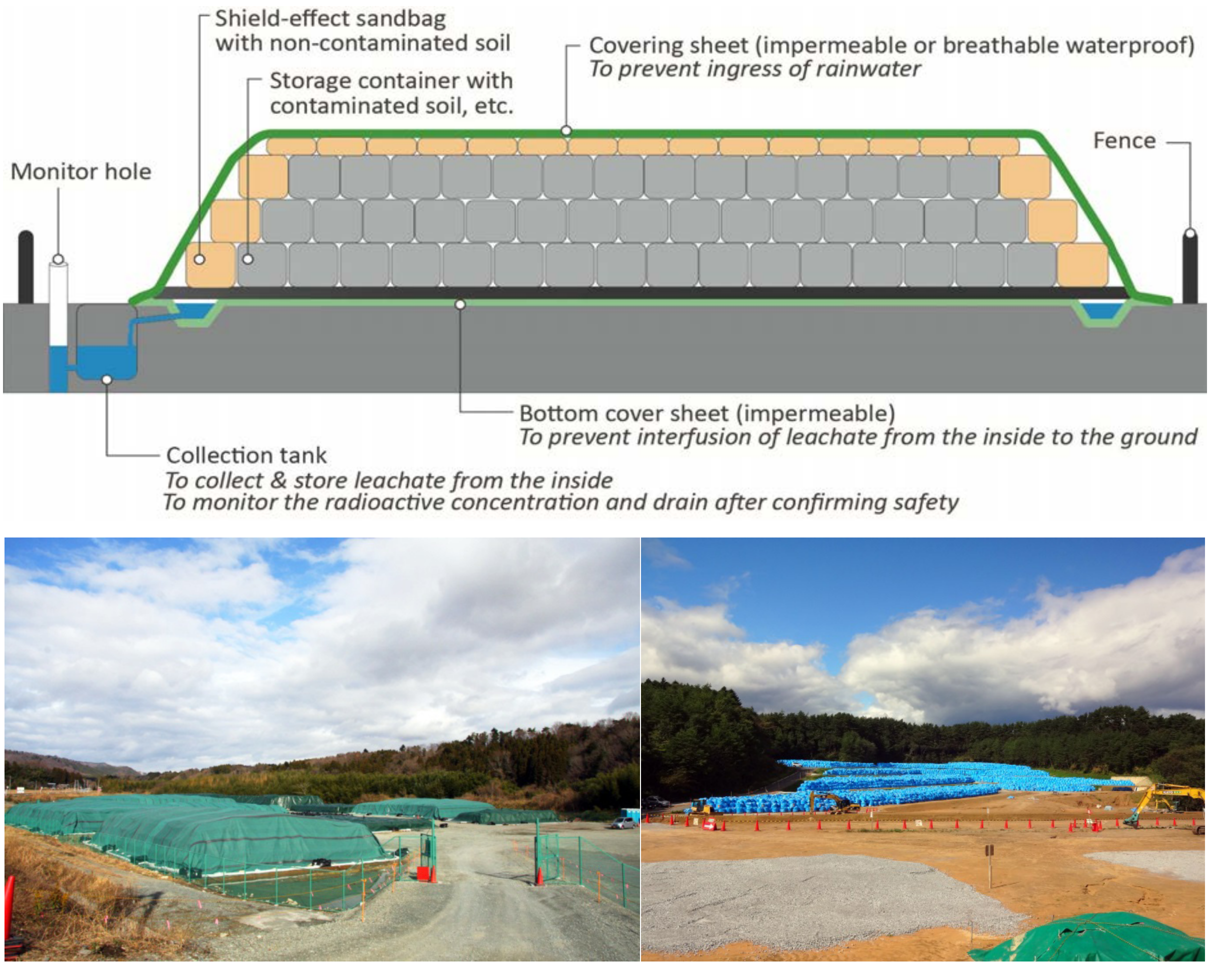


FIG. 5.4–6. Examples of TSS designs [201] (Photograph on the left courtesy of the Ministry of the Environment).

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.

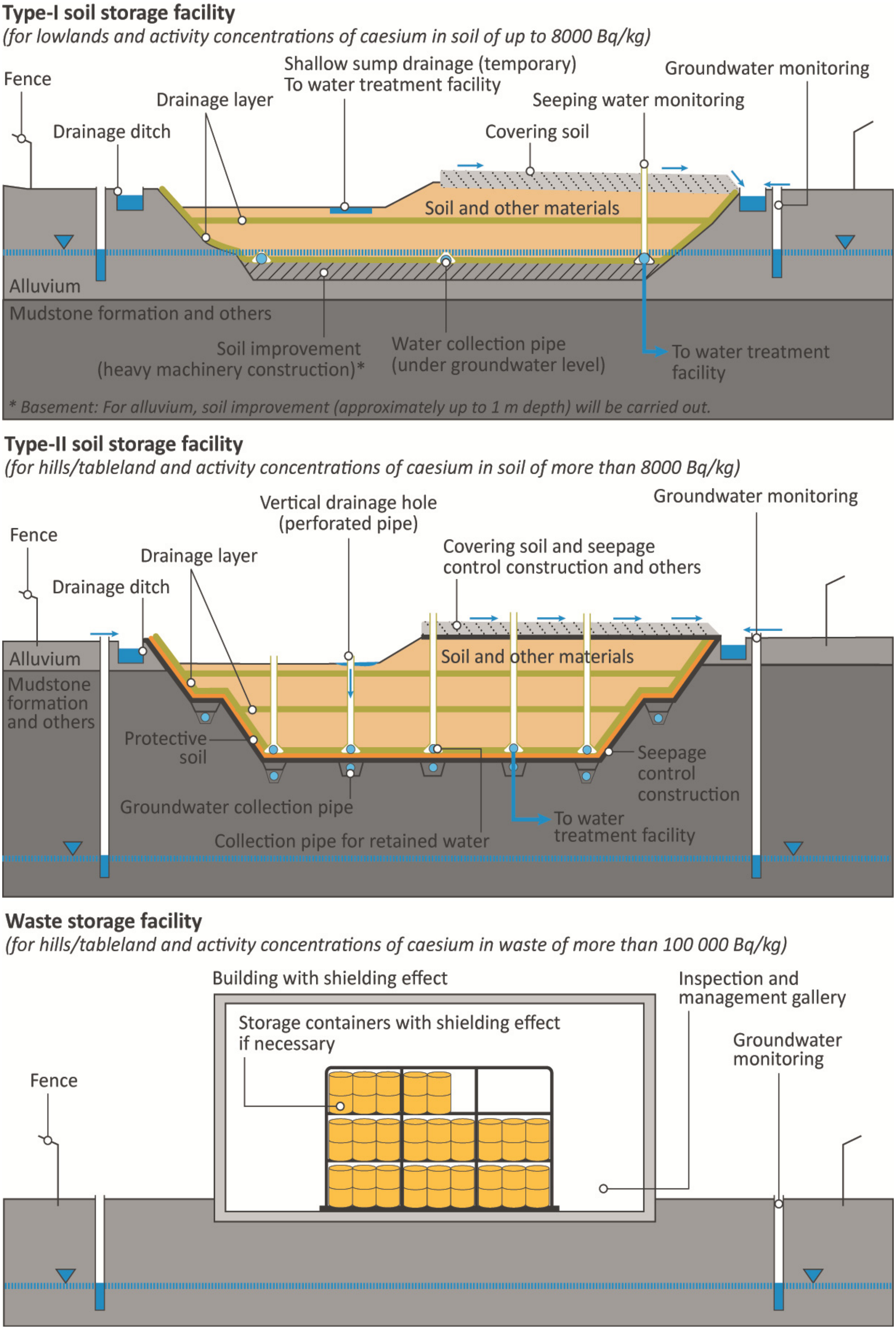


FIG. 5.4–8. Concepts of an ISF for different wastes and types of land [55, 185].

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].

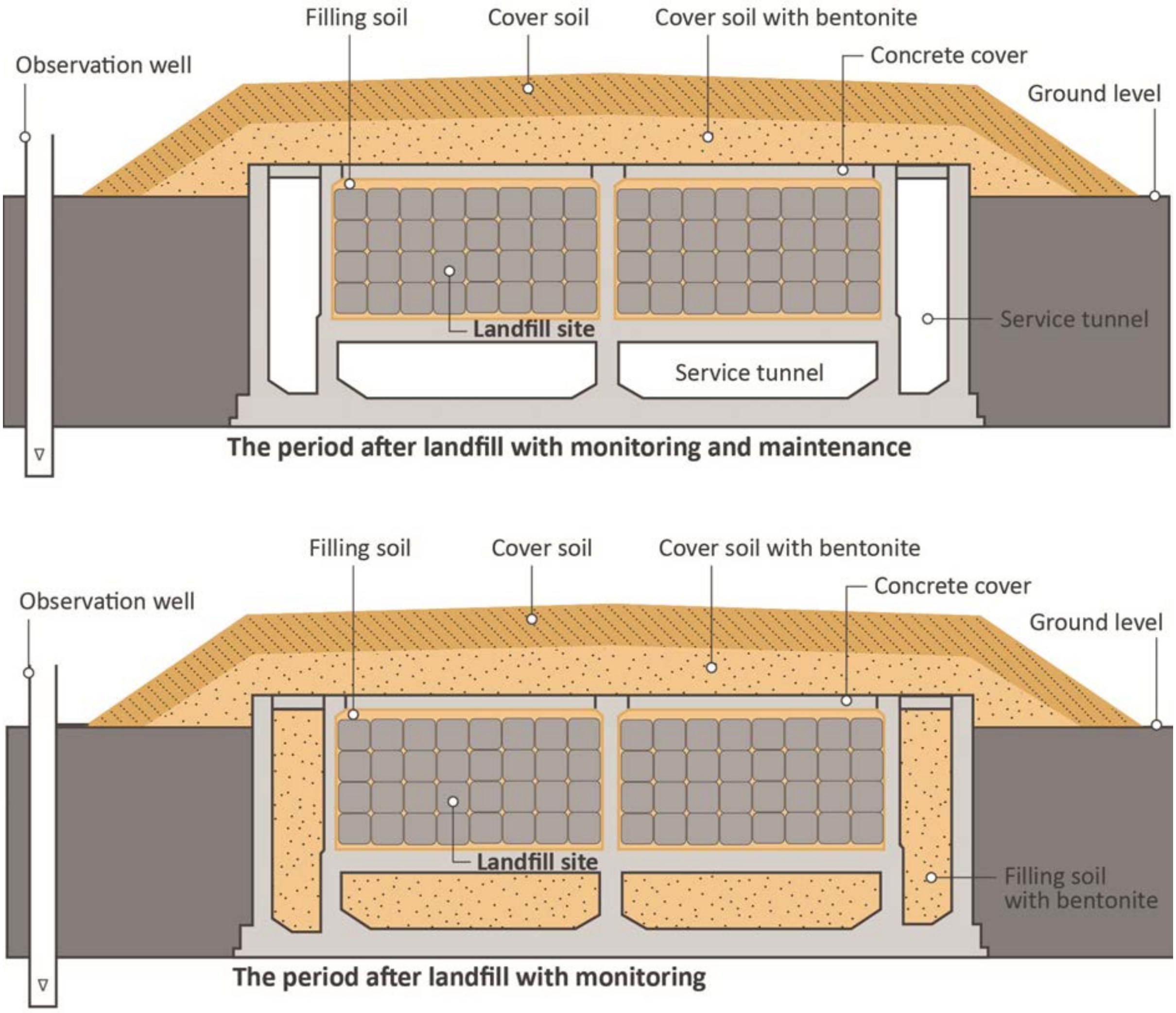


FIG. 5.4–9. Design of landfill disposal for designated waste [192].

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.

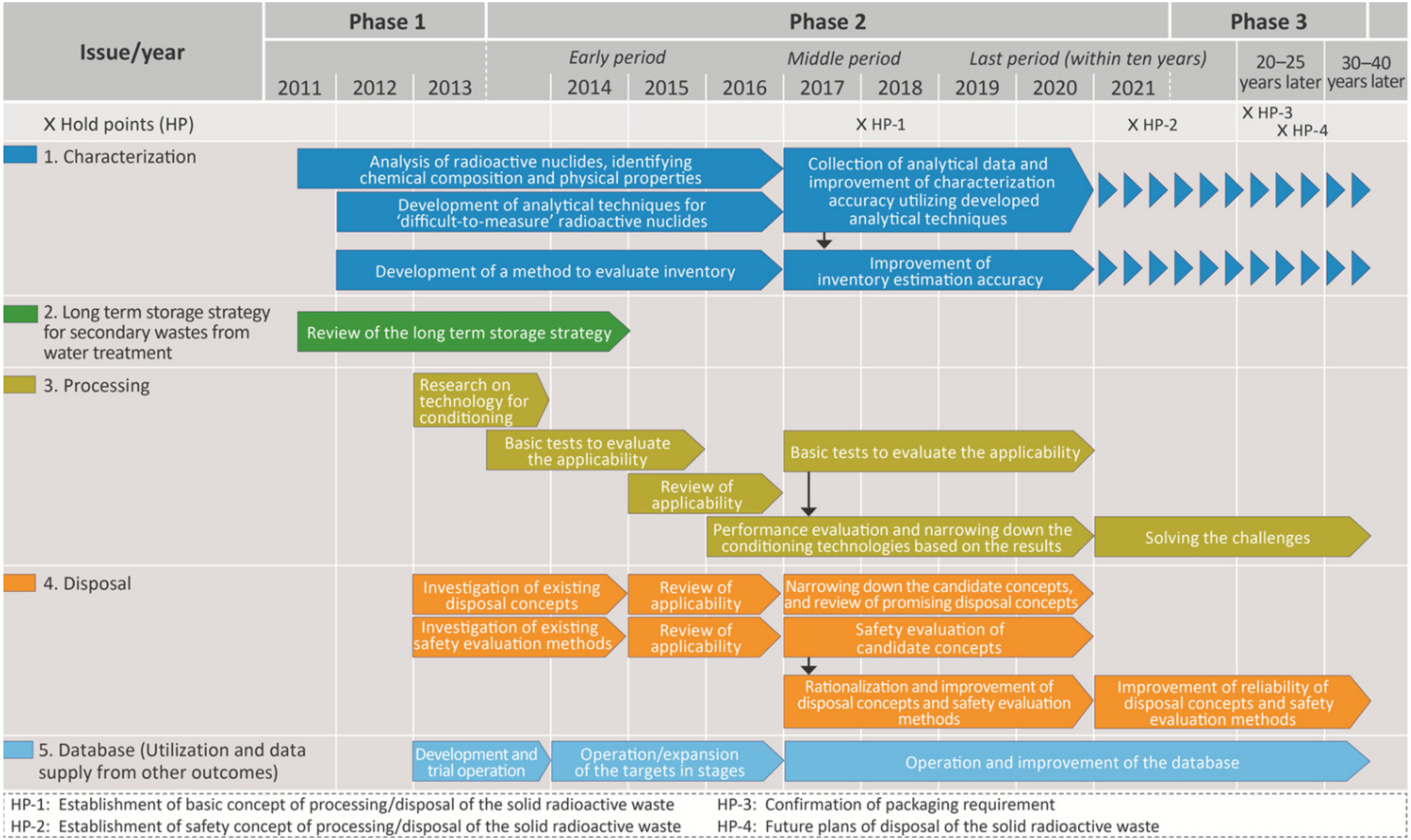


FIG. 5.4–10. Part of the strategy for on-site waste management [169].

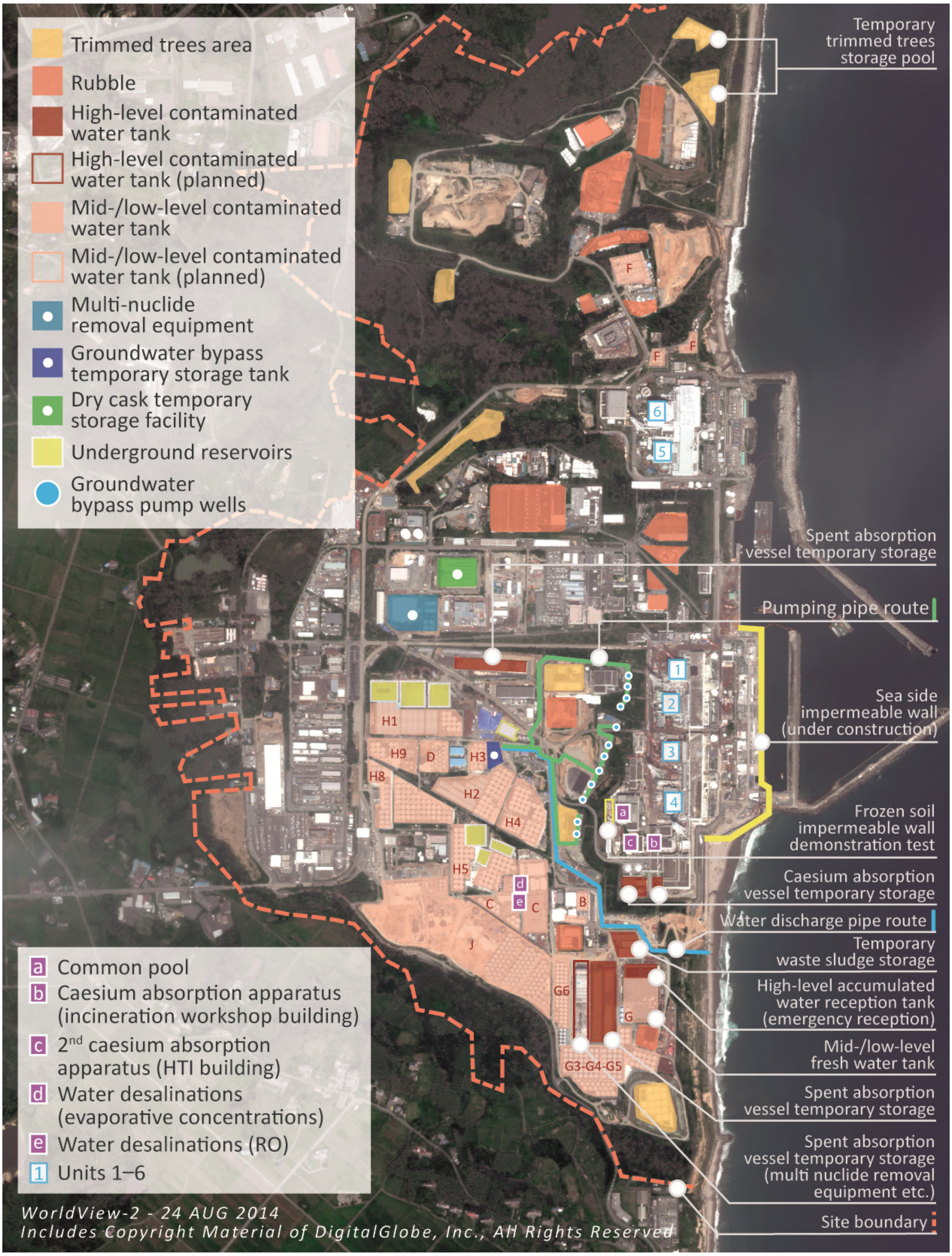


FIG. 5.4–11. Overview of the on-site area and current waste management facilities [55, 134].

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.

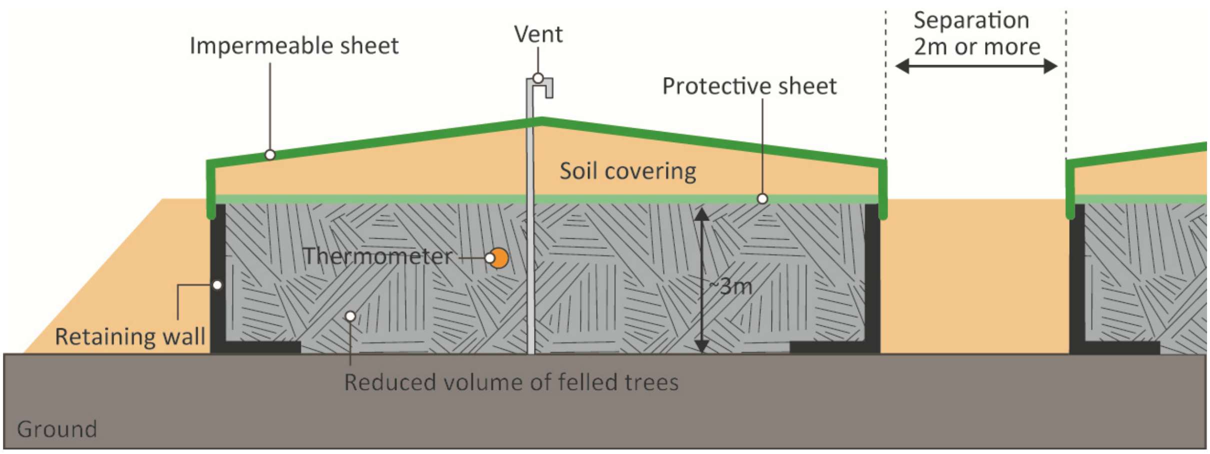


FIG. 5.4–12. Diagram of a soil covered storage facility for branches, leaves and roots [207].

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.

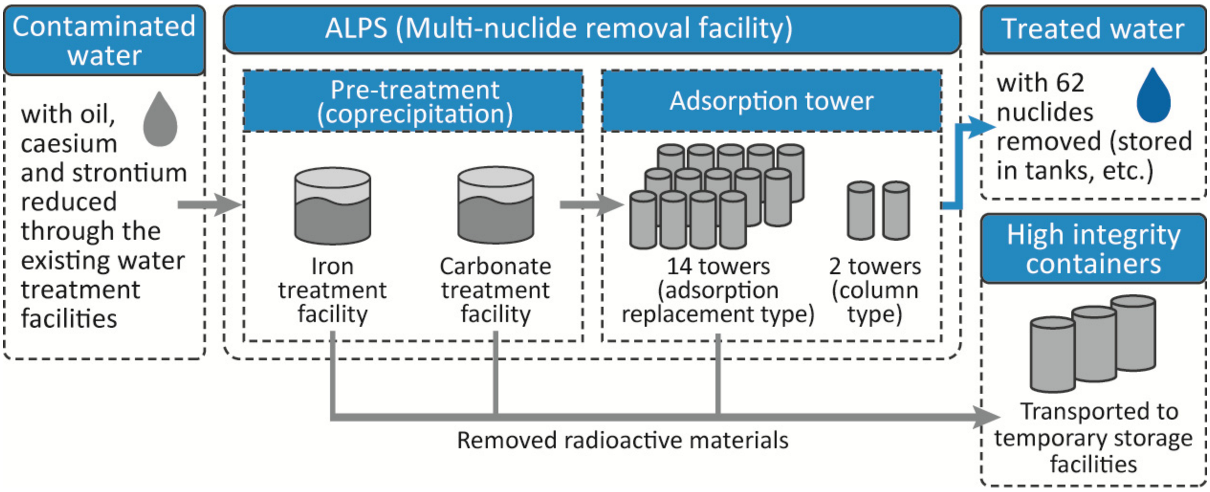


FIG. 5.4–14. The Advanced Liquid Processing System (ALPS) [207].

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.

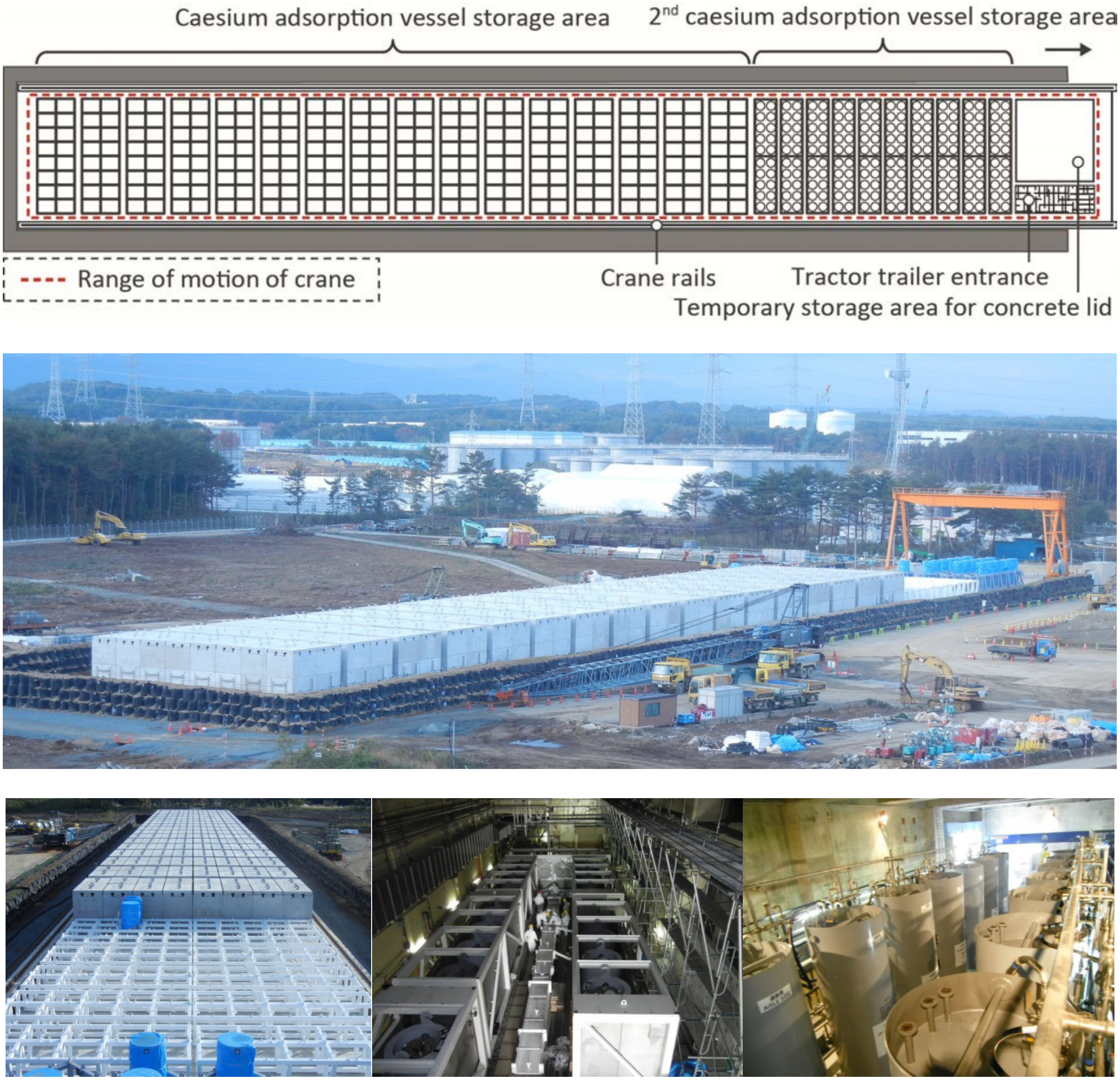


FIG. 5.4–15. Temporary storage facility for caesium adsorption vessels (top); caesium adsorption vessels (lower left), KURION vessels (middle) and SARRY vessels in the operating facilities (lower right) [207].

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.

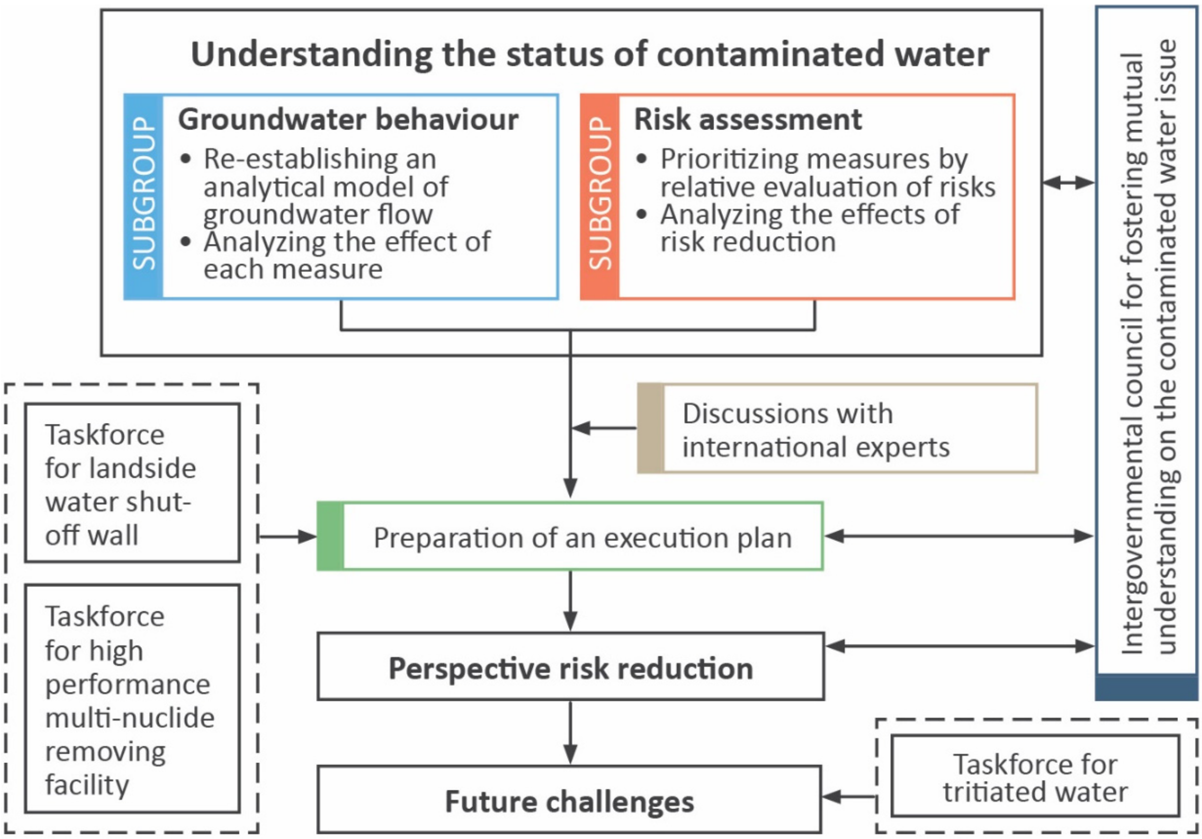


FIG. 5.4–16. Risk review approach for contaminated water [225].

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.

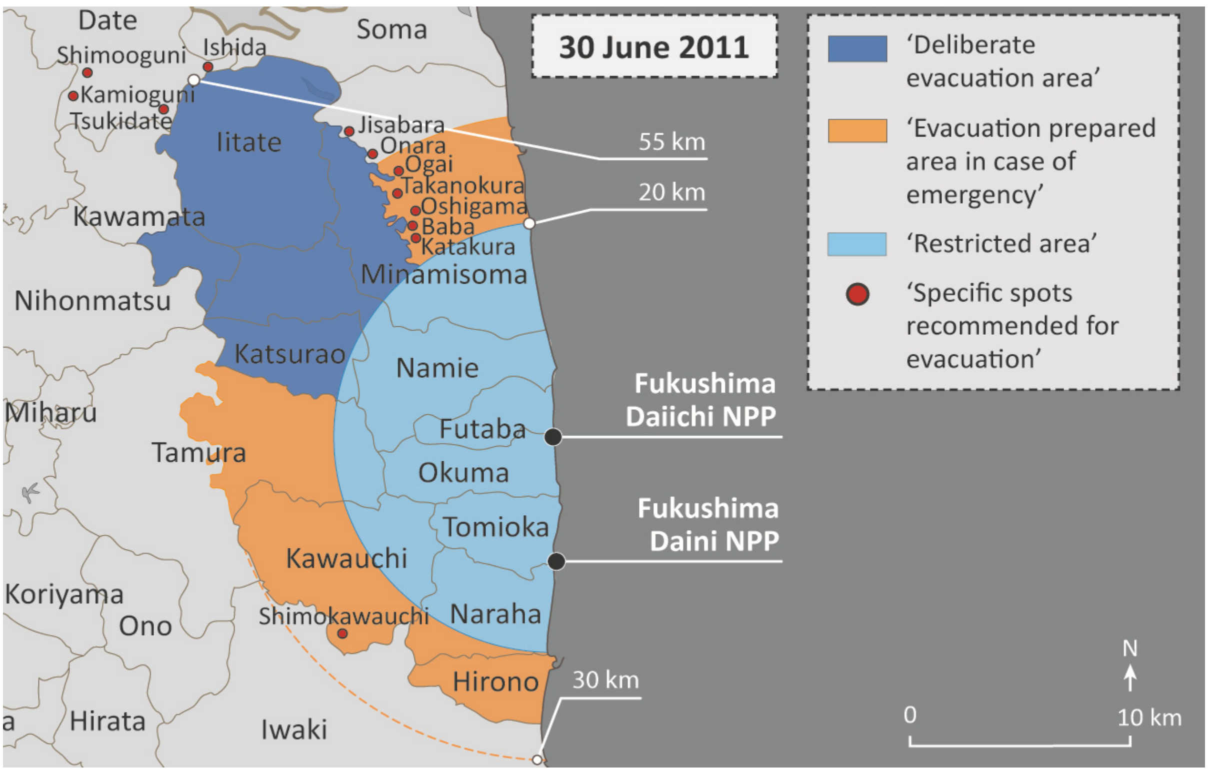
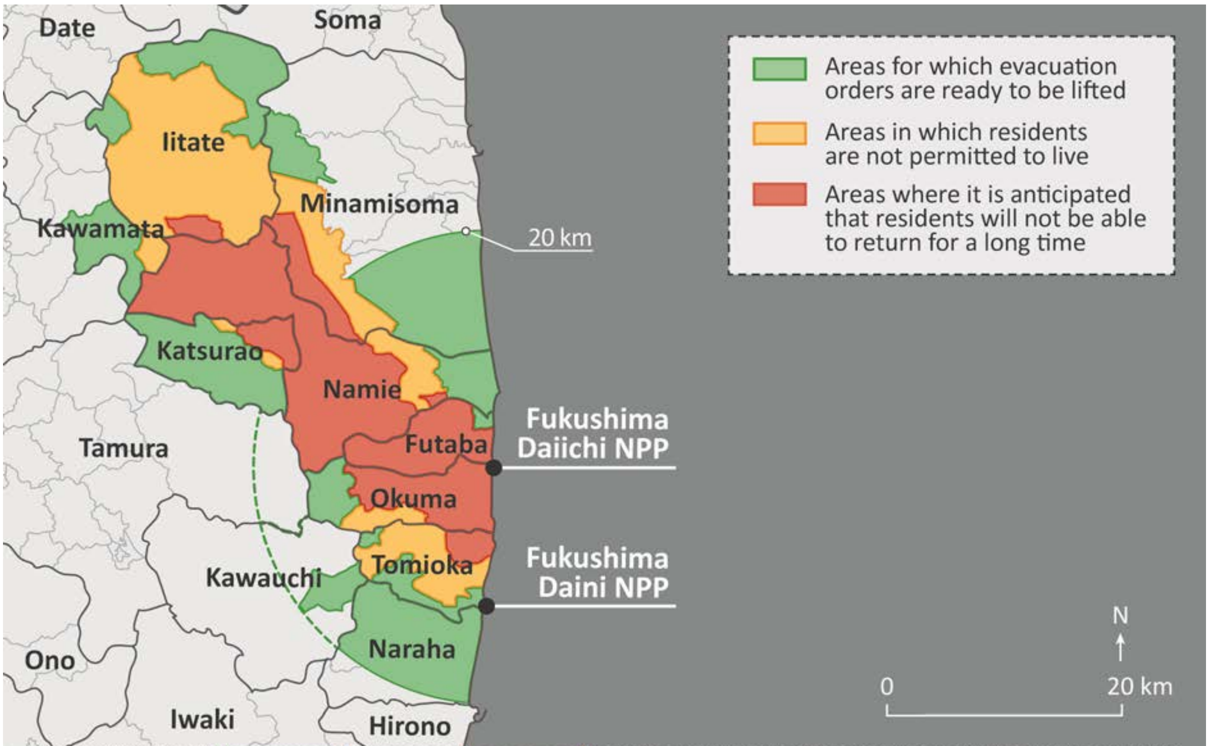


FIG. 5.5–1. Restricted area, Deliberate Evacuation Area, area prepared for evacuation in case of emergency and regions including specific spots recommended for evacuation (as of 30 June 2011) [239].



	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	-	-			
Kawauchi	54	-	-		274	
Tamura	-	-	-		351	
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

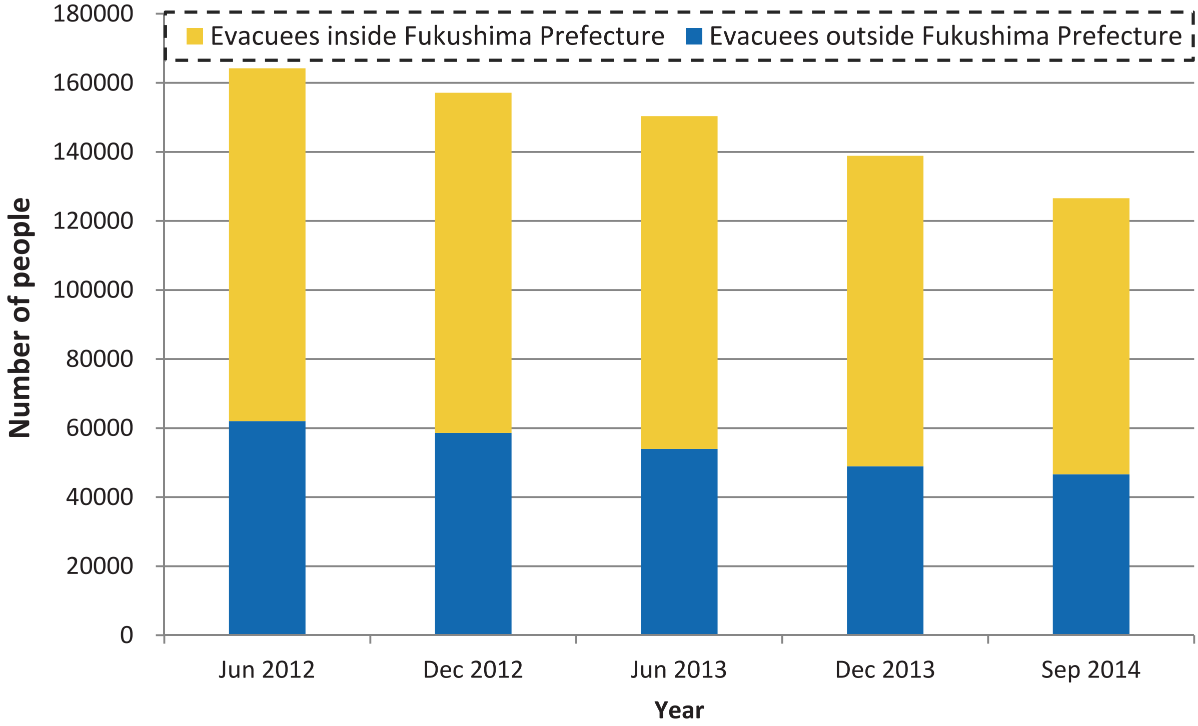


FIG. 5.5–3. Changes in the number of evacuees in Fukushima Prefecture [241].

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

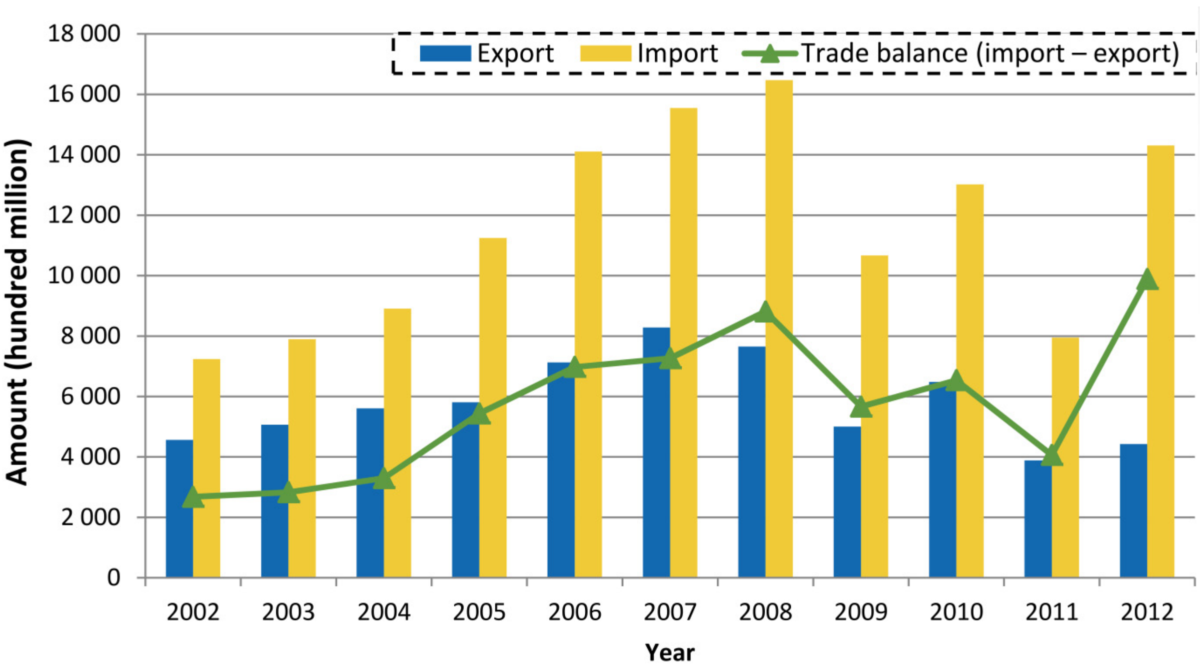


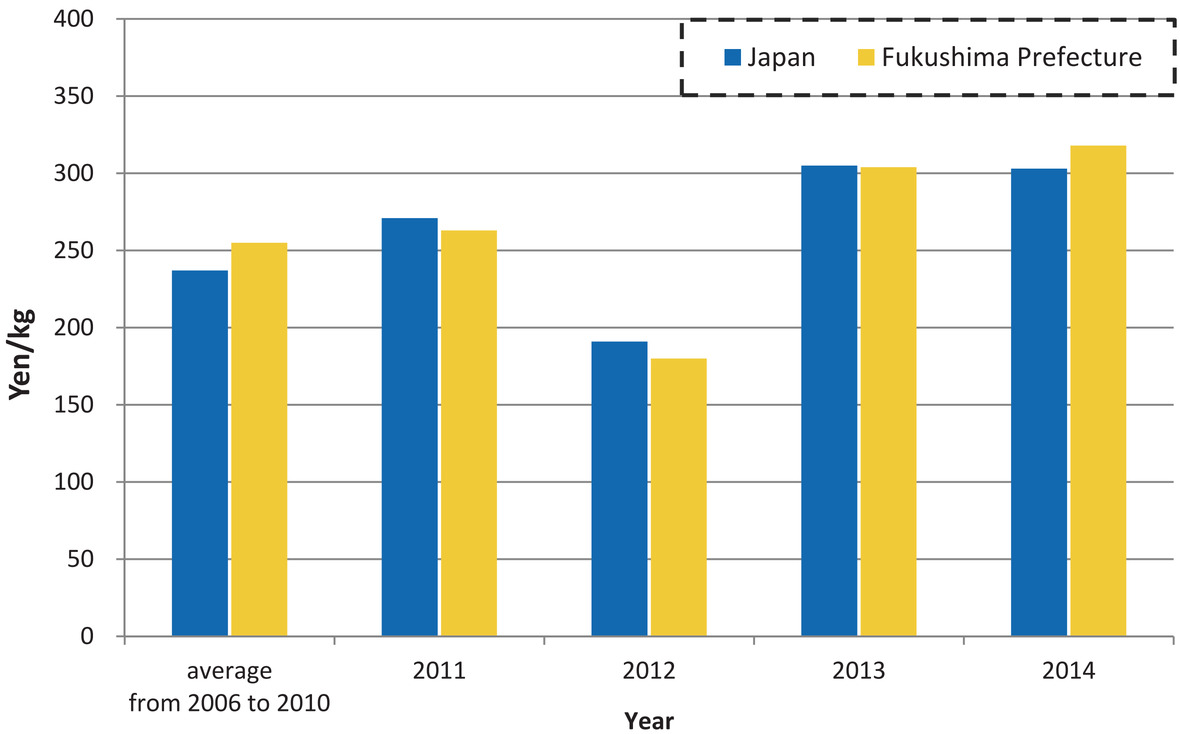
FIG. 5.5–4. Trade balance in the Tohoku area (units in hundred million) [256].

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).

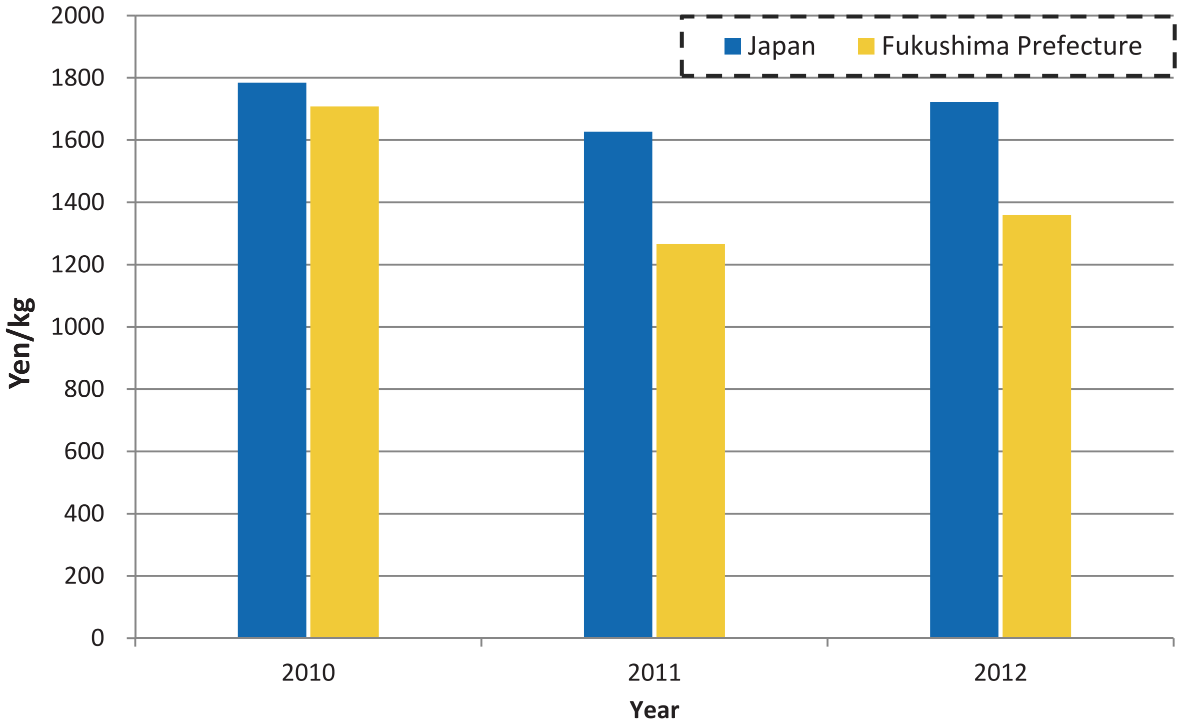
In 2011, exports of Japanese agricultural, forestry and marine products decreased significantly (by over 10%), especially to Asian countries. However, some products remained in high demand for export, including sake and green tea [252].

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].

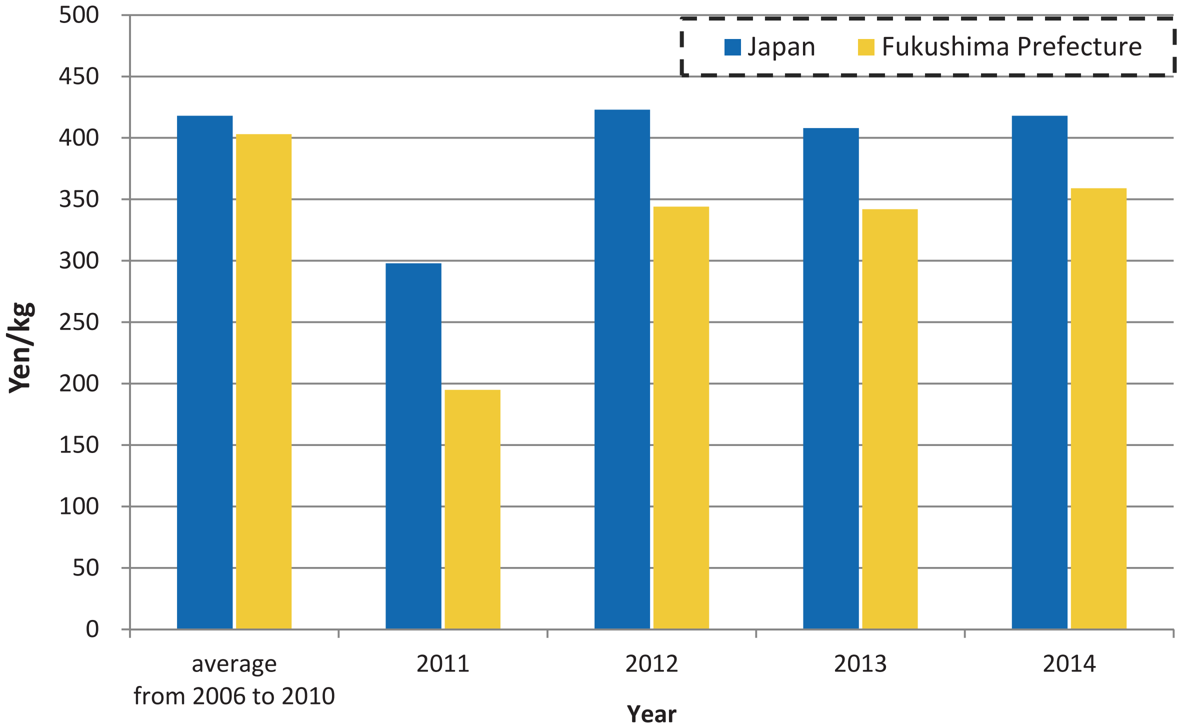
There is no direct evidence that links the price recovery to the change of the reference level for radiocaesium in food; other factors may have played a role. In fact, the prices of food, especially for fresh products, fluctuate greatly each year depending on the production quantity and the quality. 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.

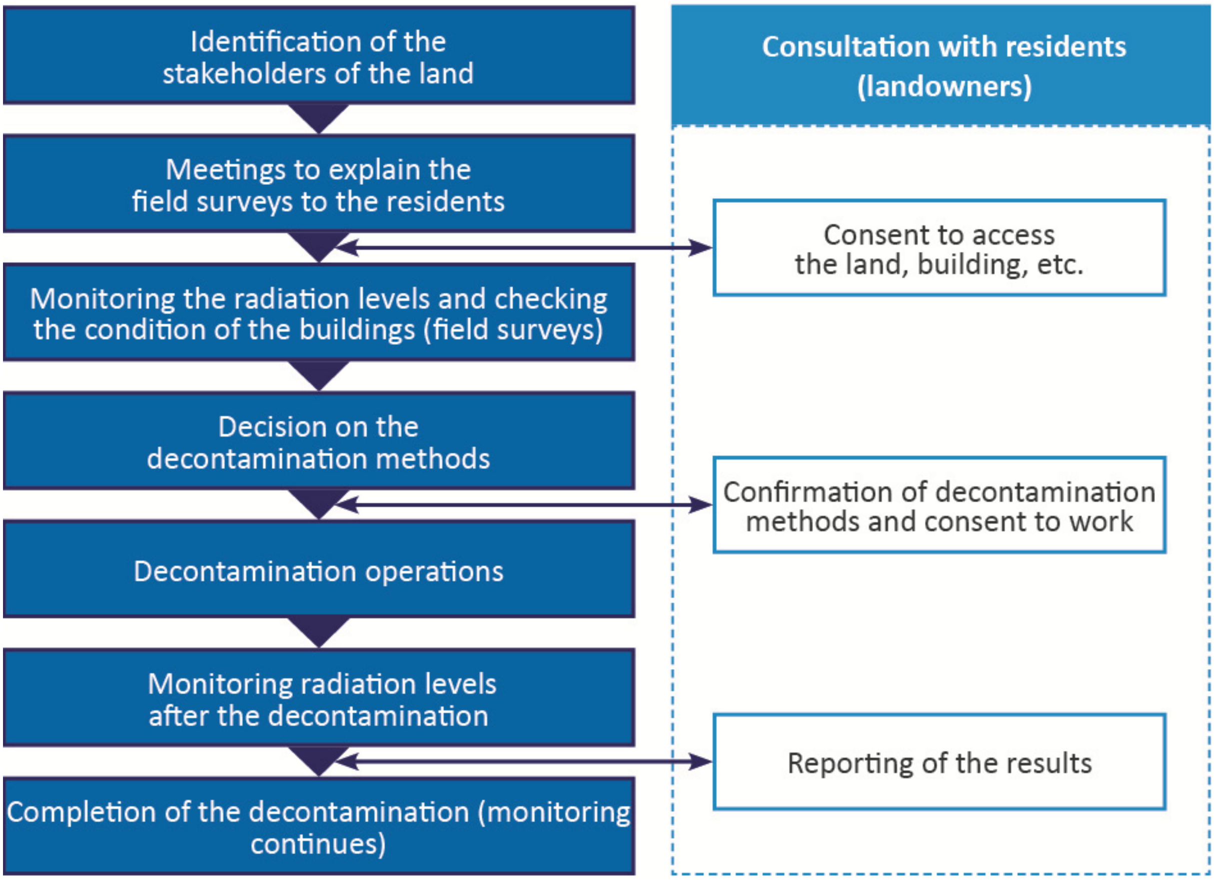


FIG. 5.5–7. Flow chart of the implementation process for remediation and consultations with residents [287].

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.

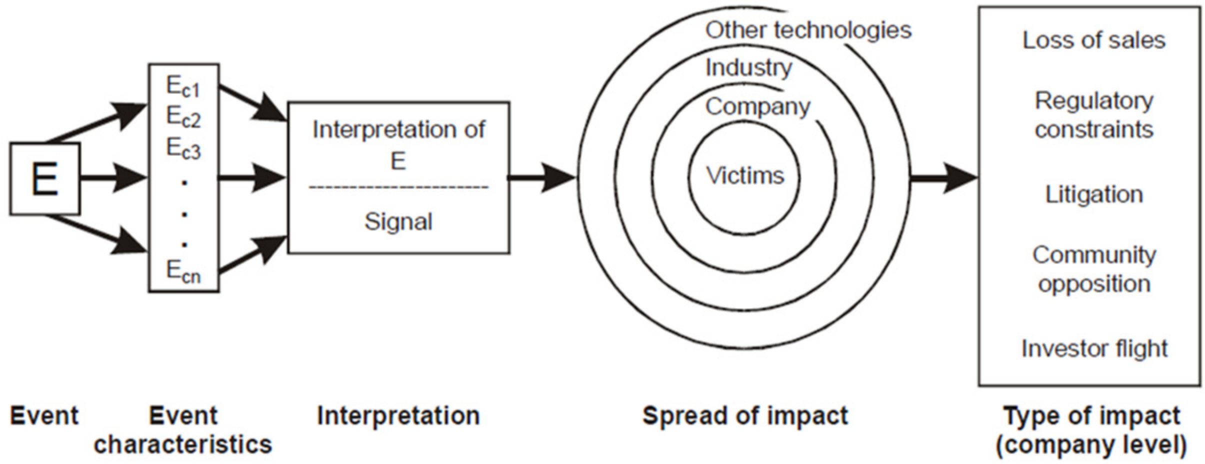


FIG. 5.5–8. Simplified representation of social amplification of risk and its potential impact on society [313].

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].

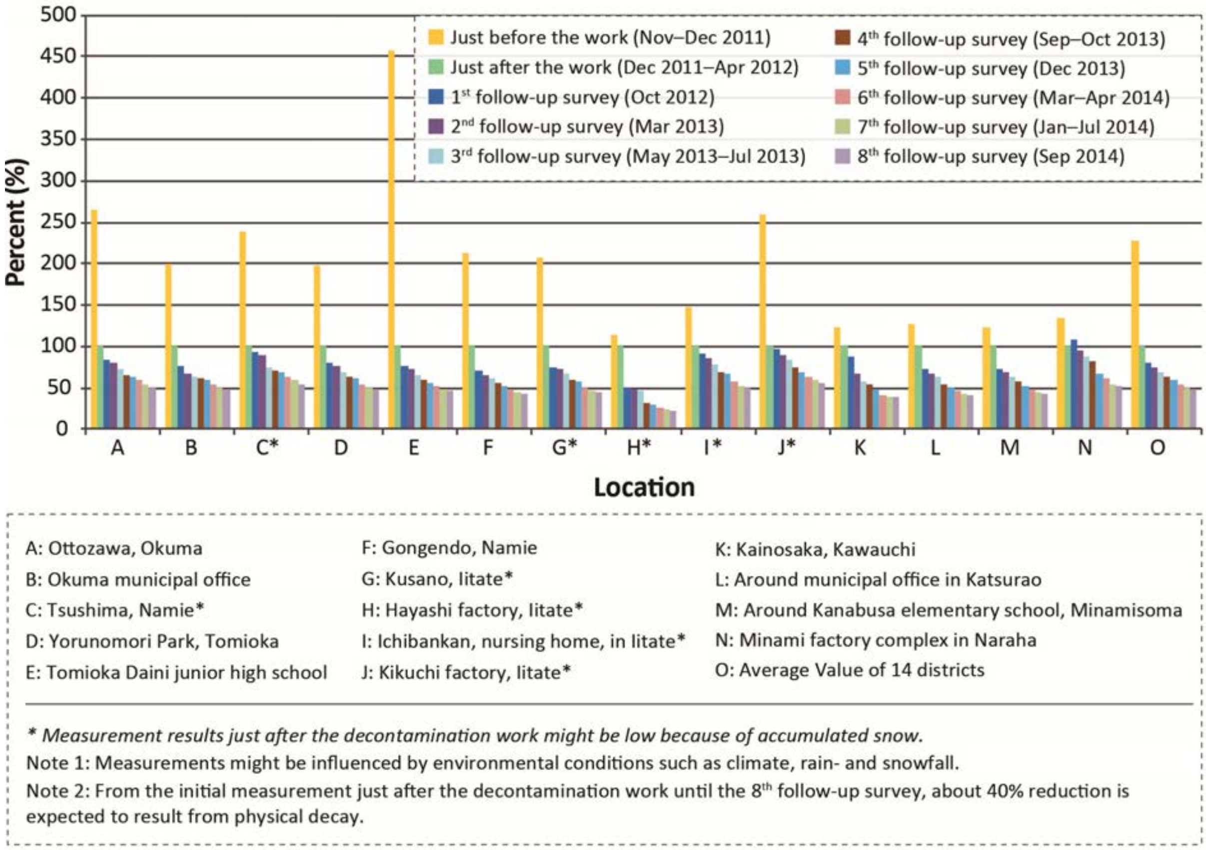


FIG. I.1. Changes with time in the ambient dose rate before and after demonstration projects in the evacuation area. The dose rate (µSv/h) is the averaged value measured in each of the sites. The value immediately after decontamination (green column) is normalized to be 100% [55].

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.

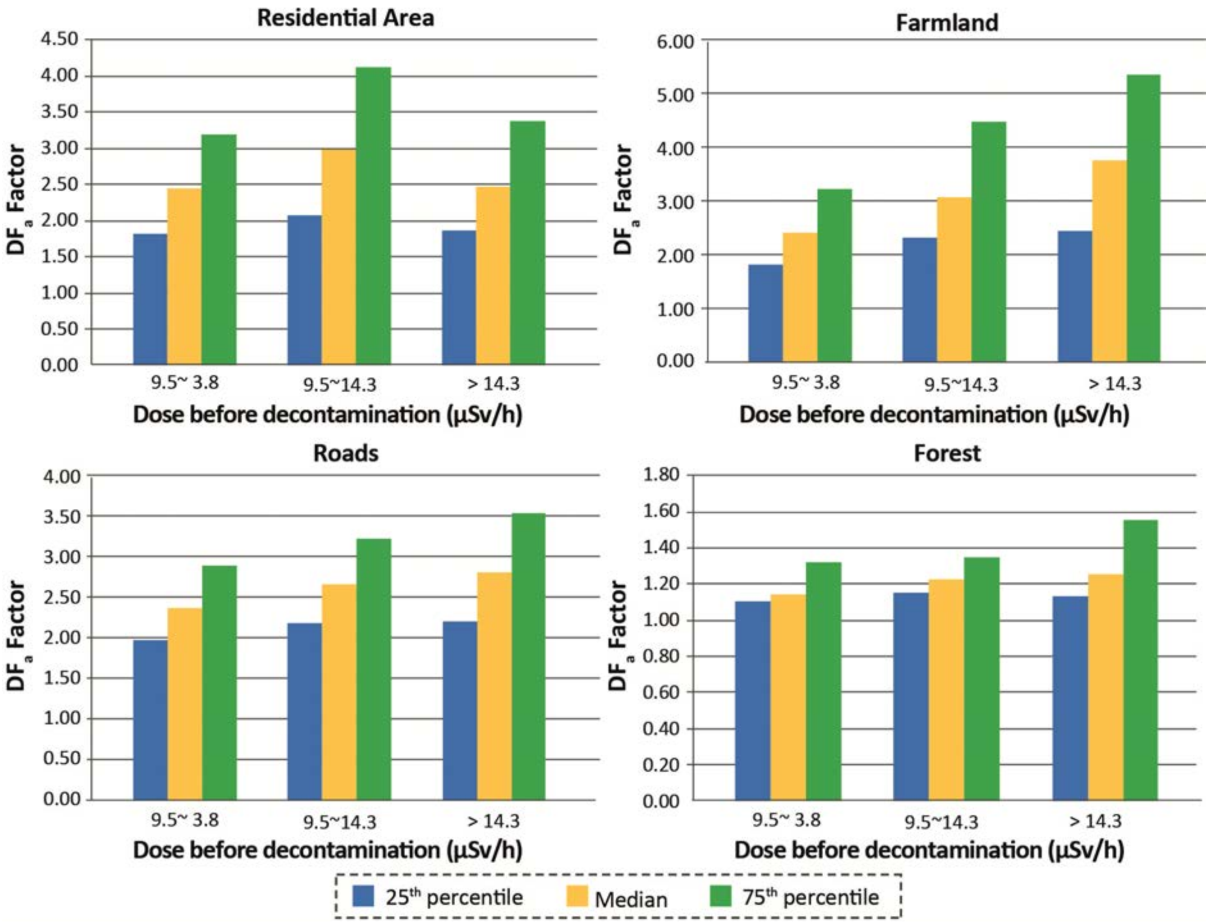


FIG. I.2. Decontamination factors (DF$_a$) for different targets achieved in the MOE decontamination model evaluation project in six SDA 3 sites [318].

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.

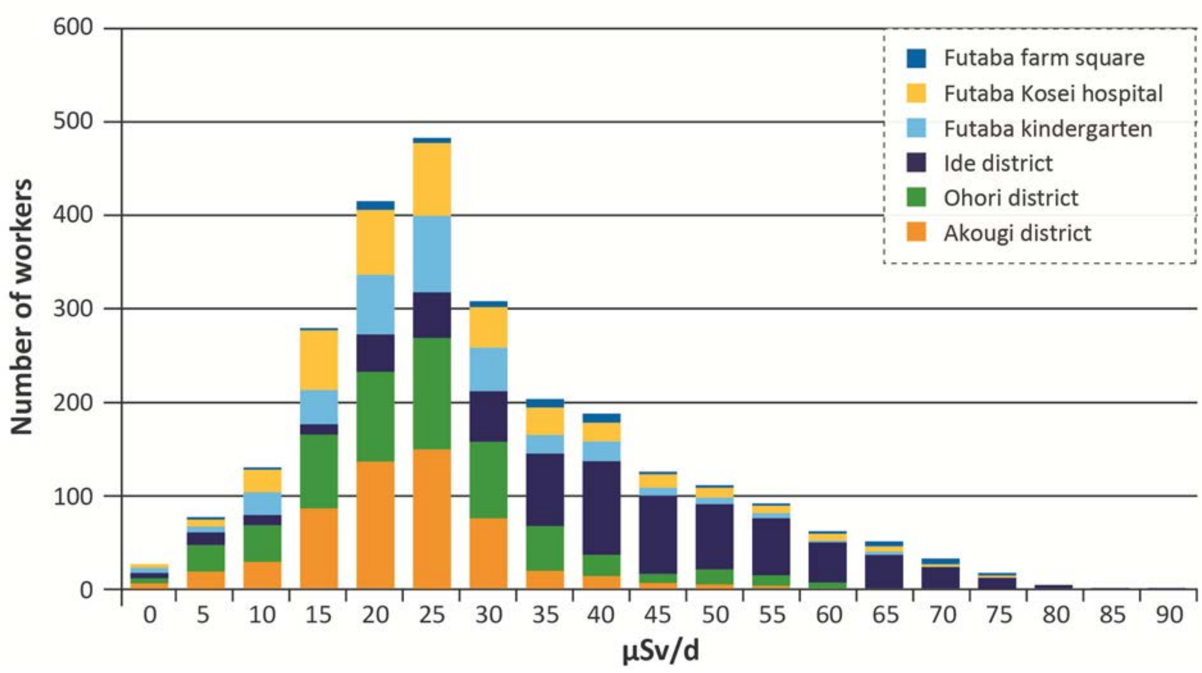


FIG. I.3. Frequency distribution of dose rates to decontamination workers in the six demonstration sites in SDA 3 [320].

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.

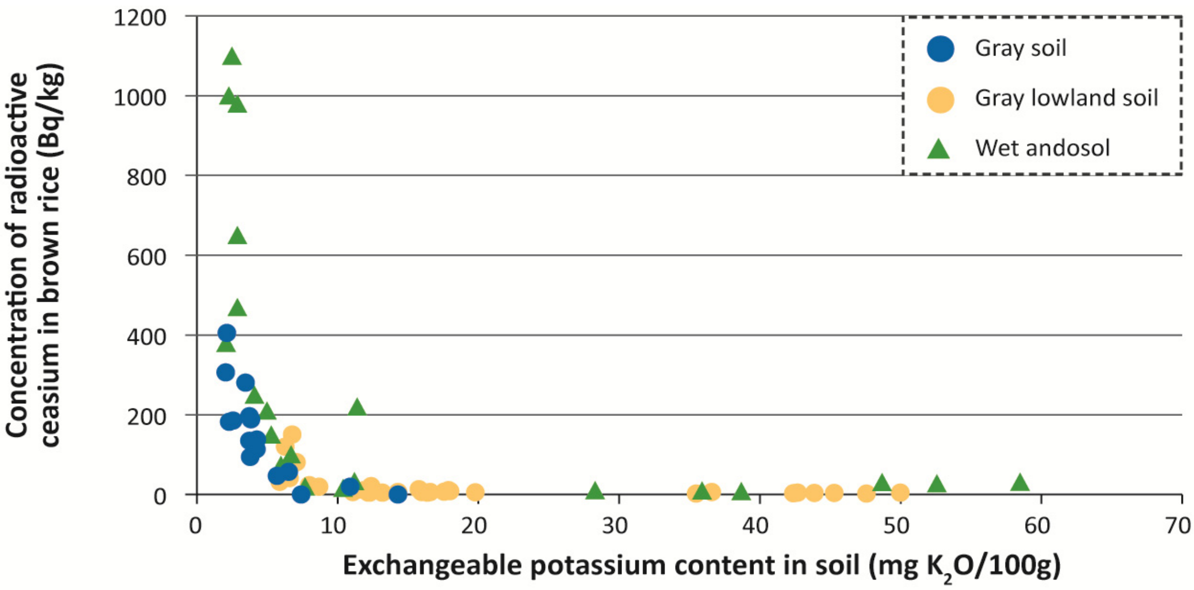


FIG. I.4. The relationship between exchangeable potassium in soil and radiocaesium activity concentration in husked rice, which can be used to determine the need for additional potassium in soil [82].

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

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)