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

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

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

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

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

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

### 3.2.2. Protective measures for emergency workers

The national legislation and guidance in Japan at the time of the accident addressed measures to be taken for the protection of emergency workers. However, the arrangements that were in place, such as the on-site plan, addressed these requirements only in a general way and not in sufficient detail. For example, the on-site plan covered the following areas: defining responsibilities; assigning generic duties in emergency preparedness and response; and listing an inventory of available instrumentation (e.g. survey meters and electronic dosimeters) [77].

Dose limits for emergency workers were set depending on their intended tasks, with an upper dose limit of 100 mSv for life saving actions and activities to prevent the development of catastrophic conditions, while efforts to minimize the exposure were required [95, 96].

During the accident, a range of impromptu measures were adopted to maintain an acceptable level of protection for on-site emergency workers under the extreme conditions. There was a lack of personal dosimeters, as most of those at the site had become inoperable after the tsunami. This made it necessary to take contingency measures to track the individual doses received by the on-site emergency workers [8]. For example, an instruction was issued to use a single electronic personal dosimeter per group of emergency workers expected to work in similar conditions. For emergency workers in the seismically isolated building, doses were measured and controlled by area dose rate monitoring and by the amount of time spent by workers in the specific areas. This situation continued until the end of March 2011, by which time a sufficient number of dosimeters had been received from other NPPs [6, 8].

On 14 March 2011, the dose limit for emergency workers undertaking specific emergency work was temporarily increased to 250 mSv to allow the necessary activities to continue on-site and within a 30 km radius from the Fukushima Daiichi NPP [97]. A dose of 100 mSv remained the limit for emergency workers from the firefighting service for life saving actions [6]. The temporary increase in the dose limit to 250 mSv was withdrawn on 1 November 2011 for on-site emergency workers who began working from this date onwards; on 16 December 2011 it was withdrawn for the majority of the remaining emergency workers; and on 30 April 2012 it was withdrawn for a small group of emergency workers with specialized knowledge and experience [98, 99].

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

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

TEPCO also faced challenges in ensuring the well-being of on-site emergency workers, for example in providing adequate facilities and conditions (for resting, sleeping, eating, sanitation, etc.) [100, 101, 102, 103].

During the response to the accident, people from the affected areas, as well as from all over Japan, including from a number of non-governmental organizations, referred to as ‘helpers’, volunteered to assist in activities such as the provision of food, water and necessities, and later in decontamination and monitoring activities. National authorities issued guidance on the type of activities helpers could carry out and on measures to be taken for their protection [104, 105, 106].

### 3.2.3. Designation of emergency workers

Many different types of emergency workers were needed to support the on-site and off-site emergency response. On-site emergency workers included NPP personnel, either directly employed by TEPCO or subcontracted, as well as personnel from the Japan Self-Defense Force, the firefighting services and police engaged in emergency work on the site [8]. Off-site emergency workers included personnel from different organizations and services (governmental and non-governmental). Their tasks included evacuation of the public and of special facilities, offering support to evacuees, providing medical care and carrying out monitoring and sampling [6, 99, 107, 108].

Not all of the emergency workers had been designated as such prior to the emergency (e.g. some TEPCO employees and employees of subcontractors), and arrangements were not in place to integrate them into the response after their designation as emergency workers. Additionally, many of those who had not been designated prior to the emergency had not been trained to work in conditions of a nuclear emergency. For example, they had not been trained in radiation protection aspects, informed of the potential health risks from radiation exposure, or trained in the use of respiratory protection or in dealing with patients potentially contaminated with radioactive material [109]. This resulted in some delay in implementation of mitigatory actions early in the response [6].

### 3.2.4. Medical management of emergency workers

Obtaining the necessary medical treatment for emergency workers with conventional injuries was difficult because several hospitals were closed as a result of the evacuation or sheltering, and some were not prepared to treat patients possibly contaminated with radioactive material [109, 110]. Until primary medical care was provided on the site, emergency workers with conventional injuries were transported to one of two local hospitals for treatment [110].

About 17 hours after the earthquake, the NIRS dispatched a Radiation Emergency Medical Assistance Team (REMAT), consisting initially of a physician, a nurse and a health physicist, to the Local NERHQ (in the Off-site Centre) to perform assessments of the contamination and decontamination for emergency workers [109].

Occupational health doctors began to provide primary care for on-site emergency workers at the Emergency Response Centre in the seismically isolated building eight days after the beginning of the accident. Two triage centres were subsequently established, one on-site and the other in 'J-Village'[73] [3, 8, 110].

From 1 July 2011, an emergency care facility was established at the Fukushima Daiichi NPP. For this facility, medical staff trained to deal with radiation emergencies were recruited from all over Japan [8, 110].

## 3.3. PROTECTING THE PUBLIC

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

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

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

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

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

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

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

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

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

### 3.3.1. Urgent protective actions and relocation

Prior to the accident, 10 km emergency planning zones, in which emergency preparedness was to be significantly enhanced, had been established around the Fukushima Daiichi and Fukushima Daini plant sites (Fig. 3.3). There were plans to implement protective actions within these zones [76].

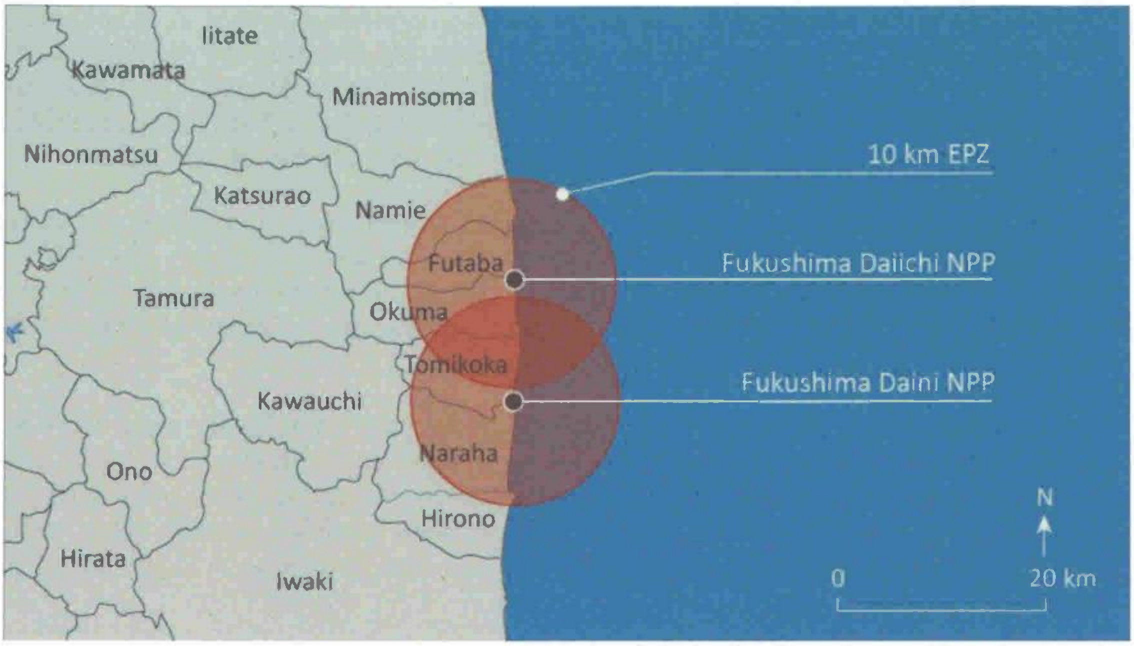


*FIG. 3.3. Emergency planning zones for the Fukushima Daiichi and Fukushima Daini NPPs established prior to the accident (based on Ref. [76]).*

The emergency response plans envisaged that decisions on protective actions would be based on dose projections performed at the time when a decision was necessary. Doses were to be projected by SPEEDI after the onset of the accident and to be compared with predetermined dose criteria to determine what protective actions were needed and where [75, 95]. This approach was not in line with IAEA safety standards, where the initial decisions on urgent protective actions for the public need to be based on plant conditions [70, 71].

Predetermined dose criteria were available for sheltering[74], evacuation[75] and iodine thyroid blocking[76] in terms of projected dose, but not in terms of measurable quantities. There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation[77] [95].

During the response to the accident, 'source term' estimates from the Emergency Response Support System (ERSS) could not be provided as an input to SPEEDI[78] owing to the loss of on-site power. Decisions on evacuation and sheltering were taken on the basis of plant conditions (i.e. loss of core cooling) rather than on dose projections as was planned [3, 7].

[74] 'Sheltering' is the short term use of a structure for protection from an airborne plume and/or deposited radioactive material [50].

[75] 'Evacuation' is the rapid, temporary removal of people from an area to avoid or reduce short term radiation exposure in an emergency. Evacuation may be performed as a precautionary action based on plant conditions [50].

[76] 'Iodine thyroid blocking' is an urgent protective action to be taken in an emergency involving radioactive iodine. Iodine thyroid blocking involves the administration of a compound of stable iodine (usually potassium iodide) to prevent or reduce the uptake of radioactive isotopes of iodine by the thyroid gland [50].

[77] 'Relocation' is the non-urgent removal of people to avoid longer term exposure (e.g. within one year) from deposited radioactive material [50].

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

The decisions of the national and local governments on protective actions were not always coordinated, mainly as a result of the severe communication problems and partly due to the difficulties in activating the Off-site Centre [94]. At 20:50 on 11 March 2011, Fukushima Prefecture issued an evacuation order for residents within a radius of 2 km of the Fukushima Daiichi NPP on the basis of information received directly from TEPCO [3, 6, 7, 72].

At 21:23, the national government issued an evacuation order for an area within a radius of 3 km of the plant, and sheltering for an area within a radius of 3–10 km. At 05:44 on 12 March 2011, the national government issued an order for the evacuation of an area with a radius of 3–10 km, and at 18:25 it was extended to an area within a radius of 20 km of the plant[79] [3, 7].

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

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

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

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

Some residents returned to their homes in the evacuated areas to collect belongings before full access controls were established by the end of March 2011 [6]. On 22 April, the existing 20 km evacuation zone around the Fukushima Daiichi NPP was established as a 'restricted area', with controlled re-entry and conditions for temporary access, based on consultation

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

with the local governments. In May 2011, short term temporary access was granted, with arrangements in place, including specific instructions and monitoring for contamination [6, 106, 111].

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

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

On 11 April 2011, the national government announced that the criterion of 20 mSv dose projected to be received within one year from the date of the accident would be used to determine areas beyond the 20 km evacuation zone from which people might need to be relocated[80] [3]. On 22 April 2011, a 'deliberate evacuation area' was established beyond the 20 km evacuation zone to include areas where this projected dose criterion of 20 mSv might be exceeded. The national government issued an order that relocation of people from this area should be implemented in approximately one month [3].

In addition to the 'deliberate evacuation area', an 'evacuation prepared area' was also established on 22 April 2011 (see Fig. 3.4). Residents of the 'evacuation prepared area' were advised to shelter or evacuate by their own means in the event of possible renewed concerns regarding the Fukushima Daiichi NPP. The designation of the 'evacuation prepared area' was lifted on 30 September 2011 [6].

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

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

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

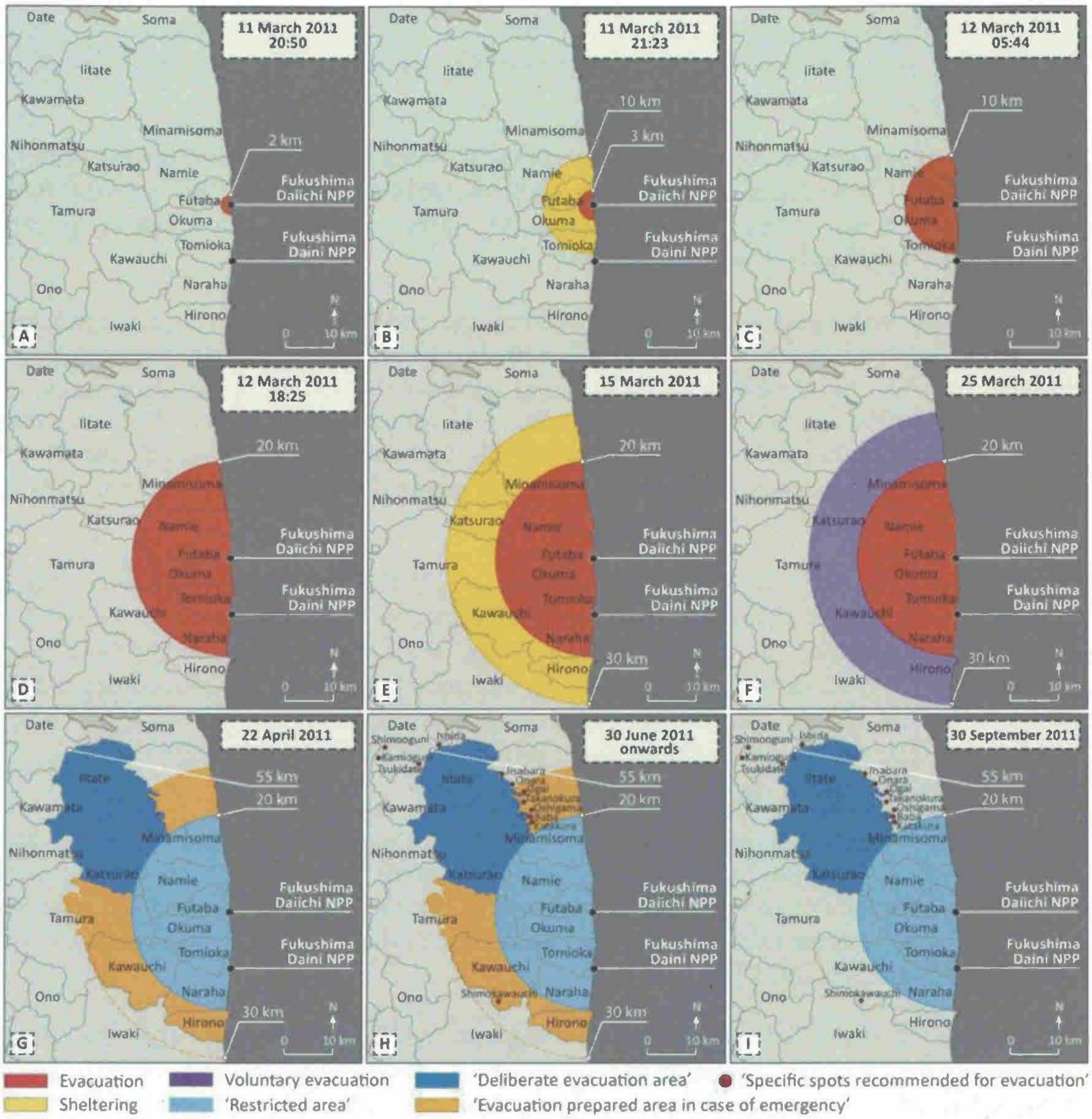


*FIG. 3.4. Areas and locations where protective actions were ordered or recommended until 30 September 2011 (based on Refs [3, 6, 7, 106]).*

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

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

The criteria of activity concentrations of specific radionuclides to be used in the case of a nuclear emergency for restrictions on food and drinking water produced in Japan had been developed before the accident [95]. However, these values had not been adopted for use in an emergency as specific regulatory limits[81] [6, 7]. On 17 March 2011, these criteria were established as provisional regulation values for radionuclide levels in food and drinking water under the Food Sanitation Act [112].

Following the detection of radioactive material in the environment, arrangements were made for controlling food and drinking water. These arrangements included: (1) radionuclide concentration levels of radioactive caesium and radioactive iodine in food and drinking water established as provisional regulation values under the Food Sanitation Act, above which food and drinking water were restricted; and (2) measurements of radionuclide concentrations in samples of food and drinking water. Within a few weeks, the levels of radioactive iodine ($^{131}I$) had decreased significantly owing to its short half-life (about 8 days), and the food restrictions in the medium to long term were based on concentrations of radioactive caesium only [112].

On 21 March 2011, the national government began to issue restrictions on the distribution of specific food [113] that evolved with the changing situation. Food restrictions were formulated on the basis of the results of monitoring of food samples that determined which foods were exceeding the criteria and defined the geographical location(s) affected [114, 115].

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

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

On 5 April 2011, based on measured concentrations of $^{131}I$ in fish samples, the provisional regulation values were added for activity concentrations of radioactive iodine in fishery products [116].

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

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

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

On 1 April 2012, standard limits came into force which replaced the provisional regulation values. These limits specified activity concentrations for radionuclides in food and drinking water on the basis of an effective dose of 1 mSv/year (while the criterion of 5 mSv/year had been used as a basis for the provisional regulation values), and taking account of the contributions to dose of a range of radionuclides released during the accident. As a consequence, these values were much lower than the provisional regulation values that they replaced [117].

### 3.3.3. Public information

Arrangements for informing the public were in place prior to the accident. At the national level, arrangements existed that recognized the need for relevant response organizations to coordinate the provision of information to the public, including the content, timing and method of announcements [75]. The Fukushima Prefecture Disaster Management Plan also included arrangements for public information [76].

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

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

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

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

Hotlines were established to answer inquiries from the public. For example, on 11 March 2011, NISA established a hotline to respond to queries relating to the evolution of the emergency and radiation safety, receiving approximately 15 000 calls between 17 March and 31 May 2011 [3]; on 13 March, a hotline of the NIRS was opened, with about 6500 calls answered by 11 April [118]; on 17 March 2011, the MEXT and the JAEA opened a hotline, receiving a total of 17 500 calls by 18 May 2011 [3]. Fukushima Prefecture set up counselling services to address questions from residents about various aspects of radiation. Feedback from the public received via hotlines and counselling services identified the need for easily understandable information and supporting material [3].

From 12 March 2011 onward, the national government posted information in English, Chinese and Korean on the web sites of the relevant ministries and agencies [119]. Information was provided to the diplomatic corps in Tokyo through regular briefings, held by the national government on a daily basis from 13 March to 18 May 2011, and three times a week from 19 May onward [6]. A notification channel via fax and email to the diplomatic corps was also established. The diplomatic missions of Japan provided information to their host States, which were posted on web sites in a total of 29 different languages [3].

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

Challenges encountered in providing information to the international community related principally to the demands on human resources for translating materials and responding to information requests by telephone [119].

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

### 3.3.4. International trade

Many activities and measures were initiated that were aimed at: (1) reassuring the public, industries and States of the safety of Japanese products; (2) facilitating international trade in Japanese products and preventing delays in distribution; and (3) providing advice and guidance to businesses and industries, in particular in Fukushima Prefecture [100, 101, 120, 121, 122, 123, 124].

Most importing States introduced control measures on Japanese goods; many increased existing import controls or requested a certificate from the Government of Japan; and some banned the import of Japanese goods or those from certain regions of Japan (mostly agricultural products) for a period of time. In June 2011, Japan established a certification system for food products intended for export, which helped to reassure the public and other interested parties that controls were in place. This system was extended in September 2011 to cover shipping containers and some industrial products intended for export [125].

### 3.3.5. Waste management in the emergency phase

Arrangements for the management of radioactive waste established in Japan prior to the accident covered waste generated in facilities such as NPPs, but it did not include radioactive waste that had been generated in public areas [126]. Detailed strategies, guidelines and instructions for radioactive waste management were developed after the accident.

The 'Near Term Policy to Ensure the Safety for Treating and Disposing Contaminated Waste Around the Site of the Fukushima Daiichi NPP' was issued by the NSC on 3 June 2011. This document provided dosimetric criteria for: recycled materials; protection of workers treating the materials; protection of members of the public in the vicinity of treatment facilities; and protection of members of the public in the vicinity of a disposal site. The NSC proposed that materials affected by the accident — i.e. debris, sludge from the water and sewage treatments, incinerated ash, trees, plants and soil resulting from decontamination activities — would be disposed of under proper management and that some materials may be considered for reuse. Products manufactured from these reused materials would be checked for contamination and managed appropriately before being released onto the market. Appropriate protective measures would ensure that radiation exposures on the part of workers and the public were kept as low as reasonably achievable [127].

The 'Basic Policy for Emergency Response on Decontamination Work' [128] was established by the NERHQ on 26 August 2011 as an interim policy until the 'Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials Discharged by the Nuclear Power Station Accident Associated with Tohoku District — Off the Pacific Ocean Earthquake that Occurred on March 11, 2011' was fully in force . The Act was enacted on 26 August 2011, promulgated on 30 August 2011 — with portions of the Act entering into force the same day — and entered fully into force in January 2012 [129]. It outlined the management of the contaminated areas and included the assignment of responsibilities to the national and local governments, the operator and the public. It facilitated the transition from an emergency exposure situation to an existing exposure situation. It also formalized the long term management of environmental monitoring, decontamination measures and the designation, treatment, storage and disposal of soil and waste contaminated by radioactive material.

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

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

***Analyses of the accident and of the emergency response were performed and presented in the form of reports, including those issued by the Government of Japan, the operating organization (TEPCO), two investigation committees created by the government and the Parliament, respectively[82].***

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

### 3.4.1 Transition from the emergency phase to the recovery phase

In developing arrangements for the transition from the emergency phase to the recovery phase after the accident, the Japanese authorities decided to apply the latest recommendations of the ICRP [132, 133, 134]. The specific policies, guidelines and criteria, as well as overall arrangements for the transition from the emergency phase to the recovery phase, were developed after the accident [135]. This process included adjusting the protective actions and

[82] Reports from academia and from the private sector were also issued (e.g. from the Atomic Energy Society of Japan and the Rebuild Japan Initiative Foundation) [130, 131].

arrangements made early in the emergency response and taking account of the information available on the conditions in the affected areas (obtained primarily through comprehensive monitoring) [136, 137]. It also included consideration of the necessary longer term recovery operations.

These actions and arrangements primarily addressed the immediate needs arising during the transition process. The provisions for the protection of workers were gradually modified, depending on the work being undertaken [6, 98].

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

On 17 May 2011, METI issued a 'Roadmap for Immediate Actions for the Assistance of Nuclear Sufferers' [135]. This listed nine groups of actions divided into steps scheduled to be implemented over different periods connected to TEPCO's roadmap. Step 1 had a target of mid-July, step 2 a target of around three to six months after achieving step 1, and step 3 for the mid-term period. This roadmap was intended to facilitate communication and preparations for the transition to long term recovery operations and the resumption of normal social and economic activity. It allocated responsibilities and specified other organizational aspects of the transition process and the objectives and conditions for termination of the emergency phase.

### 3.4.2. Analyses of the response

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

For example, the report of the Government of Japan to the IAEA Ministerial Conference in June 2011 [3] presented lessons in the following areas important for emergency preparedness and response: (1) combined natural disaster and nuclear emergency; (2) environmental monitoring; (3) allocation of roles between central and local organizations; (4) communication in an emergency; (5) response to assistance from other States and communication with the international community; (6) modelling of the release of radioactive materials; and (7) criteria for evacuation and radiation protection guidelines in nuclear emergencies.[83]

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

TEPCO's Fukushima Nuclear Accident Analysis Report [8] highlighted issues that were identified during the response to the emergency that included: emergency response

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

organization; communication of information; transportation of materials and equipment; and radiation protection.

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

On the basis of these analyses and lessons identified, corrective actions were taken to strengthen emergency preparedness and response arrangements [138, 139]. A Nuclear Emergency Preparedness Commission was established within the Cabinet to ensure that nuclear emergency response policies would be implemented and promoted by the government [139]. The NRA developed Nuclear Emergency Response Guidelines[84] [141], also taking into account the IAEA safety standards in the area of emergency preparedness and response.

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

***An extensive international framework for emergency preparedness and response was in place at the time of the accident, comprising international legal instruments, IAEA safety standards and operational arrangements[85].***

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

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

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

[84] The Nuclear Emergency Response Guidelines were based on the interim report on the revision of the Regulatory Guide for Emergency Preparedness of Nuclear Facilities [95], which was issued in 2012 [140].

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

***Different States[86] either took, or recommended, different protective actions for their nationals in Japan in response to the accident. These differences were generally not well explained to the public and occasionally caused confusion and concern.***

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

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

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

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

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

The Early Notification Convention and the Assistance Convention assign specific response functions and responsibilities to the IAEA and to the Parties. Various international organizations — by virtue of their statutory functions or of related legal instruments — have functions and responsibilities that encompass aspects of emergency preparedness and response [142, 143].

The IAEA safety standards in the area of emergency preparedness and response at the time of the accident were IAEA Safety Standards Series No. GS-R-2 (co-sponsored by seven international organizations) and IAEA Safety Standards Series No. GS-G-2.1 (co-sponsored by six international organizations) [70, 71]. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (IAEA Safety Series No. 115) also included parts that were related to emergency preparedness and response [144].

International operational arrangements comprised the Emergency Notification and Assistance Technical Operations Manual (ENATOM), the IAEA Response and Assistance Network (RANET) and the Joint Radiation Emergency Management Plan of the International Organizations (JPLAN) [145, 146, 147].

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

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

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

The IAEA, through its emergency arrangements, liaised directly with NISA, which was the official contact point in Japan [148]. Japan provided information in accordance with Article 3 of the Early Notification Convention.

The IAEA Secretariat shared information on the emergency as it developed and kept States, relevant international organizations and the public informed [148].

The IAEA's role at the time did not include providing a prognosis of the potential evolution of an accident or an assessment of the possible consequences. Its role in responding to an emergency at an NPP was expanded through the adoption of the IAEA Action Plan on Nuclear Safety [149]. This requested the Agency to provide Member States, international organizations and the general public with timely, clear, factually correct, objective and easily understandable information during a nuclear emergency on its potential consequences, including analysis of the available information, and prognoses of possible scenarios based on evidence, scientific knowledge and the capabilities of Member States.

Communication with the official contact point in Japan in the early phase of the emergency response was difficult. The visit to Japan from 17 to 19 March 2011 by the IAEA Director General, and the subsequent deployment of liaison officers in Tokyo, improved communication between the IAEA and the contact point [148].

Some States issued advice or a specific instruction for the protection of their nationals in Japan. Some advised their nationals in Japan to follow the orders and recommendations issued by the Japanese authorities in response to the emergency, while some States issued advice that differed from that provided by the Japanese authorities and other States [150]. Differences in the recommendations among States were due to various factors, including a lack of information on the evolving situation. These differences were generally not well explained to the public and occasionally caused confusion and concern.

The IAEA sent expert missions to Japan and coordinated the provision of Member State offers of assistance to Japan. The Assistance Convention was not invoked and the RANET[87] was not utilized. States provided assistance to Japan directly. This support helped the Government of Japan to manage the nuclear emergency which, together with the effects of the earthquake and tsunami, challenged the national response capability. One of the difficulties in accepting international assistance in the early stages of the national response was the absence of national arrangements for receiving such assistance [5, 148].

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

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

## 3.6. OBSERVATIONS AND LESSONS

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

— **In preparing for the response to a possible nuclear emergency, it is necessary to consider emergencies that could involve severe damage to nuclear fuel in the**

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

**reactor core or to spent fuel on the site, including those involving several units at a multi-unit plant possibly occurring at the same time as a natural disaster.**

Consideration needs to be given to the possibility of a severe nuclear accident, irrespective of the cause, possibly involving more than one unit at a site and occurring simultaneously with a natural disaster, which could result in disruption at the site and of the local infrastructure. Systems, communications and monitoring equipment for providing essential information for both on-site and off-site responses need to be able to function under such circumstances.

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

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

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

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

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

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

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

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

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

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

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

At the preparedness stage there is a need to establish arrangements to, among others: (1) define emergency planning zones and areas; (2) establish dose and operational criteria (levels of measurable quantities) for taking urgent protective actions and other response actions, including dealing with special population groups within emergency zones (e.g. patients in hospitals); (3) enable urgent protective actions to be taken before or shortly after a release of radioactive material; (4) enable prompt establishment of access controls in areas where urgent protective actions are in place; (5) extend protective actions beyond the established emergency planning zones and areas if necessary; (6) establish dose and operational criteria for taking early protective actions and other response actions, e.g. relocation and food restrictions, that are justified and optimized, taking into account a range of factors such as radiological and non-radiological consequences, including economic, social and psychological consequences; and (7) establish arrangements for revision of operational criteria for taking early protective actions on the basis of the prevailing conditions.

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

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

Protective actions need to be taken in a timely and safe manner, taking into account possible unfavourable conditions (e.g. severe weather or damage to infrastructure).

Preparations in advance are necessary to ensure the safe evacuation of special facilities, such as hospitals and nursing homes; continuing care or supervision must be provided for those who need it.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

# 4. RADIOLOGICAL CONSEQUENCES

Section 4 considers the radiological consequences of the accident at the Fukushima Daiichi NPP for people and the environment. The radiological consequences of the accident have been addressed by a number of international organizations and bodies. The WHO issued a preliminary estimation of radiation doses [151] and subsequently assessed the risk attributed to the accident [152]. More recently, UNSCEAR estimated radiation levels and effects [153]. Radiation protection lessons have been compiled by the ICRP [154, 155]. Other international organizations, notably the FAO and the WMO, have also provided relevant information. Some of these international activities are described in Box 4.1.

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

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

— The World Health Organization (WHO), a specialized agency of the United Nations concerned with public health, issued a preliminary estimate of the radiation doses incurred due to the accident [151] and, subsequently, a health risk assessment [152].

— The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), which reports to the General Assembly of the United Nations, reported its estimates of the levels and effects of radiation exposure attributable to the accident, including a considerable amount of data on environmental radioactivity and radiation doses [153].

— The International Commission on Radiological Protection (ICRP), a non-governmental international body of experts that issues widely used recommendations on radiological protection, issued a review of radiological protection issues during and after the accident, aimed at improving the international system of radiological protection [154, 155].

— The Food and Agriculture Organization of the United Nations (FAO), a specialized agency of the United Nations involved in agriculture, forestry and fisheries practices for ensuring good nutrition and food security for all, worked in partnership with the IAEA, through the Inter-Agency Committee on Radiological and Nuclear Emergencies (IACRNE), in preparing for and responding to nuclear or radiological emergencies affecting food, agriculture, forestry and fisheries, and compiled a significant database on radionuclide concentrations in food due to the accident [156].

— The World Meteorological Organization (WMO), a specialized agency of the United Nations for meteorology, operational hydrology and related geophysical sciences, issued an evaluation of meteorological analyses for the radionuclide dispersion and deposition from the accident [157].

— The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA) reported on the nuclear safety response and lessons learned from the accident [158].

— These and other organizations such as the United Nations Environment Programme (UNEP), the International Labour Organization (ILO), the Pan American Health Organization (PAHO), and the European Commission (EC) co-sponsor international *safety standards* that are issued under the aegis of the IAEA. WHO establishes *Guidelines for Drinking-water Quality* to be used in existing exposure situations, which contains parameters for radioactivity in drinking water [159]. The FAO and WHO Codex Alimentarius Commission establishes the *Codex Alimentarius*, a collection of internationally harmonized food standards to protect the health of consumers and to ensure fair practices in the international food trade, which contain standards on the presence of radionuclides in food [160].

Official bodies in many States, including Japan, carried out numerous evaluations of the radiological consequences of the accident at the Fukushima Daiichi NPP (e.g. Ref. [5]).

National professional radiation protection organizations, both in Japan and elsewhere, identified important lessons for radiation protection (e.g. Ref. [161]). Fukushima Prefecture launched the Fukushima Health Management Survey [162] in June 2011 [163]. This survey, which is described in Box 4.2, was discussed at the International Expert Symposium in Fukushima [164, 165].

**Box 4.2. The Fukushima Health Management Survey**

The Fukushima Health Management Survey is a general examination and investigation of the health situation of people in Fukushima Prefecture [162]. It is based on a series of questionnaires and has the following objectives: "(1) to assess residents' radiation dose, and (2) to monitor residents' health conditions, which result in disease prevention, early detection and early medical treatment, thereby (3) to maintain and promote their future health" [166].

Following the response, effective doses due to external exposures incurred in the four months following the nuclear accident were estimated by the National Institute of Radiological Sciences (NIRS) on the basis of recorded movements of respondents, in combination with an understanding of the relevant radiation levels. In addition, there were detailed surveys that included: (1) thyroid ultrasound examinations, covering roughly 370 000 residents aged 0 to 18 years at the time of the nuclear accident (the initial screening was performed within the first three years after the accident, followed by complete thyroid examinations from 2014 onwards, and regular monitoring of the residents thereafter); (2) a comprehensive health check aimed at the early detection and treatment of diseases, as well as the prevention of lifestyle related diseases, having as a main target 210 000 former residents of evacuation zones whose lifestyle changed drastically after the accident (additional tests such as differential leukocyte counts, are being performed apart from the routine tests included in general medical check-ups at the workplace or by the local government); (3) a mental health and lifestyle survey aimed at providing adequate care, mainly for evacuees who are at a higher risk of developing mental health problems such as post-traumatic stress disorder, anxiety and stress; and (4) a pregnancy and birth survey aimed at providing appropriate medical care and support to mothers who were given a Maternal and Child Health Handbook between 1 August 2010 and 31 July 2011, as well as to their children. (This survey is being updated every year to take account of new data, particularly on pregnancy and births [167].)

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

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

### *Quantities and units*

Specialized international *quantities*[88] and *units*[89] [168, 169] were used for monitoring and reporting radiological data of the accident. The fundamental international radiation protection quantities and units which are used in this report are briefly described in Box 4.3.

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

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

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

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

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

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

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

The following estimates of effective doses commonly incurred are provided as a reference [170]:

— Global natural background radiation delivers an annual average effective dose of 2.4 mSv, with a typical range of 1–13 mSv, and with sizeable population groups incurring up to 10–20 mSv, and in extreme cases up to around 100 mSv.

— The globally averaged annual effective dose due to medical radiodiagnosis is 0.6 mSv, and a single computed tomography examination can deliver an effective dose of around 10 mSv. (It should be noted that medical exposure is usually localized to part of the body, i.e. it is not uniformly distributed in the body.)

Other quantities used in practice are derived from the fundamental radiation protection quantities. Box 4.4 describes some of these derived quantities and a number of related issues. The many quantities and units were not easily understandable by the public in the aftermath of the accident. The ICRP, in its assessment of radiological protection issues arising during and after the accident, concluded that international action should be taken in the future to ensure that "any confusion on protection quantities and units be resolved" [154, 155].

***Box 4.4. Measurement quantities and operational terms***

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

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

— In *planned exposure situations*[1], the *additional dose* expected to be added by a planned operation is used. For these situations, the relevant individual dose restrictions are known as *dose limits*. Dose limits are values of the additional effective doses or the additional equivalent doses to individuals expected from a planned exposure situation that are not to be exceeded; they are applicable to the additional individual doses from external exposure in a given period of time plus the additional individual dose commitment from intakes of radionuclides in that time period.

— In *emergency exposure situations*[2], three concepts of dose are used: (1) the *projected dose* (the dose that would be expected to be received if no protective actions were taken); (2) the *avertable dose* (the dose that could be averted if a protective action was taken); and (3) the *residual dose* (the dose expected to be incurred in the *existing exposure situations*[3] remaining after protective actions have been terminated). *Reference levels* are applied to residual doses as guidance levels for optimizing protection. These represent the level of dose "above which it is judged to be inappropriate to plan to allow exposure to occur and below which optimization of protection should be implemented" [134].

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

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

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

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

## *Uncertainties*

The estimates of the radiological consequences of the accident are subject to a number of uncertainties, which are often expressed as the range of likely values of the relevant quantities. Some of these uncertainties have been accounted for after a statistical analysis of the variables involved, e.g. in the estimates of personal radiation dose due to external exposure, but not all uncertainties have been resolved. While the risks from radiation exposure are better understood than risks from exposure to other agents, it is important that relevant uncertainties are addressed and communicated properly [171, 172].

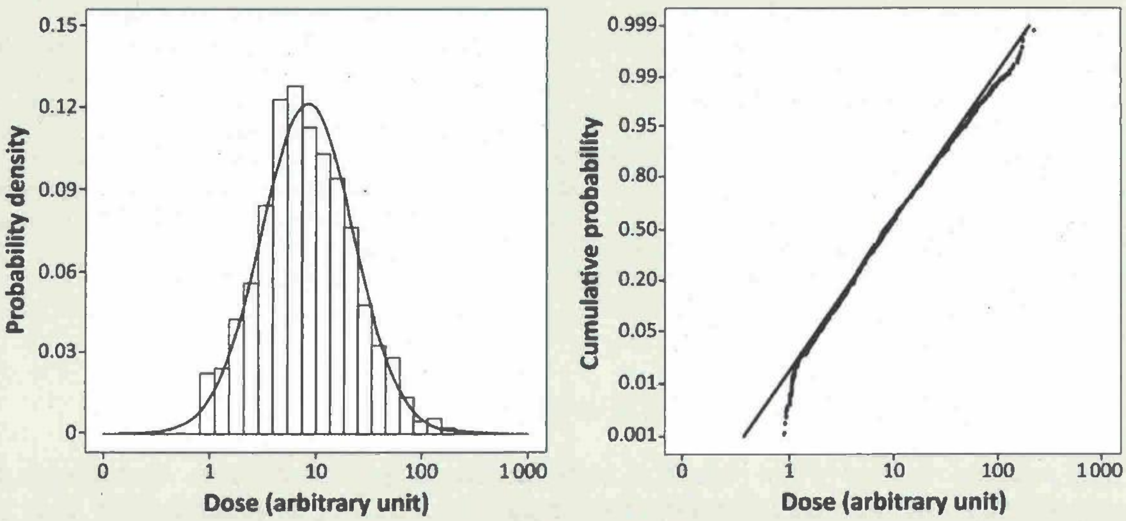
### *Statistical analyses*

In order to deal with uncertainties, statistical analyses of some relevant variable data have been performed. The variables include specific activity in food and, in particular, personal radiation doses. The analyses of radiation doses covered estimates based on the use of questionnaires and ambient and environmental radiation data, and those based on personal monitoring through personal dosimeters and whole body counting of incorporated radioactivity. The basis for the statistical analyses is summarized in Box 4.5, which describes probability distributions of data, in particular the *log-normal probability distribution* that was specifically used in the analyses. There are many circumstances in which multiple measurement data, including measurements of environmental quantities, are expected to be statistically distributed following an approximate log-normal probability distribution. A large amount of information is available on the statistical distribution of doses incurred by exposed populations, which shows approximate log-normal distributions. Relevant evidence came from UNSCEAR occupational dose estimates [173] and also from the analysis of public doses from the accident at the Chernobyl NPP in 1986 [174]. However, a number of issues have been presented in the analyses of the data submitted following log-normal distributions and some of them are summarized in Box 4.6.

***Box 4.5. Statistical analysis of estimated and measured data***

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

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




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

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

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

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

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

## 4.1. RADIOACTIVITY IN THE ENVIRONMENT

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

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

***In addition to radionuclides entering the ocean from the atmospheric deposition, there were liquid releases and discharges from the Fukushima Daiichi NPP directly into the sea***

***at the site. The precise movement of radionuclides in the ocean is difficult to assess by measurements alone, but a number of oceanic transport models have been used to estimate the oceanic dispersion.***

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

### 4.1.1. Releases

Many assessments of the releases of radionuclides from the accident at the Fukushima Daiichi NPP have been performed using established mathematical models and methods and associated computer codes (see Refs [175, 176, 177, 178, 179, 180, 181, 182]).

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

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

*Releases to the atmosphere*

Noble gases were a significant part of the early releases from the Fukushima Daiichi NPP; around 6.4 to 32.6 PBq of $^{85}$Kr and 400 to 11 000 PBq of $^{133}$Xe (almost their entire inventories) are estimated to have been discharged. The mean total activity of $^{131}$I released was around 140–200 PBq, and of $^{137}$Cs was around 12–16 PBq. The releases from the accident are estimated to be approximately one tenth of the releases from the accident in 1986 at the Chernobyl NPP [174, 183, 184]. Most of the releases were dispersed over the North Pacific Ocean; as a result, the amount and isotopic composition of material released (the *source term*) could not be reconfirmed by environmental measurements of the radionuclide deposits [182].

*Releases to the sea*

Most of the atmospheric releases dispersed over the North Pacific Ocean fell on the oceanic surface layer. There were direct releases and also discharges into the sea at the site, with the primary source of highly radioactive water from a trench at the Fukushima Daiichi NPP. The peak radioactive releases were observed at the beginning of April 2011. The direct releases and discharges of $^{131}I$ to the sea were estimated to be 10–20 PBq. The direct releases and discharges of $^{137}Cs$ were estimated to be 1–6 PBq, but some assessments reported estimates of 3.5–15 PBq [180].

### 4.1.2. Dispersion

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

#### *Atmospheric dispersion*

The transport of the atmospheric radioactive releases was directed mainly to the east and north of Japan, following the prevailing wind direction, and then around the globe. Figure 4.1 presents an example of the many atmospheric transport models that were used to estimate the atmospheric transport of the various radionuclides and their deposition patterns, which describe the results of modelling the global dispersion of $^{137}Cs$ [185]. The figure illustrates activity concentration in air by using the original code of colours of the reference, where small changes in the degree of the colour correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity concentration in the atmosphere decreased noticeably with distance to the Fukushima Daiichi NPP.

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

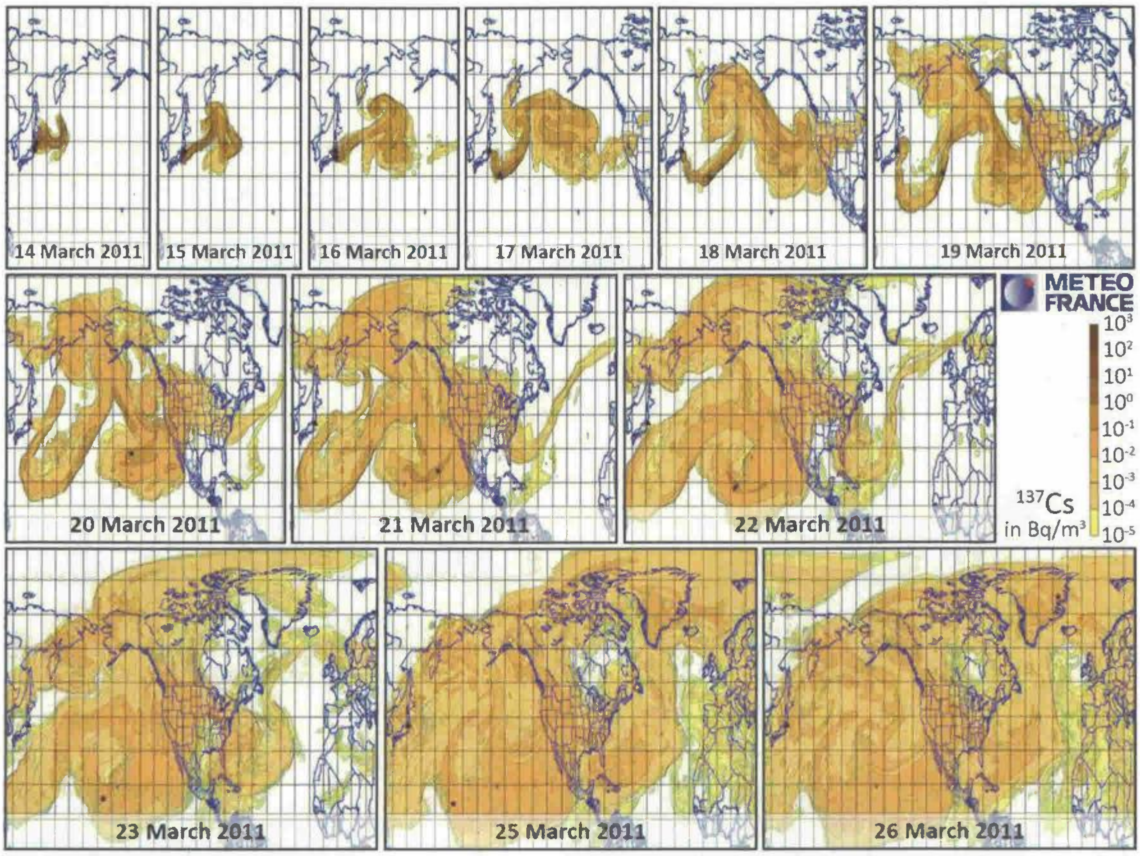



*FIG. 4.1. Results from one of the global models of the atmospheric dispersion of $^{137}Cs$, presented in its original code of colours (see Ref. [185] for details) (source: Meteo-France).*

## *Oceanic dispersion of direct releases and discharges into the sea at the site*

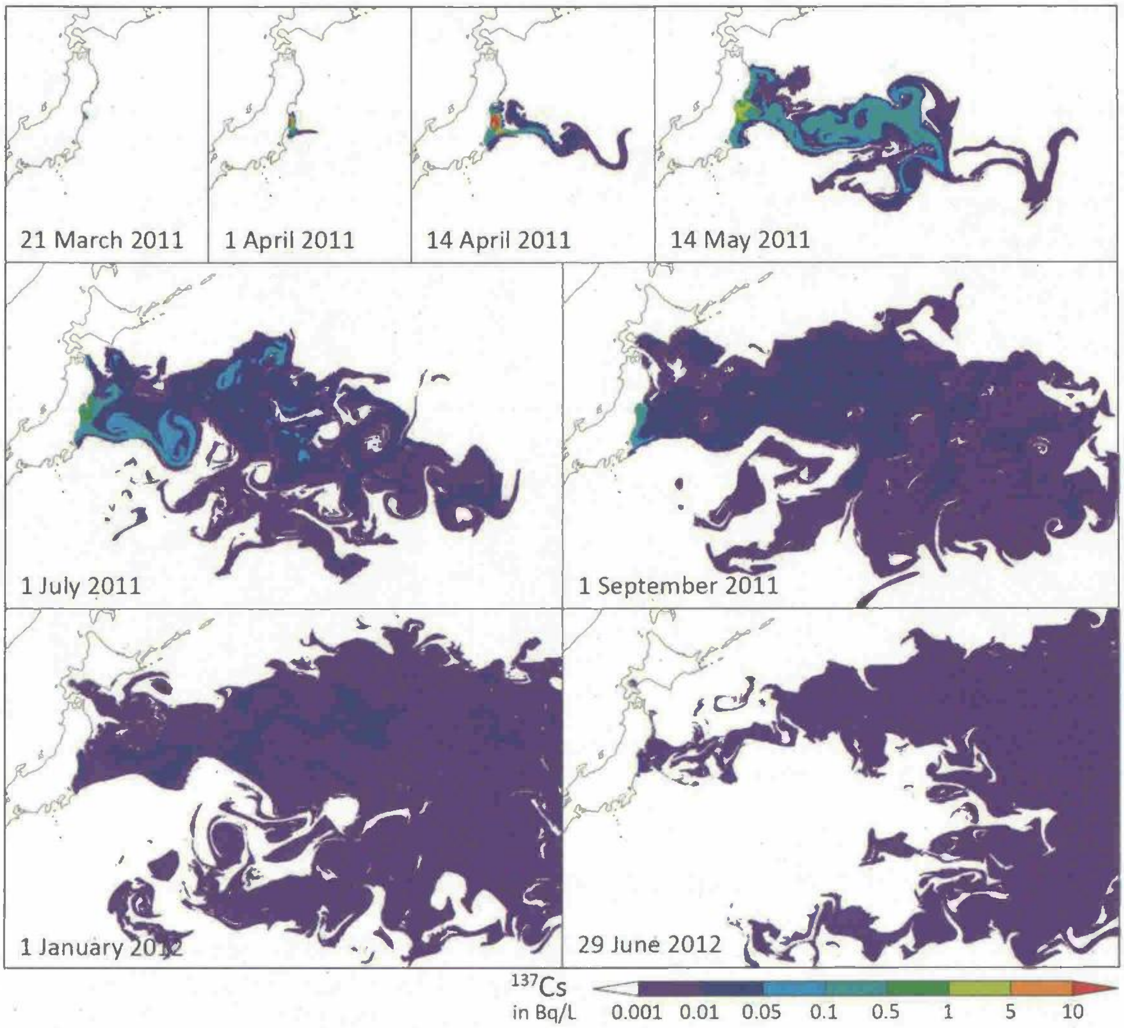
Most of the released and discharged radionuclides that entered into the sea at the site moved eastward with the Kuroshio current[90], were transported over large distances via the North Pacific Ocean gyre[91] and became highly diluted in the seawater [186]. Radioactivity spread over large oceanic distances and was detected in extremely small amounts far away from the accident, sometimes via pathways through oceanic biota, such as blue-fin tuna fish [187].

While the precise movement of radionuclides in the ocean is difficult to assess by measurements alone, a number of oceanic transport models were used to assess their dispersion patterns. Figure 4.2 illustrates examples of these models describing the dispersion of $^{137}Cs$ in the North Pacific Ocean. The figure uses the original code of colours employed in each particular reference. As in the case of atmospheric dispersion, small changes in the degree or tone of the colours correspond to one order of magnitude change in the activity concentration. The illustration is intended to support the conclusion that activity in the ocean

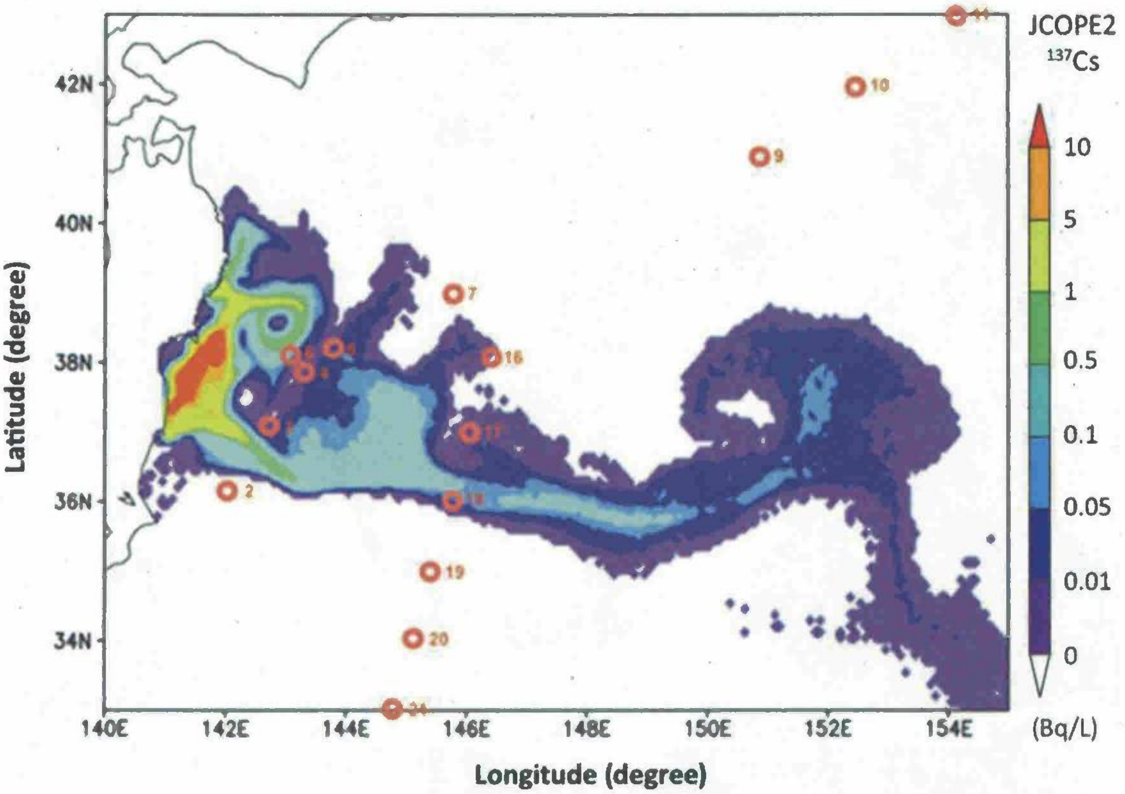
[90] The Kuroshio current is a northward flowing ocean current on the western side of the North Pacific Ocean that flows past the Fukushima Daiichi NPP.

[91] The North Pacific Ocean gyre is one of the five major oceanic gyres, covering most of the North Pacific Ocean; it has a clockwise circular pattern and is formed by the North Pacific Ocean current to the north, the California current to the east, the north equatorial current to the south, and the Kuroshio current to the west.

decreased noticeably with distance from the Fukushima Daiichi NPP. All models show that the activity of $^{137}Cs$ in the ocean was very low.




(a)


JCOPE2
137Cs
10
5
1
0.5
0.1
0.05
0.01
0
(Bq/L)
42N
40N
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36N
34N
Latitude (degree)
140E
142E
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19
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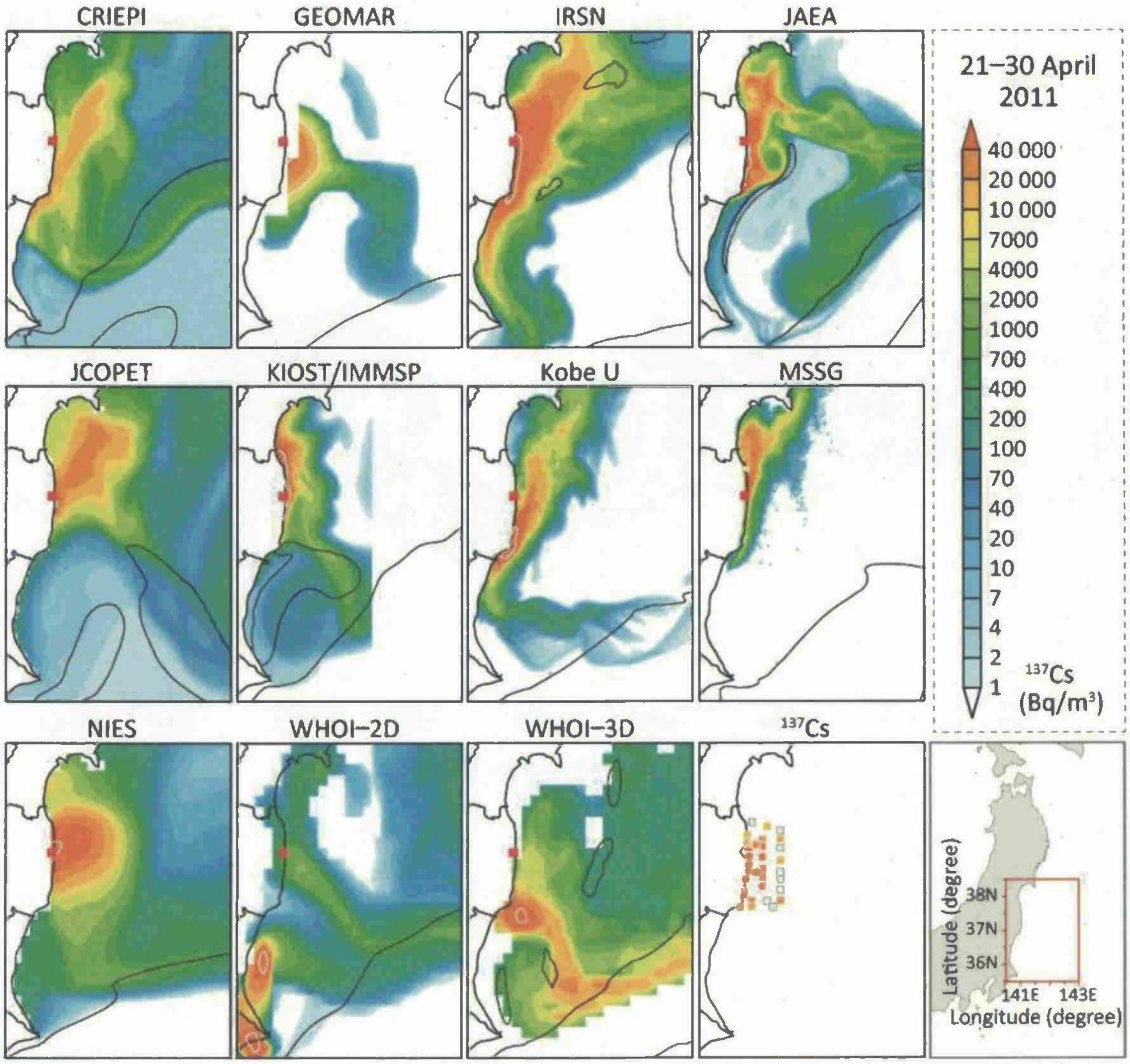
(b)




(c)

*FIG. 4.2. Various oceanic models have been used to estimate the activity concentration of $^{137}$Cs in sea water (the code of colours and the units used are those employed in the references): (a) an example of modelling contaminated waters from 21 March 2011 to 29 June 2012 [188, 189]; (b) simulated horizontal distribution of $^{137}$Cs in surface waters between 14 and 26 April 2011 [190]; (c) horizontal distribution of the $^{137}$Cs concentrations averaged over a ten day period from 21 to 30 April 2011, with the name of the models indicated above each panel [180].*

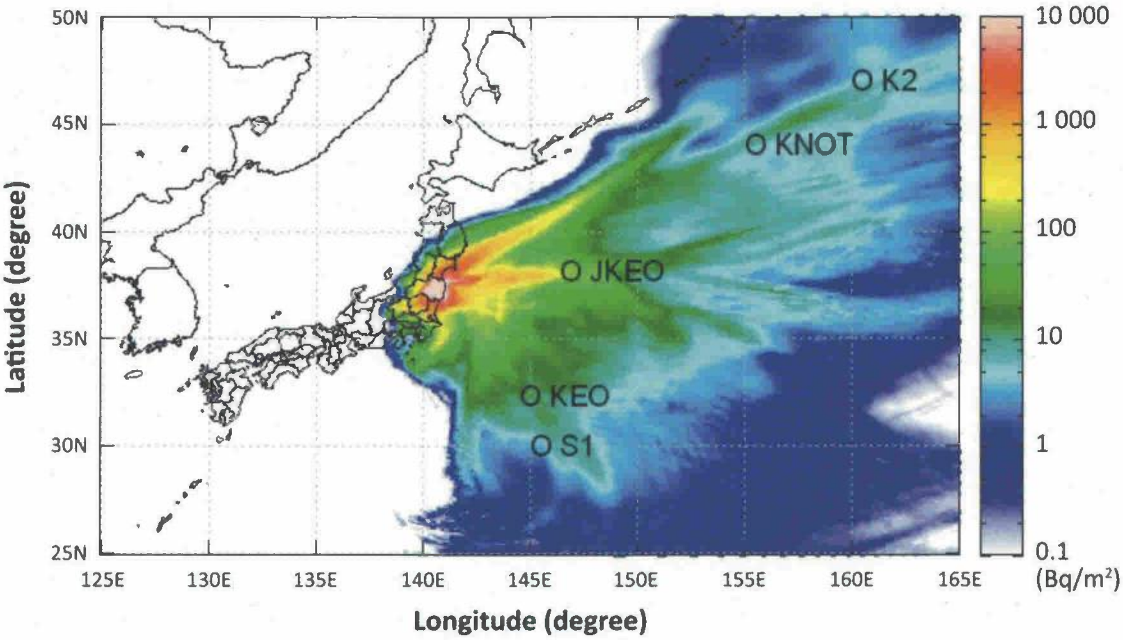
### 4.1.3. Deposition

The activity deposited on the Earth's surface is quantified as deposition density and measured in terms of activity per unit area, usually expressed in Bq/m$^2$. When the deposition is terrestrial it is usually referred to as ground 'contamination'.

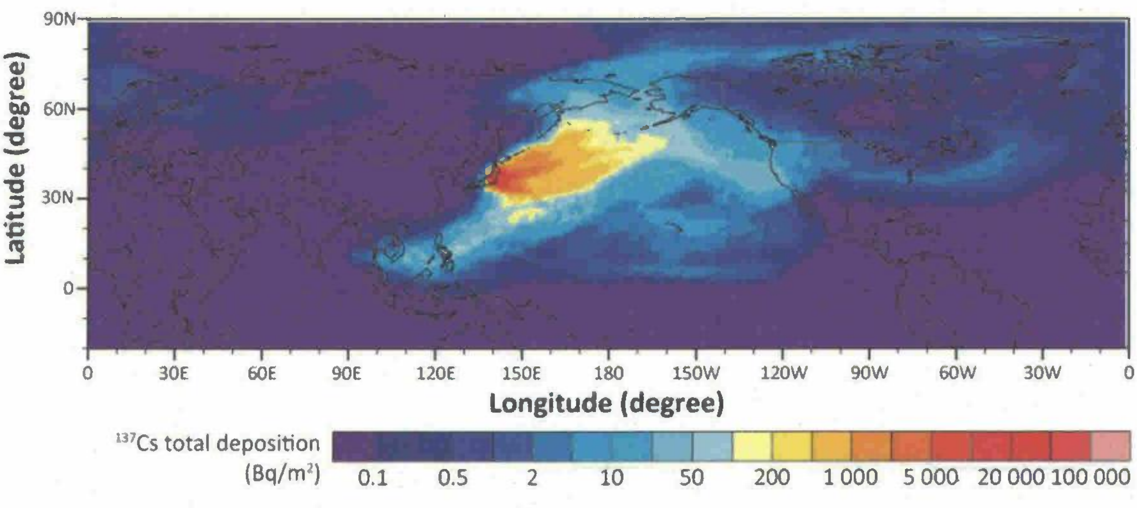
*Oceanic deposition*

The deposition of $^{137}$Cs onto the ocean was studied using different models (see Fig. 4.3).

It is difficult to produce an accurate estimate of the amount of $^{137}Cs$ released to the atmosphere which was deposited on the ocean surface [191]. As a reference, the global pre-accident deposition of $^{137}Cs$ as of 1970 is estimated at 290 ± 30 PBq and the typical (background) level of $^{137}Cs$ in the North Pacific Ocean was approximately 69 PBq [192, 193].




(a)




(b)

*FIG. 4.3. Various models have been used to estimate the oceanic deposition density of $^{137}Cs$ (the units used are $Bq/m^2$). (a) Modelling the cumulative aeolian input through 1 April 2011 [190]; and (b) an example of the ensemble averaged $^{137}Cs$ deposition (11–31 March 2011) [180].*

### *Terrestrial deposition*

While most atmospheric releases were dispersed eastward, the releases that took place on 12, 14 and 15 March were blown over land, and relevant radionuclides, notably $^{131}I$, $^{134}Cs$ and

$^{137}Cs$ were deposited on the ground. The deposition patterns varied greatly, being influenced strongly by rain, snowfall and other local or regional conditions, such as topography and land use. Another factor that influenced the pattern of deposition in the terrestrial environment was the different physical and chemical characteristics of iodine and caesium.

The largest long lived deposits of $^{137}Cs$ were found to the north-west of the Fukushima Daiichi NPP, where the total deposition of $^{137}Cs$ was estimated to have been around 2-3 PBq [193]. The deposition density reduces with time through physical and environmental decay. Caesium can move relatively easily through the environment owing to the solubility of its compounds. Weathering effects, such as wind and rain, and other environmental effects can reduce the presence of caesium in the environment. All these effects reduce the presence of $^{137}Cs$ in a time shorter than its half-life. In many affected areas, the presence of $^{137}Cs$ has been further reduced by cleanup and other remediation efforts.

Figure 4.4 presents detailed maps of the aerially measured ambient dose equivalent to the north-west of the site of the accident, and its variation with time (see also Fig. 4.2 (c)).

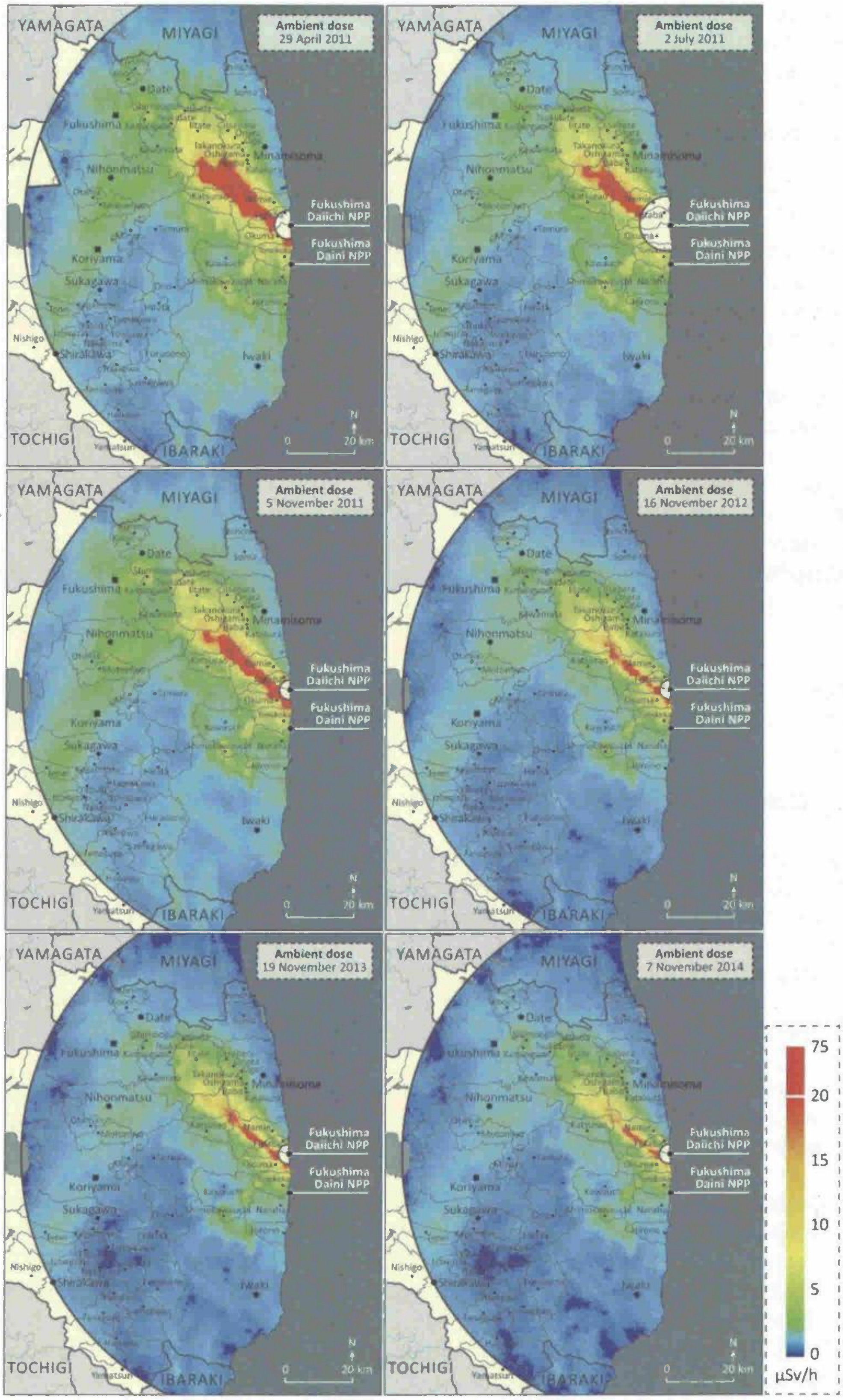



*FIG. 4.4. Measured aerial ambient dose equivalent rate (in µSv/h) resulting from deposits from the releases that spread in areas to the north-west of the plant [194].*

The presence of $^{137}Cs$ from the accident in the terrestrial environment can result in protracted exposures to individuals, in addition to the exposures they normally incur from natural background levels of radiation. There is a global background level of deposition density of $^{137}Cs$, attributable mainly to fallout from past nuclear testing. The background global levels were estimated by UNSCEAR to have been as high as approximately 4000 Bq/m$^2$, during the mid-1960s, at latitude 40°–50° in the Northern Hemisphere; the lowest global values at that time were estimated to have been around a few hundred Bq/m$^2$ at latitude 60°–70° in the Southern Hemisphere [195]. A number of studies analysed the influence of local conditions and concluded that the accumulated background deposition could have been around, or even higher than, 10 000 Bq/m$^2$ (see, for example, Ref. [192]). The global deposition levels have decayed since the 1960s. For 2000, the highest value was estimated by UNSCEAR to be around 2000 Bq/m$^2$ [195].

In areas north-west of the Fukushima Daiichi NPP, significantly higher levels of $^{137}Cs$ deposition density were measured. Presented by order of magnitude, the levels at the most affected areas were up to 10 000 000 Bq/m$^2$, with an average of around 1 000 000 Bq/m$^2$. While the distribution of deposits for the whole affected area of the Fukushima Prefecture is inhomogeneous, the average level could be estimated at around 100 000 Bq/m$^2$. The levels immediately outside the most affected areas in Fukushima Prefecture were around 10 000 Bq/m$^2$. While some other regions of Japan show elevated deposition levels, the levels attributable to the accident in most of Japan were generally lower than around 1000 Bq/m$^2$ [196, 197].

The highest levels of deposited $^{131}I$ reached around 3 000 000 Bq/m$^2$ immediately after the accident but, owing to the short half-life of $^{131}I$, the levels decreased rapidly and are no longer measurable.

#### 4.1.4. Consumer products

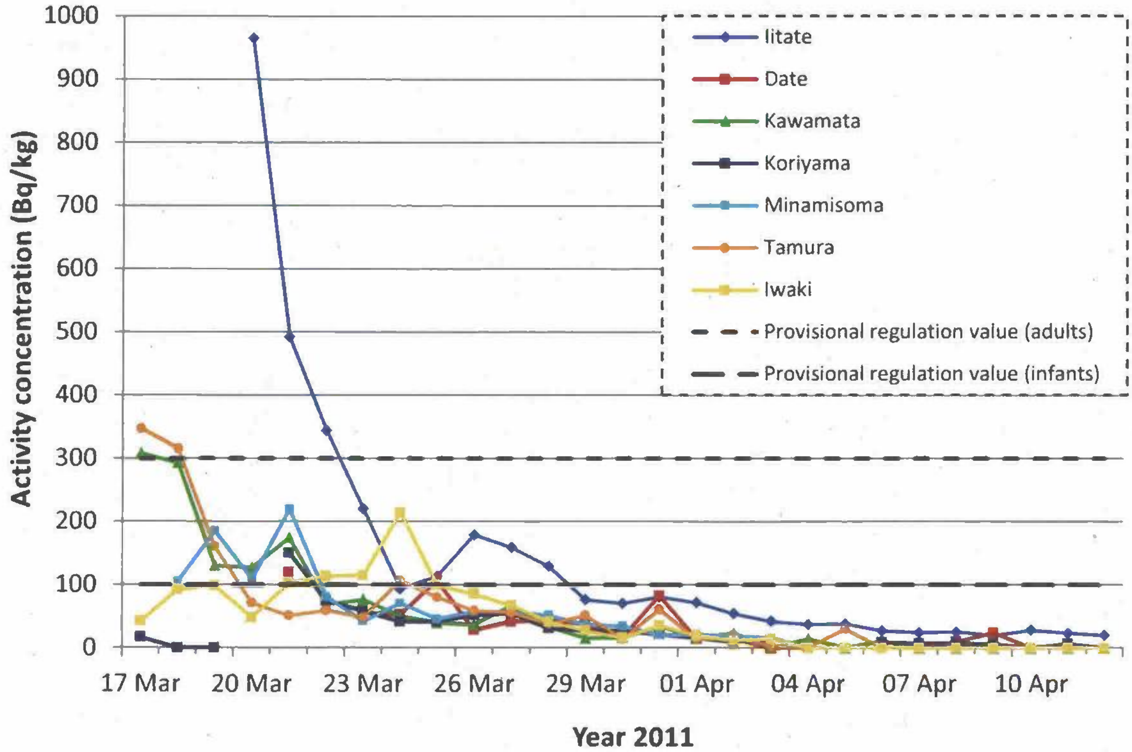
In the affected areas, radionuclides, such as $^{131}I$, $^{134}Cs$ and $^{137}Cs$, were found in some consumer products and other items in daily use by individuals and households, such as food, drinking water and some non-edible products.

Restrictions were established after the accident, on 21 March, by the Japanese authorities to prevent the consumption of drinking water and food containing radionuclides at levels that were higher than provisional regulation values (see Section 3).

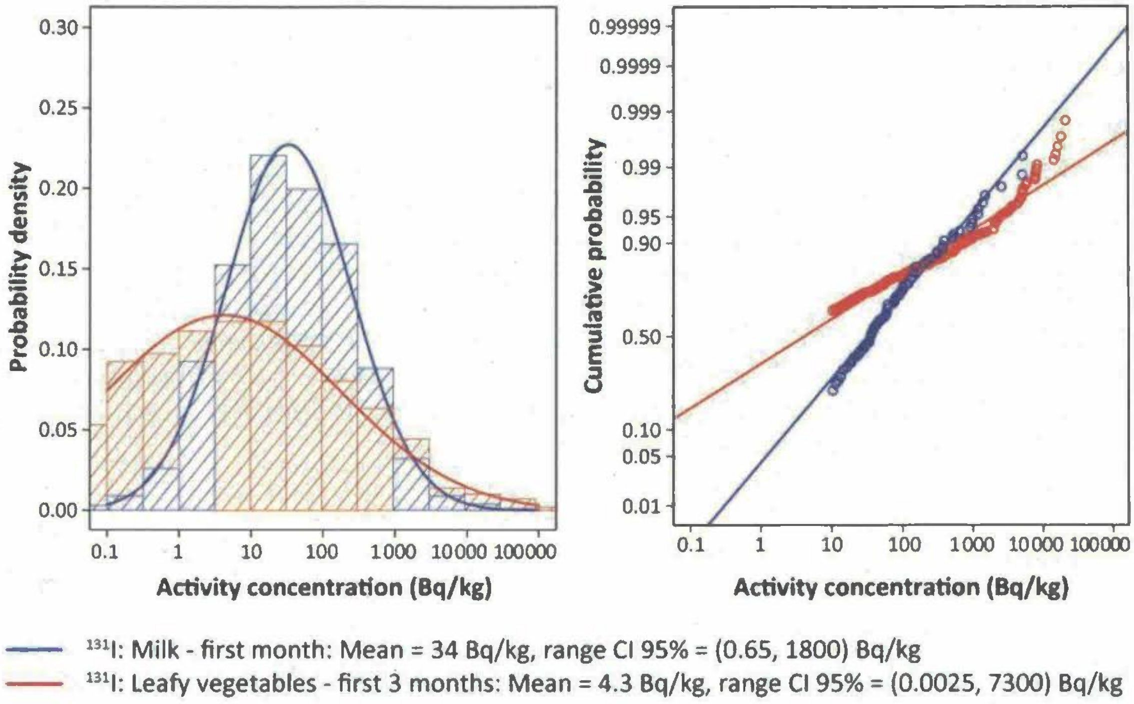
WHO guidance values for permissible levels of radionuclides in drinking water are intended for normal circumstances (see Box 4.1). After April 2012, all drinking water in Japan was below the WHO guidance values [198].

With rare exceptions, the levels of radionuclides in food available in the market did not exceed those established in the Codex Alimentarius, which are applicable to international trade (see Box 4.1). There were cases when higher levels of radionuclides were found in uncultivated foods, such as wild boar meat, wild mushrooms and wild plants, including ferns [199]. Eating uncultivated food is uncommon in Japan. Wild plants are mostly eaten for a limited period in the spring by a limited number of people. Direct sales of wild mushrooms and plants by farmers are very rare. Cultivated mushrooms are available in the market if the levels of activity concentration are under the regulated values.

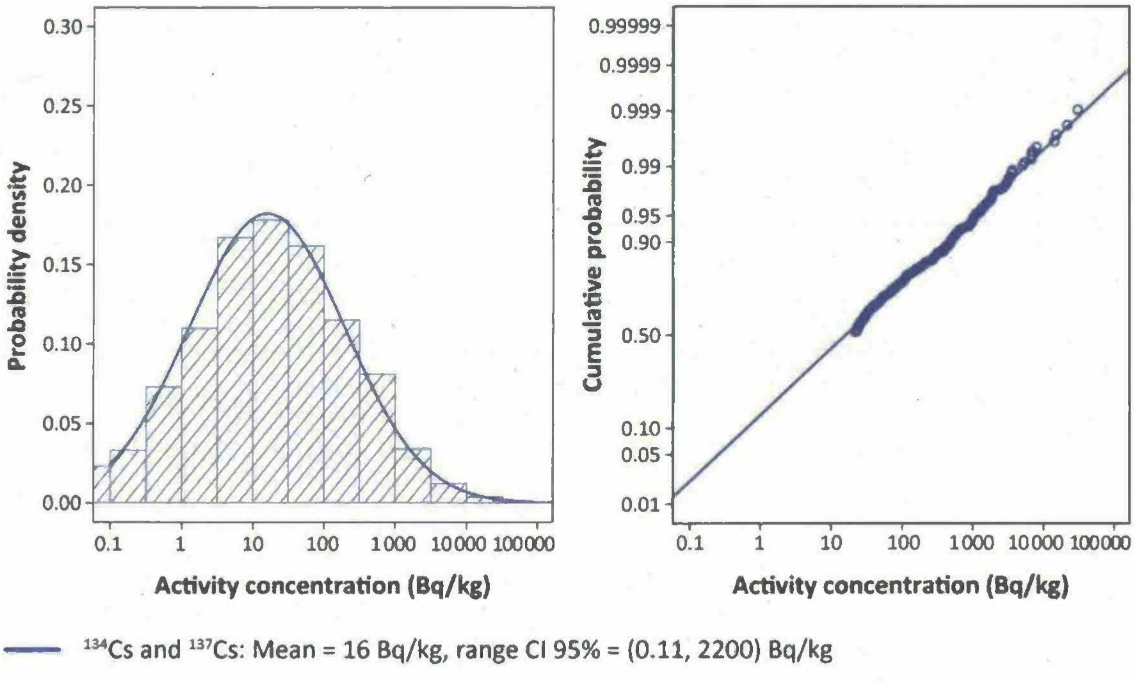
Some examples of activity concentration in drinking water and specific activity in food are presented in Fig. 4.5. The time evolution activity concentration of $^{131}I$ measured in drinking water supplies is illustrated for various locations in Fukushima Prefecture compared with the levels established in the provisional regulations issued by the Japanese authorities [200]. The log-normal probability density and cumulative probability distributions were assessed for the $^{131}I$ specific activity in milk during the first month after the accident and in leafy vegetables in the first three months after the accident. For $^{134}Cs$ and $^{137}Cs$ specific activity in mushrooms (including mainly cultivated mushrooms in the open air), they were assessed during the 12 months after the accident. These assessments, which are based on the statistical analysis of data collected by FAO [156], illustrate a likelihood of around 90% that values were below the Codex Alimentarius level of 1000 Bq/kg (the level established by the Japanese authorities was originally 500 Bq/kg and was then reduced to 100 Bq/kg [198]). This cautious approach created difficulties for producers and consumers.




(a)




(b)




(c)

*FIG. 4.5. Some examples of radioactivity in drinking water and food. (a) Time evolution activity concentration of $^{131}I$ measured in drinking water supplies in various locations of Fukushima Prefecture [200]. (b) Log-normal probability distribution of $^{131}I$ activity concentration in milk in the first month after the accident and in leafy vegetables in the first three months after the accident. (c) Lognormal probability distribution of $^{134}Cs$ + $^{137}Cs$ activity concentration in mushrooms during the 12 months after the accident [156]. (Figures (b) and (c) present the normalized idealized probability density distribution (see Box 4.6) and the cumulative probability distribution; a nominal detection limit of 10 Bq/kg was used in the activity concentration in food.)*

## 4.2. PROTECTING PEOPLE AGAINST RADIATION EXPOSURE

***Following the accident, the Japanese authorities applied conservative reference levels of dose included in the recent ICRP recommendations[92]. The application of some of the protective measures and actions proved to be difficult for the implementing authorities and very demanding for the people affected.***

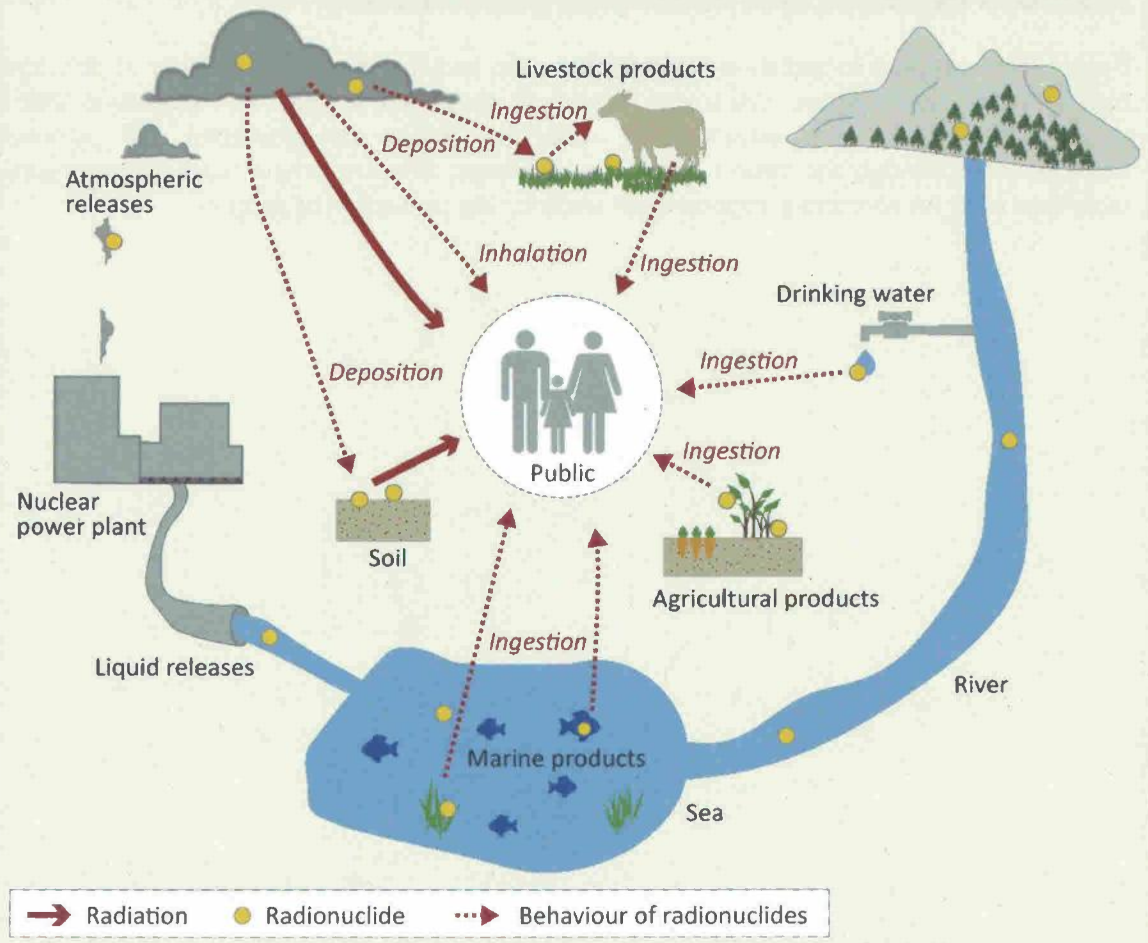
***There were some differences among the national and international criteria and guidance for controlling drinking water, food and non-edible consumer products in the longer term aftermath of the accident, once the emergency phase had passed.***

People were exposed to radiation attributable to the accident through a number of different routes, known as exposure pathways. These are discussed in Box 4.7. Radiation doses incurred by people were estimated by modelling and/or environmental and personal measurements through the various exposure pathways. These estimates and measurements were then used for restricting exposure and ensuring the protection of people.

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

**Box 4.7. Exposure pathways**

Exposure pathways are courses, sequences of changes, or events, which constitute the progression by which radioactive substances move through the environment and eventually make people vulnerable to incurring radiation doses. They are characterized by many aspects, including the process for the substances to reach the environment, the media in which the substances move from the source, the point of exposure where people are affected by radiation, the exposure routes describing how external radiation exposes people and how the radioactive substances may enter the body (e.g. by eating, drinking, via the skin) and the population that could be potentially exposed. The figure below gives a simplified description of the exposure pathways from the accident at the Fukushima Daiichi NPP.




## 4.2.1 Restriction of public exposure

The version of the Basic Safety Standards (BSS) applicable at the time of the accident had been issued in 1996 [144] and was based on the ICRP recommendations issued in 1990 [201]. It included requirements on *intervention levels* in the case of accidents, considering expected *projected doses* and potential reductions of *avertable doses*. At the time of the accident, the 1996 BSS were being revised to reflect the ICRP recommendations that had been issued in 2007 [134] (see Box 4.8). These recommendations contained a different approach for dealing with emergencies, particularly reviewing the concept of *intervention level*, which had been designed as criteria for individual protective actions, and introducing the concept of *reference* *levels* that were intended to be used for deciding protection strategies (on the understanding that generic criteria would be introduced in safety standards for dealing with individual protective actions).

The 2007 ICRP recommendations provided a framework for reference levels, with examples for all exposure situations including emergency situations. As an example for the highest planned residual dose from a radiological emergency, they recommended reference levels that could be greater than 20 mSv, either acute or annual, but not more than 100 mSv. They also recommended that consideration should be given to reducing doses, increasing efforts should be made to reduce doses as they approach 100 mSv, individuals should receive information on radiation risk and on measures to reduce doses and, assessment of individual doses should be undertaken. The Japanese regulatory body, NISA, chose to apply the lower reference level of 20 mSv/year as a reference level for public protection.

***Box 4.8. Revising the Basic Safety Standards in effect at the time of the accident: Reference levels***

The international safety standards for radiation protection in effect at the time of the accident were the 1996 International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, or 1996 BSS. These standards required that the additional effective dose that individuals may receive from planned and regulated practices be limited to 1 mSv in a year (in special circumstances, an effective dose of up to 5 mSv could apply, provided that the average effective dose over five consecutive years does not exceed 1 mSv per year). The 1996 BSS underlined that these dose limits were not relevant for decisions on whether and how to undertake an intervention in case of accidents, when consideration had to be given to projected doses and potential reductions of avertable doses and eventual residual doses. The requirements of the 1996 BSS relating specifically to emergencies provided generic intervention levels at which intervention was expected to be undertaken in an emergency, such as sheltering, evacuation and thyroid blocking, and generic action levels for food.

In addition, the IAEA had in 2002 issued safety standards with specific requirements on preparedness and response for a nuclear or radiological emergency [71], including dose criteria for the implementation of protective actions, such as sheltering, evacuation and iodine thyroid blocking. These standards established requirements for an adequate level of preparedness and response for a nuclear or radiological emergency with the aim of minimizing the consequences of an emergency if it were to occur (see Section 3 for more information).

At the time of the accident, the 1996 BSS were being reviewed, partly in the light of new general ICRP recommendations that had been issued in 2007 [134]. Just before the accident, the ICRP had issued specific recommendations on the application of its new recommendations for the protection of people in emergency exposure situations [132] and those living in long term contaminated areas after a nuclear accident or a radiation emergency [202].

The 2007 ICRP recommendations revised the approach for dealing with emergency exposure situations, including the concept of reference level to be used for protecting strategies. The recommended reference level was an effective dose (either acute or annual) that could be greater than 20 mSv but not higher than 100 mSv. This was to be used for generic criteria for dealing with individual protective actions in unusual, and often extreme, situations where actions taken to reduce exposures would be disruptive, with the understanding that an effective dose rising towards 100 mSv will almost always justify protective action. For stages in post-accident rehabilitation, the reference level could be greater than 1 mSv, but not more than 20 mSv. The new recommendations further emphasized that the chosen value for a reference level would depend upon the prevailing circumstances of the exposure under consideration.

The new approach was introduced in the revised BSS, issued in 2014 as Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [203].

## *Protection of children*

The protection of children was a special concern for parents in areas affected by the accident. For protection purposes, the current ICRP recommendations use a detriment-adjusted risk coefficient for the whole population, including children, that is higher (by about 30%) than that for an adult population. This difference is reflected in the international radiation protection recommendations and standards.

## *Impact of radiation protection measures and actions taken to protect the public*

Proper infrastructure for public facilities is essential for supporting measures to limit public exposure in the aftermath of a nuclear or radiological emergency [204]. The consequences of the earthquake, tsunami and accident had to be dealt with in a situation in which local infrastructure had collapsed. Due to the earthquake and the tsunami, many public facilities, homes and businesses were destroyed or damaged; access to telephones and the internet, supplies of electricity, gas, and drinking water, public transport, and the distribution of food, gasoline and heating oil were all severely disrupted. The outside temperature was low, it was raining and snowing, and heating was inadequate. This meant that many residents could not stay in the shelters for long periods without warm clothes and overcoats.

These difficult conditions affected the implementation of the protective measures required to protect people against radiation exposure. For example, people who were sheltered could not be decontaminated through washing because in most shelters water was rationed and reserved for drinking.

Some protective actions were very difficult for the authorities and extremely demanding for the affected individuals and communities [205, 206]. Sheltering and evacuation were particularly disruptive for around 160 000 people who were isolated from their communities and had access to only limited supplies to meet their daily needs (Fig. 4.6(a)). People were eventually relocated, but their normal living conditions were seriously affected (Fig. 4.6(b)). Employment and participation in community activities were limited. Their prospects were uncertain and planning for the future was very difficult.

*Source: Koichi Nakamura/AP Images/picturedesk.com*
(a)

*Source: Dr Yujiro Kuroda/Fukushima Medical University*
(b)

*FIG. 4.6. The initial evacuation led to crowded conditions in shelters. (a) A senior TEPCO executive apologizes to evacuees at an evacuation centre on 22 March 2011; (b) the normal living conditions of the people who were relocated were greatly affected.*

People who had already suffered the consequences of the earthquake and tsunami were also subject to additional physical and psychological stress caused by their sheltering, evacuation and relocation. Restrictions on products for public consumption were important and necessary, but caused economic and reputational or social damage to local producers.

### 4.2.2 Restriction of occupational exposure including exposure of emergency workers

Japan is a Party to the Radiation Protection Convention, 1960 (No. 115), adopted under the aegis of the ILO [169]. The Japanese regulations for occupational exposures were consistent with international recommendations and standards on occupational protection. These regulations established a dose limit for occupational exposure as an effective dose of 20 mSv per year, averaged over five years, and 50 mSv in any single year [144]. For emergency workers, "workers who may be exposed in excess of occupational dose limits while performing actions to mitigate the consequences of an emergency for human health and safety, quality of life, property and the environment" [50], a limiting effective dose criterion of 100 mSv was in place. This criterion had to be temporarily increased by the Japanese authorities to a dose limit of 250 mSv for the emergency workers who were within 30 km of the Fukushima Daiichi NPP until 16 December 2011 (see Section 3.2).

The dose limit for occupational exposure in 'special circumstances', established by the international standards at the time of the accident (1996 BSS), was 100 mSv [144]. The upper level of the internationally recommended reference levels by ICRP was also 100 mSv [134], although the recommendations indicate that, in exceptional situations, informed volunteer workers may receive doses above this level to save lives, prevent severe radiation-induced health effects, or prevent the development of catastrophic conditions. In setting the value of 250 mSv, the Japanese authorities took account of previous recommendations by the ICRP [201, 207] and the requirements in the IAEA safety standards, which suggested a guidance value of 500 mSv for persons engaged in emergency activities, or emergency operations aimed at preventing further worsening of a nuclear accident. The revised dose limit for emergency workers was implemented in the exemption ordinance of the Ministry of Health, Labour and Welfare (MHLW) three days after the declaration of the emergency by the authorities (14 March 2011). The exemption ordinance was abolished on 16 December 2011 [208].

## 4.3. RADIATION EXPOSURE

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

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

***low, and generally comparable to the range of effective doses incurred due to global levels of natural background radiation.***

***In the aftermath of a nuclear accident involving releases of $^{131}I$ and its intake by children, the uptake and subsequent doses to their thyroid glands are a particular concern. Following the Fukushima Daiichi accident, the reported thyroid equivalent doses of children were low because their intake of $^{131}I$ was limited, partly due to restrictions placed on drinking water and food, including leafy vegetables and fresh milk. There are uncertainties concerning the iodine intakes immediately following the accident due to the scarcity of reliable personal radiation monitoring data for this period.***

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

The dose estimates in this report used as a basis international dose estimates by WHO and UNSCEAR, which are summarized in Box 4.9. This report also benefited from the availability of additional data, particularly from the Fukushima Health Management Survey and data on direct measurements of dose on people and radiation in the environment. These data were provided by experts, institutions, the local authorities and the Government of Japan, as well as by TEPCO, and were subjected to a statistical analysis.

**Box 4.9. Dose estimates by WHO in 2012 [151] and UNSCEAR in 2014 [153]**

In 2012, World Health Organization (WHO) issued an early evaluation of radiation exposure from the accident, which gave an initial estimate of radiation doses to characteristic members of the public using modelling techniques applied to information made publicly available by government institutions and collected up to September 2011. At that time, the data necessary for a full evaluation were either not available or not sufficient. A number of cautious assumptions were used that may have resulted in some doses being over-estimated. For example, cautious assumptions were used to minimize the possibility of underestimating eventual health risks regarding protective actions and the consumption of food. Nevertheless, the evaluation showed that the total effective dose typically received by individual members of the public in two locations of relatively high exposure in Fukushima Prefecture during the first year after the accident was within an effective dose band of 10–50 mSv. In these most affected locations, external exposure was the major contributor to the effective dose. In the rest of Fukushima Prefecture, the effective dose was estimated to be within an effective dose band of 1-10 mSv. Effective doses in most of Japan were estimated to be within an effective dose band of 0.1–1 mSv, while in the rest of the world, all the effective doses were below 0.01 mSv and usually far below this level.

In 2014, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) issued a report on the accident that included assessed doses to workers and members of the public. Estimates of external effective doses to members of the public were based on the information available on $^{137}Cs$ deposition density in different areas as a function of time, and the estimated location and movement patterns of the population. UNSCEAR estimates indicated that, in the evacuated areas with the highest average estimates, the effective dose received by adults before and during the evacuation was, on average, less than 10 mSv, and about half of that level for those evacuated early. Adults living in the city of Fukushima were estimated to have received, on average, an effective dose of about 4 mSv in the first year following the accident; estimated effective doses for one year old infants were about twice as high.

Those living in other areas within Fukushima Prefecture and in neighbouring prefectures were estimated to have received comparable or lower effective doses; even lower effective doses were estimated to have been received elsewhere in Japan. Lifetime effective doses attributable to the accident that, on average, could be received by those continuing to live in Fukushima Prefecture have been estimated by UNSCEAR to be just over 10 mSv. Radiation exposures in neighbouring States and the rest of the world resulting from the accident were far below those received in Japan; the effective doses were less than 0.01 mSv, However, UNSCEAR emphasized that there was considerable variation among individuals around this value, depending on their location and what food they consumed.

*Note: As indicated in Box 4.3, the global natural background doses reported by UNSCEAR are an annual average dose of 2.4 mSv (which implies a total accumulated lifetime dose of around 170 mSv), with a typical range of 1–13 mSv, while sizeable population groups receive natural background doses of 10–20 mSv.*

The various estimates differed because they were carried out at different times and with different methodologies. While the WHO estimates were generally higher than those of UNSCEAR, this was primarily because they were early dose projections based on very limited data following the accident. The dose estimates for members of the public by WHO and UNSCEAR were constrained by limited availability of direct radiation measurements of individual doses incurred by people and were mainly made using dose assessment models based on environmental conditions. Although the differences make a detailed comparison difficult, the estimates in this report and those of WHO and UNSCEAR are largely consistent in showing that doses generally fell below reference levels established in international recommendations and standards.

### 4.3.1 Public exposures

*External exposure*

The initial approach for estimating the effective doses incurred by members of the public due to external exposure was mainly based on data from environmental measurements of ambient dose equivalent rates and on calculations and surveys of location and personal behaviour. The data used encompassed extensive measurements of ambient dose equivalent, including the use of car-borne instrumentation.

The NIRS estimated the effective doses due to external exposures incurred by respondents to the Fukushima Health Management Survey questionnaires in the four months following the nuclear accident [209]. The estimations were based on the declared movements of people and the relevant radiations levels in the local environments.

A number of estimates of the individual effective doses due to external exposure in the first four months have been published [210, 211, 212, 213]. For example, in the Soso area[93] (which includes the 'evacuation zone' and 'deliberate evacuation area') these doses were below 5 mSv for 98.7% of residents (with a maximum effective dose of 25 mSv). In Fukushima Prefecture as a whole, including the evacuation zone and deliberate evacuation area, the doses were below 3 mSv for 99.4% of the residents surveyed [213].

A statistical analysis was undertaken in this report of individual effective doses due to external radiation in various cities of Fukushima Prefecture that had been estimated by the NIRS using the Fukushima Health Management Survey data for the period 11 March–11 July 2011 (the effective dose due to external exposure to natural background radiation was excluded). The results of this analysis are presented in Fig. 4.7 for cities located in the area within the 20 km radius and for cities outside this area. Ninety-five per cent of residents who participated in the Fukushima Health Management Survey questionnaires were estimated to have received effective doses of less than 2 mSv. This figure also illustrates that external doses in the first four months were, on average, lower among the populations in the 20 km zone than those from locations outside this area, as a consequence of the early evacuation of this zone. The results within the 20 km zone tend to show wider distributions than those for locations outside. This is due to the evacuation of members of the same community to different locations and often further movements leading to differences in the doses received. This complicated pattern was modelled by NIRS using 18 evacuation scenarios.

[93] An area in the eastern part of Fukushima Prefecture, consisting of Soma City, Minami-soma City, Hirono Town, Naraha Town, Tomioka Town, Kawauchi Village, Okuma Town, Futaba Town, Kazurao Village, Namie Town, Shinti Town, Iitate Village, many of which were within the designated 'evacuation zone' or 'deliberate evacuation area'.

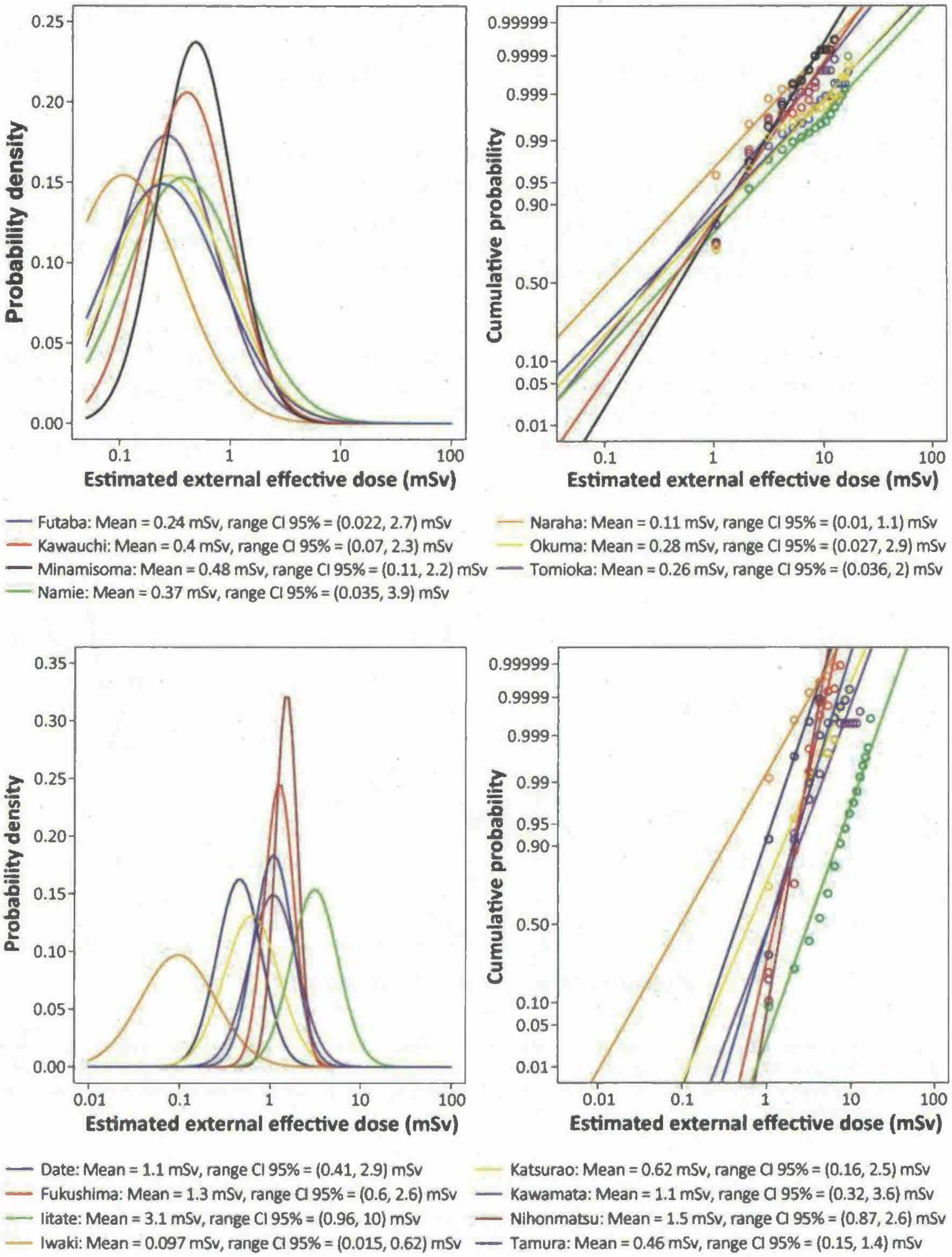



*FIG. 4.7. Log-normal normalized idealized probability density and cumulative probability distributions of the estimated external effective doses in various cities, towns and villages of Fukushima Prefecture for the four months following the accident on the basis of Fukushima Health Management Survey data. The upper part of the figure presents the analysis for places located in the area within the 20 km radius (see Section 3) and the lower part of the figure for places outside this area. The legend under the plots indicates the mean doses and the 95% confidence interval for these places. In the original data, all doses below 1 mSv were accumulated in the 1 mSv bin.*

There are uncertainties associated with the use of interviews with residents, environmental measurement and dose estimation models for assessing public doses. Personal radiation monitoring of members of the public is therefore vital for a reliable reconstruction of radiation doses.

The more important corroboration of individual doses from external radiation was provided by the data on individual monitoring using personal dosimeters. When personal monitoring data became available, they allowed comparison between the two different approaches, using assumptions about people's habits and models, to estimate the *effective dose* incurred versus monitoring the actual *personal dose equivalent* incurred[94].

The results indicated that the doses actually incurred, as measured by personal monitors, were generally lower than the estimated doses from questionnaires and modelling. An example of this comparison, which was carried out by a local government, is presented in Fig. 4.8. It shows that modelled doses are usually over-estimations compared to actually incurred doses (this was also observed during the dose assessments in the aftermath of the Chernobyl accident [174]).

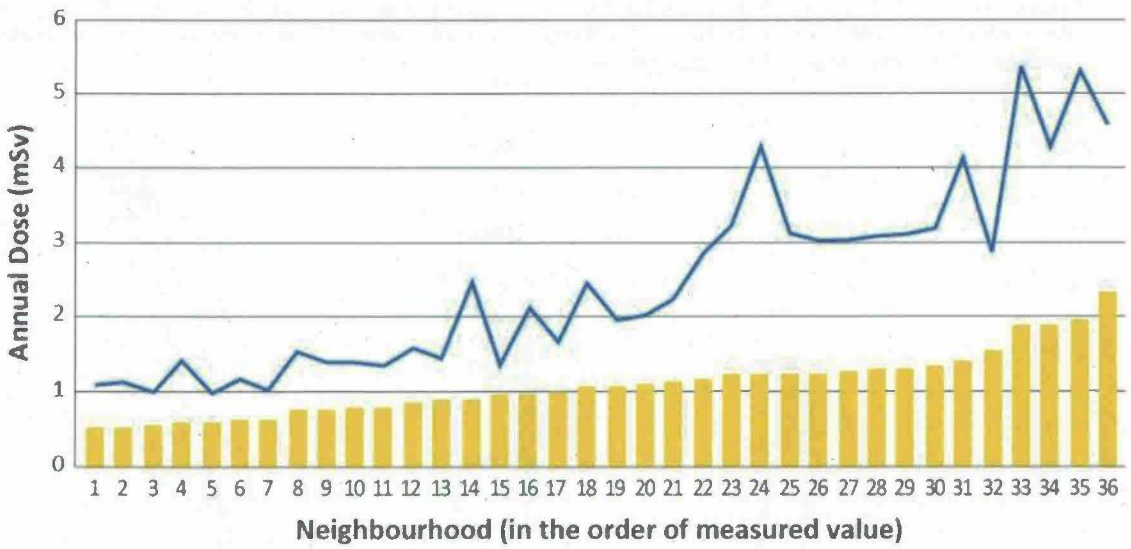



*FIG. 4.8. Comparison of external individual doses estimates with measurements for a representative affected city between July 2012 and June 2013. The effective doses are assessed by estimation (line), assuming indoor occupancy and shielding for 16 h, outdoors for 8 h; and by personal monitoring (bar) of personal dose equivalent, in various neighbourhoods of the city (numerated) [214].*

The large amount of information provided by Japan to the IAEA included data on personal dose equivalents and results from whole body counting measurements.

This information had been recorded at different times, over different periods, using different measurement techniques, and measurements were carried out in many, but not all, affected areas. What these data have in common is the fact that all personal dose equivalents are low

[94] The quantity used for personal monitoring, the *personal dose equivalent*, is a proxy of the quantity *effective dose*.