SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

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Sources, Effects and Risks of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2013 Report

Volume I

Annex A (Levels and effects of radiation exposure due to the nuclear accident after the 2011 great east-Japan earthquake and tsunami)

Corrigendum

1. Page 239, table D14

For the title of the subcolumn headed “5-10” under the column headed “TEPCO”, *for* 5-10 *read* 5-20

For the title of the subcolumn headed “5-10” under the column headed “Contractor”, *for* 5-10 *read* 5-20

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ANNEX A

LEVELS AND EFFECTS OF RADIATION EXPOSURE DUE TO THE NUCLEAR ACCIDENT AFTER THE 2011 GREAT EAST-JAPAN EARTHQUAKE AND TSUNAMI

CONTENTS

The attachments cited in this annex are electronically available for download from http://www.unscear.org/unscear/en/publications/2013_1_Attachments.html

I. INTRODUCTION

1. On 11 March 2011 at 14:46 local time, a 9.0 magnitude earthquake occurred near Honshu, Japan producing a devastating tsunami ("the great east-Japan earthquake and tsunami") that endangered people, property, infrastructure and natural resources. The tsunami flooded over 500 square kilometres of land, and the earthquake and tsunami together resulted in an estimated 18,703 fatalities, 2,674 persons missing, and 6,220 persons injured as of 1 September 2013 [M21]. More than 250,000 buildings were destroyed or partially destroyed, and at least another 750,000 were partially damaged; 22,000 fishing boats were destroyed and over 200 square kilometres of farmland were so damaged by salt water inundation that they could not be cultivated for two or more years.

2. The natural disaster also led to severe damage to the Fukushima Daiichi Nuclear Power Station (FDNPS). A large amount of radioactive material was released to the atmosphere and to the sea. At the end of 2013, more than 100,000 people were still displaced due to the accident, releases of radionuclides to the marine environment were still ongoing and workers on site were faced with complex problems related to removal of fuel from the spent fuel pools and management of damaged reactor cores. Recovery operations in the areas most affected by the accident as well as efforts on remediation of land and decommissioning of the damaged site will continue over decades and will warrant monitoring of levels of exposure[1] and the health implications, on site and off site, over extended periods.

3. At its fifty-eighth session in May 2011, the Scientific Committee decided to carry out, once sufficient information was available, an assessment of the levels of exposure and radiation risks attributable to the nuclear power plant accident following the great east-Japan earthquake and tsunami of March 2011. The General Assembly subsequently endorsed that decision in its resolution 66/70.

4. Many data were available regarding the radiation levels and deposition densities of radioactive material in every prefecture in Japan, the concentrations in foodstuffs, and public and worker exposure. Many of these data were provided by official government agencies in Japan; many were published in peer-reviewed scientific journals. Twenty-five Member States of the United Nations other than Japan officially provided information in response to the Committee's request for data to support its assessment. Additional data were made available by other international organizations, including the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), the Food and Agricultural Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the World Health Organization (WHO), and the World Meteorological Organization (WMO). The Committee also considered data made available by several non-governmental organizations. All data were evaluated to determine their suitability for the assessment. Information on the data collection process, the assessment methodologies, and quality assurance procedures can be found in appendix A; data and methodologies used for the assessment are issued as attachments to this annex and its appendices. The Committee formally agreed to rely principally on data available and literature published before the end of September 2012. However, in finalizing this scientific annex, the Committee took into account where appropriate and practicable any significant new information that became available after that date up until the end of 2013. Limited uncertainty/sensitivity studies were

[1] In this report, exposure is used in the general sense to express the act, condition or degree of being subject to irradiation, and not in the sense of a physical quantity.

conducted, as appropriate, to underpin the Committee's qualitative statements of its confidence in its conclusions.

5. The Committee received a great deal of assistance and cooperation from many scientists and institutes in carrying out this evaluation. A team of more than 80 scientific experts was formed from specialists offered by 18 countries, supplemented by a few individuals with relevant expertise not offered by countries but whose experience was deemed important for the work. All experts were required to declare any potential conflicts of interest. The secretariat and officers of the Committee reviewed these declarations, and affirmed that there were no conflicts of interest for the work in which the experts were engaged. Five international organizations were also involved in the work. The scientists were organized into various expert groups and overseen by a Coordination Expert Group, chaired by W. Weiss (Germany). Each expert group had a leader, an adviser from Japan, a rapporteur, lead and contributing writers, and commentators (see the composition in the acknowledgements section at the end of the main text of this annex). The Government of Japan appointed Y. Yonekura as a scientific focal point for the work. The experts collected and reviewed data and information, defined methodologies and processes for ensuring the quality of the data was fit for purpose, evaluated published literature, drafted material, conducted detailed radiation dose[2] assessments and evaluated the health implications as well as the implications for non-human biota in the environment. Many of the experts were also assisted in their work by supplementary support staff in their national institutes. An expert offered by the Government of Japan assisted the secretariat in Vienna.

6. The secretariat provided support to the technical work, inter alia, by convening in Vienna three All-Expert Meetings of the scientists, fostering cooperation and collaboration between the expert group leaders through online meetings every two weeks, providing an online platform for sharing and managing data and information among the experts, liaising with governments and other international organizations. Most of the work was conducted remotely using electronic communication means and tools. Many experts participated as individuals in workshops, conferences and meetings held at the international level, often in Japan. The secretariat organized only one technical visit in the name of the Committee in order to clarify information by direct interaction with those involved in preparing it. The Governments of Germany, Sweden and Switzerland made financial contributions to the general trust fund to support the work of the Committee in these regards.

7. The Coordination Expert Group planned and coordinated the work, and presented draft reports to the fifty-ninth session of the Scientific Committee in May 2012, and to the sixtieth session in May 2013. The Committee under the chairmanship of C-M. Larsson (Australia) scrutinized the draft reports, discussed methodologies, the quality of the data and interim results of the evaluation. The Coordination Expert Group adapted its work according to the direction provided by the Committee. Delegations to the Committee provided comments on the draft report after the fifty-ninth session and two times after the draft report to the sixtieth session, before final endorsement for publication. To obtain additional data, the secretariat of the Committee and the expert groups also maintained frequent and extensive contacts through advisers in Japan and discussed with them the interpretation and evaluation of results.

[2] Dose is a measure of the energy deposited by radiation in a target, and is expressed by the fundamental dosimetric quantity, absorbed dose (usually to an organ) in units of grays (Gy), equal to 1 joule per kilogramme. The Committee uses this quantity to express scientific relationships between the absorbed dose and risk of health effect. However, the Committee has also used a quantity that was strictly derived for radiation protection purposes and that is the most commonly used indicator of potential biological effects from radiation exposure, effective dose in units of sieverts (Sv). This quantity allows for the fact that different kinds of radiation have different biological effects for the same amount of energy deposited and the fact that tissues also react differently. As a reference for subsequent comparisons, the annual average per caput background dose to the Japanese population from naturally occurring sources of radiation is about 2.1 mSv. Over a lifetime of say 80 years this would correspond to about 170 mSv on average.

These contacts proved essential to the conduct of the project and they are here collectively recognized with appreciation.

8. The aim of this scientific annex is to evaluate information, mainly from 2011 and 2012, on the levels of radiation exposure due to the nuclear accident, and the associated effects and risk to human health and the effects on non-human biota. The annex presents estimates of radiation doses and discusses implications for health for different population groups inside Japan, and to a lesser degree in some neighbouring countries, using data and information available to the Committee, and against the backdrop of the Committee’s previous scientific assessments of effects of radiation on health and the environment from all sources, including accidents. The annex identifies gaps in knowledge for possible future follow-up and research. The annex does not identify lessons or address policy issues with respect to human rights[3], public health protection, environmental protection, radiation protection, emergency preparedness and response, accident management, nuclear safety, and related issues; it does not intend to provide advice to local governments, the Government of Japan or to national and international bodies.

9. The scientific annex comprises a main text with 8 chapters and 6 specialized appendices, supported by 28 electronic attachments. Chapter I introduces the aim, background, scope and method of working. Appendix A discusses the compilation of data used by the Committee for its work, and its approaches to quality assurance.

10. Chapter II briefly summarizes the chronology of the accident including the accident progression at FDNPS, how and when radioactive materials were released to the atmosphere and to the ocean, and what measures were taken to protect workers and members of the public from exposure to ionizing radiation.

11. Chapter III describes the releases of radionuclides into the atmosphere and the Pacific Ocean and how estimates have been made of time-dependent radionuclide concentrations in the surface air, on the ground, and in seawater and sediments, locally, regionally and globally. Appendix B and three electronic attachments provide technical underpinning and more details related to chapter III.

12. Chapter IV describes the Committee’s assessment of doses to the public for the first year after the accident for 20-year-old adults, 10-year-old children and 1-year-old infants. Projections were also made of doses to be received over the first 10 years and up to age 80 years. The assessment was based on measurement data as far as possible. Models were used, with realistic assumptions, to provide an objective evaluation of the situation. Protective actions taken during the first year were considered and the doses averted by them were estimated. Appendix C and 21 electronic attachments provide technical underpinning and more details related to chapter IV.

13. Chapter V describes the Committee’s evaluation of doses for workers involved in the emergency response and in clean-up operations during the period between 11 March 2011 and 31 October 2012. Reports of dose distributions for workers by time and exposure pathway are reviewed, summarized and their reliability assessed. Appendix D and one electronic attachment provide technical underpinning and more details related to chapter V.

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[3] The Committee took note of the report of the Special Rapporteur on the right of everyone to the enjoyment of the highest attainable standard of physical and mental health, Anand Grover, *Official Records of the General Assembly, Human Rights Council, Twenty-third session* (A/HRC/23/41/Add.3).

14. Chapter VI discusses the health implications of exposure to radionuclides released from FDNPS. A review of other published health risk assessments are included, and current and future health surveys are discussed. Appendix E provides technical underpinning and more details for chapter VI.

15. Chapter VII describes the Committee's evaluation of doses and effects for non-human biota inhabiting the terrestrial and aquatic (freshwater and marine) ecosystems. Appendix F and three electronic attachments provide technical underpinning and more details related to chapter VII.

16. Chapter VIII provides a summary and conclusions. The Committee envisages returning to this subject in the future to report on the levels of radiation exposure and associated effects and risks as information becomes clearer. In this regard, chapter VIII also briefly identifies some current research needs for better understanding the implications of the FDNPS accident for human health and for the environment.

17. A glossary is provided to explain some of the technical terms used throughout the report. Numerical estimates are generally quoted to two significant figures (and sometimes more in the electronic attachments). This enables better comparison between values, however the values themselves are normally associated with considerable uncertainty and this degree of precision should not be inferred.

II. CHRONOLOGY OF THE ACCIDENT

A. Accident progression

18. The Fukushima Daiichi Nuclear Power Station (FDNPS) of the Tokyo Electric Power Company (TEPCO) lies in Fukushima Prefecture of the Tōhoku region in Japan. It is located about 230 km north-east of Tokyo. The east side of FDNPS faces the Pacific Ocean (figure I). The total power generating capacity of the six reactors on site was 4.7 gigawatts of electricity.

19. On 11 March 2011, an earthquake of magnitude 9.0 occurred along the Japan Trench at 14:46 Japan Standard Time (JST). The earthquake and the following tsunami triggered a severe nuclear accident at FDNPS. On 12 April 2011, the Nuclear Industrial and Safety Agency (NISA)[4] in Japan declared the accident at level 7 ("Severe Accident") on the International Nuclear Event Scale (INES). A timeline of the events that followed the earthquake and tsunami is provided in table 1.

[4] In September 2012, NISA and the Nuclear Safety Commission were unified to form the Nuclear Regulation Authority (NRA).

Figure I. Layout of the Fukushima Daiichi Nuclear Power Station, including location of the automatic monitoring posts [T12]

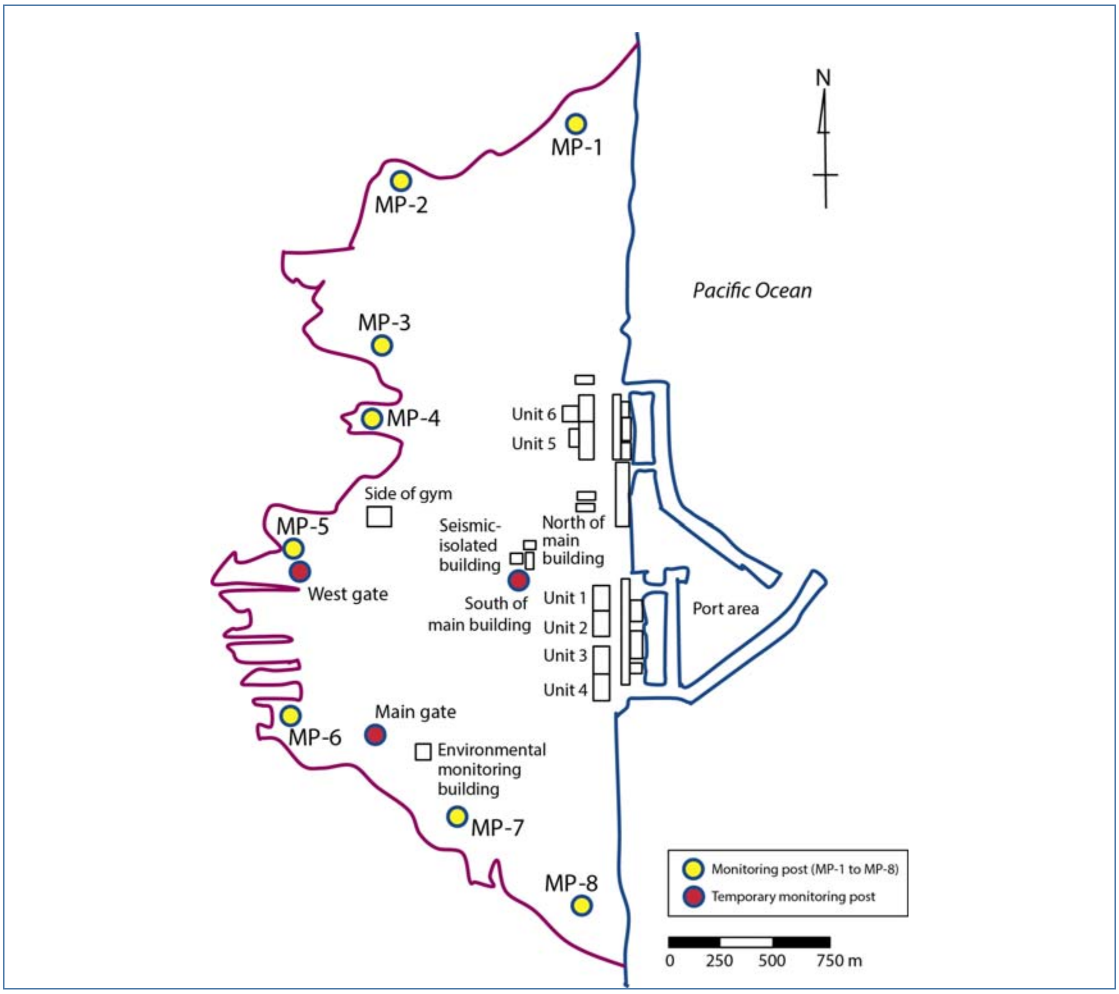


Table 1. Timeline of events following the earthquake and tsunami

All times are JST

Date	*Reactor*	*Environment*	*Public*	*Workers*
2011-03-11	14:46, EARTHQUAKE			
	Scram in Units 1, 2 and 3 of TEPCO's FDNPS[a]			
	Loss of external electricity			
	15:35, MAJOR TSUNAMI			
	15:37, loss of all electricity, except DC on Unit 3		16:40, MEXT[b] activated SPEEDI[c] and started making daily predictions of concentrations in air and deposition densities for unit release of radioactive material	
	Around 20:00, possible start of damage to reactor core and pressure vessel in Unit 1		20:50, evacuation within 2 km ordered 21:23, evacuation within 3 km ordered 21:23, sheltering from 3 km to 10 km ordered	
2011-03-12	02:45, strong likelihood of reactor pressure vessel failure in Unit 1	Ambient dose equivalent rate[5] near main gate of FDNPS: 04:00, about 0.1 µSv/h 04:50, 1 µSv/h 10:30, 390 µSv/h Emergency monitoring teams of Fukushima Prefecture and JAEA[d] started to measure ambient dose rates and airborne dust, including iodine within 20-km radius	05:44, evacuation within 10 km	
	15:36, reactor building of Unit 1 damaged by hydrogen explosion		18:25, evacuation within 20 km ordered Screening began of residents at refuges using Geiger–Müller survey meters	Some workers remained in the main control room for several days following the explosions at Units 1 and 3. Presumed to have inhaled radioactive material (mainly radioiodine) because they lacked protective equipment (e.g. face masks)

[5] Portable or fixed equipment for area monitoring took measurements of the dosimetric quantity, H*(10), ambient dose equivalent rate, expressed in units of microsieverts per hour (µSv/h) or millisieverts per hour (mSv/h). In this report, the unqualified term "dose rate" refers to "ambient dose equivalent rate".

Date	*Reactor*	*Environment*	*Public*	*Workers*
2011-03-13	02:42, high pressure coolant injection in Unit 3 ceased Around 06:30 to 09:10, likely damage to reactor pressure vessel in Unit 3			Potassium iodide tablets provided for emergency workers at FDNPS
2011-03-14	11:01, reactor building of Unit 3 damaged by hydrogen explosion			Emergency dose limit for emergency workers raised from 100 mSv to 250 mSv[f]
	12:30, failure of reactor core isolation cooling system in Unit 2 By 18:22, indications that core in Unit 2 completely uncovered Around 21:18, failure of reactor pressure vessel in Unit 2			
2011-03-15	Between 06:00 and 06:12, hydrogen explosion occurred at Unit 4 from backflow of gases vented from Unit 3; peak dose rate about 0.6 mSv/h at site boundary			
	From around 07:38, major discharge of radioactive material from Unit 2	09:00, maximum dose rate of about 12 mSv/h recorded near the main gate	11:00, Sheltering in place between 20-km and 30-km radius ordered Evacuation from within 20 km of FDNPS completed. Off-site centre in Okuma Town evacuated	
2011-03-16		Monitoring of food and drinking water started	Guidance on taking stable iodine when evacuating from within 20 km of FDNPS was issued. Stable iodine not taken because evacuation already completed	
2011-03-17			Instructions first issued on restrictions on distribution of foodstuffs	

Date	*Reactor*	*Environment*	*Public*	*Workers*
2011-03-18		Monitoring of airborne dust, soil and deposition started		
2011-03-19			MHLW[e] advised against drinking tap water if levels exceeded 300 Bq/kg of radioiodine and 200 Bq/kg of radiocaesium	
2011-03-23		Marine monitoring started	Restrictions begin on consumption of foodstuffs. Tokyo Municipal Water Authority urges residents to use bottled water for infant formula	
2011-03-24			Ban on tap water lifted by Tokyo Metropolitan Government	Contamination of feet of three workers confirmed; caused by stepping into puddles of contaminated water wearing low-cut shoes
2011-03-26			Radiation measurements made of the thyroids of 1,080 children living in Kawamata Town, Iitate Village and Iwaki City (until 30 March)	
2011-03-30			Re-configuration of the restricted areas and other evacuation areas decided by the Government	
2011-04-01	Highly-contaminated water unintentionally released to the Pacific Ocean (until 2011-04-06)			
2011-04-04	Weakly-contaminated water deliberately discharged to the Pacific Ocean (until 2011-04-10)			
2011-04-22			“Deliberate evacuation areas" and “evacuation-prepared area in case of emergency” established	

Date	*Reactor*	*Environment*	*Public*	*Workers*
2011-05-10	Moderately-contaminated water unintentionally released to the Pacific Ocean (until 2011-05-11)			
2011-06-30			"Specific spots recommended for evacuation" were specified in Date City	
2011-07-19	Step 1 of the Roadmap to Recovery (i.e. dose rates steadily in decline etc.) attained[g]			
2011-09-30			"Evacuation-prepared area in case of emergency" was terminated	
2011-12-16	Step 2 of the Roadmap to Recovery (i.e. cold shutdown state, releases under control etc.) attained[g]			
2012-03-31				Dose assessments (due to internal and external exposure) completed for about 21,000 workers

[a] *Fukushima Daiichi Nuclear Power Station of the Tokyo Electric Power Company.*

[b] *Ministry of Education, Culture, Sports, Science and Technology.*

[c] *System for Prediction of Environmental Emergency Dose Information.*

[d] *Japan Atomic Energy Agency.*

[e] *Ministry of Health, Labour and Welfare.*

[f] *Expressed in effective dose, the "emergency dose limit" in Japan corresponds to an ICRP "reference level" (see section V.A). The increase in the emergency dose limit was repealed on 1 November 2011 for new workers and on 16 December 2011 for most emergency workers registered before 31 October (footnote g).*

[g] *Roadmap towards settlement of the accident at FDNPS, TEPCO. Step 2 completion report (2011), Nuclear Emergency Response Headquarters [N6]. This triggered the repealing of the emergency dose limit (footnote f).*

20. When the earthquake occurred, Units 1–3 of FDNPS were in normal operation; Units 4–6 were undergoing periodic maintenance and refuelling operations, with Unit 4 being completely defuelled. As designed, the emergency shutdown feature, or scram[6], went into operation at Units 1–3 immediately after seismic activity started. The seismic tremors damaged electricity transmission facilities inside and outside the site of FDNPS, resulting in total loss of off-site electricity. However, the emergency diesel generators automatically activated, as designed, to provide backup power for the reactor cooling systems and other plant safety systems.

21. The earthquake caused a tsunami to hit the Japanese coastline. A major wave arrived at FDNPS at 15:35 JST with an estimated maximum wave height of about 15 m, much higher than the 6 m seawall and above the elevation of approximately 10 m where key buildings were constructed. The tsunami damaged or destroyed the emergency diesel generators, the seawater cooling pumps, the electric wiring system and the DC power supply for Units 1, 2 and 4, resulting in the loss of all on-site power, except for Unit 6 that was supplied with electricity from an air-cooled emergency diesel generator. In short, Units 1, 2 and 4 lost all power; Unit 3 lost all AC power, and later lost DC power before dawn of

[6] A scram is a safety feature that triggers immediate shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a "reactor trip".

13 March 2011. Unit 5 lost all AC power. Damage caused directly by the earthquake is still unclear and is yet to be fully quantified by further analyses.

22. The tsunami damaged more than just the power supply. It also destroyed or washed away vehicles, heavy machinery, oil tanks, and gravel. It destroyed buildings, equipment, installations and other infrastructure generally. Seawater from the tsunami inundated a large portion of FDNPS. After the water retreated, debris was scattered all over the site, hindering movement. Recovery tasks were further interrupted as workers reacted to the intermittent and significant aftershocks and successive tsunami waves. The loss of electricity deactivated monitoring equipment and the control functions in the central control room. Lighting and communications were also affected. Decisions and responses to the accident had to be made, on the spot, by operational staff at the site, without valid tools and manuals.

23. Cooling the reactors, and monitoring whether the measures taken had any effect, was heavily dependent on electricity, which was not available. The difficulties in accessing the control rooms and the debris littering the site further hindered the provision of alternative power supplies and means of cooling (e.g. by water injection using fire trucks).

24. With no cooling to remove heat generated by the radioactive material in the reactor core, damage to the core may have begun at Unit 1 on 11 March. Injection pumps (driven by steam generated by the reactors) were used to provide cooling water to the reactors on Units 2 and 3, but these pumps eventually stopped working, and all cooling to the reactors was lost until fire engines were used to restore water injection. Without adequate cooling, pressure inside the reactor vessels increased, and was relieved to some degree for Units 2 and 3 by venting through the safety relief valves. In addition, water or steam in direct contact with the over-heated fuel assemblies reacted with the zirconium of the fuel cladding to produce hydrogen gas. This hydrogen then accumulated in the upper portion of the reactor buildings (secondary containment) and ignited, producing explosions in the Unit 1 and Unit 3 reactor buildings on 12 and 14 March, respectively. Hydrogen generated in Unit 3 seems to have migrated into the Unit 4 reactor building, resulting in a subsequent explosion and damage there on 15 March. Severe damage, including meltdown, occurred in the cores of the three reactors (Units 1, 2 and 3). In all three units, melted fuel fell to and subsequently penetrated the bottom of the reactor pressure vessels, resulting in molten-fuel–concrete interactions beneath the pressure vessels that further increased the pressure within the containments [T17]. As of December 2013, the fuel was covered by injected water which, depending on the integrity of the containment, may be a source of release of radionuclides to the surrounding area.

25. The core damage including melting of the overheated fuel assemblies resulted in the release of the more volatile fission products into the reactor vessels. Operations to reduce pressure in, or possibly leaks from, the reactor vessels resulted in releases of volatile radionuclides into the containment vessel, the reactor buildings and the outside environment. These volatile radionuclides were not only in gaseous form (such as noble gases and gaseous iodine), but some were also in aerosol form, although a significant fraction of the aerosols was trapped in the water in the reactor containment and in the turbine buildings. Several tens of per cent of the inventories of the more volatile elements (i.e. hydrogen/tritium, iodine and caesium) in the cores of the three damaged reactors have been found [N15] in stagnant water, mainly in the basements of the turbine and reactor buildings but also in surrounding areas. Less volatile elements (e.g. strontium, barium and lanthanum) were also found but at levels that were between about one and ten per cent of those for the more volatile elements in terms of their relative inventories. The processes of the underground liquid-phase releases are still uncertain and yet to be clarified in further analyses.

26. As well as the overheated fuel in the reactors, there was also concern about cooling of fuel assemblies that had been removed from the reactors and stored under water in spent fuel pools prior to the earthquake and tsunami. Unit 4 was in a periodic inspection on 11 March and all fuel assemblies had been removed from the reactor into the Unit 4 spent fuel pool. With the loss of electricity, the ability to replenish the water and maintain the temperature of these storage pools was also lost. Concern was to a large extent focused on the storage pool of Unit 4 because the reactor building in which the storage pool was located had suffered significant damage owing to the explosion on 15 March and also because it contained the entire core of the defuelled reactor and spent fuel from previous defuelling. However, because a large amount of water was supplied to the spent fuel pool of Unit 4 early on, Japanese officials considered the water level in the pool to have been sufficiently high do not believe that the stored fuel assemblies did not sustain any significant damage [N7].

27. As of 16 December 2011, the Government of Japan announced that conditions equivalent to a cold shutdown state[7] had been achieved at FDNPS [I5].

28. It is clear, from the experience of the accidents at the Chernobyl and Three Mile Island nuclear power plants, that the next several years will provide more information on the factors contributing to the accident's progression. In particular, it is critical to quantify the liquid-phase release and dispersion that would have occurred underground following core meltdown.

B. Release to the environment

29. As a result of the earthquake and tsunami, the fixed automatic radiation monitoring posts around the boundary of FDNPS (MP 1−8, shown in figure I) were disabled, so measurements could only be made with mobile monitoring equipment, until three temporary automatic posts were established on 29 March and the fixed monitoring posts restored in early April. Dose rates measured at several locations around FDNPS increased drastically during the period from 12 March to beyond 20 March, indicating significant releases of radioactive material to the environment [T9] (see figure II). Dose rates higher than 10 Sv/h were measured for short periods of time at some locations [N6]. Further discussion on the nature of the releases, how they varied over time and the resulting dispersion of released material in the environment is provided in chapter III and in appendix B.

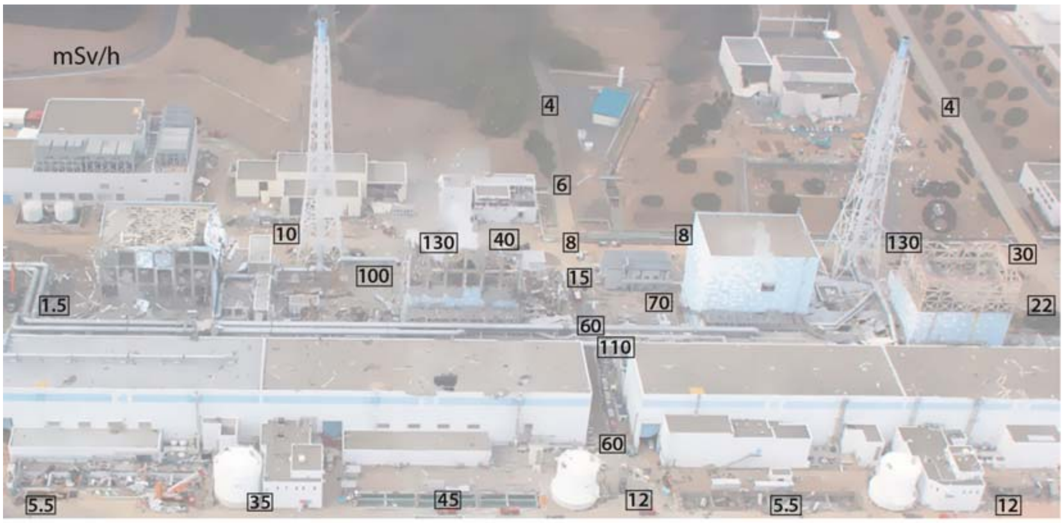
30. On 2 April 2011, workers discovered that highly-contaminated water had accumulated in a trench outside of Unit 2 and that the water was flowing from the trench into the ocean. The outflow was stopped on 6 April. There were several other, smaller scale releases of radioactive material into the ocean, including the deliberate discharge of low-level radioactive water being stored in tanks to create storage capacity for the highly-contaminated water from the trench. These releases and their dispersion in the marine environment are discussed further in chapter III and appendix B.

[7] Defined by TEPCO and the Nuclear Emergency Response Headquarters (NERHQ) as the state where the coolant water temperatures of Units 1–3 were less than 100ºC, the pressure inside the reactor vessels was the same as the outside air pressure, and where any further releases would not result in an annual effective dose greater than 1 mSv at the site boundary.

Figure II. Dose rates on the Fukushima Daiichi Nuclear Power Station site

View is looking inland, westwards from the ocean. The buildings of Unit 1 (on the far right) and of Units 3 and 4 (on the left of centre and far left) have been destroyed by explosion. The building of Unit 2 (right of centre) remains intact. Measurements of ambient dose equivalent rate (mSv/h) were made in surveys conducted 15:00–18:00 JST on 20 March, 11:00–14:00 JST on 22 March and 11:30–12:30 JST on 23 March 2011

(Photo: Courtesy of Air photo service Co. Ltd., Myoko, Japan)



C. Actions taken relevant to public exposure

31. The Japanese authorities decided on a number of measures to protect the public, including immediate and late ("deliberate") evacuation, sheltering in homes, restricting distribution and consumption of contaminated foodstuffs (milk, vegetables, grains, meat, fish, etc.) and water, and instructions to take stable iodine[8]. These actions were supported by radiation contamination surveys of people and places (see table 1).

32. At 20:50 JST on 11 March 2011, the Governor of Fukushima Prefecture issued instructions to evacuate settlements within 2 km of FDNPS (Futaba Town and Okuma Town). Shortly afterwards (at 21:23 JST), the Director-General of the Nuclear Emergency Response Headquarters (NERHQ) ordered the evacuation of residents and others within 3 km of FDNPS and the sheltering indoors of all residents and others within 10 km. At 05:44 JST the next morning, the people within 10 km were then ordered to be evacuated. At 18:25 JST that same day (12 March), the evacuation radius was expanded to 20 km (an area of approximately 600 km^2). Following the hydrogen explosion between about 06:00 and 06:12 JST on 15 March, an instruction was issued ordering all people living between 20 km and 30 km from FDNPS to shelter indoors. In addition, on 16 March, an instruction was issued that anyone still remaining within 20 km of FDNPS should take stable iodine. This instruction was not implemented, because the area was considered to have already been evacuated (although the number of people who

[8] If stable iodine (as potassium iodide or iodate, usually in a tablet form) is taken in the appropriate dosage and within the appropriate timescale, it can help prevent uptake into the thyroid gland of radioactive iodine released from nuclear accidents ("thyroid blocking").

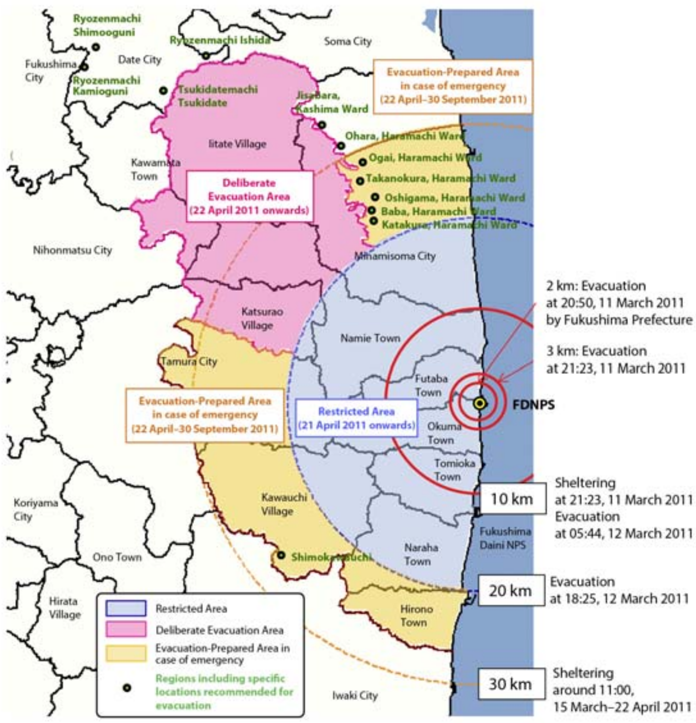
did not immediately follow the instructions to evacuate is uncertain). At the time of the earthquake, about 78,000 people were living within what became the 20-km evacuation zone and about 62,000 were living between 20 km and 30 km from FDNPS [N8].

33. Monitoring of food and drinking water by Japanese and prefectural governments began on 16 March 2011. Selected foodstuffs (milk, vegetables, grains, meat, fish, and so on) containing radioactive material that exceeded the provisional regulation values, as recommended on 17 March 2011 by the Ministry of Health, Labour and Welfare (MHLW) of Japan, were prohibited from distribution on 21 March 2011 and from consumption on 23 March 2011.

34. On 25 March, the residents in the area between 20-km and 30-km radius of the site, who had been sheltering since 15 March, were advised by the Government of Japan to begin voluntary evacuation and instructed to be prepared to evacuate depending on future developments at FDNPS. This instruction was terminated on 30 September [N8]. In addition, environmental monitoring revealed that there were areas where radioactive material had been deposited at high levels even outside of the 20-km evacuation zone. Deposition densities of ^{131}I and ^{137}Cs were estimated from samples of soil collected by IAEA teams at distances from 32 km to 58 km in the north to north-west direction from FDNPS between 18 and 26 March 2011. Average values of deposition density for ^{131}I ranged from 0.2 to 25 MBq/m^2 and for ^{137}Cs from 0.02 to 3.7 MBq/m^2 with the highest values located near Iitate Village. On the basis of these measurements, IAEA advised the Government of Japan to carefully assess the situation in that region [I3]. On 22 April, “deliberate evacuation areas” were established for specific areas beyond the 20-km zone where the effective dose might exceed 20 mSv within a year [N8]. Most residents of these areas were then evacuated between April and June. Figure III shows the extent of all of these areas as of 3 August 2011 [N7].

Figure III. Areas subject to measures to protect the public (as of 3 August 2011) [N7]

All times are JST



35. On 16 June 2011, the Government announced the concept of “specific spots recommended for evacuation” for localized areas more than 20 km away from FDNPS and outside the deliberate evacuation areas. These were areas where the estimated effective dose might exceed 20 mSv over the first year after the accident because of radioactive material deposited on the ground; they were delineated based on environmental monitoring conducted by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The local municipalities notified potentially affected residents and provided them with information on their options for relocating or remaining, and on methods to mitigate future radiation exposures. Such designations were announced for Date City on 30 June 2011, for Minamisoma City on 21 July and 3 August, and for Kawauchi Village on 3 August. On 25 November, additional locations were established in Date City and Minamisoma City [N7].

36. On 12 March 2011, staff of the Nuclear Emergency Response Headquarters (NERHQ) of Fukushima Prefecture started surveying residents, including those who were evacuated, for contamination of skin and clothing using Geiger–Müller survey meters. Screening criteria were 40 Bq/cm^2 from beta/gamma contamination (corresponding to 13,000 cpm) for decontamination by wiping, and 100,000 cpm for decontamination of the surface of the body. Most of the 195,354 people checked between 12 March and 31 May did not require any decontamination [N8]. Between 26 and 30 March, staff of NERHQ conducted radiation surveys using hand-held sodium iodide (NaI) monitors of the thyroid glands of 1,080 children aged 0 to 15 years living in Kawamata Town, Iitate Village and Iwaki City. None of the surveyed children exceeded the established screening level corresponding to an absorbed dose to the thyroid due to internal exposure from ^{131}I of 100 mGy for a 1-year-old infant [N8].

D. Actions taken relevant to occupational exposure

37. On 14 March 2011, the pre-existing “emergency dose limit” for occupationally-exposed workers (“radiation workers”[9]) in Japan performing emergency work was raised from 100 mSv to 250 mSv effective dose by a special ministerial order, for the purposes of dealing with the particular circumstances of the accident [I9, N6]. On 1 November 2011, this “emergency dose limit” was reduced to 100 mSv for new workers.

38. Initially, there was a shortage of personal dosimeters and other essential equipment on site. Over the first few weeks, successive measures were implemented to prevent external and internal exposure[10] to radiation. The distribution of potassium iodide tablets to FDNPS workers engaged in emergency work was initiated on 13 March for those who were under 40 years of age and others who requested it. Subsequently, physical barriers were introduced between different areas, working time in designated areas was limited, and a coordination centre was established. Workers were issued with tight-fitting full-face respirators (to minimize inhalation of radioactive particles and gases), and protective overalls, gloves, safety shoes, cotton hats and helmets (to minimize contamination of body surfaces).

[9] In Japan, the term “radiation worker” applies to personnel engaging in radiation work in a controlled area, such as in the installation, operation, utilization or maintenance of nuclear reactors, or in the transport, storage, disposal or removal of nuclear-fuel material or nuclear-fuel-contaminated material.
[10] External and internal exposure are exposures from sources outside and inside the body, respectively.

III. RADIONUCLIDE RELEASES, DISPERSION AND DEPOSITION

39. Events in the progression of the accident at FDNPS, summarized in chapter II above, led to releases of radioactive material to the environment. Estimates of the amounts and temporal pattern of these releases, both to the atmosphere and to the marine environment, are described in detail in appendix B and summarized in this chapter. These estimates were made for two purposes:

(a) To indicate the amounts of radioactive material released to the environment;

(b) To be used, in combination with models (e.g. for atmospheric and marine dispersion), to infer the dispersion and deposition of radionuclides at locations in the environment where either data were not available or measurements can no longer be made.

40. Knowledge of the spatial and temporal distribution of released radioactive material in the environment (e.g. concentrations of radionuclides in air, deposition densities of radionuclides on the ground, and concentrations of radionuclides in seawater and sediments) is a prerequisite for estimating the radiation exposure of members of the public (see chapter IV) and for assessing the exposures and effects in the environment (see chapter VII). Measurements of radiation levels or radioactive material in the environment provide, in general, a reliable basis for estimating doses. The available measurements and their origins are summarized in appendix A. Where measurements were not available, the Committee has relied on estimates, and this chapter describes the nature of the estimates made for assessing doses.

A. Radionuclide releases

1. Release to the atmosphere

41. Radioactive material was released from FDNPS over an extended period. The pattern of release was complex, both temporally and spatially. Significant releases began on 12 March and the rate of release varied considerably in magnitude over the following week, with marked increases associated with particular events at each unit (e.g. hydrogen explosions, venting, and leakage from the reactors and their containment systems). After the first week, the rates of release gradually declined, albeit with some fluctuations over more limited periods. By the beginning of April, the release rates had fallen to a thousandth or less of the release rates that occurred during the first week of the accident, although these much lower release rates persisted for many weeks. The releases occurred from different locations, at different heights and with quite different characteristics, all of which affected their subsequent dispersion in, and deposition from, the atmosphere.

42. Numerous estimates have been published of the magnitude, time profile and nature of the release of radionuclides (commonly referred to as the “source term”) from FDNPS; in general, their quality has improved over time as more information has become available. Two distinct approaches have been taken to derive such estimates, based on:

(a) Detailed simulations of the progression of the accident at FDNPS;

(b) “Inverse” or “reverse” modelling using measurements of levels of radiation or radioactive material in the environment.

Both approaches have their limitations and are associated with much uncertainty.

43. In general, the published estimates of the "total" releases were broadly consistent, given their inherent uncertainties and the fact that, strictly, many were not directly comparable; some estimates were of the total release, while others were of releases over a limited period of time or only included that fraction of the release partly or wholly dispersed over the Japanese land mass. The estimates of the "total" release of ^{131}I fell within the range of about 100 to about 500 PBq[11] and those of ^{137}Cs generally in the range 6–20 PBq[12] (with some estimates that had been based on more limited information ranging up to 40 PBq). These ranges comprised about 2-8% of the total inventory of ^{131}I and about 1–3% of the total inventory of ^{137}Cs in the three operating reactors (Units 1–3) at the time of the accident. For perspective, the estimated releases (based on the averages of published estimates) of these radionuclides from FDNPS were about 10% and 20% for ^{131}I and ^{137}Cs, respectively of those estimated for the Chernobyl accident. Further details are given in appendix B.

44. Numerous estimates have also been made of the temporal pattern of the rate of material released, in particular for ^{131}I and ^{137}Cs. Notwithstanding the broad agreement between the various published estimates of the total amounts of radioactive material released, there were large differences in the temporal patterns of release rates and in the extent to which they correlate with events on site.

45. The Committee has carefully assessed the numerous published estimates of the source term, including the temporal patterns of the release rates. For its purposes, the Committee had to specify a source term to provide a sound basis for estimating levels of radioactive material in the terrestrial environment where no measurements existed; these levels were an essential input to the subsequent estimation of doses to the public (see chapter IV below). Estimates based on reverse or inverse modelling, as opposed to simulation of accident progression, were clearly preferable in this context because they were derived from, and the models were already optimized to fit, measurements of radioactive material in the environment. Having considered a number of options, the Committee chose to use the source term estimated by Terada et al. [T19], which was selected from among those that had been derived on the basis of reverse or inverse modelling[13]. The total releases of ^{131}I and ^{137}Cs estimated by Terada et al. were 120 and 8.8 PBq, respectively, and were both at the lower end of the ranges of published values (see above). There were indications that they may have underestimated the total amounts of these radionuclides released, perhaps by a factor of up to about two, because of assumptions made about releases dispersed over the ocean. However, for reasons outlined above and detailed in appendix B, they provided a sound basis for the purposes of estimating the levels of radioactive material in the terrestrial environment where measurements did not exist.

46. Terada et al. estimated the release rates of ^{131}I and ^{137}Cs as a function of time. These two radionuclides, together with ^{134}Cs, made by far the largest contribution to the exposure of the public. Other radionuclides that could have contributed significantly were also included in the source term and comprise other radioisotopes of iodine and caesium, ^{132}Te and ^{133}Xe. The release rate pattern for the other radionuclides was derived in general by considering the amounts of these radionuclides relative to ^{131}I or ^{137}Cs in the estimated inventories of the three reactors and their relative levels in environmental measurements. A large number of radioisotopes of other elements would also have been released, with their relative amounts determined by their volatility. For example, the volatilities of strontium, barium and plutonium are much lower than those of iodine and caesium; consequently, their releases were

[11] The activity released or measured in a sample represents the number of radioactive decays per unit time and its unit is the becquerel (Bq). One becquerel is defined as one decay per second. One gigabecquerel (GBq) is equal to 10^9 becquerels; one terabecquerel (TBq) is equal to 10^{12} becquerels; and one petabecquerel (PBq) is equal to 10^{15} becquerels.
[12] The release of ^{134}Cs was comparable with that of ^{137}Cs.
[13] This was chosen in preference to a later refinement by Kobayashi et al. [K18] that considered measurements of radioactive material in the Pacific Ocean in addition to those over the Japanese land mass. If the Committee had adopted the Kobayashi et al. source term, it would have overestimated the levels of radioactive material in the terrestrial environment, which would have been inconsistent with its intent to make a realistic assessment of radiation exposure.

relatively much lower. This was confirmed by measurements of their levels in the environment[14]. This contrasts markedly with the Chernobyl accident, where much larger fractions of the less volatile elements (e.g. strontium and plutonium) were released directly to the atmosphere. The total release assumed by the Committee of each of the radionuclides included in the source term is given in table 2. The temporal pattern of the release of these radionuclides is shown in table B5, figure B-I and figure B-XVI of appendix B.

Table 2. The total release of radionuclides to the atmosphere assumed by the Committee for the purposes of estimating levels of radionuclides in the environment where no measurements existed or measurements could no longer be made

The values represent the sum of the activity released to the atmosphere whenever that occurred

Radionuclide	*Total release (PBq)*	*Radionuclide*	*Total release (PBq)*
^{132}Te	29	^{133}Xe	7 300
^{131}I	120	^{134}Cs	9.0
^{132}I	29	^{136}Cs	1.8
^{133}I	9.6	^{137}Cs	8.8

2. Release to the marine environment

47. Radioactive material from FDNPS entered the marine environment directly and indirectly. Direct release into the ocean is at least known to have resulted from leakage of highly-contaminated water from a trench outside Unit 2 (discovered on 2 April 2011), and the deliberate discharge of weakly-contaminated water from storage tanks; the latter were emptied to create capacity for the storage of highly-contaminated water remaining in the trench (see chapter II). Further direct releases occurred subsequently (for example, in May and December, 2011) but, in general, these were small compared with those that occurred in the first month after the accident. Radioactive material entered the ocean indirectly via two routes: *(a)* most importantly, from the deposition onto the ocean surface of material released to the atmosphere and dispersed over the ocean; and *(b)* from run-off into rivers of material deposited over the land mass and transported downstream into the ocean.

48. At the end of 2013, releases of radionuclides to the marine environment continued to be reported [T18], apparently emanating largely from contaminated groundwater on the FDNPS site. As described in chapter II, the sources of stagnant water mainly in the basement of the turbine and reactor buildings [N15] were contained to varying extents in the respective buildings. However, they are likely to be one of the major contributors to the continuing releases of radionuclides to the groundwater. Monitoring results published by the Nuclear Regulation Authority [N21]indicate that these continuing release rates during 2013 were at a level much lower than the major releases that occurred in the immediate aftermath of the accident. Furthermore, measures were being taken to attempt to control them (e.g. the building of a containment wall between the FDNPS site and the ocean). It was considered that those releases were unlikely to significantly affect the Committee's assessment of doses to the public. However, continued monitoring and assessment of the implications of the releases is warranted.

[14] The release of each of three radionuclides, ^{238}Pu, ^{239}Pu and ^{240}Pu, has been estimated to be about 1 GBq [Z5]. Their contribution to exposure of the public would have been insignificant.

49. Various estimates have been published of the total amounts of the more radiologically-significant radionuclides reaching the ocean by each route, and of the pattern of release over time. The estimates of direct releases to the ocean were made from measured levels of radionuclides in seawater. From a review of the published estimates, the Committee considered that the total direct release of ^{137}Cs to the ocean was likely to have fallen within a range of about 3 to 6 PBq; that of ^{131}I was considered likely to have been about three times higher. The temporal pattern of the direct releases to ocean has been estimated by Kawamura et al. [K3], Tsumune et al. [T24] and Estournel et al. [E4]; the largest releases were estimated to have occurred during the last week in March and the first week in April, with direct releases continuing at much lower, and slowly declining, levels for many weeks thereafter.

50. The estimates of the indirect releases (principally the contribution due to deposition onto the ocean of radionuclides released to atmosphere) were made by modelling the dispersion of material released to the atmosphere and its deposition over the ocean. For a significant fraction of the period when the atmospheric releases were largest (that is from 12 March until the beginning of April 2011), the wind was blowing out to sea. Kobayashi et al. [K18] have estimated that about 50% and 60%, respectively, of the total atmospheric releases of ^{131}I and ^{137}Cs were deposited over the ocean. The total amounts that entered the northern Pacific Ocean by deposition from the atmosphere were estimated by various authors to have been about 5 to 8 PBq and 60 to 100 PBq for ^{137}Cs and ^{131}I, respectively. Only a small percentage (about 5%) of these amounts, however, was estimated to have been deposited within a radius of 80 km from the FDNPS site.

51. Other radionuclides, in addition to ^{131}I and ^{137}Cs, were also released to the ocean, both directly and indirectly. Radioisotopes of strontium, plutonium and other elements have been measured in seawater and/or in sediments. Estimates have been made by Povinec et al. [P12] of the direct release of ^{90}Sr to the ocean and these range from about 0.04 to 1 PBq. The levels of radioisotopes of plutonium in seawater were generally below the limits of detection.

3. Summary of releases to the environment

52. A summary of published estimates of the release to the environment of the more radiologically-significant radionuclides from FDNPS is given in table 3 (see appendix B for details). Consideration is given to releases *(a)* to the atmosphere and *(b)* to the Pacific Ocean (both directly in liquid form and indirectly as deposits from the radionuclides released to the atmosphere). In general, the tabulated values encompass the range of published releases; in some cases, the ranges of tabulated values are smaller and exclude estimates that the Committee judged to be less reliable. All estimates of release are associated with much uncertainty. The total inventory of each radionuclide in the three reactors at the time of their shutdown is also indicated for perspective.

Table 3. Summary of release estimates for the more significant radionuclides to the environment from FDNPS

Given their uncertainties, values are quoted to just one significant figure

Radionuclide	*Inventory in Units 1 to 3 at reactor shutdown*[a] *(PBq)*	*Release to the atmosphere (PBq)*	*Release to the ocean (PBq)*	
			Direct	*Indirect*[b]
^{131}I	6 000	100 to 500[c]	about 10 to 20[e]	60 to 100[g]
^{137}Cs	700	6 to 20[d]	3 to 6[f]	5 to 8[g]

[a] *Values quoted to two significant figures.*

[b] *Indirect releases comprise radionuclides initially released to the atmosphere and subsequently deposited onto the ocean surface.*

[c] *Encompasses the full range of estimates reviewed by the Committee (see table B2).*

[d] *Encompasses the full range of estimates reviewed by the Committee apart from two (these two extended up to about 40 PBq but were based on limited information and were less reliable) (see table B2).*

[e] *Based on very limited information indicating that the direct release of ^{131}I was about 3 times greater than that of ^{137}Cs (see table B6).*

[f] *Range of estimates derived from more reliable three-dimensional modelling; other estimates were larger, extending up to about 30 PBq, but were less reliable (see table B6).*

[g] *Encompasses the range of (few) estimates reviewed by the Committee (see table B6).*

53. Improvements in the estimation of the releases to both the atmosphere and the ocean can be expected in future, in particular as more information becomes available on the progression of the accident, greater use is made of measurements in the environment, and improved assessment methods are implemented. This is an active area of research; notwithstanding these expected improvements, significant uncertainties are likely to remain, in particular surrounding the temporal pattern of the releases.

B. Dispersion and deposition in the environment

1. Atmosphere and terrestrial environment

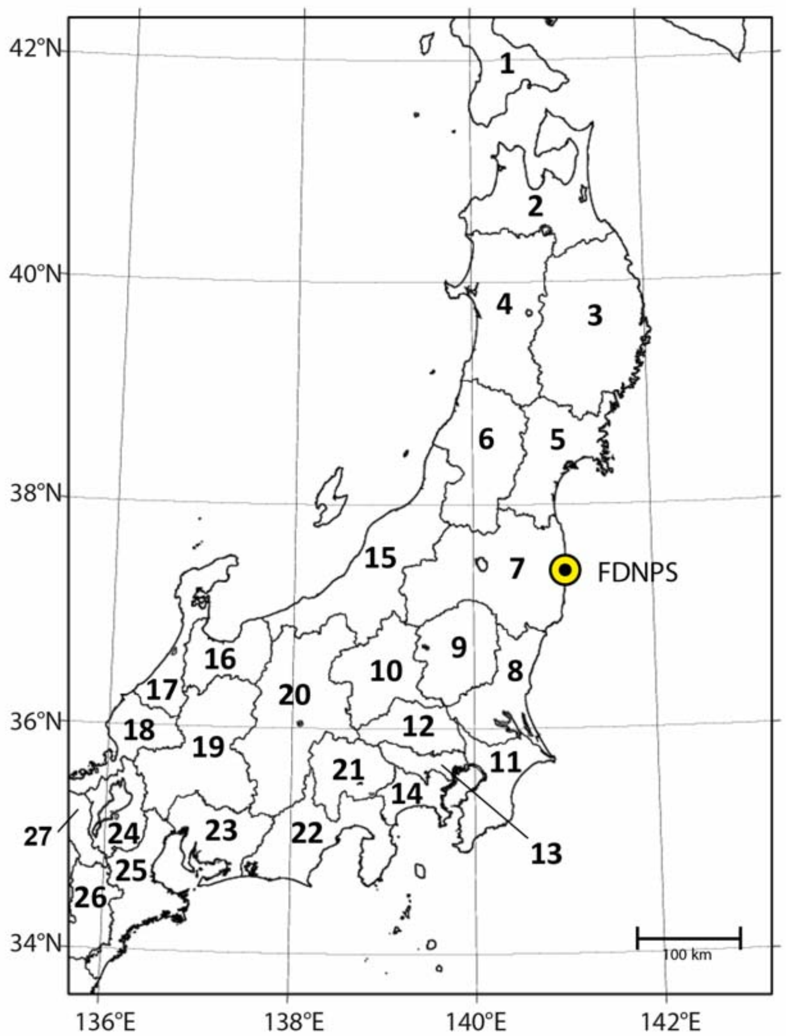
54. The fate of radioactive material released to the atmosphere during the accident at FDNPS was determined by the meteorological conditions pertaining at the time and the physical characteristics of each release, such as its height and whether it was in gaseous or particulate form. These conditions, which varied considerably during the period of releases, determined where the material was dispersed and the rate at which it was diluted in and deposited from the atmosphere. The releases that largely determined the levels and patterns of radionuclides on the Japanese land mass occurred on 12, 14–16, and 20–23 March. The meteorological features that determined their fate were as follows:

(a) Material initially released on 12 March went towards the Pacific Ocean, but the release in the afternoon of 12 March, in particular resulting from the hydrogen explosion in Unit 1 initially spread northwards along the eastern coast of the main island with significant dry deposition (particulate matter that settles on the ground), and later shifted to a north-north-easterly direction, over the coastal area of Miyagi;

(b) Material released from late at night on 14 March moved towards the south, depositing along the south-eastern coastal area of Fukushima Prefecture and the north-eastern area of Ibaraki Prefecture (see figure IV) on the morning of 15 March; this material was further dispersed and resulted in dry deposition of radionuclides in the prefectures of Tokyo, Saitama and Kanagawa, albeit at reduced levels. By the afternoon of 15 March, this dispersing material encountered precipitation, which resulted in enhanced levels of wet deposition (brought to the ground with rain and snow) in areas of the prefectures of Gunma, Tochigi and Fukushima. A further major release occurred in the morning of 15 March; this material moved towards the south then progressively to the north-west, leading to significant wet and dry deposition of radionuclides north-west of FDNPS;

(c) Material released during the period 20 to 23 March was dispersed over parts of the Japanese territory encountering rainfall on occasions and resulting in wet deposition, for example in areas of the prefectures of Iwate, Miyagi, Ibaraki and Chiba.

Figure IV. Location of Fukushima Daiichi Nuclear Power Station (FDNPS) and surrounding prefectures



No.	Prefectures
1	HOKKAIDO
2	AOMORI
3	IWATE
4	AKITA
5	MIYAGI
6	YAMAGATA
7	FUKUSHIMA
8	IBARAKI
9	TOCHIGI
10	GUNMA
11	CHIBA
12	SAITAMA
13	TOKYO
14	KANAGAWA
15	NIIGATA
16	TOYAMA
17	ISHIKAWA
18	FUKUI
19	GIFU
20	NAGANO
21	YAMANASHI
22	SHIZUOKA
23	AICHI
24	SHIGA
25	MIE
26	NARA
27	KYOTO

55. The prolonged and varying releases, and the fluctuating meteorological conditions they encountered, resulted in specific patterns of dispersion (see figures B-VIII to B-XIII in appendix B) for each of the more significant release episodes.

56. Dose-rate measurements from automatic stations within Japan were the most abundant data available for the course of the accident, although in Fukushima Prefecture many of the automatic monitoring posts were inoperative and thus measurements there came mostly from portable dose-rate monitors. In addition, extensive surveys were made of radionuclides deposited on the ground and in soils following the accident, and also of dose rates due to deposited material. The more notable were the ground-based and airborne surveys carried out by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Agriculture, Forestry and Fisheries (MAFF), and the airborne survey carried out by the United States Department of Energy (see appendix A). Measurements of concentrations of radionuclides in air over Japan while the release was happening were much more limited, in particular, in the early stages of the accident and in the areas devastated by the tsunami.

57. Measurements of radionuclides in Japan were largely focused on ^{131}I, ^{134}Cs and ^{137}Cs. Limited data were also available for other radionuclides, such as ^{132}Te, ^{129m}Te, ^{132}I and ^{133}I, both measurements of concentrations in the air and measurements of deposition density on the ground. Measurements of ^{89}Sr, ^{90}Sr, ^{238}Pu and $^{239+240}$Pu were also reported from a small fraction (fewer than 5%) of the sampling points, generally in locations within Fukushima Prefecture. The levels of ^{238}Pu and $^{239+240}$Pu deposited on the ground were very low and mostly below detection limits. The levels of ^{89}Sr and ^{90}Sr deposited on the ground were significantly lower than those of ^{137}Cs and these radionuclides were therefore not included in the Committee's estimation of doses to the public. The available measurements are discussed further in appendices B and C. The CTBTO network measured a broader range of radionuclides, including ^{133}Xe, but many of these were not significant radiologically.

58. The dispersion and deposition of released material has been modelled by many groups, including Terada et al. [T19], WMO [W18], and the French Institute for Radiation and Nuclear Safety [I33], with a view, inter alia, to determining how well they could replicate the measured levels in the environment. All were able to replicate the broad pattern of deposition density of ^{137}Cs over the Japanese land mass. At specific locations, the model estimates are generally within a factor of 10 (higher or lower) of the measured levels (see appendix B) but sometimes better. Notwithstanding these limitations, such analyses are the only means available for inferring levels of radionuclides in the environment where no measurements exist and/or can no longer be made.

59. Members of a WMO Task Team made estimates of the levels of radionuclides in the environment, based on the source term adopted by the Committee (see section III.A above) and modelling the dispersion of radionuclides in the atmosphere. The approach used and the resulting estimates are summarized in appendix B, including comparisons of the estimates with measured levels. The Committee used the modelled estimates to assess doses to members of the public when measured levels in the environment were not available (see appendices B and C). Doses estimated in this manner are inevitably more uncertain than those estimated directly from measurements in the environment. To provide insight into their robustness and nature of the uncertainty, the estimated levels of radionuclides in the environment were compared for alternative dispersion models, meteorology and an independently derived source term.

2. Marine environment

60. Extensive measurements were made of concentrations of ^{131}I, ^{134}Cs, ^{137}Cs and other radionuclides in seawater and sediments, as well as in fish and other marine biota. TEPCO made daily measurements from 21 March of samples taken from close to the discharge outlets to the north and south of the FDNPS site, from locations to the north and south along the shore and at 3 km, 8 km and 15 km offshore. MEXT made measurements along a line of locations 30 km offshore, and independent researchers made measurements in the waters off the coast of Japan (e.g. [B25, H7]).

61. The results of these measurements are summarized in appendix B and appendix F. They indicate peak concentrations in seawater in the vicinity of the FDNPS site at the end of March and at locations further away in early April. Measured concentrations in seawater subsequently fell steadily and, by August 2011, radioiodine was undetectable and radiocaesium concentrations were around or below the limit of detection even at the discharge outfalls from the site. The more limited number of measurements of concentrations of other radionuclides in seawater, including ^{89}Sr and ^{90}Sr, generally showed a similar pattern, but with concentrations less than 1−10% of those of ^{137}Cs. The exception concerned concentrations of ^{89}Sr and ^{90}Sr measured in December 2011 following an accidental leakage of treated water from which radiocaesium had been removed. The elevated concentrations of radioisotopes of strontium were temporary and had fallen below those of ^{137}Cs again by January 2012.

62. Low concentrations of radiocaesium detected in samples of seawater taken off the coast of Fukushima Prefecture and across the northern Pacific Ocean indicate an easterly movement of the released radioactive material at a rate close to 80 mm/s [A12]. Measurements have also been made of radionuclide concentrations in seabed sediments. These measurements were again focused on ^{131}I, ^{134}Cs and ^{137}Cs, but some were also of radioisotopes of strontium, plutonium and americium. Measurements by TEPCO showed a maximum concentration of ^{137}Cs in sediments of the order of 100,000 Bq/kg dry weight within the port of FDNPS, although measured levels were generally many orders of magnitude lower. Measured concentrations in sediment have not fallen as rapidly over time as measured concentrations in seawater. Further details are given in appendix B.

63. These measurements have been used by several authors (e.g. [E4, K3, P3, T13, T24]) to estimate the total direct release to the sea, and/or to predict the subsequent dispersion of radionuclides in the Pacific Ocean. Model estimates were generally able to reproduce the measurement data well. Material entering from the atmosphere was dispersed and deposited onto the ocean surface over a wide area. On the other hand, for radionuclides released directly, the models suggest that the released radionuclides initially moved southwards along the coast for around 200 km in a relatively confined plume, in response to winds from the north, and then, away from the coast in an eastward direction with greater dispersion and dilution in response to the Kuroshio current (see figures B-XXI and B-XXII in appendix B). The results of the models generally indicate that, in the most affected areas, material deposited from the atmosphere contributed more to levels in the ocean before about 26 March, but that, after that date, the greater contribution came from direct releases into the ocean.

IV. ASSESSMENT OF DOSES TO THE PUBLIC

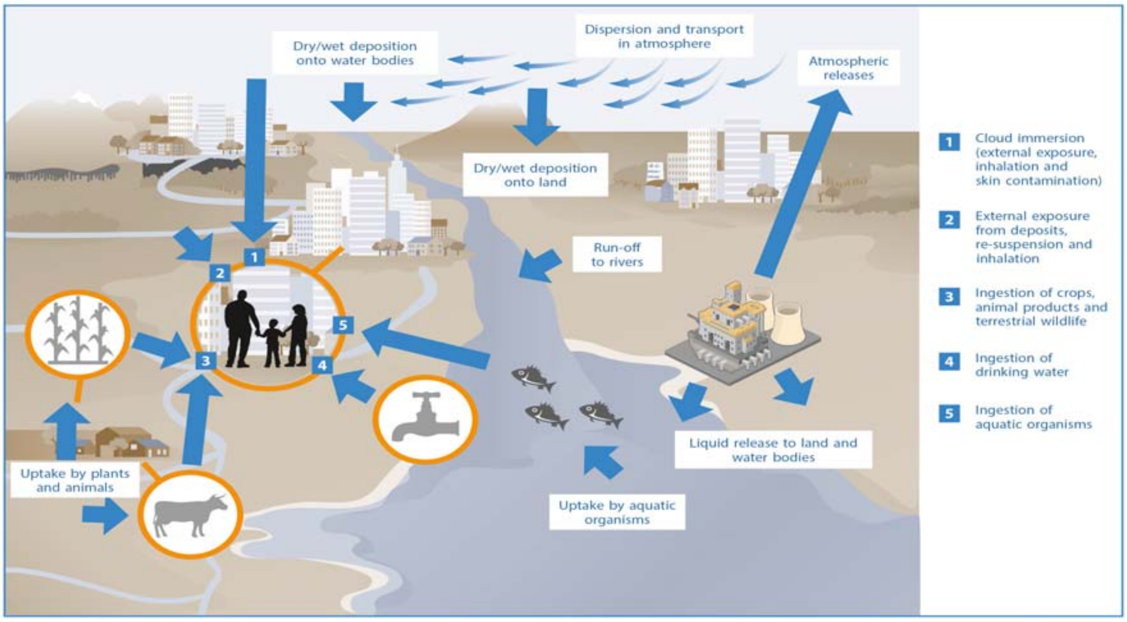
64. This chapter sets out how the knowledge about the distribution of radioactive material in the environment discussed in chapter III was used to estimate doses to the public in Japan and presents a summary of the doses estimated. The Committee's aim was to make realistic estimates of doses and, to that end, its main focus was on estimating doses to defined groups of individuals considered to be representative of the different subsets of the Japanese population. Estimates were made for 20-year-old

adults, 10-year-old children and 1-year-old infants. The main dosimetric endpoints were the absorbed dose to selected critical organs (in grays, Gy), most importantly the thyroid but also the red bone marrow and female breast, and the effective dose[15] (in sieverts, Sv). Projections were also made for effective doses and absorbed doses to the thyroid, and for collective effective doses, over the first 10 years after the accident and until an attained age of exposed individuals of 80 years.

A. Exposure pathways

65. For releases of radioactive material to the atmosphere, there are several routes by which people can be exposed (figure V). Firstly, as the released material moves through the atmosphere as radioactive plumes into an area where people are living, they can be exposed *(a)* externally to radiation from radioactive material in the passing plumes, and *(b)* internally as a result of inhaling radioactive material from the plumes. Once the material released to the atmosphere has passed, people will continue to be exposed to any radioactive material deposited on to the ground. They will be exposed externally from this deposited material and internally as a result of its transfer into food and drink that is subsequently ingested. Deposited material can also be resuspended into the air and inhaled but, for the more significant radionuclides released from FDNPS (that is ^{131}I, ^{134}Cs and ^{137}Cs), this route of exposure is of less significance [I1, J7]. Radionuclides that are incorporated into the body via either the inhalation or ingestion pathways remain in the body for varying lengths of time, depending on their physical and biological half-lives.

Figure V. Exposure pathways from releases of radioactive material to the environment



[15] The effective doses estimated were the sum of the effective doses from external exposure received during the period of interest and the committed effective doses from intakes of radionuclides by ingestion and inhalation during the same period. The effective dose includes a contribution that derives from a weighted absorbed dose to the thyroid.

66. For direct or indirect releases of radioactive material into the sea, people can be exposed externally from radionuclides in the sea or in sea sediments. However, doses through these pathways are not expected to make significant contributions to overall exposure. People can also be exposed internally through transfer of radioactive material into seafood that is then consumed; this pathway was considered in the Committee's assessment of internal exposure.

B. Data for dose assessment

67. Measurements of radionuclides in people provide a direct source of information on their internal exposures. Two main sets of such data were available to the Committee: the first from measurements of ^{131}I in the thyroid, particularly of children; and the second from whole-body monitoring of ^{134}Cs and ^{137}Cs. Such measurements only indicate the internal exposures from the radionuclides present in the person at the time of monitoring. The measurements covered only a limited number of people and locations, and were insufficient to estimate directly the internal exposure of people in either Fukushima Prefecture or the rest of Japan. Therefore the Committee's estimates of internal exposure were based on measurements of radioactive material in the environment, combined with models describing how people were exposed to this material.

68. Appendix A catalogues the extensive body of data available that were considered by the Committee as input to its assessment, and outlines the processes it used to ensure that the data quality was sufficient for its assessment. Measurements had largely focused on the radionuclides ^{131}I, ^{134}Cs and ^{137}Cs, because these were the most significant contributors to exposures. The radionuclide ^{131}I was largely responsible for determining absorbed doses to the thyroid, which were delivered over a relatively short period after the accident (via inhalation and ingestion of radioiodines, specifically ^{131}I, ^{132}I and ^{133}I). The radionuclides ^{137}Cs and, to a lesser extent ^{134}Cs, are responsible for the continuing longer term exposure of the population, in particular from radioactive material deposited on the ground. Although the main source of data was the official information provided by the Japanese authorities, data from other sources were also used, including data provided by other Member States (such as those obtained by personnel of the United States of America in Japan), and other published information, such as those obtained by IAEA field teams. The Committee made extensive checks to determine whether the measurements had been carried out using established methodologies that assured quality and were appropriate. The measurements were used in one of two ways: *(a)* as direct input into the dose assessment; or *(b)* as a check on the validity of the assessment.

69. In Japan, extensive measurements have been made of the levels of various radionuclides deposited on the ground. These included measurements made at ground level, and surveys using instruments carried on aircraft flying over the affected areas. These measurements were used by the Committee as the preferred basis for estimating external exposures of the public from deposited material. Where no information was available about the levels of radionuclides deposited on the ground (generally only in the evacuated areas in the weeks following the accident), the Committee relied on estimates derived from the source term and simulations of the transport of radioactive material through the atmosphere using "atmospheric transport, dispersion and deposition models" (ATDM) referred to in chapter III and further outlined in appendix B.

70. Because measurements of concentrations of radionuclides in the air were insufficient for its assessment, the Committee had to estimate values. Such estimates were also obtained from the source term and simulating the transport of radioactive material through the atmosphere using ATDM. However, these estimates have large uncertainties at specific times and locations, not only because of

incomplete knowledge about the quantities of radionuclides released and how these varied over time and location, but also because of uncertainties in the models used to simulate the subsequent dispersion of the released material in the atmosphere. In view of these uncertainties, the Committee chose to use the measurements of deposition density to adjust the estimates of concentrations in the air from the ATDM analysis.

71. While the estimates of radionuclide concentrations in air and of radionuclides deposited on the ground provided by the source term and ATDM analyses at any specific location are uncertain, the ratio of these two estimates is much less so. In particular, the ratios are relatively insensitive to the uncertainties in the source term. The main factors influencing the uncertainties in these ratios were uncertainties in the assumed parameters describing wet and dry deposition. The Committee used location-dependent ratios, derived from the ATDM analyses, to infer time-integrated concentrations of radionuclides in air from measured deposition density of radionuclides on the ground. It used these inferred concentrations to assess the exposures from radionuclides in air in all regions of Japan except in the evacuated areas.

72. For areas that were evacuated during the early stages (days to a few weeks) of the accident, only a limited number of measurements of radionuclide concentrations in air and deposited on the ground were made during the periods of evacuation. Therefore, the Committee relied on estimates of these quantities—over the period of the evacuation—from the source term and the ATDM analyses as the basis for estimating doses to the populations who had undergone precautionary evacuation and deliberate evacuation. This method was also used to estimate concentrations in air of radionuclides, including ^{133}Xe, which were not deposited on the ground.

73. A considerable amount of information was available on levels of radionuclides in a wide range of foodstuffs, including marine foods, and in drinking water (see appendix A). The Committee used data for marketed foods, thereby implicitly taking account of restrictions on the supply of foodstuffs with concentrations of radionuclides in excess of the prescribed limits (see table C4 in appendix C). The Committee used these data (from the "FAO/IAEA food database") as the primary basis for its assessment of exposures from ingestion of radionuclides in food and drink in the first year. The assessment was based on the mean concentrations of radionuclides measured in groups of foods *(a)* in Fukushima Prefecture, *(b)* in the five neighbouring or nearby prefectures considered together, and *(c)* in the rest of Japan. Data were insufficient for the first months following the accident to allow the Committee to adopt a finer spatial resolution. Moreover, in Japan, most people obtain their food from supermarkets where foods are sourced from the whole of the country, so using mean concentrations over wide areas was considered appropriate for the Committee's purposes. In Japan, significant amounts of some foods are imported from elsewhere in the world, and this was allowed for in the assessment.

74. The Japanese authorities provided the Committee with the results of measurements they had made of radionuclides in drinking water. Levels were elevated for a limited period. The Committee estimated doses based on these measurements, taking account of any restrictions introduced.

75. The Committee relied on information on levels of radioactive material in food and drink to estimate the exposure from ingestion in the first year after the accident. To estimate future levels of exposure from ingestion, the Committee used models to assess concentrations of radionuclides in foodstuffs from the available measurements of deposition density of radionuclides on the ground. Information was obtained on the agricultural practices in Japan, such as the times when different crops are planted and harvested, crop yields and any Japanese-specific data on the transfer of radionuclides to specific foods. These data were then used to modify a version of the FARMLAND model [B21] for estimating the transfer of radionuclides through terrestrial foodchains. The results of modelling the

dispersion of radionuclides in the sea off Fukushima Prefecture by Nakano and Povinec [N3] were used to estimate possible exposures beyond the first year from ingestion of marine foods (see appendix C).

76. As outlined in chapter II, the Japanese authorities implemented a number of urgent measures to protect the public. Approximately 85,000 residents within the 20-km evacuation area around the FDNPS site, and some nearby areas, were evacuated as a precautionary measure between 11 and 15 March, and consequently most were not present in those areas when the major radionuclide deposition occurred. “Deliberate evacuation”, based on environmental measurements, was undertaken between March and June for about 10,000 residents of several settlements beyond the 20-km area. These were settlements to the north-west of the FDNPS site where substantial deposition of radionuclides took place following the major releases. The total number of evacuees was ~118,000, which includes evacuees who had been living outside the 30-km radius and people evacuated for reasons other than the nuclear emergency situation. In addition, restrictions were introduced on foodstuffs: food and drink containing more than prescribed concentrations of radioactive material were prohibited from sale. The Committee took these protective measures into account in its assessment.

77. The Japanese authorities also issued directives with regard to protective measures other than evacuation and food restrictions. These included directives to members of the public in the area 20-30 km from the FDNPS site who were advised to shelter in place during the main releases, as well as directives to some members of the public to take stable iodine. However, precise information was limited on how and when, and for which settlements these measures were implemented. Thus, the Committee was not able to take these other protective measures into account in its estimation of doses to the public.

78. In some of the more affected parts of Fukushima Prefecture (e.g. evacuated areas where the forecasted annual dose would have exceeded 20 mSv), large land remediation programmes have been implemented and these have the potential to reduce future exposures of the public residing in the affected areas. Experimental studies and tests of technologies for decontamination of inhabited areas, and of countermeasures in agriculture and in forestry, were started in mid-2011. Detailed information about the scale and efficiency of the implemented land remediation actions was not available at the time of this assessment, and thus the Committee did not take into account the possible reduction in exposure levels due to any remedial measures.

C. Overview of methodology for assessing public exposures

79. In order to estimate doses to the members of the public in Japan, the Committee focused on four groups of geographical areas (table 4).

80. For the same exposure, the doses vary according to the age at the time of exposure. Therefore, the Committee considered three main age groups as at the time of the releases: adults, children and infants. For the estimation of doses, 20-year-old adults were chosen to represent all adults, 10-year-old children to represent all children older than 5 years old, and 1-year-old infants to represent all infants younger than 5 years old. The Committee did not explicitly estimate doses to the foetus or breast-fed infants because they would have been similar to those to other age groups for both external and internal radiation exposure (see appendix C). For example, doses to the foetus and breast-fed infant due to external exposure would have been approximately the same as those to adults and 1-year-old infants, respectively. The Committee focused on estimating the accumulated exposures in the first year following the accident (these would generally be higher than annual exposures in subsequent years).

However, it also estimated accumulated exposures over the first 10 years after the accident, and up to the age of 80 years, taking into account the ageing of the three age groups over those periods.

Table 4. Delineation and spatial resolution adopted for each group of geographical areas

Group	*Areas*	*Spatial resolution for public dose assessment*
1	Settlements[a] in Fukushima Prefecture[b] where people were evacuated in the days to months after the accident	Representative locations were used for each settlement identified in 18 evacuation scenarios
2	Districts[c] of Fukushima Prefecture not evacuated	District level for external and inhalation pathways, based on the estimates for each of the 1-km-grid points, averaged over the district Prefecture level for ingestion pathway
3	Selected prefectures in eastern Japan that were neighbouring (prefectures of Miyagi, Tochigi, Gunma and Ibaraki) or nearby (prefectures of Iwate and Chiba) to Fukushima Prefecture	District level for external and inhalation pathways, based on the estimates for each of the 1-km-grid points, averaged over the district Estimated dose due to ingestion for Iwate Prefecture same as for Group 4; for other five prefectures was based on average for the five prefectures
4	All remaining prefectures of Japan	Prefecture level for external and inhalation pathways Average for rest of Japan for ingestion pathway

[a] *Settlements: This term is used in this report to represent an evacuation scenario. There were 18 evacuation scenarios that covered 12 districts of Fukushima Prefecture. Some of these districts were associated with more than one evacuation scenario so the term "settlement" was selected to be representative of localized areas within a district that were considered in evacuation scenarios.*

[b] *Prefecture: Japan comprises 47 prefectures. In Japanese the word "prefecture" is used for translating references to an administrative district, ken (県). Figures IV, VI and VII show the prefectures close to Fukushima Prefecture and those further afield.*

[c] *District: Each prefecture of Japan is divided into districts (or shi or gun in Japanese). This is a local administrative unit; the districts are used primarily in the Japanese addressing system to identify the relevant geographical areas and collections of nearby towns and villages.*

81. The models used to estimate doses due to external exposure to deposited radioactive material are well established (for example, the Committee used similar models for its assessment of radiation doses from the Chernobyl accident [U12]). They take into account processes such as radioactive decay, removal of radionuclides from surfaces through weathering, and the movement of radionuclides through the soil, as well as the shielding effects of buildings when people are indoors. The Committee considered a number of different types of building (and hence degrees of shielding) and different amounts of time spent indoors. In Fukushima Prefecture and the Group 3 prefectures, the majority of houses were of wooden construction, and the Committee therefore presented its dose estimates for people living in wooden houses.

82. Doses due to inhalation of radionuclides in the air were assessed using standard, internationally-recognized models and data [I12, I15, I25]. An age-dependent breathing rate was used to estimate the quantities of the radionuclides in the air which entered the body, and the normalized dose resulting from unit of inhaled activity of each radionuclide (known as the dose coefficient) was then used to estimate the dose received.

83. Similarly, doses due to ingestion of radionuclides in food and drinking water were estimated from radionuclide concentrations in food, using age-dependent intake rates for different types of foodstuffs

and dose coefficients for unit of ingested activity of each radionuclide [I25]. For assessing doses in Japan due to ingestion in the first year, the Committee primarily used the measurement data in the FAO/IAEA food database (see appendix A). However, in order to estimate doses due to ingestion beyond the first year, the Committee had to use modelling approaches. The Ministry of Health, Labour and Welfare (MHLW) in Japan conducted surveys of the per caput consumption of particular foods, and its data were used by the Committee. The most extensive data available were for adults, but there were also data for infants and children.

84. For those who had been evacuated (Group 1), the Committee estimated exposures prior to and during their evacuation and for the remainder of the year at the evacuation destination. The estimation was based on the concentrations of radionuclides in the air and deposition densities on the ground in the areas from which people had been evacuated (as estimated from the source term and the ATDM analyses), and knowledge of the movements of the evacuees during this period (obtained from a survey conducted within Fukushima Prefecture [A5]; this survey identified 18 evacuation scenarios, which are discussed in detail in appendix C). Estimates of the effective doses due to external exposure that would have been received by the adult residents of evacuated settlements if they were to have returned to their homes and regular lifestyle were also assessed for the period March 2012 to March 2015 assuming no environmental remediation. These estimates provide an upper bound on the effective doses to these communities in the future.

85. The Committee could not exclude the possibility that individuals may have remained in or gained access to the 20-km evacuation zone during and after passage of the radioactive plumes. The Committee estimated the doses to the evacuees, and the doses that they would have received if they had not been evacuated (this can be used as an estimate of doses to those persons who might have stayed in the zone, and as an upper bound for any individual who might have gained access to the zone). From these two sets of estimates, the Committee also estimated the doses averted by evacuation.

86. The Committee also estimated the collective effective dose and the collective absorbed dose to the thyroid to the population of Japan. These estimates were based on the age and social composition of the population of Japan and the population distribution by district and prefecture taken from the Japan 2010 Census (see table A1, appendix A). The collective doses were estimated for populations living in Fukushima Prefecture and the other prefectures of Japan.

87. The Committee did not undertake a comprehensive assessment to estimate doses to members of the public in the rest of the world. The assessment of doses for countries other than Japan was based on a review of estimates published in the literature, including the results of the WHO preliminary exposure assessment [W11], supported by the extensive measurements and dose assessments carried out by Member States of the United Nations.

D. Results of dose estimation

88. The Committee produced an extensive set of estimates of effective doses and absorbed doses to particular organs for the public in Japan, which is presented in more detail in appendix C.

1. Doses in the first year to members of the public not evacuated

89. Table 5 summarizes the estimated district- or prefecture-average effective doses and absorbed doses to the thyroid for the first year following the accident for adults, 10-year olds and 1-year olds living in areas of Japan that were not evacuated. Doses were summed over the three main exposure pathways (external exposure, and internal exposure due to inhalation and due to ingestion).

Table 5. Estimated district- or prefecture-average effective doses and absorbed doses to the thyroid for the first year following the accident for typical residents of Japan that were not evacuated

The doses are in addition to the background doses due to natural sources of radiation. The values were the ranges of the district-average doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates were intended to be characteristic of the average dose received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations. They may overestimate actual average doses because of assumptions made where data were inadequate (see sections E and F of this chapter)

Residential area	*Effective dose (mSv)*			*Absorbed dose to the thyroid (mGy)*		
	Adults	*10-year old*	*1-year old*	*Adults*	*10-year old*	*1-year old*
Group 2[a] - Fukushima Prefecture	1.0–4.3	1.2–5.9	2.0–7.5	7.8–17	15–31	33–52
Group 3 prefectures[b]	0.2–1.4	0.2–2.0	0.3–2.5	0.6–5.1	1.3–9.1	2.7–15
Group 4[c] - rest of Japan	0.1–0.3	0.1–0.4	0.2–0.5	0.5–0.9	1.2–1.8	2.6–3.3

[a] *Group 2 - Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

[b] *Group 3 - Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate.*

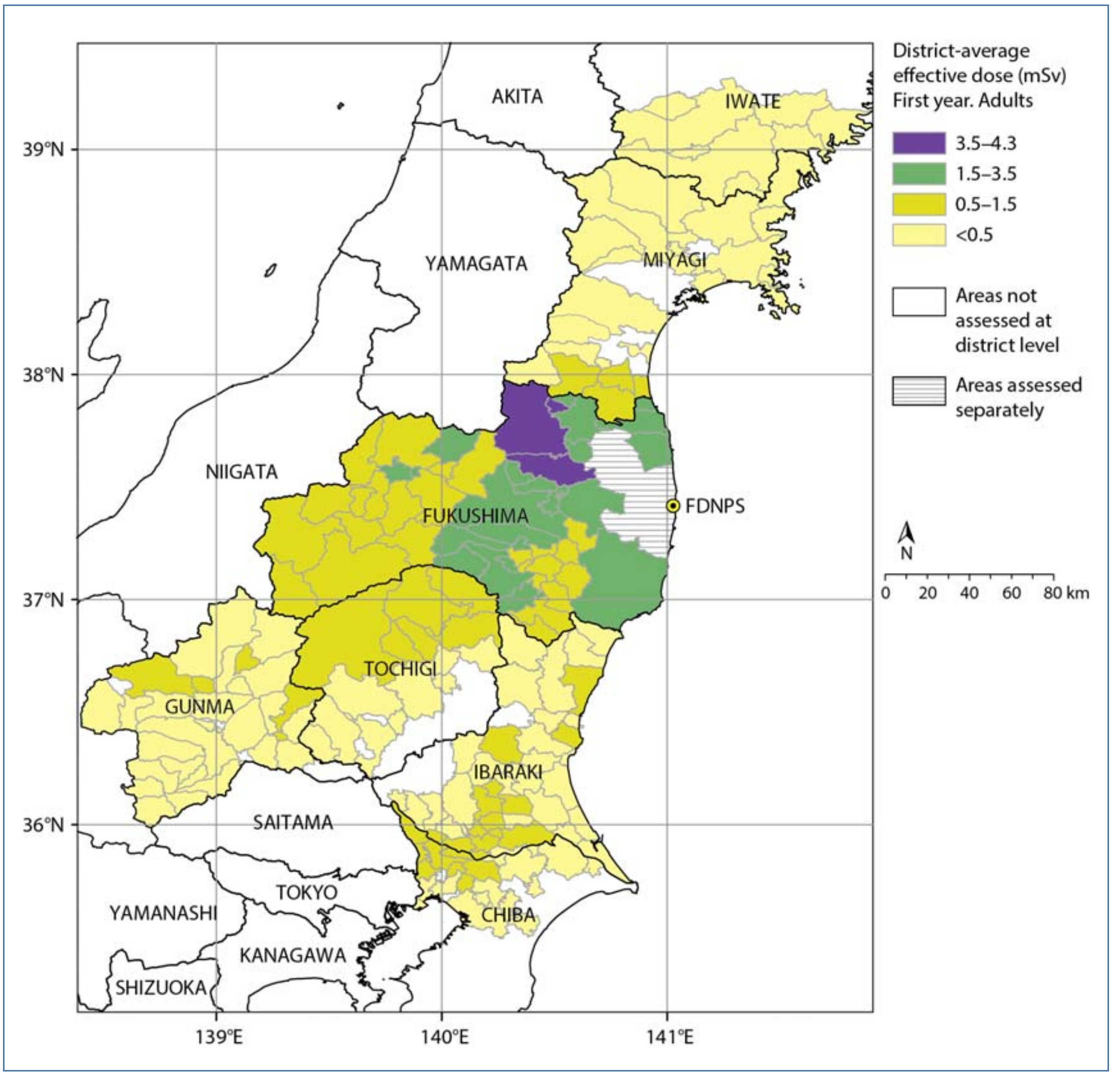
[c] *Group 4 - Members of the public living in the remaining prefectures of Japan.*

90. *Effective doses.* Figure VI shows a map illustrating district-average effective doses in the first year to adults living in districts of Fukushima Prefecture that were not evacuated (Group 2) and in some Group 3 prefectures. Absorbed doses to the thyroid (all ages) and effective doses to 10-year-old children and 1-year-old infants show a similar geographical pattern that reflects the deposition density of radionuclides in the different areas (see appendix C).

91. The relative contribution of each exposure pathway varied from location to location reflecting the levels and composition of radionuclides in the environment and in foods. In the areas of higher deposition density, the greater contribution to effective dose was from external exposure to deposited material. The relative contribution to effective dose in the first year for Fukushima Prefecture due to ingestion of food varied. This was because effective doses due to ingestion reflected concentrations of radionuclides averaged over much larger areas than effective doses from other routes. In areas of Japan far away from the FDNPS site, effective doses due to ingestion predominated for most prefectures.

Figure VI. Estimated district-average effective doses in the first year following the accident to adults living in districts of Fukushima Prefecture and some districts of Group 3 prefectures that were not evacuated

The effective doses include contributions from all relevant pathways and radionuclides



92. Within Fukushima Prefecture, the districts that partly fall within the 20-km evacuation zone (Minamisoma City) and those with high ground deposition density (Fukushima City, Nihonmatsu City, Koori Town, Otama Village, Koriyama City, Motomiya City and Date City) had the highest estimated effective doses to individuals who were not evacuated, with the district-average effective doses to adults in the range 2.5 to 4.3 mSv in the first year. In those districts, the contribution of external dose from deposited radionuclides to effective dose was dominant. Average effective doses in the first year for 1-year-old infants were estimated to be up to twice those for adults.

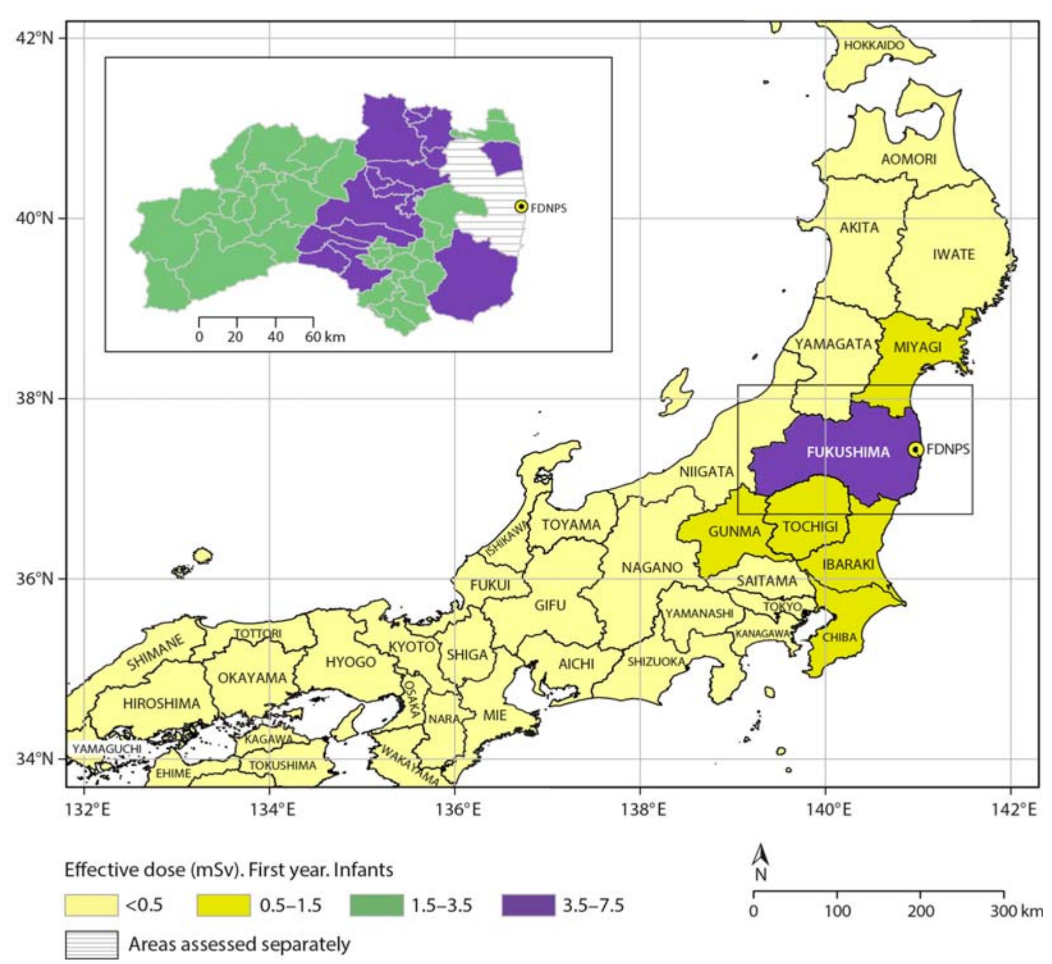
93. For the districts of the Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average effective doses to adults were in the range 0.2 to 1.4 mSv for the first year, including 0.2 mSv from ingestion of food in the prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi. In Iwate Prefecture, the effective dose due to ingestion of food was 0.1 mSv, the same as for the remainder of Japan. The prefecture-average effective dose to adults for the prefectures in the

remainder of Japan was in the range 0.1 to 0.3 mSv for the first year, with ingestion contributing 0.1 mSv and generally being the dominant pathway.

94. Figure VII shows the prefecture-average effective dose in the first year for 1-year-old infants in the rest of Japan (the Group 4 prefectures). Prefecture-average doses for other prefectures were lower than those for Fukushima Prefecture and are considerably lower for the more distant prefectures, where the effective dose estimates were less than the normal variations in background effective doses due to natural sources of radiation.

Figure VII. Estimated prefecture-average effective doses in the first year following the accident to 1-year-old infants

The effective doses include contributions from all relevant pathways and radionuclides. The main map shows the prefecture-average effective doses. The average dose for Fukushima Prefecture includes only districts that were not evacuated. The inset map shows the district-average effective doses for the districts of Fukushima Prefecture that were not evacuated



95. *Absorbed doses to organs.* For districts of Fukushima Prefecture that were not evacuated (Group 2), the highest estimated absorbed doses to the thyroid in the first year were to individuals living in Iwaki City and Fukushima City. The highest district-average absorbed dose to the thyroid of a

1-year-old infant in the first year was estimated to be about 50 mGy for Iwaki City (see table 5). Approximately one third of this dose was due to inhalation and two thirds due to ingestion. The estimated doses to the thyroid for adults in the first year were about 30% of those for 1-year-old infants. These doses were mostly received over the first few weeks after the accident. The average absorbed doses to the red bone marrow and the female breast in the first year for the districts within Fukushima Prefecture that were not evacuated were estimated to be less than 6 mGy for all age groups.

96. For Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average absorbed doses to the thyroid of infants in the first year were estimated to be in the range of 3 to 15 mGy. Ingestion was the dominant exposure pathway; the contribution of the inhalation pathway ranged from a few per cent to about thirty per cent. The district-average absorbed doses to the red bone marrow and the female breast in the first year were estimated to be less than 2 mGy for all age groups. For the remainder of the 40 prefectures of Japan, the prefecture-average absorbed doses to the thyroid of infants in the first year were estimated to have been about 3 mGy, with between 75% and 100% of the dose from the ingestion of food.

97. All of these estimated doses are representative of the average doses to the populations in the respective districts for Group 2 and Group 3 prefectures and in the respective prefectures for Group 4. There would have been variation about these averages for particular individuals depending on factors such as what foods they consumed and where they were located relative to the dispersion of the released radioactive material. Individuals may also have taken personal protective measures that the Committee did not consider.

98. The Committee also undertook some indicative analyses of the likely variability in the doses due to external exposure and due to internal exposure from inhalation within a district. These indicated that within each district there was marked spatial variability in both the measured radionuclide deposition densities and the ^{131}I concentrations in air. The variability was such that the estimates of both the effective doses and the absorbed doses to the thyroid from inhalation could be from 30–50% of the district-average dose up to about two to three times higher than the district-average dose.

99. For external exposure from deposited material, a further factor affecting variability in the dose estimates was the shielding effect of building materials. The main results presented were for people living in wooden houses which are the most common in Fukushima Prefecture. But, for people living in concrete multi-storey apartments or wooden plastered houses, their doses would be about 25% or 50%, respectively, of those estimated.

100. There was also significant variability in measured levels of radionuclides in different foodstuffs depending on where they were grown, the amount of radioactive material deposited on the ground, as well as local factors such as the time of planting of the crop and the soil type. A key factor was where people obtained their food; the majority of people in Japan use supermarkets, and so the approach used to assess doses for the first year—based on mean concentrations in foodstuffs in Fukushima Prefecture, in five of the six Group 3 prefectures (excluding Iwate), and in the rest of Japan—was considered appropriate for the purpose of this assessment.

101. The transfer of radionuclides to foods is very dependent on the time of year that a release occurs. The accident at FDNPS occurred in March when only few crops were being grown and animals were being given stored feed. This led to lower concentrations in foodstuffs than would have been the case if the accident had happened later in the year (as was the case for the Chernobyl accident in 1986). The Committee could not exclude the possibility that some individuals, particularly those in the deliberate evacuation areas, might have consumed locally-grown food or have collected mushrooms or wild plants, or caught or hunted local fish and game with high concentrations of radionuclides before their

evacuation. Such food habits have the potential to increase the estimates of effective dose from ingestion for these individuals by up to perhaps a factor of 10, however there is no evidence of such higher doses in the extensive sets of in vivo whole body measurements of the general public. Also, because of the time of year of the accident there was limited locally-grown food and many people in Japan took measures to reduce their intake of radionuclides in food by avoiding fresh produce or anything that might have come from Fukushima Prefecture. For these people doses due to ingestion would have been significantly lower than those estimated by the Committee [S2].

2. Doses to evacuees

102. Doses in the first year to people evacuated from Group 1 areas (Futaba, Hirono, Namie, Naraha, Okuma, Tomioka, Iitate, Kawamata, Minamisoma, Tamura, Kawauchi and Katsurao) were estimated as the sum of doses received before and during evacuation, and doses received during the remainder of the year at the location to which they were evacuated. The estimated settlement-average effective doses and absorbed doses to the thyroid are summarized in table 6.

Table 6. Estimated settlement-average effective doses and absorbed doses to the thyroid for evacuees for the first year following the accident

The doses are in addition to the background doses due to natural sources of radiation. The values were the ranges of the settlement-average doses for the evacuation scenarios. These estimates of dose were intended to be characteristic of the average dose received by people evacuated from each settlement and do not reflect the range of doses received by individuals among the population of the evacuated settlement. They may overestimate actual average doses because of assumptions made where data were inadequate (see sections E and F of this chapter)

Age group	*Precautionary evacuated settlements*[a]			*Deliberately evacuated settlements*[b]		
	Before and during evacuation	*At the evacuation destination*	*First year total*	*Before and during evacuation*	*At the evacuation destination*	*First year total*
	EFFECTIVE DOSE (mSv)					
Adults	0–2.2	0.2–4.3	1.1–5.7	2.7–8.5	0.8–3.3	4.8–9.3
Child, 10-year old	0–1.8	0.3–5.9	1.3–7.3	3.4–9.1	1.1–4.5	5.4–10
Infant, 1-year old	0–3.3	0.3–7.5	1.6–9.3	4.2–12	1.1–5.6	7.1–13
	ABSORBED DOSE TO THE THYROID (mGy)					
Adults	0–23	0.8–16	7.2–34	15–28	1–8	16–35
Child, 10-year old	0–37	1.5–29	12–58	25–45	1.1–14	27–58
Infant, 1-year old	0–46	3–49	15–82[c]	45–63	2–27	47–83[c]

[a] *Precautionary evacuation refers to the evacuation of settlements that was instructed between the 12 and 15 March 2011 as an urgent protective action to prevent high exposure. The dose assessment considered evacuation scenarios 1−12 (see appendix C) for towns of Futaba, Okuma, Tomioka, Naraha and Hirono, and parts of the cities of Minamisoma, Namie and Tamura and villages of Kawauchi and Katsurao.*

[b] *Deliberate evacuation refers to evacuation of settlements (based upon environmental measurements) that was instructed between late March and June 2011. The dose assessment considered evacuation scenarios 13−18 (see appendix C) for Iitate Village and parts of Minamisoma City, the towns of Namie and Kawamata, and of Katsurao Village.*

[c] *These absorbed doses to the thyroid were principally due to internal exposure from inhalation during the passage of the airborne radioactive material through the affected areas before and during evacuation in the early days of the accident and from ingestion over the subsequent period.*

103. The settlement-average effective doses in the first year ranged from a few millisieverts to about ten millisieverts or slightly above for all age groups and both evacuation scenarios. The corresponding settlement-average absorbed doses to the thyroid in the first year ranged up to about 35 mGy for adults and up to about 80 mGy for 1-year-old infants. For the precautionary evacuated settlements the settlement-average absorbed doses to the red bone marrow and the female breast in the first year were estimated to be in the range of 0.6 to 7 mGy and for the deliberately evacuated settlements the settlement-average doses were in the range of 4 to 10 mGy for all age groups.

104. The Committee estimated that the evacuation of settlements within the 20-km zone averted effective doses to adults of up to about 50 mSv and absorbed doses to the thyroid of 1-year-old infants of up to about 750 mGy (see tables C11 and C12 of appendix C).

3. Estimation of doses in Japan for exposure over future years

105. The Committee also estimated district-average and prefecture-average doses accumulated over the first 10 years after the accident, and accumulated up to the age of 80 years. These are presented in table 7 only for residents of districts who were not evacuated. Children who had been infants (1-year-old) at the time of the accident had the highest estimated effective doses, followed by 10-year-old children and then adults. The differences in the estimated effective doses among these age groups were not large, being less than a factor of two. Estimates of the effective doses due to external exposure that would be received by adult residents of evacuated settlements if they were to return to their homes and regular lifestyle (not accounting for any environmental remediation) are discussed in appendix C (see table C19).

106. Generally, the district-average or prefecture-average effective doses that would be incurred over the first 10 years were estimated to be up to twice the effective doses in the first year, and the lifetime effective doses were up to three times higher, assuming there was no remediation. The Committee did not consider the effects of remediation measures in its dose assessment, because the effectiveness of the different measures being applied in Japan had not yet been established. However, estimates of the effective doses that would be received by those who were evacuated if they were to return to their homes and regular lifestyle without any environmental remediation provide an upper bound on the doses that might be received in the future. For the evacuated location with the highest deposition density, the settlement-average effective dose for adults from external exposure was estimated to be 12 mSv for the period March 2012 to March 2013, falling to 5 mSv for the period March 2014 to March 2015. The lifetime absorbed dose to the thyroid was estimated to be less than 50% higher than the absorbed dose to the thyroid in the first year. This is because most of the absorbed dose to the thyroid in the first year is due to ^{131}I (delivered over a relatively short period), while in subsequent years the dose is due to ^{134}Cs and ^{137}Cs (see appendix C).

Table 7. Estimated district- or prefecture-average effective doses to adults, 10-year-old children and 1-year-old infants (as of 2011) over the first year, first 10 years and up to the age 80 years

The estimated doses are in addition to the background effective doses due to natural sources of radiation. The values are the ranges of the district-average effective doses for the Group 2 and Group 3 prefectures and the prefecture-average effective doses for the Group 4 prefectures. These estimates of effective dose were intended to be characteristic of the average received by people living at different locations and do not reflect the range of effective doses received by individuals among the population at these locations. They may overestimate actual average effective doses because of assumptions made where data were inadequate (see sections E and F of this chapter)

Age group as of 2011	*District- or prefecture-average effective dose (mSv)*		
	Geographical area of Japan		
	Group 2 Fukushima Prefecture[a]	*Group 3*[b] *prefectures*	*Group 4*[c] *– rest of Japan*
1 YEAR EXPOSURE			
Adult	1.0–4.3	0.2–1.4	0.1–0.3
Child, 10-year old	1.2–5.9	0.2–2.0	0.1–0.4
Infant, 1-year old	2.0–7.5	0.3–2.5	0.2–0.5
10 YEAR EXPOSURE			
Adult	1.1–8.3	0.2–2.8	0.1–0.5
Child, 10-year old	1.3–12	0.3–4.0	0.1–0.6
Infant, 1-year old	2.1–14	0.3–6.4	0.2–0.9
LIFETIME EXPOSURE			
Adult	1.1–11	0.2–4.0	0.1–0.6
Child, 10-year old	1.4–16	0.3–5.5	0.1–0.8
Infant, 1-year old	2.1–18	0.4–6.4	0.2–0.9

[a] *Group 2 - Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

[b] *Group 3 - Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate. The prefectures of Chiba, Gunma, Ibaraki, Miyagi, and Tochigi were grouped together to calculate the effective dose from ingestion in these prefectures. For Iwate Prefecture the effective dose from ingestion was assumed to be the same as that for the rest of Japan.*

[c] *Group 4 - Members of the public living in the remaining prefectures of Japan.*

107. To provide some perspective on the overall exposure of the Japanese population from the accident, the Committee also estimated collective effective doses and collective absorbed doses to the thyroid for the Japanese public. The resulting collective effective dose and collective absorbed dose to the thyroid for the first year, for the first 10 years and over a lifetime are given in table 8. The main contributors to the collective effective dose were the long-term exposure pathways of external exposure from ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure from ingestion of the same radionuclides in foods. The major contributor to the collective absorbed dose to the thyroid in the first year was internal exposure due to inhalation and ingestion of ^{131}I.

Table 8. Estimated collective effective dose and collective absorbed dose to the thyroid for the population of Japan (approximately 128 million in 2010)

Dose category	*Exposure duration*		
	Over first year	*Over ten years*	*Up to age 80 years*
Collective effective dose (thousand man-sieverts)	18	36	48
Collective absorbed dose to the thyroid (thousand man-grays)	82	100	112

108. These estimates of the collective doses to the population of Japan due to the FDNPS accident can be compared with estimates for populations of European countries exposed to radiation following the 1986 Chernobyl accident in the former Soviet Union. The collective effective dose and collective absorbed dose to the thyroid estimated by the Committee for a 20-year period (1986–2005) from the results of both environmental and human measurements were about 360,000 [16] man Sv and 2,300,000 man Gy, respectively. Taking account of continuing lifelong exposure, those values would be about 400,000 man Sv and 2,400,000 man Gy, respectively. The collective effective dose to the population of Japan due to a lifetime exposure following the FDNPS accident is approximately 10–15% of the corresponding value for European populations exposed to radiation following the Chernobyl accident. Correspondingly, the collective absorbed dose to the thyroid was approximately 5% of that due to the Chernobyl accident.

4. Estimation of doses in other countries

109. The Committee's assessment of doses to the public in countries neighbouring Japan and in the rest of the world was based on a review of estimates published in the literature, including the results of the WHO preliminary exposure assessment [W11], supported by the extensive measurements and dose assessments carried out by Member States (appendix C). Based on an analysis of this body of information, the Committee concluded that the average effective doses to populations living outside Japan due to the accident were less than 0.01 mSv in the first year.

E. Uncertainties

110. There are uncertainties associated with the results of any assessment of this type because of incomplete knowledge and information, and the assumptions that were made. The main sources of uncertainty are discussed in detail in appendix C, but some important factors are outlined below.

111. The estimates of dose due to external exposure were largely based on measured levels of radionuclides deposited on the ground. The uncertainties associated with individual measurements of ^{137}Cs and ^{134}Cs were relatively small, but those for ^{131}I were larger because of the significant amount of radioactive decay that occurred before the measurements were made. There were also uncertainties in how well the measurements represented the spatial distribution of radionuclides for each district or prefecture when estimating district-average doses. For Fukushima Prefecture, there were extensive

[16] About 260,000 man Sv without the contribution of the thyroid dose [U12].

measurements with adequate spatial coverage, and the district-average doses estimated for specific districts were considered to be accurate within a factor of two. For the Group 4 prefectures, there were comparatively fewer measurements, and the uncertainties in the prefecture-average doses were likely to be larger.

112. Another source of uncertainty stemmed from the incomplete knowledge of the release rates of radionuclides over time and the weather conditions during the releases. The results of the ATDM analyses had large uncertainties when used to estimate doses at a specific location. Although measurements of concentrations of radionuclides in the environment were used to assess dose wherever possible, some estimates were made using the assumed pattern of release of radionuclides and the output of the ATDM analyses. The estimates of doses due to inhalation and external exposure for the communities evacuated in March, before and during the evacuation, were based on the estimates of release rates and ATDM analyses directly. The settlement-average effective doses and absorbed doses to organs for these population groups may be over- or underestimated by a factor of up to typically four to five because of uncertainties in the ATDM results for specific locations and times.

113. An additional factor that affected the estimation of absorbed dose to the thyroid due to inhalation was the ratio of particulate to gaseous forms of ^{131}I in the air. The atmospheric measurement data were limited and available mostly at substantial distances from the release site. For Fukushima Prefecture, where the absorbed doses to the thyroid could have been more significant, there were no measurement data for the relative amounts of particulate and gaseous forms of ^{131}I in air: the value of this ratio was obtained from the ATDM results assuming that equal amounts of iodine were released in particulate and gaseous forms. The estimated value for this ratio has an uncertainty of up to about a factor of two over the periods of the principal exposures.

114. There was an uncertainty associated with the doses derived from the measurements of radionuclides in foodstuffs (appendix C), and this was difficult to quantify. Foodstuffs were not sampled randomly, because the authorities gave priority to identifying foods with the highest concentrations. It was therefore likely that the values of average concentrations used by the Committee were overestimates, particularly for the first months after the accident when there were relatively few measurements. Many measurement results were less than the detection limits and were assumed by the Committee to have a fixed value at the detection limit; this also led to some overestimation of the doses to people due to ingestion. Changes in the pattern of food distribution and consumption were another source of uncertainty. If it had been assumed that only 25% of food consumed in Fukushima Prefecture was from the prefecture, then the estimated effective doses from ingestion for the first year would have been 30% of the Committee’s estimates.

115. Standard models were used to determine effective doses and absorbed doses to relevant organs following intakes of radionuclides into the body. These were based on a standard-sized person with particular metabolic characteristics. The Japanese diet is relatively high in stable iodine. This could have resulted in less transfer of radioiodine to the thyroid than implied by the standard model, and thus in slightly lower doses from this source. However the overall effect would have been small when compared to other uncertainties associated with the dose assessment (see appendix C).

F. Comparison with direct measurements and other assessments

1. Direct measurements of radionuclides in people

116. Available measurements of radionuclides in people provided a direct source of information on exposures of members of the public. There were two main sets of data: *(a)* measurements of ^{131}I in the thyroid, particularly of children; and *(b)* whole-body monitoring results for ^{134}Cs and ^{137}Cs. These measurements provided one means of checking the validity of the dose assessment conducted by the Committee.

117. There is likely some overestimation introduced by the methodology adopted by the Committee to estimate absorbed doses to the thyroid for the evacuees (e.g. in the assumptions on protective measures owing to lack of information, and in dosimetric factors). Thyroid monitoring was carried out by local authorities on 1,080 children aged between 1 and 15 years in Iwaki City, Kawamata Town and Iitate Village over the period from 26 to 30 March 2011 using hand-held dose-rate instruments [K13]. The absorbed doses to the thyroid from internal exposure were calculated assuming exposure was continuous over the period 12 to 24 March 2011. The results of the Committee's analysis of the measurement data for 10-year-old children and 1-year-old infants were consistent with the assessment by the Japanese authorities. (In its analysis the Committee assumed a single exposure on the 15 March 2011.) The Committee's estimates of settlement-average absorbed doses to the thyroid from internal exposure were up to about five times higher than the corresponding values derived from direct monitoring of this group. Thyroid monitoring results were also reported for measurements made on 62 evacuees between 12 and 16 April 2011 [T20]. The settlement averages for absorbed dose to the thyroid from internal exposure estimated by the Committee were up to four times higher than those estimated by Tokonami et al. (see appendix C).

118. As part of the Health Examination for Citizens in Fukushima Prefecture, whole-body counting of more than 106,000 residents of Fukushima Prefecture and neighbouring prefectures was conducted up to December 2012 [H5, M24]. Momose et al. [M24] reported that, for the period from July 2011 to January 2012, the presence of ^{134}Cs and ^{137}Cs in the body could be detected in 20% of the 10,000 evacuees examined. Hayano et al. [H5] reported that, for the period from October 2011 to February 2012, the presence of ^{134}Cs and ^{137}Cs in the body could be detected in 12% of the 33,000 residents of Fukushima Prefecture and neighbouring prefectures examined. By March–November 2012, this proportion had fallen to 1%. The estimates of average effective dose due to internal exposure based on these large monitoring programmes are discussed in appendix C and were substantially lower than those estimated by the Committee from the inhalation and ingestion of ^{134}Cs and ^{137}Cs.

2. Other assessments

119. A number of published scientific papers and reports contain various dose assessments for members of the public. A preliminary dose estimation [W11] and related health risk assessment [W12] were carried out for WHO based on data available to September 2011. The results obtained in the Committee's assessment (using more realistic assumptions and more comprehensive and recent data, particularly for the evacuated areas) and the doses estimated in the WHO studies were essentially consistent; in general the ranges of estimates presented by WHO (see appendix C) encompassed the results of the Committee's assessment, but were higher for some of the evacuated settlements. Takahara et al. [T3] also assessed the doses to adults in Fukushima Prefecture using a probabilistic approach.

Where similar assumptions were made, the results were broadly consistent with those obtained by the Committee. The National Institute for Radiological Sciences (NIRS) in Japan has assessed effective doses due to external exposure to those evacuated. The NIRS assessment used a similar methodology to that used by the Committee but a different atmospheric dispersion model. Estimated doses were generally consistent with those of the Committee's assessment.

V. ASSESSMENT OF DOSES TO WORKERS

A. Introduction

120. The effective dose limit for workers given in the Japanese regulations is 100 mSv over a period of 5 years, with a maximum of 50 mSv in a single year; however, for female workers the effective dose limit is 5 mSv in any three-month period. An effective dose reference level (in Japan termed "emergency dose limit", which is used hereafter in this report) of 100 mSv was adopted immediately after the accident [I9] for those workers dealing with the emergency. However, on 14 March 2011, after further assessment of the conditions at the FDNPS site, the emergency dose limit was increased by the authorities to an effective dose of 250 mSv, for all exposures received during the emergency period (i.e. up to 16 December 2011). This increase was to enable essential mitigation activities to be carried out while maintaining the protection of workers. TEPCO adopted a lower emergency dose limit of 200 mSv (effective dose) to ensure compliance with the level set by authorities [I6].

121. The exposure of workers to radiation decreased with time following the accident due to radioactive decay and the decline in the amounts of radioactive material being released from the damaged reactors. The Ministry of Health, Labour and Welfare reinstated the pre-existing emergency dose limit of 100 mSv (effective dose) on 16 December 2011 [T16, W1] following the cold shutdown of reactors in Units 1, 2 and 3.

122. Before the accident, a few thousand occupationally-exposed workers were employed at the site. This number increased dramatically following the accident with almost 25,000 occupationally-exposed workers having been involved in recovery and related operations by October 2012. The majority of these (about 21,000) were employed by contractors of TEPCO. TEPCO workers were mainly involved in plant operation, recording of data and supervision of construction activities. Contractors' workers were mainly involved in work of restoration and construction of facilities; some of them also supported TEPCO workers in stabilizing the nuclear reactors and managing the discharges of radioactive materials.

123. In addition, a few hundred workers from the emergency services were deployed on the site of FDNPS; these included fire-fighters (260), police (13) and personnel of the Self-Defense Force[17] (168). Of these, 84 Self-Defense Force personnel were engaged in the on-site operations discharging water for cooling from helicopters and the remaining workers were engaged in similar activities on the ground. In

[17] When disasters such as natural disasters occur in any part of the country, the Self-Defense Force works in collaboration with municipal governments, engaging in, for example, search and rescue operations, offering medical treatment, supplying water, and transporting personnel and goods. Over 100,000 personnel of the Self-Defense Force were dispatched for relief operations in general after the 2011 great east-Japan earthquake and tsunami.

addition, tens of thousands of fire-fighters, police and Self-Defense Force personnel were engaged in emergency response activities off-site.

124. By the end of December 2011, about 350 municipal employees of the Prefectural Office of Fukushima Prefecture had been involved in emergency operations within the restricted area (the 20-km evacuation zone). Their main activities included monitoring of environmental radiation levels, evaluating the damage caused by the disaster, restoring power supplies and radiation monitors, protecting pets, capturing and slaughtering livestock, on-site inspecting at FDNPS and coordinating and collaborating with relevant organizations. A further 34,000 or so municipal workers were involved with numerous and diverse emergency activities within the area designated for evacuation [Y7].

125. The United States Department of Defense (DoD) and the United States National Nuclear Security Administration (DOE/NNSA) provided about 24,000 personnel in support of the Japanese government in the aftermath of the earthquake, tsunami and the reactor accident. United States personnel generally remained outside the restricted area. They conducted environmental radiation measurements and supported humanitarian missions (e.g. restoring the operational capability of Sendai airport, which allowed air transport of humanitarian relief supplies including food, fuel and clothing).

B. Conditions affecting doses and health

126. Following the accident, TEPCO and other organizations worked in and around the FDNPS site to bring the nuclear reactors under control and to reduce the release of radioactive material [I29]. In the early phase of the accident (days to first few weeks), the first priority was to mitigate the radiological consequences and further progression of the accident, in particular restoring the cooling system by re-establishing electrical power (achieved on 26 March 2011) [I6]. Reactor stabilization and water decontamination became the next priority.

127. The earthquake and tsunami caused widespread destruction of many buildings, roads, tanks and other aspects of the infrastructure on the FDNPS site. The operators were faced with a catastrophic emergency, with a more or less complete and prolonged loss of electrical power, reactor control or instrumentation, and with little hope of immediate outside assistance. Communications systems both within and external to the site were severely affected, although the TEPCO in-house communications network between the site and headquarters was mostly intact [I6].

128. The response required exceptional dedication by workers on-site and elsewhere. Immediately after the tsunami, approximately 400 workers (about 130 operators and 270 maintenance personnel) were available for recovery operations [I29]. They had to work exceptionally long hours in very adverse conditions (i.e. loss of almost all power supplies; dark, wet and cold conditions; lack of proper equipment including compressed air and other services; loss of all safety systems including instrumentation and control) to secure the safety of the six reactors, the six nuclear fuel storage pools, a common fuel storage pool and the dry cask storage facilities. Some workers had lost their homes and families as a result of the earthquake and/or tsunami, yet continued to work. Many workers slept on-site, on the floor, and, because of food shortages, were only provided with minimal nutrition [I29]. They continued to work despite high personal risk from the successive aftershocks (i.e. very high dose rates and levels of contamination at various locations on site), and the damage to the reactors following the hydrogen explosions [I6].

129. Hazards at the site varied as mitigation measures were put in place. Four major hazards were identified for the workers: radiation, heat, stress, and machine operation including manual handling.

Initially, high radiation levels were the most serious hazard as a result of the hydrogen explosions and the continuing releases of radioactive material from the damaged reactors. From May to September 2011, heat exposure became an extremely important hazard. This was because of the hot summer weather and workers having to work outdoors wearing double-layer Tyvek protective overalls and full-face respirators (these inhibited cooling by evaporation). They were also at risk of injury from machine operation, manual clean-up of the rubble, and stabilizing the nuclear reactor for cold shutdown [W1]. Many workers were exposed to multiple stressors, both work-related and personal; the latter were mainly a result of the evacuation of their families from within the 20-km zone where they had previously lived, the loss of family members and their homes due to the earthquake and tsunami; TEPCO workers also suffered public harassment and discrimination [I29, S8, W1].

C. Actions taken to protect workers from radiation

130. Initial capabilities for monitoring radiological conditions effectively, both on-site and off-site, were severely hampered. Few on-site monitoring systems remained following the tsunami. Most electronic personal dosimeters, computer systems for activating and recording dose from these devices, and many portable survey instruments were lost in the flooding. Installed radiation monitors, essential for monitoring core, containment, and spent fuel pool conditions, were also lost when the tsunami flooded the electrical distribution equipment [I29]. It was not possible to gather information on access to controlled areas or on personal dose data. The loss of individual monitoring capabilities resulted in the need for emergency responders to share electronic personal dosimeters, with only one worker in a team wearing a dosimeter for many missions, and workers having to log their individual doses manually [I6].

131. Inside FDNPS, the main earthquake-proof building was reconfigured as a direct command centre for operations and had some rooms for workers to stay overnight. This building was equipped with a high-quality purified-air ventilation system to control the ingress of airborne radioactive material [W1]. However, the high surface and airborne levels of radioactive material around the site combined with damage to the entry of the command centre led to the centre becoming contaminated at an early stage in the accident. The build-up of contamination within the command centre was not recognized until air samples taken in the building were first analysed on 24 March 2011. As a result, controls were not in place prior to this time, during which some workers were exposed internally to radioactive material taken into the body by inhalation [I29].

132. The operator gradually improved on-site radiological monitoring. From 1 April 2011, personal dosimeters were provided to every worker. Dose rates were measured in different areas of the plant and comprehensive radiation maps of the site became available and were updated on a regular basis. These were used to optimize the protection of workers, for example, through the establishment of clear physical barriers between different areas, and the prevention of unauthorized entry to those areas with higher risk. Individual daily working time in designated controlled areas was limited to a maximum of 2 hours. Gradually, special tools were introduced to support work in areas with the highest radiation levels, such as robots and other unmanned equipment [I6].

133. A coordination centre was established at J-Village, a soccer training facility located 20 km to the south of FDNPS to manage and oversee radiation protection of all personnel entering the restricted area and the facility. To protect workers from internal exposure (that is, from inhaling radioactive particles and gases), the centre provided around 2,000 workers daily with tight-fitting full-face respirators with filters that could provide 99.97% filtering efficiency against airborne particles. To avoid contamination

that might otherwise be inadvertently ingested and lead to internal exposure, and to minimize skin exposure, workers wore double-layer (to guard against tears during operations) Tyvek protective overalls, gloves (inner cotton and double outer rubber gloves), safety shoes covered by vinyl shoes, and a cotton hat. A safety helmet was also issued, depending on the nature of the operations. All personal protective equipment once used was stored in a restricted area. A Geiger-Müller survey meter was used at the J-Village gate to measure any contamination on individuals leaving the area [W1].

134. Medical countermeasures included the use of stable iodine for thyroid blocking[8]. Potassium iodide tablets were prescribed to workers from 13 March 2011 onwards in accordance with previously defined criteria, and subject to them being interviewed by a physician regarding iodine hypersensitivity and any pre-existing thyroid condition [W1, W10]. Approximately 17,500 potassium iodide tablets (50 mg) were distributed to about 2,000 workers involved in the emergency response, including TEPCO workers, contractors' workers, fire-fighters, policemen and Self-Defense Force personnel (see appendix E for further information).

D. Reported doses

135. Results of the analyses of doses to workers are summarized below. More details of these analyses are presented in appendix D. In order to judge the extent to which the individual doses reported in Japan provided an accurate and reliable measure of the doses actually incurred, the Committee adopted a two-stage approach: first, it reviewed the methodologies used in Japan for assessing doses; and second, it made independent dose assessments for defined groups of workers, and compared results with those reported. Nevertheless the assessments were necessarily based on information provided by TEPCO, contracting companies and Japanese authorities, because it was clearly not possible to verify the conditions on site at the times of exposure.

136. TEPCO published regular press releases describing the status of dose evaluations for occupationally-exposed workers at FDNPS. Up to the end of October 2012, a total of 24,832 workers were reported to have been involved in mitigation and other activities on the site and were occupationally exposed to radiation; of these, about 15% were employed by TEPCO, with the remainder employed by contractors and subcontractors. Tables presenting the numbers of workers with reported doses[18] in specified dose bands for each month since the accident up to October 2011 have been published [T8] (see tables D1, D2 and D3 in appendix D). These tables show that the highest doses resulted mainly from intakes of radioactive material, and that effective doses[19] due to monthly intakes were observed in March 2011 to be in excess of 100 mSv. The exposure of workers to radiation decreased over time due to radioactive decay and the decreases in the amounts of radioactive material being released from the damaged reactors. From May 2011 onwards, none of the exposed workers received more than 50 mSv effective dose in a month (from both external and internal exposure).

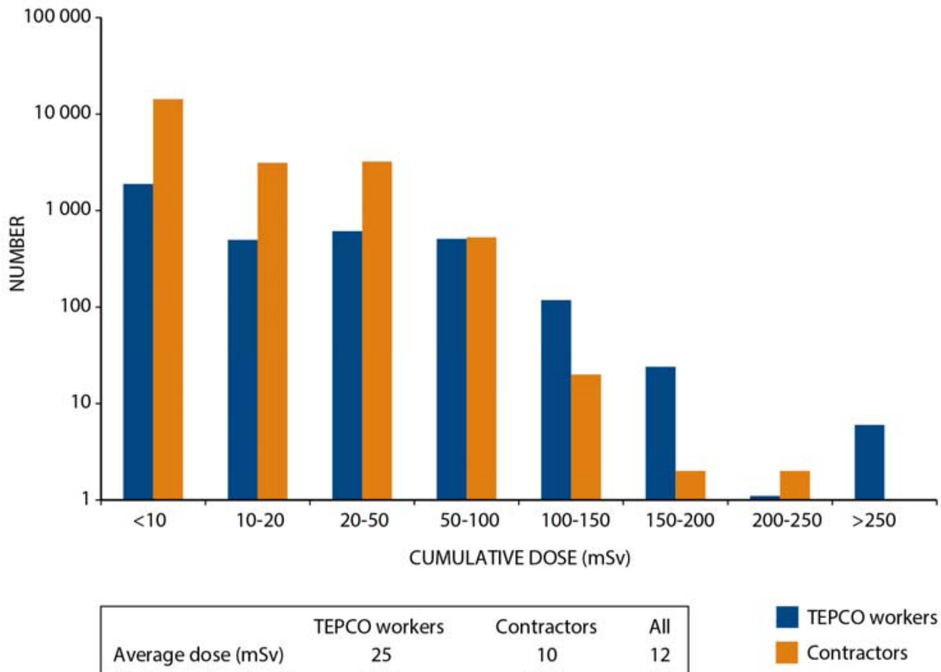
137. After November 2011, TEPCO presented the data in terms of cumulative totals for the number of workers in each dose band; the data published in November 2012 are reproduced in table D4 in appendix D [T16] and are illustrated in figure VIIIa. The data indicate that 34% of the workforce received cumulative doses greater than 10 mSv, and that 0.7% of the workforce (corresponding to 173 individuals, mainly TEPCO workers) received cumulative doses greater than 100 mSv. Six TEPCO

[18] Unless otherwise indicated, all references to "dose" in section V refer to the quantity "effective dose".
[19] Effective doses due to internal exposure for workers are calculated as the 50-year committed effective dose.

workers received cumulative doses greater than 250 mSv. TEPCO has published data only on effective doses, although results for absorbed doses to the thyroid have been published elsewhere [K27].

Figure VIIIa. Numbers of occupationally exposed FDNPS workers with effective doses in each cumulative dose band for the periods in which they worked between 11 March 2011 and 31 October 2012

The effective doses include contributions from external and internal exposure



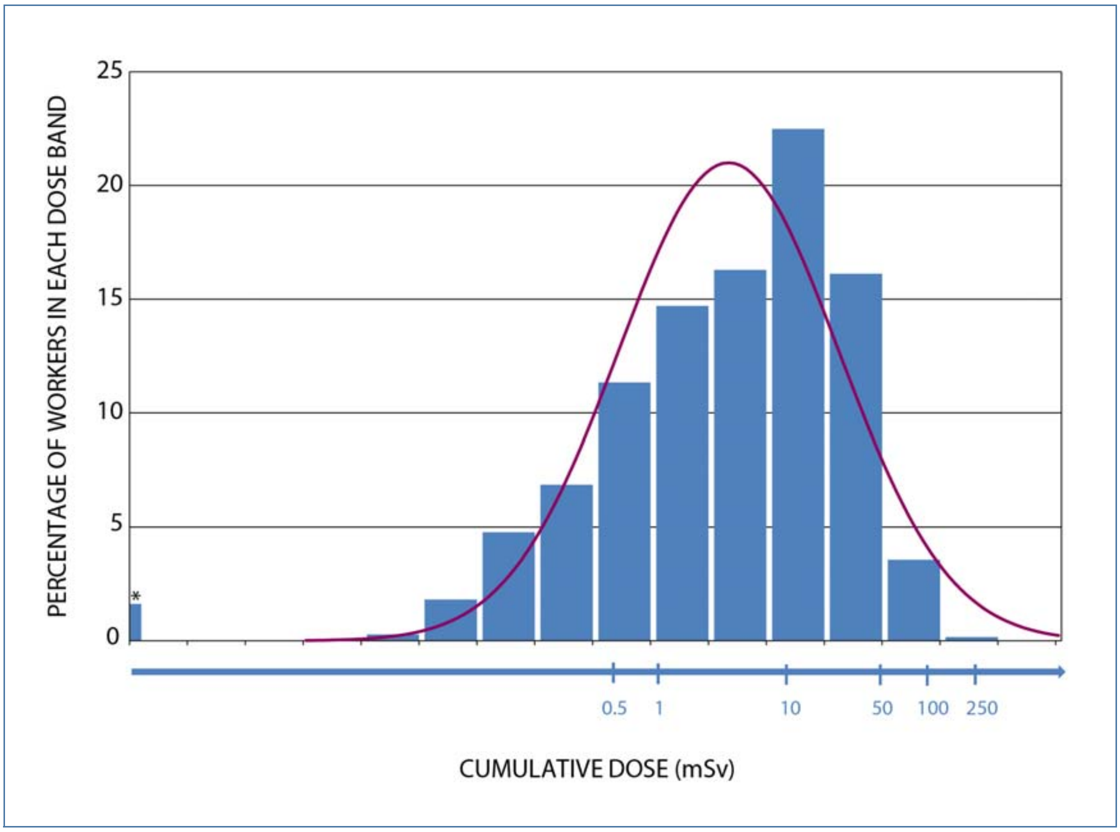
	TEPCO workers	Contractors	All
Average dose (mSv)	25	10	12
Maximum dose (mSv)	679	238	679

138. Additional information on doses due to internal and external exposure up to April 2012 for 21,776 workers was provided to the Committee (see appendix D). The highest reported effective dose was 679 mSv for the TEPCO worker who also had received the highest reported committed effective dose due to internal exposure (590 mSv). The highest reported effective dose due to external exposure was 199 mSv for a contractor's worker who had a reported effective dose that totalled 238 mSv. The distribution of the doses within the workforce is illustrated in figure VIIIb. The median value (i.e. the dose below—or above—which is received by half of the workforce) of the distribution is about 5 mSv with 6 extreme values greater than 250 mSv. The distribution of doses is skewed or asymmetric (i.e. there is an increased frequency of higher values) but is not well represented by a log-normal distribution.

139. The exposure of female workers received particular attention because of the more restrictive standards applied to them. Nineteen women who had worked at FDNPS before the accident (five of whom were not occupationally exposed) received an effective dose of more than 1 mSv following the accident; the two highest doses as a result of the accident were assessed to have been 7 mSv and 18 mSv [O3]. Their doses were, with one exception, less than those of the average dose received by occupationally-exposed workers involved in emergency working conditions. Female workers were not allowed to enter the FDNPS plant after the accident [W1].

Figure VIIIb. Distribution of log-transformed effective doses received by occupationally-exposed FDNPS workers in each cumulative dose band for the periods in which they worked between 11 March 2011 and 30 April 2012

The effective doses include contributions from external and internal exposure. The red curve is the probability density of a normal distribution, with parameters $\mu = 1.3$ and $\sigma = 1.9$ estimated among workers with non-zero doses; * represents workers with effective doses recorded as zero ($n = 352$)



140. Data on reported doses due to internal and external exposure for 249 of the 260 fire-fighters were also provided to the Committee by the Government of Japan. In vivo measurements of ^{131}I in their thyroids were performed in the period September–November 2011 and were all reported to be below the minimum detectable activity[20] (38 Bq for ^{131}I). This was to be expected given the delay in performing measurements. Whole-body measurements of radiocaesium were below or close to the minimum detectable activities (320 Bq for ^{134}Cs and 570 Bq for ^{137}Cs). The assessed doses due to internal exposure were reported to be less than 1 mSv for all these workers, who worked from 18 March 2011 to 25 March 2011. The maximum value of the reported doses from external exposure was 29.8 mSv. Unfortunately, in the absence of data from in vivo thyroid monitoring in the early stages of the accident, no reliable estimates could be made of the doses due to intakes of radioiodine. By analogy with the assessed doses due to internal exposure for on-site workers, who may have been working in similar locations in the early stages of the accident, the effective doses due to intakes of radioiodine by fire-fighters could have been significantly higher than those from intakes of the longer-lived radionuclides (i.e. radiocaesium) that were detected during whole-body monitoring.

[20] The minimum detectable activity represents the smallest activity of a radionuclide that can be detected with 95% confidence.

141. Table 9 presents data on reported effective doses due to external exposure for *(a)* 147 of the 168 on-site Self-Defense Force personnel and *(b)* 8,458 off-site Self-Defense Force personnel that have been provided to the Committee by the Government of Japan. None of the Self-Defense Force personnel was exposed to an effective dose due to external exposure that was greater than 100 mSv. Doses due to internal exposure were also provided for eight on-site and four off-site workers: the assessed committed effective doses were reported to be less than 0.2 mSv for seven workers and equal to 3.8 mSv for one on-site worker.

Table 9. Effective doses due to external exposure reported for the Self-Defense Force personnel

The data refer to the period 11 March 2011 to 31 August 2011

Location	*Number of workers in dose band*			
	<10 mSv	*10–20 mSv*	*20–50 mSv*	*50–100 mSv*
On-site	132	3	8	4
Off-site	8 453	5	–	–

142. The Government of Japan provided data to the Committee on reported doses due to internal and external exposure for 13 policemen who were present on the site on 17 March 2011. The reported doses due to external exposure were less than 10 mSv and the assessed committed effective doses due to internal exposure were less than 0.1 mSv for all of the 13 policemen (see appendix D for further information). The Committee recognized that many municipal workers were involved in various response activities (such as support for evacuation, and conducting monitoring for contamination of people and commodities), but information on their exposures was insufficient for the Committee to estimate their doses.

143. The Committee had insufficient information on beta irradiation to make an informed assessment of doses to the eye lens of workers.

144. In vivo monitoring of 8,380 United States Department of Defense-affiliated personnel was carried out between 11 March 2011 and 31 August 2011 to assess their doses due to internal exposure. About 3% of those monitored had detectable activity within their bodies with a maximum committed effective dose of 0.4 mSv and a maximum committed absorbed dose to the thyroid of 6.5 mGy.

E. Evaluation of monitoring and dosimetry

145. One of the aims of the Committee's work was to judge the extent to which the individual doses reported in Japan provided a true and reliable measure of the doses actually incurred, and therefore the extent to which the reported doses could support a reliable assessment of potential effects on health. A two-stage approach was adopted. First, the methodologies for assessing doses used in Japan were reviewed. The results are described in appendix D and summarized in this subsection. Second, independent assessments of doses due to internal exposure were made for defined groups of workers, and comparisons made with the doses reported in Japan for these workers; the results are summarized in subsection F below.

1. Internal exposure

146. Initial in vivo measurements on the workers who were responding to the emergency were made with simple whole-body monitoring equipment at Onahama, 55 km south of the FDNPS site. This equipment was not capable of performing measurements of radioactive material in the thyroid, and was subject to relatively high environmental background levels because of its location. Where an assessed effective dose due to radionuclide intake was over 20 mSv, the worker was additionally monitored at the Japan Atomic Energy Agency (JAEA), with the results provided to TEPCO for dose assessment. Where an assessed effective dose (due to both external and internal exposure combined) was in excess of the emergency dose limit (250 mSv), the National Institute of Radiological Sciences in Japan (NIRS) additionally monitored the worker and further assessed intake and associated dose due to internal exposure. For some of these cases, TEPCO staff then made a re-assessment of the dose. For most workers, results were reported only for ^{131}I, ^{134}Cs and ^{137}Cs. For some of the workers with higher effective doses, results were also reported for ^{136}Cs and ^{129m}Te, but the contribution to effective dose from these radionuclides was small. Data on their exposures to other short-lived radionuclides such as ^{132}Te, ^{132}I, ^{133}I and ^{133}Xe were lacking. A limited amount of in vitro monitoring of urine samples was performed, but the results were not used for formal dose reporting.

147. Detailed information on the in vivo monitoring systems used was provided to the Committee, specifically: *(a)* information on the in vivo measurement systems used at Onahama by TEPCO, and also those used by JAEA and NIRS; *(b)* information on the calibration phantoms used for in vivo measurements by JAEA; and *(c)* comprehensive data related to calibration and quality control of in vivo measurements made both by JAEA at its own laboratories, and by JAEA and TEPCO at Onahama. The information was sufficient to judge that the measurement systems, calibration phantoms and methods, and quality control procedures were adequate for conducting in vivo measurements during a radiation emergency. In addition, assessments of dose from internal exposure for TEPCO workers were performed either by TEPCO or (for a few cases with high exposures) by NIRS, using the software packages MONDAL [N12] and IMBA [B12] respectively. Both software packages were quality-assured, and the Committee judged them appropriate for assessing intakes of internally-incorporated radionuclides and the corresponding committed effective doses and absorbed doses to workers due to internal exposure. More details on this information and of its evaluation by the Committee are presented in appendix D.

2. External exposure

148. The Committee received information for TEPCO and contractors' workers on the types of individual dosimeter used, the technical standards and calibration methods used, and the system used for allocating electronic personal dosimeters to individuals during March 2011 when the availability of these dosimeters was limited. However, it did not receive similar information for emergency service workers, for example, policemen, fire-fighters, and Self-Defense Force personnel.

149. The information provided, and the results of the Committee's evaluation of it, are presented in appendix D. In summary, the instrumentation, technical standards and calibration methods used appear to meet generally-accepted requirements for individual monitoring. Conclusions over the reliability of the reported doses due to external exposure need some qualification, however, because of the use of shared personal dosimeters during March 2011. According to TEPCO, the Automatic Personal Dosimeter System was inoperable and 5,000 dosimeters could not be used during this period. For the first few days, only 320 dosimeters were available. This meant that the initial emergency responders had to share dosimeters, with only one worker in a team wearing a dosimeter for many missions, and

workers had to log individual doses manually [T11]. Conditions were developed setting out when it was appropriate for dosimeters to be shared (appendix D). As long as these conditions were consistently met, the results of the measurements made with the shared dosimeters should have provided an adequate basis for the assessment of dose due to external exposure.

F. Evaluation of assessment of internal exposure

150. The Committee performed its own assessments of the doses due to internal exposure for selected workers, and compared the results with the doses reported in Japan for these workers. Several assessors were involved in evaluating the cases, each using his/her own established procedures and expert judgement to make decisions on issues such as choice of monitoring data and the values of parameters to be used in biokinetic models.

151. Doses received by workers with the highest exposures were of particular interest for the assessment of potential effects on health. Assessments were therefore performed for 12 workers[21] with the highest reported internal exposures (committed effective doses higher than 100 mSv), with the aim of judging the reliability of the doses reported for these workers. While the assessment and recording of external exposure resulted from a direct reading of the information provided by electronic personal dosimeters, internal exposure assessments relied on expert judgment and assumptions related to the exposure conditions as well as the use of biokinetic models and complex software. Thus, the uncertainty and potential for differing estimates between experts of internal exposure was greater than those associated with the estimation of external exposure.

152. The 12 workers with the highest internal exposures for whom the Committee conducted assessments were all TEPCO workers; measurements had all been performed at the same (or similar) facilities and the methods of internal exposure assessment had also been similar. On the other hand, the much larger number of workers with lower assessed internal exposures had different types of employment status (e.g. TEPCO, contractor, subcontractor and emergency service workers), and both the type of facilities used for measurements of radionuclide activities and the method used to assess internal exposure could have depended on the level of the internal exposure. The reliability of the internal exposure assessments for these groups of workers was evaluated by performing independent internal exposure assessments for samples of workers randomly selected from the various groups. In total, 42 workers were randomly selected, of whom 21 were TEPCO workers and 21 were contractors[22]. In addition, 13 workers from the emergency services (understood to be all from the police force) were selected. The assessments and comparisons are described in detail in appendix D and summarized below.

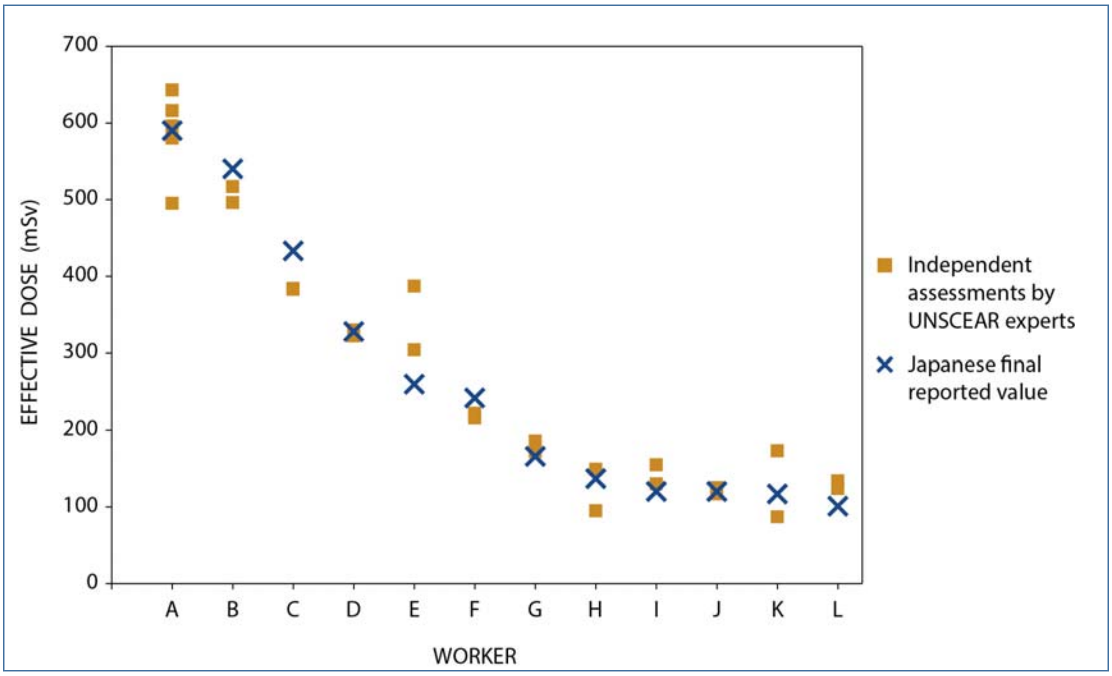
[21] Following the Committee's independent assessment of internal exposure for the 12 most exposed workers, the relevant Japanese organizations reviewed their estimates of doses due to internal exposure in July 2013; this resulted in the identification of one further TEPCO worker with a committed effective dose greater than 100 mSv (i.e. there were then 13 workers in total with effective doses due to internal exposure in excess of 100 mSv). The Committee did not make an independent assessment of the dose due to internal exposure for this thirteenth individual owing to the late acquisition of this information.

[22] Following the Committee's independent assessment of internal exposure for the random sample of 21 contractor workers, TEPCO carried out a re-assessment in July 2013 of the doses due to internal exposure to these workers based on new information provided by the contractor companies. The Committee was not able to update its assessment of internal exposure for this sample of workers because of the late acquisition of this information (i.e. after the Committee's assessment had been completed). The implications of changes in the internal exposure assessments by TEPCO are addressed in appendix D—in general, they do not affect the broad conclusions previously reached and presented in this section.

153. Comparisons between the results of the Committee's independent assessments of internal exposure for twelve workers[21] with the highest doses and those formally reported by the Japanese authorities are shown in figure IX. These assessments were all based on in vivo measurements of radionuclide activities in the whole body and ^{131}I activities in the thyroid. Appendix D gives more detailed results, including the contribution from ^{131}I intakes to effective dose and to the absorbed dose to the thyroid (tables D9, D10, D11). The effective dose—and contributions due to internal and external exposure—for these workers can be found in tables D5, D6 and D7 in appendix D.

Figure IX. Assessed committed effective doses for occupationally-exposed workers with the highest internal exposures

The committed effective doses are from internal exposure only and from all measured radionuclides



154. The following conclusions were drawn for the 12 workers with the highest internal exposures for whom the Committee conducted assessments:

(a) For quality assurance purposes, all five assessors conducted an internal exposure assessment for worker A, and good agreement was found. The other eleven cases were reviewed by at least two assessors and again good agreement was found;

(b) There was good agreement between the Committee's own internal exposure assessments for the twelve workers and the assessments reported in Japan;

(c) For all 12 workers, the Committee concluded that the effective dose due to internal exposure from the measured radionuclides arose almost completely from the contribution of ^{131}I in the thyroid (on average, 99%);

(d) The largest assessed committed absorbed dose to the thyroid due to internal exposure was for worker A. The Committee's assessments of absorbed dose to the thyroid due to internal exposure from the measured radionuclides for this worker range from 9.7 to 12.6 Gy (with an average value of 12 Gy), depending on assumptions made in the simulation, including the timing of main intakes of ^{131}I;

(e) For most of the workers, in vivo monitoring of ^{131}I in the thyroid did not start until mid- to late-May, although for three workers (workers A and B, with the highest internal exposures, and worker F, with the highest external exposure), it started in mid-April. This delay in starting monitoring increased the uncertainty in the dose assessments;

(f) The delay in starting in vivo monitoring of the thyroid meant that shorter-lived radionuclides, such as ^{132}Te and ^{133}I, were not detected. Indicatively, the additional contribution to effective dose due to internal exposure from the intakes of these short-lived radionuclides by those workers on site in the first few days of the accident may have been in the order of 20% relative to the contribution from ^{131}I; this contribution is likely to have varied considerably between individuals. Owing to these factors and other uncertainties, further work is needed to fully characterize occupational exposures during the very early stages of the accident;

(g) The absence of adequate data from urine monitoring means that it was not possible to confirm the reliability of doses assessed from the measurements of activity in the thyroid using results obtained independently with a different bioassay monitoring method.

155. The results of the Committee's internal exposure assessments for the 55 workers with lower internal exposures, and comparisons with values reported by the Japanese authorities, are presented and discussed in appendix D. The following conclusions were drawn:

(a) Reasonable agreement was found between the Committee's independent internal exposure assessments and the assessments reported by TEPCO for those workers for whom a positive measurement of ^{131}I in the body was made;

(b) For all of the workers with assessed committed effective doses due to internal exposure above 0.1 mSv, the committed absorbed dose to the thyroid resulting from ^{131}I intake made the dominant contribution to the effective dose (on average, 98%);

(c) Overall, the internal exposure assessments made by TEPCO for its workers were suitable for the assessment of effects on health. The reliability of assessments reported by TEPCO for those of its workers where a positive measurement of ^{131}I in the body was made could be confirmed. On the other hand, the reliability of assessments reported by TEPCO for those of its workers for whom ^{131}I was not detected in the body could not be confirmed. Neither of the methods available to estimate ^{131}I intake in these circumstances provided a reliable estimate of true intake, and the resulting internal exposure estimates could have been subject to a high degree of uncertainty. Although workers in this category could have comprised about 40% of the total, they were, in general, more likely to have received lower committed effective doses due to internal exposure than the overall average;

(d) Evidence from this investigation indicates that estimates of dose due to internal exposure reported by contractors for their workers were less than about 50% of those of the Committee for eight cases out of the nineteen where a comparison could be made. For the other eleven cases, the Committee's dose estimates were broadly in agreement with those of TEPCO's initial alternative assessments (which were not normally reported). Based on the comparative assessments carried out, the Committee was unable to confirm the reliability of the internal exposure assessments reported by contractors for their workers[23];

[23] After this conclusion was drawn by the Committee, doses due to internal exposure for contractors' workers were reassessed in Japan [M18], and the Committee understands that at least some of the discrepancies were resolved. Further work would be required to determine whether the reliability of the contractors' assessments could be confirmed; this would require a detailed analysis of the reassessments.

(e) Effective doses due to internal exposure for the police appear to have been very low, in the microsievert range;

(f) Effective doses due to internal exposures reported for emergency service workers (e.g. fire-fighters and Self-Defense Force personnel) were all below 1 mSv with one exception (3.8 mSv). The Committee was unable, however, to confirm the reliability of these reported exposures because it lacked sufficient detailed information to enable it to carry out independent assessments.

VI. HEALTH IMPLICATIONS

156. The Committee has provided a commentary on the immediate and long-term health implications of exposures to ionizing radiation resulting from the FDNPS accident based on the Committee's interpretation of information on the exposures and their consequences (see appendix E).

A. General considerations

157. Decades of clinical experience, and evidence from animal and laboratory experiments and epidemiological studies of human populations underpin the current understanding of the health effects of radiation exposure. Part of the mandate of the Committee has been to undertake broad reviews of the effects of ionizing radiation exposure on human health, most recently reported in [U7, U9, U10, U12, U13, U16]. The Committee has applied this pre-existing knowledge and understanding to the estimates of doses to the public (chapter IV and appendix C) and workers (chapter V and appendix D) in its assessment of the health implications of the FDNPS accident.

158. As stated in chapter IV, there were uncertainties associated with the estimates of district averages of effective doses for the public. Local variability in deposition density and between members of the exposed population contribute to a distribution of estimated effective doses around the average, indicatively between 30–50% of the average and two to three times higher than the average. Thus, in some cases sizeable population groups may have been exposed to doses at the higher end of this distribution.

159. Generally and in the absence of better available information, assumptions were made that would have tended to overestimate the doses to members of the public. This may particularly have been the case for estimating doses due to ingestion of radionuclides and not being able to take account of protective measures because of lack of information on their degree of implementation. Some direct in vivo measurements of activity in the thyroid (a particularly important factor for those exposed as children or infants when considering the risk of thyroid cancer later in life) and whole-body counting also indicated that the Committee's estimates were somewhat higher than the doses implied by these measurements. Nevertheless, it cannot be excluded that some individuals incurred doses somewhat higher than those estimated by the Committee.

160. For workers, uncertainties were mainly related to exposures in the early phase of the accident. At that time, monitoring was impaired by the shortage of dosimeters, and thyroid monitoring was not performed until later.

161. In 2012, WHO published a preliminary dose estimation that had used information available up to September 2011 [W11]. The Committee’s estimates of doses were based on a considerably expanded database and were generally within the dose ranges estimated by WHO. In March 2013, WHO published a health risk assessment [W12] based on its preliminary dose estimation. The Committee’s assumptions underpinning its estimates of health implications are generally well aligned with those of WHO (see appendix E).

162. The Committee also drew on the experiences and direct observations of health effects in the aftermath of the Chernobyl accident. It was clear that the radiation exposures of the public and workers, as well as the number of individuals exposed to higher doses, following the FDNPS accident were considerably lower than following the Chernobyl accident.

163. Health, in its broad definition used by WHO, concerns physical, mental, and social well-being and is not just characterized by the absence of disease. It is clear from both the Chernobyl accident [U12] and from the FDNPS accident that nuclear accidents of such magnitudes and the associated protective measures tend to lead to distress and anxiety from, among other things, disruption of life, and loss of homes and livelihoods; the distress and anxiety can have major impact on mental and social well-being. Evaluating such effects is not part of the Committee’s mandate; however, they were important for understanding the broader health implications and the Committee refers to them as appropriate to provide context for its assessment of the health implications directly related to radiation exposure.

164. Traditionally, health effects associated with radiation exposure have been classified in two categories:

(a) Deterministic effects occur after high doses of radiation normally delivered over a short period of time, which kill large numbers of cells leading to possible tissue damage, major effects on body function, and even death. The effects include acute radiation syndrome, skin burns, loss of hair, hypothyroidism, and developmental damage to an unborn child. Most deterministic effects occur shortly after exposure (although some can appear later in life) above dose thresholds specific for each exposed tissue. The pattern of symptoms for most of these effects is usually so specific that trained medical professionals can diagnose a deterministic effect of irradiation. The ICRP has introduced the term, “tissue reaction”, which encompasses deterministic effects, circulatory disease and cataracts [I26].

(b) Stochastic effects. Exposure to radiation can also induce non-lethal changes to cell constituents. Unrepaired or misrepaired abnormal cells escaping the body’s immune defence may lead to hereditary effects in future offspring or, after a period known as the “latency”, to the development of effects such as cancer. At present, there is no way of distinguishing by observation or testing whether or not a specific stochastic effect has been caused by radiation exposure. Thus, if the disease occurs in an individual, it is not possible to conclude unequivocally that it was caused by radiation. However, stochastic effects can manifest as an increased incidence of disease in a population, and the incidence after irradiation tends to increase with increasing dose. From this it is possible to infer an increased risk of stochastic effects in an exposed population.

165. When considering health implications, it is important to distinguish between those diseases that have already been observed from those that may occur in the future. In this context, particularly when considering stochastic effects over a lifetime, it is important to recognize different ways of expressing the risk of future disease, including:

(a) Lifetime risk of a disease is the probability that it occurs from a given point of time (e.g. at exposure) until the end of life, and can be expressed variously. For example, a 1 in 10 risk of

developing a disease can also be expressed as a 10% or 0.1 risk. The “lifetime baseline risk” refers to the probability of a disease occurring over a lifetime without exposure additional to the background from natural sources of radiation; and “lifetime risk due to exposure” [24] to the additional probability of a disease occurring over a lifetime due to additional radiation exposure.

(b) Relative risk[25] is used to compare the disease risk in two different groups of people, and is the ratio of the risk to each group. For example, the risk of a particular disease occurring in an exposed group could be say 20% higher than that in a non-exposed group, then the relative risk would be 1.2. If the lifetime baseline risk of a particular disease in the non-exposed group were 1 in 200, then the lifetime risk in the exposed group would be higher by 20%, i.e. 1/200 × 1.2 = 1.2 in 200 or 1 in 167.

166. Studies can quantify with some confidence values of relative risk that are high enough to overcome the normal variability in cancer statistics (the ability to achieve this depends among other things on whether a large enough group of people are exposed to high enough doses). In such cases the Committee has confidence to make risk assessments based on direct evidence. If the relative risks are not high enough, then the Committee draws an inference about the risks and estimates their value from the existing knowledge and understanding on the relationship between radiation exposure and health effect in question. For example, an increased incidence of hereditary effects has not been reliably demonstrated in humans for any level of exposure, and is not expected to be possible to demonstrate among the general public or workers following the accident at FDNPS, although risk estimates have been made to take them into account based on animal studies. Such estimates are based on expert judgement rather than direct evidence. While direct evidence mean that risks cannot have been grossly underestimated, the underlying assumptions and variability make risk estimates at low doses highly uncertain and of low predictive value, as well as potentially misleading.

167. In this chapter, the Committee has estimated values of the risk due to exposure for members of various exposed groups. Where the estimated risk of the disease is sufficiently large in a large enough population, compared to the normal statistical variability in the baseline incidence of the disease in that population, an increased incidence due to irradiation may be “discernible” in disease statistics and epidemiological studies. Conversely, when risks may be inferred on the basis of existing knowledge, but the level of inferred risk is low and/or the number of people exposed is small, the Committee has used the phrase “no discernible increase” to express the idea that currently available methods would most likely not be able to demonstrate an increased incidence in the future disease statistics due to irradiation. This does not equate to absence of risk or rule out the possibility of excess cases of disease due to irradiation, nor the possibility of detection of a biomarker for certain types of cancer in certain subgroups being identified in the future that can be associated with radiation exposure; moreover, it is not intended to disregard the suffering associated with any such cases should they occur.

[24] The more technical term “lifetime attributable risk” was used in the WHO report [W12] and in other technical reports of the Committee.
[25] Another expression is the “excess relative risk”, the proportional increase in risk for the exposed group over the unexposed group.

B. Health implications for the public

1. Observed health effects

168. The Committee's understanding of the exposures is that they fell well below the thresholds for deterministic effects. This was consistent with no acute health effects (i.e. acute radiation syndrome or other deterministic effects) having been reported that could have been attributed to radiation exposure.

169. The Committee did not assess non-radiation-related health effects, which vary in their symptoms and degree of severity. For example, more than 50 hospitalized patients were reported to have died either during or soon after evacuation, probably because of hypothermia, dehydration and deterioration of underlying medical problems [T4]. Many people have been suffering from distress caused by the earthquake, tsunami and nuclear accident, and may also have been exposed to various hazards that have given rise to physical symptoms of disease.

170. Mental health problems and impaired social well-being were the major health impacts observed following the accident. They were the results of understandable reactions to the enormous impacts of the earthquake, tsunami and nuclear accident, as well as fear and stigma associated with radiation exposure. Psychological effects, such as depression and post-traumatic stress symptoms, among the public have been observed [Y4, Y5] and may have serious health consequences.

2. Estimated health risks

171. The lifetime baseline risk of solid cancer (i.e. the lifetime risk of solid cancer in the absence of radiation exposure from the accident) in the general Japanese population is normally about 35% but varies for individuals according to sex, lifestyle and other factors. The Committee previously estimated that a hypothetical acute absorbed dose to the whole body of 100 mGy for a typical population of Japan would lead to an additional lifetime risk of solid cancers due to exposure of approximately 1.3%, i.e. a relative risk of 36.3/35 = 1.04 [U9]. For exposures from the accident, the Committee estimated (see chapter IV and appendix C) both the settlement-average effective doses in the first year received by adult evacuees, and the district-average lifetime effective doses to adults living in the non-evacuated and most affected districts of Fukushima Prefecture, to be up to about 10 mSv (tables 6 and 7). Higher district-average effective doses, by a factor of about two, were estimated for children and infants. Individual effective doses would have varied between perhaps 30−50% of this and two to three times higher. While risk of cancer and hereditary effects at such doses can be inferred by assuming for example a linear relationship between dose and risk, the inferred relative risk values are small (i.e. the inferred relative risk of solid cancer after an exposure to an effective dose of 10 mSv is approximately 35.13/35 = 1.004) when compared to the normal statistical variability of the baseline rates. A general radiation-related increase in the incidence of health effects among the exposed population would not be expected to be discernible over the baseline level.

172. While the lifetime cancer risks due to radiation exposure may not result in a discernible increase in disease incidence for the whole of the general population, the risks for some cancers and age groups in principle might. Past experience provides an understanding of the organs, age groups and time periods for which increased risk is more prone to become discernible as an increase in the incidence of the disease, and the Committee focused its attention on these. Moreover, for some organs, the relative

risk from exposure during infancy and childhood is considerably higher than during adulthood [U16]. Risk estimates for exposure were based on estimates of absorbed doses to those specific organs.

173. *Thyroid cancer*. The first-year average absorbed doses to the thyroid of adults were within a few tens of milligrays (tables 5 and 6), for which the risk of thyroid cancer was considered low. The Committee did not attempt to quantify the risk of thyroid cancer after such exposures during adulthood.

174. The baseline risk of developing thyroid cancer over the course of life is normally about 1 in 200 for 10-year-old children and 1-year-old infants in Japan [W12], although highly sensitive ultrasonographic surveys could increase the rate of detection by several times. The Committee previously estimated that, following a hypothetical absorbed dose to the thyroid of 200 mGy at 10 years of age, the risk was nearly doubled (i.e. a relative risk of 2 with estimates ranging from 1.15 to as much as 4—see appendix E). However, most of the increased risk is associated with long times after exposure; only about 10% of the lifetime risk is expressed during the first twenty years.

175. For exposures from the accident, the Committee used the methodologies outlined in appendix C to estimate settlement-average absorbed doses to the thyroid of up to about 80 mGy for 1-year-old infants who were evacuated (table 6). For infants who remained in the non-evacuated areas, district-average doses were up to about 50 mGy (table 5). The estimated doses would have varied considerably between individuals (indicatively, from about 30–50% of the average to about two to three times higher than the average). Direct in vivo measurements of radioiodine in the thyroid have indicated lower doses than estimated in the Committee's assessment (see paragraph 117). As explained in appendix E, most of the absorbed doses to the thyroid were in a range for which an excess incidence of thyroid cancer has not been observed in epidemiological studies. Nevertheless, doses towards the upper bounds of the ranges could imply an increased risk for individuals that among sufficiently large population groups might lead to discernible increases in the incidence of thyroid cancer due to the radiation exposure. The WHO estimates of the relative risk of thyroid cancer due to radiation exposure from the accident [W12] are consistent with the results of the Committee, assuming a linear dose–response relationship for absorbed doses to the thyroid below several hundred milligrays. Information on dose distributions was not sufficient for the Committee to draw firm conclusions as to whether any potential increased incidence of thyroid cancer would be discernible among those exposed to higher thyroid doses during infancy and childhood. The occurrence of a large number of radiation-induced thyroid cancers as were observed after the Chernobyl accident can be discounted because doses were substantially lower.

176. *Leukaemia*. The lifetime baseline incidence of leukaemia in Japan is about 1 in 200 or 0.5%, and for childhood leukaemia around 1 in 1,500 or about 0.07% [I7]. The risk of leukaemia induced by irradiation has been assessed previously by the Committee for the general Japanese population [U9]. The lifetime risk due to exposure for children aged 0 to 9 years receiving an absorbed dose to the red bone marrow of 1 Gy was estimated to be in the range from 0.11% to 0.85%. After infants are exposed, most of the risk of leukaemia would be expressed during childhood. For the FDNPS accident, the Committee estimated absorbed doses to the red bone marrow of up to about 10 mGy in the first year for both the settlement averages for infants who were evacuated and the district averages for infants in the non-evacuated areas. The WHO estimates of the risks of leukaemia due to radiation exposure from the accident [W12] are consistent with the previous general assessments of the Committee. Considering the exposures and risks, and the size of the exposed group, any increase in childhood leukaemia is not expected to be discernible.

177. *Breast cancer*. The lifetime baseline risk of breast cancer among Japanese females is about 5.5% [W12]. For a hypothetical exposure of the general female Japanese population with an absorbed dose to the breast of 100 mGy, the Committee calculated previously a lifetime risk of breast cancer due to the irradiation of about 0.3% [U9]. The assessment of the difference in risk from childhood exposure

compared to adult exposure depends on the model used [U16]. In some studies the breast cancer risk after exposure as a child is a factor of three to five times higher than after exposure as an adult [U16]. The Committee estimated settlement-average absorbed doses to the breast of girls before and during the evacuation to be less than 10 mGy. The Committee does not expect that any radiation-induced increase in breast cancer incidence will be discernible.

178. *Prenatal exposure*. The prenatal exposure resulting from the accident at FDNPS is not expected to increase the incidence of spontaneous abortion (miscarriages), perinatal mortality, congenital effects or cognitive impairment. However, the Committee has previously estimated that absorbed doses in utero of about 10 mGy may lead to an increased incidence of cancer during childhood, especially of leukaemia (with a relative risk of 1.4) [U7]. It cannot be excluded that a small number of pregnant women had absorbed doses to the uterus of about 20 mGy, perhaps doubling the risk of leukaemia for their unborn children. However, the number of pregnant women involved was relatively small and childhood cancer is a rare disease. Thus it is expected that any increase of the risk would not lead to a discernible increase in the incidence of childhood leukaemia or other childhood cancers.

3. Health screening

179. The Fukushima Health Management Survey [A4, Y4, Y5] was launched to "evaluate radiation doses of citizens and [record] their health conditions, with the intention of utilizing the results for prevention, early detection and treatment of possible illness". It includes a basic survey to estimate external exposure to radiation of all 2 million residents of Fukushima Prefecture at the time of the accident, a thyroid ultrasound examination of children, and for selected population groups a health check, a mental health and lifestyle survey, and a pregnancy and birth survey. The investigation is planned to continue for 30 years.

180. Thyroid ultrasound examinations were to be made for all individuals in Fukushima Prefecture who were aged 18 years or younger on 11 March 2011 (about 360,000) and were expected to be completed within 3 years (by March 2014). Thereafter, children would undergo thyroid examinations every 2 years until age 20 and every 5 years thereafter [Y5]. By the end of July 2013, about 175,000 children living in Fukushima Prefecture had received thyroid examinations using modern, highly sensitive ultrasound equipment [F3]. Thyroid nodules had been detected in about 1% of those surveyed and thyroid cysts in about 40% of those surveyed. A survey, using similar equipment, of about 4,000 children and adolescents had also been made in the prefectures of Aomori, Yamanashi and Nagasaki [T5] which were largely unaffected by the accident; the observed prevalence of thyroid nodules and cysts there was even larger than that observed in Fukushima Prefecture. This indicates that the high detection rate of nodules and cysts in all of these surveys is a consequence of the intensive screening and the highly sensitive nature of the equipment being used, and not of additional radiation exposure resulting from the accident.

181. The ongoing ultrasonography survey in Fukushima Prefecture is expected to detect relatively large numbers of thyroid abnormalities, including a number of cancer cases, which would not normally have been detected without such intensive screening [J8, W12]. Thyroid cancer is frequently detected at autopsy even in subjects free of any clinical disease, and the survey would likely detect some of these cancers. Surveys of thyroid cancer incidence in populations of areas unaffected by the accident would provide useful input to estimates of the impact of such intensive screening.

C. Health implications for workers engaged in emergency work

1. Observed health effects

182. No acute health effects (i.e. acute radiation syndrome or other deterministic effects) or deaths have been observed among workers engaged in emergency work that could be attributed to radiation exposure.

183. Three contractor workers were hospitalized in March 2011 after the skin of their feet and lower legs were exposed to contaminated water in a turbine building. The Committee confirmed that the dose estimates by TEPCO were far below the threshold for skin damage and they were released from hospital after four days with no expectation of significant long-term harm.

184. In order to block the uptake of radioiodine into the thyroid, approximately 17,500 potassium iodide tablets were administered to about 2,000 workers involved in emergency work [K11]. Approximately 230 workers received health check-ups because either *(a)* they took potassium iodide tablets repeatedly for more than 14 days, or *(b)* they took more than 20 tablets. No side effects were reported by the workers, but changes to thyroid hormone levels were observed in eight workers. For three cases, the changes were temporary; for the other four cases, the changes could not be attributed to taking potassium iodide tablets because the observed rate of hypothyroidism was comparable with the baseline rate for a male population.

185. Initial observations have identified severe psychological effects among the FDNPS workers engaged in emergency work [M8, S7, S8, W1]. These effects are attributable to a number of causes, including distress and anxiety associated with the effects of the earthquake, the tsunami, very harsh working conditions, the loss of family members, separation from family, difficult living conditions during emergency operations, worries about possible effects of radiation in the future and discrimination and stigma associated with being a radiation worker.

2. Estimated health risks

186. *Risks of future deterministic effects.* Thirteen workers[21] were estimated to have received absorbed doses to the thyroid in the range of 2 to 12 Gy from inhalation of ^{131}I, with an average dose of about 5 Gy. Given the magnitude and inherent uncertainties in these dose estimates, the Committee cannot preclude the possibility of hypothyroidism in the more exposed workers; the likelihood of such effects is, however, low. Risks for circulatory disease due to radiation exposure among the workers who were most exposed is very low. The Committee had insufficient information on exposures of the eye lens of workers from beta radiation to reach an informed judgement on the risk of cataracts.

187. *Cancer in general.* For most workers (99.3% out of 24,832 as of 31 October 2012), the effective doses were low (less than 100 mSv)—on average about 10 mSv. Even when taking account of some variability and uncertainty in the estimates, the doses for the majority of the workers were below those at which there is reliable evidence from epidemiological studies of an increased cancer risk. While risk models, by inference, suggest increased risks even for such doses, such risks would be low and no discernible increase in health effects among this group of workers is expected that could be attributed to their radiation exposure.

188. The Committee took note of the estimates made by TEPCO that many workers received effective doses of several tens of millisieverts and as of 31 October 2012, about 0.7% of workers (corresponding to 173 individuals) had received effective doses of 100 mSv or more, with an average dose of about 140 mSv. Among this group, a small increased risk of cancer would be expected. Risk estimates would, for this subgroup of exposed workers, correspond to about two to three additional cases of cancer in addition to about seventy cancers that would occur spontaneously, given the baseline risk of about 40%; however, such predictions are associated with significant uncertainties. While the cancer risk among these workers remains a justified concern for the Japanese health authorities (see paragraph 191 below), it is unlikely that such increased incidence of cancer due to irradiation would be discernible, because of normal statistical variability of cancer incidence and other risk factors. However, special attention needs to be paid to certain subgroups of the more highly exposed workers and specific cancers. Such conclusions are drawn with regard to thyroid cancer and leukaemia below.

189. *Thyroid cancer and leukaemia*. The Committee took note of the estimates of TEPCO that approximately 2,000 workers had received absorbed doses to the thyroid exceeding 100 mGy. Evidence for an elevated risk of thyroid cancer following exposures during adulthood in the range from 100 to 1,000 mGy remains to some degree equivocal (see appendix E). Nevertheless, the magnitude of any inferred risk is such that any increase in the incidence of thyroid cancer within this group of workers would likely not be discernible (i.e. any increase in incidence due to radiation exposure would be small compared with statistical variability in the background incidence).

190. The risk of thyroid cancer is particularly enhanced for the group of thirteen workers who received absorbed doses to the thyroid in the range of 2 to 12 Gy, although the numbers of workers exposed at such doses are likely too small to discern an increased incidence in thyroid cancer. Absorbed doses to the red bone marrow, which is relevant for leukaemia risk, were estimated by the Committee for these workers to be up to about 100 mGy. Because of the small number of workers in this group, any increase in incidence of cancers is not expected to be discernible.

3. Health screening

191. In August 2011, the Japanese Ministry of Health, Labour and Welfare [M14] announced a "grand design of a long-term health management of all the emergency operations workers at TEPCO's No. 1 Fukushima Nuclear Power Plant". A database was constructed containing exposure and health records for workers involved with managing the emergency at, and the recovery of, the FDNPS site. Special health examinations are to be given to workers with the highest exposures, including annual eye check-ups (for lens opacity) and monitoring of the thyroid, stomach, large intestine and lung for cancer. Ultrasonography surveys of these workers will, inevitably, result in increased detection of thyroid cancer; the overwhelming majority of the cases detected are expected to have developed independently of radiation exposure.

VII. ASSESSMENT OF DOSES AND EFFECTS FOR NON-HUMAN BIOTA

A. Introduction

192. As for humans, any organism in the natural environment can be exposed both internally and externally to radioactive substances in its habitat. The Committee assessed the consequences of such exposures in its scientific annexes to the 1996 [U6] and 2008 [U12] Reports. The Committee concluded that chronic dose rates of less than 100 µGy/h to the most highly-exposed individual organisms would be unlikely to have significant effects for population integrity of most terrestrial communities, and that maximum dose rates of 400 µGy/h to any individual in aquatic populations of organisms would be unlikely to have any detrimental effects at the population level [U12]. Other benchmark dose rates have been derived, mainly for guiding efforts to protect the environment [A10, G2, I22]; these are broadly consistent with those provided by the Committee.

193. The Committee has examined the impact of the FDNPS accident on non-human biota inhabiting terrestrial, freshwater and marine ecosystems. Its assessment was largely based upon measured data provided to the Committee, other relevant reports, and published scientific papers. The radiation exposures were considered in terms of the intermediate phase after the accident (approximately the first two months) and the late phase (months to years). The areas considered in detail were some of the more affected areas of Fukushima Prefecture and any neighbouring prefectures within approximately 100 km of the FDNPS site, covering a land area of 7,000 km^2 and extending to 30 km off the coast. Further details of the methods used to estimate exposures dose estimation, the associated uncertainties and results can be found in appendix F.

B. Exposure and effects

1. Terrestrial ecosystems

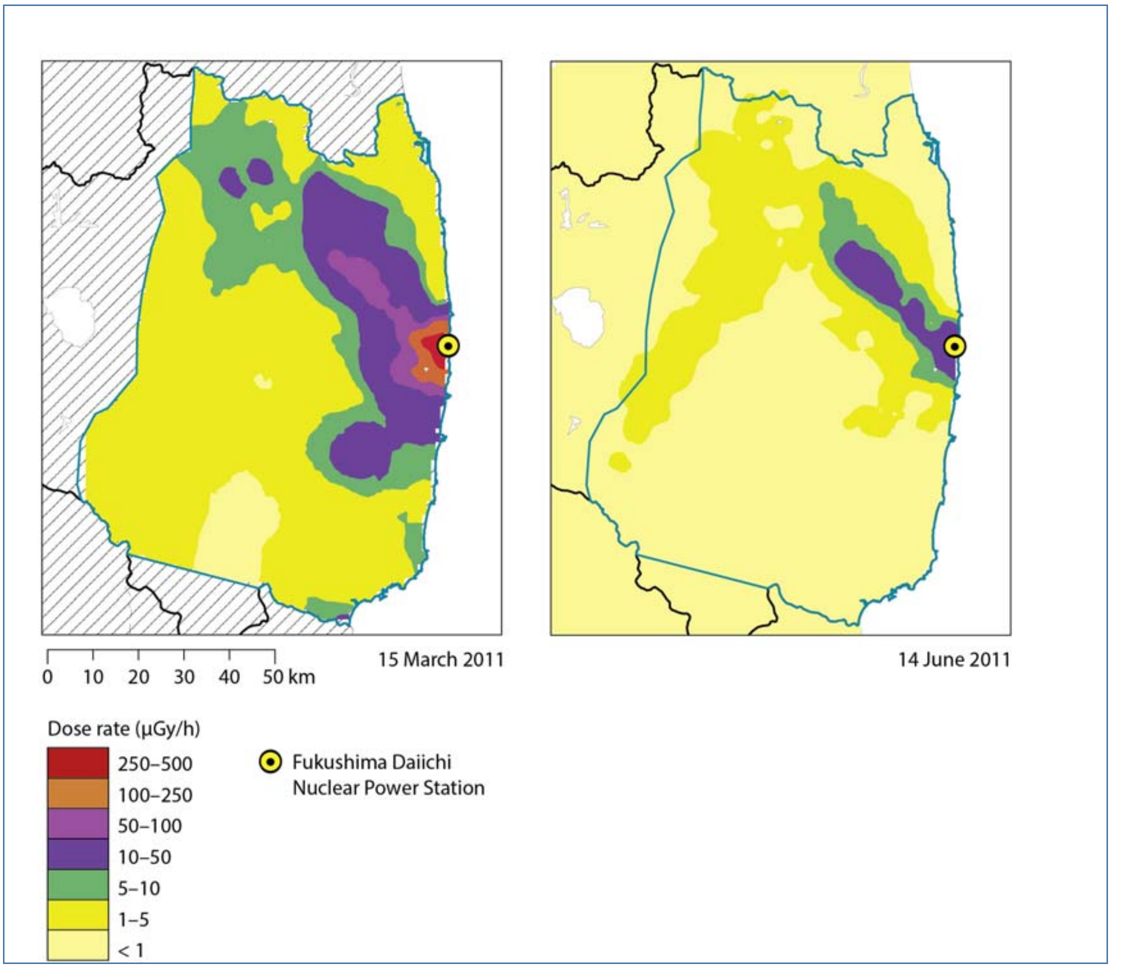
194. An interpolated map of estimated weighted[26] absorbed dose rates from internal and external exposure for a large mammal is provided in figure X.

195. From measured radionuclide concentrations in animals corresponding to the late phase of the accident (June 2011), terrestrial mammals and birds were estimated to have been exposed to dose rates between 1.2 and 2.2 µGy/h in areas encompassing most of the range of ^{137}Cs deposition densities. These dose rates are approximately one order of magnitude greater than those from naturally occurring radionuclides in the environment [B5]. Dose rates of 300 µGy/h have been estimated for soil-dwelling organisms in areas of high deposition density such as Okuma Town during the earlier intermediate phase. Inclusion of the very short-lived radionuclides, ^{132}Te and ^{132}I, indicates that dose rates may have been as high as 1 mGy/h (1,000 µGy/h) for some organisms over short periods (hours to days). While

[26] Weighted to account for radiation quality (see paras. 122-129 of annex E to the UNSCEAR 2008 Report [U12]).

higher than the benchmark level of 100 μGy/h, these dose rates are unlikely to have resulted in observable effects on populations; and any effects would have been transient in nature [U12].

Figure X. Map of interpolated estimates of weighted absorbed dose rates for a large mammal



196. For the late phase after the accident, a potential risk of effects on individuals of certain species, especially mammals, may exist in areas of relatively high deposition density but observable population effects for terrestrial biota are considered unlikely. Nonetheless, changes in biomarkers of various types cannot be ruled out, especially in mammals [G5], and such effects may persist in the late phase for areas of highest deposition density.

197. A few field studies have reported effects in areas affected by FDNPS releases, such as decreases in bird and insect populations [M22, M23] and morphological and genetic disturbances in butterflies [H6]. The relationship between exposure and effect has not been unequivocally established in these studies. Furthermore, the observations are not consistent with the Committee's assessment and suggest that further analysis is needed to establish whether radiation exposure was an important factor, among many others, including the impact of the tsunami itself, in causing the environmental effects observed.

2. Aquatic ecosystems

198. *Freshwater ecosystem.* Although dose rates calculated for freshwater fish were in some cases more than an order of magnitude above the natural background level (see [H13]), they did not reach threshold levels pertaining to chronic exposures above which observable effects in freshwater biota are expected.

199. *Marine ecosystem*. For coastal locations where biological samples were available, dose rates in the period 10 May 2011 to 12 August 2012 were low relative to the benchmarks. The highest dose rates, from compiled arithmetic means of dose rates to all organism groups, were in the range of 0.10-0.25 µGy/h. Such levels were commensurate with background dose rates in the marine environment [H13].

200. The highest dose rates were calculated from estimated concentrations in seawater for the intermediate phase of the accident (before 10 May 2011, when biological samples were not available), using a dynamic model for the northern drainage channel near the FDNPS site. For fish, the maximum estimated dose rate occurred within the first month (approximately 140 µGy/h), and the accumulated dose over 1 year was approximately 0.32 Gy. Maximum calculated exposures for macroalgae (exceeding 20 mGy/h) at the same location occurred at 23 days after the accident, but fell rapidly, with ^{131}I being the dominant component. The accumulated dose for macroalgae over 1 year was approximately 7 Gy. Comparisons with reported benchmarks [G2, I22, U6] indicate that the calculated doses, with the exception of the transient exposures for macroalgae at locations very close to the discharge point, were substantially below those where observable effects on populations would be expected.

201. As of August 2012, marine fish were still being found with radionuclide concentration levels above the Japanese regulation value of 100 Bq/kg (fresh weight) for sale and human consumption [B24]. Although such a level may be of relevance to radiation protection of the public, the corresponding dose rates for non-human biota are insignificant, falling far below any relevant benchmarks.

202. The Committee concluded that the possibility of effects on non-human biota in both the terrestrial and aquatic (freshwater and marine) environments was geographically constrained and that, in areas outside of that considered by this assessment, the potential for effects on biota may be considered insignificant. The Committee also noted that releases to the marine environment were ongoing at the end of December 2013; this may warrant further follow-up of exposures and trends in the coming years.

VIII. SUMMARY AND CONCLUSIONS

203. In the afternoon of 11 March 2011 a magnitude 9.0 earthquake struck Japan. This was followed within the hour by the first of a series of tsunami waves that hit the coast of the Tōhoku region of northern Honshu. The natural disaster (referred to as “the 2011 great east-Japan earthquake and tsunami”) left devastation in its path, including the loss of 20,000 lives and damage to infrastructure, economy and society. It also led to severe damage to the Fukushima Daiichi Nuclear Power Station (FDNPS), including core melt in the three reactors in operation at the time and large releases of radioactive material to the atmosphere and the Pacific Ocean. The rapid accident progression at FDNPS prompted “precautionary evacuation” (within days) of the population living close to the plant (mainly within the 20-km zone) and subsequent “deliberate evacuation” (within weeks up to few months) of people living further afield in areas where the deposition density of radioactive material were high.

204. This scientific annex to the Committee's report to the General Assembly records the results of the Committee's assessment of the levels of radiation exposure due to the nuclear accident at FDNPS, and discusses the implications for the health of people exposed and for non-human biota in the environment. The Committee considered the dispersion and deposition of radionuclides in the environment, public and worker exposures, health risks and effects, and exposures and effects in non-human biota; it also identified a number of issues requiring future research and study.

205. The Committee formally used data requested from the Government of Japan, published data, and other datasets available to it up to September 2012 (18 months after the accident); some more recent information was taken into account when particularly relevant. The Committee notes that significant challenges remain to remove spent and damaged fuel, to decommission the facility and to perform remedial work on and off the FDNPS site. Releases of radioactive material to the Pacific Ocean are still ongoing at the time of publication of this report. Significant health surveys of the public and workers are ongoing and will continue for many years. The Committee considers it will be appropriate to re-evaluate the exposures and effects of radiation following the accident at FDNPS in due course. This approach is consistent with the Committee's several re-evaluations over more than two decades following the Chernobyl accident [U4, U7, U8, U12].

A. Basis for dose estimates

206. The Committee reviewed existing estimates of atmospheric releases for ^{131}I and ^{137}Cs (the two most significant radionuclides from the perspective of exposures of people and the environment); these range generally from 100 to 500 petabecquerels (PBq) and from 6 to 20 PBq, respectively. The averages of the published estimates are about 10% and 20%, respectively, of the corresponding atmospheric releases estimated for the Chernobyl accident. On a number of occasions, the meteorological conditions were such that radioactive material released to the atmosphere was dispersed over mainland Japan and radioactive material was deposited on the ground by means of *(a)* dry deposition and *(b)* wet deposition with rain and snow. The main deposition occurred to the north-west of the FDNPS site, but significant deposition also occurred to the north, south and west of the FDNPS site.

207. In general, the Committee relied on measured deposition as a basis for its estimates of doses due to external exposure and doses due to inhalation. Doses due to ingestion were estimated mainly on the basis of available information on concentrations of radionuclides in food and drink. In order to estimate doses where measurement data were unavailable for the periods when exposures occurred (e.g. for precautionary evacuated individuals from mainly the 20-km zone) or could no longer be obtained, the Committee used an estimate of the source term, results from atmospheric transport, dispersion and deposition modelling (ATDM) and knowledge of accident progression. For this purpose, the Committee relied on a published source term, where the releases of the radiologically dominant radionuclides ^{131}I and ^{137}Cs were 120 and 8.8 PBq, respectively. While at the lower end of the range of published estimates and possibly an underestimate of the total release, the Committee assessed this source term as appropriate for estimating doses incurred as a result of dispersion over the land mass of Japan, i.e. relevant for estimating doses to the Japanese population.

208. In contrast to the dose assessment for the public where it was possible to use a large number of independent sources of relevant information (e.g. data on concentrations of radionuclides in the environment), the Committee had to rely on data provided by TEPCO, contractors and subcontractors and the Japanese authorities for the assessment of doses to workers. Information on doses due to

external and internal exposure for more than 20,000 workers (TEPCO workers, contractors and subcontractors) at FDNPS was made available to the Committee. In addition, doses to other worker categories irradiated during work to stabilize the reactors and prevent releases, as well as more generally during activities both on-site and off-site, were made available. This included doses incurred by non-Japanese personnel involved, for example, in activities aimed at restoring essential infrastructure that had been damaged by the earthquake and tsunami. Details of the methodology to estimate doses were supplied to the Committee, which enabled the Committee to assess whether the methods were fit for purpose.

B. Public exposures

209. The Committee estimated exposure of the general public to ionizing radiation using the quantity effective dose, expressed in millisieverts (mSv). The Committee also estimated organ-specific absorbed doses, expressed in milligrays (mGy), to a number of organs. The estimates were made for 20-year-old adults (representing all adults), 10-year-old children (representing all children older than 5-years old) and 1-year-old infants (representative of infants 0–5 years old). Measured deposition densities for different locations within a district, which were used to calculate doses for non-evacuees, varied from between 30–50% of the district average, to two to three times the district average. For evacuees where the dose estimates were based on the ATDM results, the values may have been under- or overestimated by a factor of about four because of the choice of source term and ATDM. It is likely that some overestimation has been introduced generally by the methodology used by the Committee (e.g. in the assumptions on protective measures). Comparison between the Committee's estimates of doses due to internal exposure and estimates based on a limited number of in vivo whole-body and thyroid measurements that were conducted in a timely manner supports this view.

210. The Committee estimated effective doses for the first year following the accident for typical residents of evacuated settlements and for non-evacuated districts and prefectures of Japan (see table 10). The average effective doses for adults in evacuated and non-evacuated areas of Fukushima Prefecture, caused by the releases from FDNPS, range from a few up to about ten millisieverts. The effective doses for 10-year-old children and 1-year-old infants were estimated to be about twice as high. For neighbouring prefectures and for the rest of Japan, doses were lower. To provide context, the average effective dose received annually in Japan from natural background radiation is about 2.1 mSv.

211. Average absorbed doses to the thyroid among those most exposed ranged up about 35 mGy for adults and up to about 80 mGy for a 1-year old (table 10). This is significantly higher than absorbed doses to the thyroid from natural background radiation; the average annual absorbed dose to the thyroid from naturally occurring sources of radiation is typically of the order of 1 mGy. Absorbed doses to the thyroid were considerably lower in less affected areas of Japan.

212. The Committee estimated settlement-average absorbed doses to the red bone marrow of 1-year-old evacuees to be up to 10 mGy, and in the non-evacuated areas, district-average doses were estimated to be up to about 6 mGy. For girls and women who had been evacuated, the settlement-average absorbed doses to the breast were estimated to be up to about 10 mGy for all age groups. Doses to the foetus and breast-fed infants were not explicitly estimated but would have been approximately the same as those to adults and 1-year-old infants, respectively.

Table 10. Estimated district or prefecture-average effective doses and absorbed doses to the thyroid for the first year following the accident for typical residents of evacuated settlements and non-evacuated areas of Japan

The doses are in addition to the background doses due to natural sources of radiation. The estimates were intended to be characteristic of the average dose received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations. They may overestimate actual average doses because of assumptions made where data were inadequate (see sections E and F of chapter IV)

Residential area	*Effective dose (mSv)*		*Absorbed dose to the thyroid (mGy)*	
	Adults	*1-year old*	*Adults*	*1-year old*
EVACUATED SETTLEMENTS				
Precautionary-evacuated settlements (towns of Futaba, Okuma, Tomioka, Naraha and Hirono, and parts of cities of Minamisoma, Namie and Tamura and villages of Kawauchi and Katsurao)	1.1–5.7	1.6–9.3	7.2–34	15–82
Deliberately-evacuated settlements (for Iitate Village and parts of Minamisoma City, the towns of Namie and Kawamata and of Katsurao Village)	4.8–9.3	7.1–13	16–35	47–83
AREAS NOT EVACUATED				
Non-evacuated districts of Fukushima Prefecture	1.0–4.3	2.0–7.5	7.8–17	33–52
Prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate	0.2–1.4	0.3–2.5	0.6–5.1	2.7–15
Remaining prefectures of Japan	0.1–0.3	0.2–0.5	0.5–0.9	2.6–3.3

213. The Committee also projected district-average and prefecture-average doses for the three age groups integrated over the first 10 years after the accident and up to an age of 80 years. Generally, the district-average or prefecture-average effective doses that would be incurred over the first 10 years were estimated to be up to twice the doses in the first year, and those incurred up to an attained age of 80 years are up to three times higher, if no remediation were to take place (such activities would reduce exposures in the long term). To provide context, 80-year cumulative doses from background exposure to natural sources of radiation in Japan are on the average about 170 mSv.

214. The evacuation of the population living within the 20-km zone considerably reduced doses to the evacuees. The Committee estimated that effective doses thus averted ranged up to 50 mSv for adults; the absorbed doses to the thyroid of 1-year-old infants averted by evacuation ranged up to about 750 mGy.

C. Worker exposures

215. By the end of October 2012, about 25,000 workers had been involved in emergency work and other activities at the FDNPS site. The average effective dose to these workers over the first 19 months after the accident was about 10 mSv. About 34% of the workforce received effective doses over this

period above 10 mSv, while 0.7% of the workforce (corresponding to 173 individuals) received effective doses more than 100 mSv; the maximum effective dose reported was 679 mSv.

216. The Committee conducted assessments of the doses due to internal exposure for twelve workers (out of a total of thirteen[27]) who had committed effective doses due to internal exposure higher than 100 mSv, with the aim of judging the reliability of the doses reported for these workers. The Committee confirmed that they had received absorbed doses to the thyroid due to inhalation of ^{131}I in the range of 2 to 12 Gy.

217. Overall, the dose assessments made by TEPCO for its workers were suitable for the assessment of effects on health. The dose estimates were, however, associated with uncertainty, in particular for the early phase of the accident (days to few weeks) where personal radiation monitors were scarce. In addition, in vivo monitoring in general began too late to make reliable estimates of the contribution of shorter-lived radionuclides such as ^{132}Te and ^{133}I. Further work is needed to fully characterize occupational exposures during the very early stages of the accident.

D. Health implications for the public and for workers

218. No acute health effects (i.e. acute radiation syndrome or other deterministic effects) had been observed among the workers and the general public that could be attributed to radiation exposure from the accident. The most important health effects observed so far among the general public and among workers were considered to be on mental health and social well-being, relating to the enormous impact of the earthquake and tsunami, causing loss of family and friends and loss of livelihood and necessitating evacuation; and the impacts of the nuclear accident, including not only further evacuation and loss of livelihood, but also fear and stigma related to real and perceived health risks associated with ionizing radiation. Estimation of the occurrence and severity of such health effects is outside of the Committee’s remit but information relevant to mental and social well-being remains important when considering the total health impact of the accident at FDNPS.

219. Risks for stochastic health effects (such as cancer) are reasonably well quantified for doses that are considerably larger than those estimated for the vast majority of the people (public and workers) irradiated due to the accident at FDNPS. Where such estimated risks of disease are sufficiently large in a large enough exposed population, compared to the normal statistical variability in the baseline incidence of the disease in that population, an increased incidence due to irradiation may be discernible in the disease statistics. Conversely, when risks are small or may only be inferred on the basis of existing knowledge and risk models, and/or the number of people exposed is small, the Committee has used the phrase “no discernible increase” to express the idea that currently available methods would most likely not be able to demonstrate an increased incidence in disease statistics due to radiation exposure. This does not rule out the possibility of future excess cases or disregard the suffering associated with any such cases should they occur.

[27] Following the Committee’s independent assessment of doses for the 12 most exposed workers, the relevant Japanese organizations reviewed their estimates of dose due to internal exposure in July 2013; this resulted in the identification of one further TEPCO worker with a committed effective dose greater than 100 mSv (i.e. there were then 13 workers in total with doses due to internal exposure in excess of 100 mSv). The Committee did not make an independent assessment of the dose due to internal exposure for this thirteenth individual owing to the late acquisition of this information.

1. Public health implications

220. The average first-year effective doses to evacuees and to the population in the non-evacuated areas most affected by the accident were estimated to be in the range from about 1 to 10 mSv for adults and about twice as large for a 1-year old. Risk models, by inference, suggest a small increased risk of cancer for such doses; however, any overall increase in disease incidence in the general population due to radiation exposure from the accident would be too small to be observed against the lifetime baseline risk for members of the Japanese population (which, for all solid cancers, is on the average 35%, although this figure is subject to individual variation related to sex, lifestyle and other factors).

221. Notwithstanding the above, previous experience indicates that the relative risks for certain cancers in certain population groups (notably following exposure as foetus, or during infancy and childhood) are higher than for the population average.

222. *Thyroid cancer* later in life following exposure to radioiodine during infancy and childhood is of high relevance in this regard. For 1-year-old infants, settlement-average absorbed doses to the thyroid among the population that underwent precautionary evacuation were estimated to be up to about 80 mGy. The uncertainties around the estimates of average doses based on the ATDM results suggest that higher doses were possible; however, data from in vivo thyroid monitoring indicate that the average absorbed doses to the thyroid may have been overestimated by up to a factor of five. Most of the doses were in a range for which an excess incidence of thyroid cancer due to radiation exposure has not been confirmed. However, absorbed doses to the thyroid towards the upper bounds could among sufficiently large population groups lead to a discernible increase in the incidence of thyroid cancer. Information on dose distributions was not sufficient for the Committee to draw firm conclusions as to whether any potential increased incidence of thyroid cancer would be discernible among those exposed to higher thyroid doses during infancy and childhood. The occurrence of a large number of radiation-induced thyroid cancers in Fukushima Prefecture—such as occurred after the Chernobyl accident—can be discounted, because absorbed doses to the thyroid after the FDNPS accident were substantially lower than those after the Chernobyl accident.

223. For *leukaemia*, the Committee considered the risk to those exposed as foetuses during pregnancy, and during infancy and childhood. The Committee also considered risks of *breast cancer*, in particular for those exposed at young ages. Based on assessed doses and available risk estimates, the Committee does not expect discernible increases in the incidence of these diseases among those groups.

224. The Committee does not expect any increase in spontaneous abortion, miscarriages, perinatal mortality, congenital effects or cognitive impairment resulting from exposure during pregnancy. In addition, the Committee does not expect any discernible increase in heritable disease among the descendants of those exposed from the accident at FDNPS.

225. The Fukushima Health Management Survey of about 2 million residents has been launched to monitor the long-term health of residents of Fukushima Prefecture (including a pregnancy and birth survey), to promote their future well-being, and to examine whether long-term low-dose-rate radiation exposure has unexpected health effects. Thyroid ultrasound examinations are to be made for all children in Fukushima Prefecture (about 360,000) who were aged 18 years or less on 11 March 2011 and are expected to be completed within 3 years (by March 2014). The ongoing ultrasonography survey in Fukushima Prefecture has detected relatively large numbers of thyroid anomalies, corresponding to similar surveys in areas unaffected by the accident at FDNPS. The ongoing ultrasonography survey in Fukushima Prefecture is expected to detect relatively large numbers of thyroid abnormalities (including a number of cancer cases) that would not normally have been detected without such intensive

screening. Surveys of thyroid cancer incidence in populations of areas unaffected by the accident would provide useful input to estimates of the impact of such intensive screening.

2. Health implications for workers

226. For most of the about 25,000 workers (99.3% as of 31 October 2012) involved in emergency work and other activities, the effective doses reported were less than 100 mSv, with an average of about 10 mSv. Risk models indicate low risks (but increasing with dose) for diseases due to radiation exposure at such doses. For the 173 workers that were estimated to have received effective doses of more than 100 mSv (average about 140 mSv), predominantly due to external irradiation, risk estimates correspond to about two to three additional cases of cancer in addition to about seventy cancers that would occur spontaneously given the lifetime baseline risk for solid cancer of about 40%; however, such predictions are associated with significant uncertainties and any increased cancer incidence in this small group may not be discernible against the variability of cancer incidence. No increase in other disease is expected in this group of workers; note, however, that the Committee could not estimate the risk of cataract from exposure of the lens of the eye to beta radiation.

227. For the thirteen workers[27] who were estimated to have received absorbed doses to the thyroid from ^{131}I in the range of 2 to 12 Gy, an increased risk of developing thyroid cancer can be inferred. However, the numbers exposed are likely too small to discern an increased incidence in thyroid cancer. Given uncertainties in the estimated doses, the possibility of thyroid disorders (e.g. hypothyroidism) in the most exposed workers cannot be totally precluded, but the likelihood of them occurring is low.

228. Workers who received effective doses greater than 100 mSv are being specially examined, including annual examinations of the thyroid, stomach, large intestine and lungs for potential late radiation-related health effects. Ultrasonography surveys and close medical surveillance of these workers would result in increased detection of thyroid cancer (and possibly cases of other cancers); the overwhelming majority of the cases detected are expected to have developed independently of radiation exposure.

E. Radiation exposures and effects on non-human biota

229. The doses and associated effects of radiation on non-human-biota following the accident were evaluated by comparing with the Committee’s generic evaluations of such effects that were conducted before the accident. Exposures of both marine and terrestrial non-human biota following the accident were, in general, too low for acute effects to be observed, though there may have been some exceptions because of local variability. In general:

(a) Effects on non-human biota in the marine environment would be confined to areas close to where highly radioactive water was released into the ocean;

(b) Continued changes in biomarkers for certain terrestrial organisms, in particular mammals, cannot be ruled out but their significance for population integrity is unclear. Any radiation effects would be constrained to a limited area where the deposition density of radioactive material was greatest; beyond this area, the potential for effects on biota is insignificant.

F. Future scientific research needs

230. Similar to the experience of the Chernobyl and Three Mile Island accidents, the next years and decades will continue to provide more information on the factors contributing to the accident progression, the releases to the environment, the resulting exposures to the public, workers and the environment, and the associated health risks. The Committee is aware that close to three years after the accident, the collective effective doses to workers on site are inevitably increasing, radioactive water is leaking on the site, and groundwater is transporting radionuclides into the aquatic environment (although control measures are being put in place). Scientific research will be desirable to extend, corroborate and increase confidence in the Committee's evaluations. Some of the key priorities for scientific research are to:

(a) Improve estimates of the amount and characteristics of releases to the atmosphere as a function of time, based on better understanding of the accident progression, the weather conditions during the releases and the use of model predictions to reconstruct the atmospheric transport, dispersion and deposition patterns;

(b) Continue to measure and improve the characterization of the leaks of radioactive water and releases to the aquatic environment, including groundwater and ultimately the Pacific Ocean, over time; and forecast and quantify the long-term transport and mixing of these releases and the consequent exposures through aquatic pathways;

(c) Continue to measure the dose rates due to external exposure to deposited material, forecast and track changes over time, and quantify the impact of environmental remediation programmes;

(d) Better characterize distributions of doses to the public expressing variability between individuals, using probabilistic approaches, available data and appropriate models (this would include further consideration of individual behaviours, detection limits, sampling procedures and the distributions of measurement results), and better quantify the uncertainties in the dose estimation;

(e) Further conduct in vivo measurements of radionuclides in people to support refinement in the estimation of doses and their distributions, and to estimate current and future levels of exposure;

(f) Continue the ongoing health survey in Fukushima Prefecture; continue the ultrasonographic survey of children in Fukushima Prefecture based on the current protocol; analyse and quantify the impact of this screening on the apparent incidence rates of thyroid cancer in Fukushima Prefecture (surveys of thyroid cancer incidence in areas unaffected by the accident would be useful in this regard); consider the feasibility of establishing a cohort for epidemiological study with members whose individual doses could be adequately assessed;

(g) Quantify the uncertainties in reported doses to workers considering the work histories of individual workers during the early days of the accident, the time-varying levels of radionuclides (including short-lived radionuclides) and ambient dose equivalent rates where they worked and rested, the reliability of dose estimates based on shared personal dosimeters, and the protective measures taken by individual workers; estimate absorbed doses to the lens of the eye for workers involved in on-site mitigation activities (and associated uncertainties) in order to assess the risk of cataracts; conduct further investigations to assure the quality of the effective dose estimates reported by contractors;

(h) Consider establishing a tissue bank for *(a)* unexposed workers and *(b)* workers who had effective doses greater than 100 mSv, and subsequently underwent surgery for possible use in future investigations;

(i) Measure and assess the environmental exposures typical for certain species of non-human biota; and further analyse whether radiation exposure was an important factor in causing environmental effects that were reported in field studies but were inconsistent with the Committee's assessment.

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[28] Until mid-2013, owing to a major change in career.

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APPENDIX A. DATA COMPILATION

I. INTRODUCTION

A1. The Government of Japan and 25 other Member States of the United Nations responded to the Committee's request for information[29] and provided extensive datasets. The Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO), the Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), the World Health Organization (WHO) and the World Meteorological Organization (WMO) also made available data, analysis and expertise.

A2. This appendix summarizes the data compiled by the Committee for its assessment. It outlines the main sources of data, how these data were compiled, the processes used by the Committee to assure sufficient quality of the data for the purpose of the assessment, and the Committee's views on the quality of the data. The data themselves are presented in electronic form as attachments.

A3. The Committee also drew upon other relevant information and analysis published in peer-reviewed scientific journals or other publication formats as appropriate. This material and its interpretation and use by the Committee is not summarized in this appendix, but is cited and addressed, as appropriate in the relevant technical appendices that describe the Committee's assessment in detail.

[29] The Netherlands, although not requested, voluntarily submitted data to the secretariat.

II. DATA COMPILATION AND QUALITY ASSURANCE

A4. The Committee designated experts to be responsible for reviewing and analysing data, conducting assessments and delivering quality-assured contributions to its main report and the supporting appendices.

A5. A list of data requirements (confined to those data that were or could be available before the 10 March 2012) was submitted to the Government of Japan, other selected United Nations Member States, and several international organizations. The Government of Japan and 25 other Member States submitted information to the Committee in response. After reviewing these materials, the Committee made requests for supplemental information or for clarification of information or datasets previously submitted. Many Japanese ministries, commissions, agencies, prefectures, universities and non-governmental organizations provided information and data. Organizations contributing information or data to this assessment are acknowledged in section III of this appendix. The datasets provided to the Committee through this process and used for the assessment are summarized in table A1. In this table, datasets are classified as either primary or secondary: *(a)* primary denotes that the dataset was used to provide direct input into the Committee's analysis or calculations; and *(b)* secondary denotes that the dataset was used to cross-check and compare with the results of the Committee's analysis or calculations. Some datasets were classified as both primary and secondary; they were used to provide input to one part of the Committee's assessment and to cross-check another part.

A. Submitted datasets

A6. Datasets received upon request were uploaded together with their metadata (descriptive information) into a restricted online workspace on an electronic collaboration platform. Some datasets related to the measurements performed in workers were provided to the secretariat and a few authorized experts on a confidential basis. These datasets were not shared generally nor are they published here, because they contain medically-confidential information. Nevertheless they provided important and useful insights to the experts conducting the analysis on behalf of the Committee.

A7. The Committee made arrangements for each dataset received to be reviewed for its relevance and scientific quality. If the originator of the dataset provided sufficient information and assurance on how the data were collected, what protocols were followed, what technical specifications were implemented to ensure that high quality and reliable data were obtained, and what quality control procedures were performed, then no additional quality assessment by the Committee was deemed necessary. If the originator of the dataset did not or could not submit sufficient or accurate information to provide assurance about the quality of their data, the Committee made arrangements for the dataset to undergo additional scrutiny. For example, where it was possible, datasets were compared and cross-checked with datasets from other sources. Table A1 includes brief general comments on the quality of each dataset. The criteria used to assess data quality varied across the datasets and no single set of criteria could be applied to all of them. Only information that was deemed of acceptable quality and fit for the purpose of the Committee's assessment was used.

B. Radionuclide releases and dispersion

A8. To assess the releases of radionuclides from the Fukushima Daiichi Nuclear Power Station (FDNPS) to the atmosphere and to the ocean, the Committee largely relied on analyses conducted by others and published in the peer-reviewed literature. These analyses made use of environmental measurements of ambient dose equivalent rates, of concentrations of radionuclides in the air, in seawater and sea sediments, and of deposition densities on the ground surface made during the release and afterwards. (These data were also used by the Committee both as primary and secondary datasets.) The Committee reviewed these analyses, as well as other analyses that had been made publicly available but had not been subject to peer review (e.g. some very early analyses published in press releases), and came to a view about the ranges of likely releases of the radiologically significant radionuclides generally considered in its assessment. The literature reviewed is cited in appendix B.

A9. To provide an input into the assessment of doses to the public and workers, the Committee adopted one of the peer-reviewed estimates of the releases to atmosphere of the radionuclides ^{131}I and ^{137}Cs. To estimate releases of other radiologically significant radionuclides to atmosphere, the Committee used *(a)* estimates of the inventories of radionuclides in each of the reactors of Units 1-3 of FDNPS at the time of shutdown, provided by the Japan Atomic Energy Agency (JAEA), and *(b)* measurements in air samples made in Japan and global measurements of radionuclide concentrations in air that it had requested from CTBTO.

A10. Measurements of radionuclide concentrations in air made within the International Monitoring System of the CTBTO followed clear, documented, standardized protocols and were considered high quality data. However, the CTBTO monitoring system and procedures are tailored for detecting traces of radioactive material from clandestine nuclear tests and were not per se appropriate for monitoring comparatively high levels of radionuclides following a reactor accident. The data on radionuclide concentrations in air received from CTBTO were thus reviewed internally under arrangements made by the Committee taking into account detailed descriptions of sampling, measurement and analysis methods applied by the CTBTO monitoring system.

A11. To gain an understanding of the transport and dispersion of radionuclides released to the ocean, the Committee reviewed the data on measurements of radionuclides in seawater and in sea sediments made by the Tokyo Electric Power Company (TEPCO) and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), and the results of analysis and modelling carried out by others and published in the peer-reviewed literature. To gain an understanding of the transport and dispersion of radionuclides released to the atmosphere and, in particular of the influence of meteorological data and analyses, the Committee received input from a task team of WMO. The task team evaluated meteorological analyses by comparing measurements of concentrations of radionuclides in air and of deposition densities of radionuclides deposited on the ground with calculations made for an assumed release using each participating organization's own atmospheric transport and dispersion model (ATDM) and meteorological analysis data fields available to it, supplemented by higher spatial and temporal resolution fields provided by the Japan Meteorological Agency (JMA). The performance of the model–meteorology combinations was evaluated using a number of statistical measures. Further details can be found in a report on this work prepared by the task team [W17, W18]. On the basis of this analysis, one of the better performing ATDM–meteorology combinations was used to provide estimates of concentrations in air and deposition densities of radionuclides released to atmosphere from FDNPS. These estimates were used to supplement the measurement data in assessing doses to the public (see below and appendices B and C for further details).

C. Assessment of doses to the public

A12. Data required for the assessment of doses to the public and non-human biota included: deposition densities of radionuclides on the ground; radionuclide concentrations in air, soil, water (freshwater and marine), drinking water, food, biota (vegetation, terrestrial biota, marine biota, and wildlife), and freshwater and marine sediments; ambient dose equivalent rates; in vivo measurements of activity in the human body (including whole body and thyroid); population demographics; foodstuff consumption; occupancy factors; dose reduction factors (location factors); land use; background levels of ambient dose equivalent rates and radionuclide concentrations in the environment; and information on protective measures.

A13. During the review process most data were reformatted to be suitable for the dose assessment calculations, for combination with other datasets, or for visualization in a range of Geographic Information Systems (GIS-software). The visualization process enabled checking to ensure that data points were valid, for example, that marine samples were correctly reported for marine locations. Some datasets required conversion of units. All data reformatting or manipulation was checked by a second person to ensure the integrity of the data was maintained and conversions were correct.

A14. For areas in Fukushima Prefecture where no measured data were available, the data from ATDM were utilized. Modelled data were provided in Network Common Data Form (NetCDF), and a script was developed to extract data into an Excel®-compatible format. Subsets of these data were then extracted to match the MEXT spreadsheets (see appendix C). All data manipulations were cross-checked by a second person.

A15. Derived datasets were also produced during the quality assurance process. These included the MEXT datasets on ground deposition density that were combined with population density data. The procedures utilized to derive and check these datasets are detailed in appendix C and associated attachments. After review, all datasets were cleared for use in the dose assessments using the methodologies described in appendices C and F. Subsequent checks and quality assurance of the results produced from the assessments are generally described in these appendices and their attachments.

D. Assessment of doses to workers

A16. In contrast to the dose assessment for the public where it was possible to use a large number of independent sources of relevant information, the Committee had to rely on data provided by TEPCO, contractors and subcontractors and the Japanese authorities for the assessment of doses to workers. It was necessary to judge the extent to which the individual doses reported in Japan provided an accurate and reliable measure of the doses actually incurred. Moreover, it was not feasible for the Committee to review or reassess the assessments of dose to each of the approximately 25,000 workers involved. Therefore, the Committee adopted a two-stage approach: first, it reviewed the methodologies used in Japan for assessing doses; second, it made independent dose assessments for defined groups of workers, and compared its estimates with the values reported in Japan for these workers. The starting point for the Committee’s assessment was therefore to review data on the doses to FDNPS workers from internal and external exposure as reported by their employers.

A17. Following requests to the Government of Japan, TEPCO, JAEA and the Japanese National Institute of Radiological Sciences (NIRS), provided detailed information to the Committee on instruments, measurement systems, calibration phantoms and methodologies used for in vivo monitoring, and on measurement data for selected workers (the dataset of reported doses was supplemented by data in spreadsheet form on the individual monthly and cumulative doses from internal and external exposures reported for 21,776 TEPCO and contractors' workers up to April 2012).

A18. The Committee compared its estimates of doses, the doses estimated by NIRS and TEPCO, and the doses reported formally. Appendix D gives more detailed results, including the contribution made by intakes of ^{131}I to the absorbed dose to the thyroid and to the effective dose.

A19. This comparative approach could not be used to validate reported results of external exposure assessments because they were made from personal dosimeter readings which could not be independently verified on an individual basis. Therefore, information provided by TEPCO on personal dosimeters, technical standards, calibration methods and the system used for allocating personal dosimeters to individuals (as described in appendix D) was reviewed and evaluated.

Table A1. Datasets provided to the Committee that were used for the assessment

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Measured radioactivity in air	Tabulated data from selected stations for the time period. Measurements of particulate ^{95}Nb, ^{99}Mo, ^{110m}Ag, ^{113}Sn, ^{129}Te, ^{129m}Te, ^{132}Te, ^{131}I, ^{133}I, ^{136}Cs, ^{137}Cs and ^{140}Ba at 38 stations between 15 March and 24 May 2011	Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)	Primary Input to nuclide spectrum and source term	Officially provided by CTBTO as issued in its specific “Radionuclide Reviewed Reports” The full CTBTO internal quality assurance system applied and this was also checked by the Committee. The Committee deemed these datasets acceptable and fit for purpose. Data are confidential. Data used by the Committee have been declassified (attachment B-1)
Measured radioactivity in air	Air filter samples over the period of 15 to 20 March 2011 from NIES site, Tsukuba City, Ibaraki, double filter (quartz and activated carbon filters), high-resolution Germanium detector	KEK High Accelerator Research Organization, National Institute for Environmental Studies (NIES), Ibaraki	Primary Input to source term and its nuclide composition	Datasets extracted from [K5] The Committee reviewed this dataset and considered it acceptable and fit for purpose
Measured radioactivity in air	Measurement of particulate radionuclides (^{99m}Tc, ^{132}Te, ^{129}Te, ^{129m}Te, ^{131}I, ^{132}I, ^{133}I, ^{134}Cs, ^{136}Cs, ^{137}Cs), and gaseous (^{131}I, ^{132}I, ^{133}I) concentrations in air at JAEA site in Tokai-mura	Japan Atomic Energy Agency (JAEA)	Primary Input to deriving nuclide spectrum of source term, including radioiodine and its chemical speciation Secondary Used to compare with ATDM calculations	Data taken from [F7, O2] The Committee reviewed this dataset and considered it acceptable and fit for purpose
Measured radioactivity in air	Data from high quality, continuous air sampling at the Yokota Air Base, which provided measurements of daily concentrations in air of ^{99}Mo, ^{99m}Tc, ^{86}Ru, ^{106}Ru, ^{102}Rh, ^{129}Te, ^{129m}Te, ^{131m}Te, ^{132}Te, ^{130}I, ^{131}I, ^{132}I, ^{133}I, ^{134}Cs, ^{136}Cs, ^{137}Cs and ^{140}La over the period 11 March 2011 to July 2011	United States Air Force via United States Department of State	Secondary Input to source term assessment and public dose assessment	Datasets extracted from [U17] Subsequent quality checks and reformatting conducted. The Committee reviewed this dataset and considered it acceptable and fit for purpose
Measured radioactivity in air	Measurements of daily concentrations in air of ^{99}Mo, ^{99m}Tc, ^{129}Te, ^{129m}Te, ^{131m}Te, ^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{134}Cs, ^{136}Cs, ^{137}Cs carried out over the period 13 March 2011 to 10 April 2011 at Setagaya, Tokyo	Tokyo Metropolitan Government/ Bureau of Industrial and Labour Affairs	Secondary Input to public dose assessment	Summarized radionuclide sampling data accessed from [T21] The Committee reviewed this dataset and considered it acceptable and fit for purpose

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Measured ground deposition density and ambient dose equivalent rates	Ambient dose equivalent rates were measured and soil samples collected from 6 June to 8 July 2011 for areas within 100 km from FDNPS. From FDNPS out to 80 km these were undertaken on 2 km × 2 km grids. Between 80 km and 100 km from FDNPS they were divided into 10 km × 10 km grids. Ambient dose equivalent rates were measured at a height of 1 m above the ground surface at one location in each of these divided grids (nearly 2,200 locations in total), and soil samples were collected at five points at each location. Around 11,000 soil samples were taken; deposition densities of five gamma-emitting radionuclides (^{110m}Ag, ^{129m}Te, ^{131}I, ^{134}Cs and ^{137}Cs) were measured using germanium semiconductor detectors	Ministry of Education, Culture, Sports, Science and Technology (MEXT)	Primary Basis for dose assessments for public and non-human biota in Fukushima Prefecture Secondary Used to compare with ATDM calculations	JAEA conducted the survey with cooperation of various universities and research institutes. MEXT was responsible for the coordination of the measurement data and assessment of validity [M12, M13] The Committee reviewed this dataset and supporting documentation and considered it acceptable and fit for purpose (attachments C-1, C-2, C-3, C-4, C-5, C-6 and C-7)
Measured ground deposition density and airborne monitoring	Radiation was measured from 2 April 2011 to 9 May 2011, using large thallium-activated sodium iodide (NaI(Tl)) crystals attached to a fixed-wing aircraft. Ground teams performed measurements with High-Purity Germanium (HPGe) detectors to determine the isotopic composition of the deposited activity. This was used to project the time evolution of dose rate from the deposits, and the contribution of caesium isotopes to the dose rate as a function of the deposition density. In order to combine the data collected over the 5 weeks represented by the dataset, the projected dose rates and deposition densities were calculated for the common date of 30 June 2011	United States Department of Energy (USDOE) via United States Department of State	Primary Input data for public dose assessment Secondary Used to compare with ATDM calculations	Dataset downloaded from the US Government website [U17] Files downloaded in Google Earth™ KML formats and converted to spreadsheet format for use by the Committee The Committee reviewed this dataset and considered it acceptable and fit for purpose (attachment C-7)
Measured activity concentrations in soils	3,422 measurements of ^{134}Cs and ^{137}Cs in cultivated soils in 15 prefectures in eastern Japan (Fukushima, Iwate, Miyagi, Yamagata, Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, Kanagawa, Nigata, Yamanashi, Nagano and Shizuoka), based on samples collected from 26 April 2011 to 3 February 2012. The cultivated soil activities were adjusted to a reporting date of 5 November 2011	Japanese Ministry of Agriculture, Forestry and Fisheries (MAFF)	Primary Input to public dose assessment	Officially provided by the Government of Japan The original datasets were supplied as pdf files, data were converted and cross-checked to produce data in spreadsheet format The Committee reviewed this dataset and considered it acceptable and fit for purpose
Measured ground deposition densities, ambient dose rates, concentrations in air, in situ gamma spectroscopy	Data from monitoring performed by IAEA teams in locations between 20 km and 80 km from FDNPS and in Tokyo during period 18 March 2011 to 18 April 2011. Data included ambient dose equivalent rates, surface activity concentration, activity concentrations in air and gamma spectra for selected locations. Radionuclides detected included ^{99}Mo, ^{99m}Tc, ^{129}Te, ^{129m}Te, ^{131m}Te, ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs, ^{136}Cs, ^{137}Cs and ^{140}La	IAEA	Secondary Used for general comparison in the public dose assessment	Officially provided by IAEA The processes by which these samples were made, analysed and presented were reviewed by the Committee. The Committee deemed these datasets acceptable and fit for purpose

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Monitored radiation dose rates	The Commission de Recherche et d'Information Indépendantes sur la RADioactivité / Commission for Independent Research and Information about RADiation (CRIIRAD) is a French non-governmental organization whose teams carried out radiation measurements in Japan at the end of May 2011	CRIIRAD	Secondary Used for general comparison in the public dose assessment	Data in the form of a CRIIRAD Communiqué were downloaded from the CRIIRAD website [C9] The Committee did not review the quality of these data in detail
Monitored radiation dose rates	Data comprising measurements of dose rate at more than 4,000,000 data points, collected using Geiger-Mueller tube based radiation monitors	Safecast	Secondary Comparison with results of public dose assessment	Safecast is a global community group providing a web-based network for collecting, sharing and displaying radiation measurements using Geiger-Mueller tube based radiation monitors. Data downloaded from the Safecast website [S1] The Committee did not review the quality of these data
Measured activity concentrations in environmental samples	The Association for Radioactivity Control in west France (ACRO) measured radioactivity in environmental samples collected in the prefectures of Fukushima and Miyagi over the period March 2011 to June 2012	ACRO	Secondary Used for general comparison in the public dose assessment	Data downloaded from the ACRO website [A3] The Committee did not review the quality of the sample collection methods; however, the samples were analysed in laboratories that follow internationally recognized procedures and quality standards
Measured activity concentrations in drinking water	Drinking water samples were first collected in Fukushima Prefecture on 16 March 2011. Some districts did not begin sampling until late March or early April 2011. Outside Fukushima Prefecture data were only available for ^{131}I, ^{134}Cs and ^{137}Cs. Within Fukushima Prefecture ^{132}I was also detected. Data fields were translated into English by the Nuclear Safety Commission Office prior to submission to the Committee	Japanese Ministry of Health, Labour and Welfare (MHLW)	Primary Input to public dose assessment	Officially provided by the Government of Japan The Committee deemed this dataset acceptable and fit for purpose
Measured activity concentrations in marine water and sediments	Data for ^{131}I, ^{134}Cs and ^{137}Cs in water and sediments from marine systems in the coastal region around FDNPS	TEPCO, JAEA, MEXT, JAMSTEC, MERI, FRA, JCAC, NIRS, MOE, Fukushima Prefectural Fisheries Experimental Station, the University of Fukui	Primary Input to review of marine dispersion and to dose assessment for non-human biota	Officially provided by a number of organizations through the Government of Japan The processes by which these samples were sampled, analysed and presented were reviewed by the Committee. A small number of anomalies in some of these datasets were identified, queried and subsequently corrected prior to their use The Committee deemed this dataset acceptable and fit for purpose

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Measured activity concentrations in foodstuffs	A database has been compiled on radionuclide concentrations in foodstuffs under the guidance of FAO/IAEA and in collaboration with MAFF and MHLW. This "FAO/IAEA food database" includes over 500 types of foodstuffs sampled in all 47 prefectures	FAO/IAEA, MHLW and MAFF	Primary Input to public dose assessment	Data provided through the FAO/WHO International Food Safety Authorities Network (INFOSAN) based on information provided by MHLW and compiled by FAO/IAEA FAO/IAEA and MAFF/MHLW undertook an extensive quality assurance process to produce this database (attachment C-8) The Committee reviewed the quality assurance process and considered the database acceptable and fit for purpose
Population data	Population data, including sex/age structure, urban and rural population, distribution by professions, dwelling/settlement type. The data from both the 2005 census (which provided the grid for which the population data was mapped) and the 2010 Japan census (which provided population information) were utilized	Japanese Ministry of Internal Affairs and Communications (MIC) / Statistics Bureau	Primary Input to public dose assessment	Data downloaded from [M20]. The Committee accepted this dataset as quality-assured by the Government of Japan and fit for purpose
Occupancy factors	Data on typical occupancy factors for various population and age groups were derived from national survey data specific for Japan and obtained from the official website	Japanese Ministry of Internal Affairs and Communications (MIC)	Primary Input to public dose assessment	Data downloaded from [M19] The Committee accepted this dataset as quality-assured by the Government of Japan and fit for purpose
Protective measures	In November 2011 the Fukushima Prefecture government reported on a Health Management Survey that accounted for residents' activities over a four-month period from 11 March to 11 July 2011. Based on the results of a questionnaire issued to all residents, information was provided on 18 scenarios representative of the movements of residents evacuated following the accident at FDNPS. Description of the status of the protective measures in evacuated localities, including information on food and drinking water restrictions and on distribution of stable iodine tablets	Fukushima Prefecture government, Government of Japan, National Institute of Radiological Sciences in Japan (NIRS)	Primary Input to public dose assessment	Officially provided by the Government of Japan The Committee accepted this dataset as quality-assured by the Government of Japan and fit for purpose
Food intake	Information on food consumption habits for various population groups, age groups and food groups	MAFF, MHLW	Primary Input to public dose assessment	Officially provided by the Government of Japan The Committee accepted this dataset as quality-assured by the Government of Japan and deemed it fit for purpose. These data were provided in confidence and are not publicly available

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Agricultural production and products	Detailed data on agricultural production including major planting and animal breeding habits in Japan	MAFF	Primary Input to public dose assessment	Officially provided by the Government of Japan The Committee accepted this dataset as quality-assured by the Government of Japan and deemed it fit for purpose
Measured radioactivity in the human body	Results of in vivo measurements of radionuclides in people, in particular thyroid monitoring for ^{131}I and whole-body monitoring for ^{134}Cs and ^{137}Cs	Fukushima Prefecture Health Survey	Secondary Comparison with results of public dose assessment	Officially provided by the Government of Japan The Committee independently analysed the measurements of radionuclides in people that were provided for use in the dose assessment and deemed the datasets acceptable and fit for purpose. Many of these results were subsequently published in peer-reviewed journals and are cited in appendix C
Measured activity concentrations in marine biota	Data for ^{131}I, ^{134}Cs and ^{137}Cs in a range of marine biota from the coastal area around FDNPS	TEPCO, JAEA, MEXT, JAMSTEC, MERI, FRA, JCAC, NIRS, MOE, the Fukushima Prefectural Inland Water Fisheries Experimental Station, the University of Fukui	Primary Input to dose assessment for non-human biota	Officially provided by a number of organizations through the Government of Japan The processes by which these samples were sampled, analysed and presented were reviewed by the Committee. The Committee deemed these datasets acceptable and fit for purpose
Measured activity concentrations in media in freshwater systems	Data for ^{131}I, ^{134}Cs and ^{137}Cs in water and sediments from freshwater systems in Fukushima Prefecture	MOE, NIRS and the Fukushima Prefectural Inland Water Fisheries Experimental Station	Primary Input to dose assessment for non-human biota	Officially provided by the Government of Japan The processes by which these samples were sampled, analysed and presented were reviewed by the Committee. The datasets were very limited in data quantity and some information about sampling was unavailable. Samples were however analysed in laboratories that follow recognized procedures and quality standards The Committee deemed these datasets acceptable and fit for purpose
Measured activity in terrestrial wildlife	Data for ^{131}I, ^{134}Cs and ^{137}Cs in a range of terrestrial biota within about 100 km of the FDNPS	Fukushima Prefecture Nature Conservation Division	Primary Input to dose assessment for non-human biota	Officially provided by the Government of Japan The processes by which these samples were sampled, analysed and presented were reviewed by the Committee. The Committee deemed this dataset acceptable and fit for purpose

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Measured activity in marine biota and seawater	Data for ^{131}I, ^{134}Cs and ^{137}Cs in a range of marine biota from the coastal area around FDNPS	Greenpeace	Secondary Used to compare with results of models in dose assessment for non-human biota	Data accessed from the Greenpeace website [G11] The Committee deemed these datasets acceptable and fit for purpose. The collection methods for some of these samples were not always well documented, however the samples were analysed in laboratories that followed internationally recognized procedures and quality standards
Dose information recorded for 24,832 TEPCO and contractors' workers	Statistics on dose distribution for workers as of 31 October 2012; numbers of TEPCO and contractors' workers for several dose bands	TEPCO	Primary Used for analysis and presentation of dose distributions	The Committee checked the consistency of information provided [T8], compared to information provided in previous TEPCO press releases
Monthly dose information recorded for 21,776 TEPCO and contractors' workers	Dataset provided the following information for 21,776 workers: employer (TEPCO/contractors), age of the worker at end of April 2012, monthly dose from external exposure from March 2011 to April 2012, monthly dose from internal exposure from March 2011 to April 2012, cumulative dose from external exposure, cumulative dose from internal exposure, cumulative dose from March 2011 to April 2012	TEPCO	Primary Used for analysis and presentation of dose distributions, identification of 12 workers with highest internal exposure, and random selection of 42 workers for the Committee's own dose assessment Secondary For selected workers, used to compare with results of Committee's own dose assessment	Data provided by TEPCO to the Committee An aim of the Committee's assessment was to judge the reliability of the doses to workers reported by TEPCO and set out in this dataset This dataset could not be made publicly available because it contained personal confidential information

Dataset title	*Dataset description*	*Data provider(s)*	*Usage*	*Remarks on source and quality assurance*
Dose information for the 12 workers with highest internal exposure	Dataset comprised for each of 12 workers: worker ID, age on 12 March 2012, height, weight, sex, working period (start/end), numeration of the measurement, date/place of measurements, activity for ^{129m}Te, ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs, ^{136}Cs and ^{137}Cs, assumed date of intake, number of days between assumed date of intake and date of measurement, retention rate for ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs, intake for ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs, effective dose coefficient for ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs, committed effective dose due to ^{129m}Te, ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs, ^{136}Cs and ^{137}Cs, effective dose from external and internal exposure, organization which performed the dose assessment (NIRS or TEPCO), body surface activity levels measured on head, neck and hand and background value, dose rate at neck surface and background value	NIRS and TEPCO	Primary Used for the Committee's own dose assessment	Data provided by NIRS and TEPCO to the Committee This dataset could not be made publicly available because it contained personal confidential information
Dose information for 13 emergency workers randomly selected in the lower dose bands	Dataset comprised for each of 13 emergency workers: worker ID, date of measurement, assumed date of intake, dose from external exposure, activity of ^{131}I measured for 5 minutes in the thyroid, thyroid committed equivalent dose from ^{131}I, activity of ^{134}Cs measured for 10 minutes in the whole body, activity of ^{137}Cs measured for 10 minutes in the whole body, whole body committed effective dose from ^{134}Cs, whole body committed effective dose from ^{137}Cs, hypothesis considered for the internal exposure assessment (type of intake, AMAD, assumed day of intake, chemical type)	National Police Agency (NPA)	Primary Used for the Committee's own dose assessment	Data provided by NPA to the Committee This dataset could not be made publicly available because it contained personal confidential information
Dose information for 21 TEPCO workers and 21 contractors' workers randomly selected in the lower dose bands	Dataset comprised for each of 42 workers: worker ID, dose range (0-5 mSv/5-10 mSv/20-100 mSv), company (TEPCO/contractors), age on 3 March 2012, sex, working period (start/end), date/place of measurement, activity measured for ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs, assumed date of intake, number of days between assumed date of intake and date of measurement, intake for ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs committed effective dose due to ^{132}Te, ^{131}I, ^{132}I, ^{134}Cs and ^{137}Cs, total committed effective dose	TEPCO	Primary Used for the Committee's own dose assessment	Data provided by TEPCO to the Committee This dataset could not be made publicly available because it contained personal confidential information
Information about personal dosimeters used for monitoring workers' external exposure	Document containing detailed information on types of personal dosimeter used, technical standards and calibration methods used for both TEPCO and contractors' workers	TEPCO	Primary Used to assess the reliability of external exposure measurements	Data provided by TEPCO to the Committee are reported in tables D8 and D9 of appendix D

III. ACKNOWLEDGEMENTS TO PROVIDERS OF DATA

Japan	Fire and Disaster Management Agency (FDMA) Fukushima Medical University Fukushima Prefecture Nature Conservation Division Fukushima Prefectural Fisheries Experimental Station Fukushima Prefectural Inland Water Fisheries Experimental Station Fisheries Research Agency (FRA) Geospatial Information Authority of Japan Institute for Environmental Sciences Japan Agency for Marine-Earth Science and Technology (JAMSTEC) Japan Atomic Energy Agency (JAEA) Japan Chemical Analysis Center (JCAC) Japan Coast Guard (JCG) Japanese Meteorological Agency (JMA) Japan Nuclear Energy Safety Organization (JNES) Marine Ecology Research Institute (MERI) Ministry of Agriculture, Forestry and Fisheries (MAFF) Ministry of Defence (MOD) Ministry of Education, Culture, Sports, Science and Technology (MEXT) Ministry of Economy, Trade and Industry (METI) Ministry of Foreign Affairs (MOFA) Ministry of Health, Labour and Welfare (MHLW) Ministry of Internal Affairs and Communications (MIC) Ministry of Land, Infrastructure, Transport and Tourism (MLIT) Ministry of the Environment (MOE) National Institute of Radiological Sciences (NIRS) National Police Agency (NPA) Nuclear and Industrial Safety Agency (NISA) (former) Nuclear Regulation Authority (NRA) Nuclear Safety Commission (NSC) (former) Radiation Effects Association Radiation Council Federation of Electric Power Companies of Japan Tokyo Electric Power Company (TEPCO) Tokyo University of Marine Science and Technology University of Fukui
OTHER MEMBER STATES	
Argentina	Nuclear Regulatory Authority
Australia	Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) Bureau of Meteorology
Belarus	Ministry of Natural Resources and Environmental Protection
Belgium	Federal Agency for Nuclear Control
Brazil	Institute for Radioprotection and Dosimetry Nuclear and Energy Research Institute
Canada	Canadian Meteorological Centre (CMC) Health Canada Natural Resources Canada

China	Ministry of Environmental Protection
Finland	Radiation and Nuclear Safety Authority (STUK)
France	Institute for Radiological Protection and Nuclear Safety (IRSN) Alternative Energies and Atomic Energy Commission (CEA)
Germany	Federal Office for Radiation Protection (BfS)
India	Bhabha Atomic Research Centre
Indonesia	Badan Tenaga Nuklir Nasional (BATAN)
Malaysia	Ministry of Health Ministry of Science, Technology and Innovation
Mexico	National Commission for Nuclear Safety and Safeguards
Pakistan	Pakistan Nuclear Regulatory Authority
Philippines	Philippines Nuclear Research Institute
Poland	National Atomic Energy Agency (PAA)
Republic of Korea	Korea Meteorological Administration
Russian Federation	Federal Medical Biological Agency of Russia Institute of Radiation Hygiene
Singapore	National Environmental Agency
Slovakia	Public Health Authority of the Slovak Republic
Spain	Nuclear Safety Council
Sweden	Linköping University Lund University Swedish Defense Research Agency Swedish Radiation Safety Authority Swedish University of Agricultural Sciences Swedish Women's Voluntary Defense Organization
United Kingdom	Public Health England (PHE) (the former Health Protection Agency) Met Office
United States of America	Department of Defense (DoD) Department of Energy (DOE) Environmental Protection Agency (EPA) Food and Drug Administration (FDA) National Oceanic and Atmospheric Administration (NOAA) Nuclear Regulatory Commission (NRC)
INTERNATIONAL ORGANIZATIONS	
International intergovernmental organizations	Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) Food and Agricultural Organization of the United Nations (FAO) International Atomic Energy Agency (IAEA) World Health Organization (WHO) World Meteorological Organization (WMO)

APPENDIX B. RADIONUCLIDE RELEASES, DISPERSION AND DEPOSITION

I. INTRODUCTION

B1. This appendix sets out the Committee's evaluation of information on the releases of radionuclides from the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS) to the atmosphere and to the ocean and their subsequent dispersion in the environment (see chapter I of the main text of the scientific annex for the timescale of the evaluation).

B2. An overview of estimates of the radionuclide releases to the atmosphere and to the ocean, both of the total amounts and the rates of release over time, is provided in section II. The meteorological conditions that prevailed during the period when the releases to the atmosphere were greatest (11-31 March) are described in section III; the influence of these conditions on how and where the released material was dispersed in, and deposited from, the atmosphere onto the Japanese land mass and the ocean surface is illustrated. Based on these meteorological conditions and the time-dependent releases to the atmosphere, estimates have been made—using atmospheric transport, dispersion and deposition models (ATDM)—of the spatial and temporal distribution of radioactive material in the environment (that is, concentrations of radionuclides in air and deposited on the ground as a function of time). This was done to estimate levels of radioactive material in the environment at places and times for which measurements did not exist; these measured and estimated levels underpinned the assessment of doses to the public described in appendix C. The dispersion of radioactive material released to the ocean (directly or indirectly) is described in section IV.

II. RADIONUCLIDE RELEASES

A. Releases to atmosphere

B3. The accident at FDNPS resulted in the release of large amounts of radioactive material into the environment. A large number of fission and activation products were released from the molten fuel in the reactors, generally as aerosols or in a gaseous form. Those that contributed most to the radiation exposure of members of the public and workers were isotopes of iodine, caesium, tellurium and the noble gases. The accident was classified by the Japanese Nuclear and Industrial Safety Agency (NISA) at the highest level (level 7) on the International Nuclear Event Scale (INES). The main sequence of events in each reactor that resulted in the release of radioactive material is summarized below.

1. Accident sequence

B4. The earthquake that occurred off the eastern coast of Japan at 14:46 Japan Standard Time[30] (JST) on 11 March 2011 resulted in reactors in Units 1–3 of FDNPS shutting down automatically. The three other reactors (Units 4–6) had already been shut down for routine outages and Unit 4 had been completely de-fuelled. The earthquake damaged the power transmission grids from the Shin–Fukushima electrical substation and FDNPS lost all connection with its off-site electricity supply. In addition, the tsunami inundated the FDNPS site less than one hour later and flooded a number of emergency safety systems, in particular the on-site power distribution system and the DC power supply system. Units 1, 2 and 4 lost all of their power supplies. Unit 3 initially lost its AC power followed by loss of DC power during the night of 12−13 March. The tsunami also washed away vehicles, heavy equipment and oil tanks, ruined buildings, equipment and facilities, and devastated the site more generally. This exceptional situation resulted in the melting of the reactor cores of Units 1, 2 and 3 and the substantial release of radioactive material into the atmosphere and the ocean.

B5. The main events that influenced the release of radioactive material from Units 1–3 of FDNPS (as set out in the July 2012 final report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company [I9], and supplemented by the 2012 report Fukushima Nuclear Accident Independent Investigation Commission of the National Diet of Japan [N2]) are summarized in table B1.

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[30] In this appendix, unless specifically stated otherwise, all dates and times are given in Japan Standard Time (JST).

Table B1. Summary of the main events that influenced the release of radioactive material from Units 1–3 of FDNPS [I9, N2]

All times are JST

<table>
<tr><th>Date (2011)</th><th>Unit 1</th><th>Unit 2</th><th>Unit 3</th></tr>
<tr><td rowspan="6">11 March</td><td colspan="3">14:46 EARTHQUAKE</td></tr>
<tr><td colspan="3">Automatic shutdown (Scram[31])
Loss of external AC electricity
Automatic activation of emergency diesel generators</td></tr>
<tr><td>14:52 Start of core cooling by isolation condenser (IC)</td><td>14:50 Start of core cooling by Reactor Core Isolation Cooling (RCIC) system</td><td>15:05 Start of core cooling by Reactor Core Isolation Cooling (RCIC) system</td></tr>
<tr><td colspan="3">15:35 MAJOR TSUNAMI</td></tr>
<tr><td colspan="2">15:37 Loss of all electricity</td><td rowspan="2">15:37 Loss of AC power
16:03 RCIC manually restarted; RCIC continued to operate for about 21 hours; DC power enabled measuring instruments to function correctly</td></tr>
<tr><td>IC stopped operating following loss of all power
~20:00 Possible start of damage to core and reactor pressure vessel
~21:50 Radiation in reactor building reached levels for building to be declared off-limits
~22:00 Core likely to have been damaged to considerable degree</td><td>RCIC continued to operate for about 70 hours, but its operation could not be controlled because of lack of DC power</td></tr>
<tr><td>12 March</td><td>02:45 Strong likelihood of reactor pressure vessel failure
04:50 First indications of off-site release detected; ambient dose equivalent rate at site boundary 1 μSv/h
15:36 Explosion of hydrogen accumulated in reactor building; possible release of large amounts of radioactive material into the atmosphere; dose rates at site boundary increased to around 1 mSv/h
19:04 Fire trucks started to fill reactor with seawater</td><td>Between ~04:20 and ~05:00 water source for RCIC switched to suppression chamber
15:36 Explosion in Unit 1 caused blow-out panel in reactor building to open</td><td>11:36 RCIC and water injection into reactor stopped
12:35 High pressure coolant injection (HPCI) system started automatically and restored water level
~19:00 HPCI operated below allowable operating range
20:36 Reactor water level measurement devices became inoperable and water injection capacity of HPCI started to become insufficient to maintain water level</td></tr>
</table>

[31] A scram is a safety feature that triggers immediate shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a “reactor trip”.

Date (2011)	*Unit 1*	*Unit 2*	*Unit 3*
13 March			02:42 HPCI manually stopped, because of concern about possible damage, before confirming availability of alternative diesel-driven fire-pump system; unsuccessful attempt to restart HPCI ~02:45 Unsuccessful attempt to reduce pressure in reactor pressure vessel through safety relief valve ~06:30 to ~09:10 Likely damage to reactor pressure vessel and degradation of its containment function ~08:45 Start of venting of primary containment vessel 09:25 Start of injection of fresh water 12:20 Water tank emptied; reactor water level dropped again 13:12 Seawater injection started, but occasionally interrupted, and flow rate never sufficient to fully re-cover core
14 March		04:30 Started monitoring pressure of suppression chamber 09:00 Water injection functionality of RCIC started to degrade 12:30 RCIC failure and cessation of water injection into reactor ~13:45 to ~18:10 Possible damage to primary containment vessel ~16:34 Start of depressurization of reactor pressure vessel through safety relief valve by 18:22 Indications that core may have been completely uncovered 19:57 Seawater injection started but disrupted several times ~21:18 Failure of reactor pressure vessel containment function	11:01 Hydrogen explosion occurred in reactor building with possible release of large amounts of radioactive material 16:30 Seawater injection restarted, but sometimes interrupted
15 March		From ~07:38 Release of large amounts of radioactive materials; peak dose rate at ~09:00 about 12,000 µSv/h at site boundary 19:54 More seawater successfully injected into reactor; continued in following days with varying degrees of success as reactor pressure varied	~06:00 to ~06:12 Hydrogen explosion occurred at Unit 4 from backflow of gases vented from Unit 3

Date (2011)	*Unit 1*	*Unit 2*	*Unit 3*
20 March	Off-site power restored and Unit 1 progressively brought back under control	Off-site power restored and Unit 2 progressively brought back under control	
22 March			Off-site power restored and Unit 3 progressively brought back under control

Note: Concerns were frequently expressed during the accident over the adequacy of the cooling of the spent fuel in the storage pool of Unit 4, in particular whether the fuel may have become uncovered (due to possible earthquake damage), and thus overheated. Notwithstanding these concerns, there was no release of radioactive material to the atmosphere from the spent fuel pool. Furthermore, the hydrogen explosion which damaged Unit 4 on 15 March was caused by the backflow of gases from the venting of Unit 3 (see above).

2. Approaches to estimating the source term

B6. Estimates of the source term (that is the time-dependent release of radioactive material to the environment) were made for two main purposes:

(a) To indicate the amounts of radioactive material released to the environment;

(b) To be used, in combination with models (for example, for atmospheric and marine dispersion), as support for inferring the dispersion and deposition of radionuclides at locations in the environment where measurements were not available or could no longer be made.

Measured and estimated levels of radionuclides in the environment were used by the Committee to estimate exposure levels to members of the public (see appendix C).

B7. Estimates of the release of radioactive material to the atmosphere can be made using two complementary approaches: *(a)* based on analyses of how an accident progressed; and *(b)* based on measurements of radioactive material in the environment and using reverse or inverse methods to reconstruct their transport through the atmosphere back to the source of the release. Both approaches have their limitations and are associated with much uncertainty.

B8. The first approach, based on analyses of the progression of an accident, uses reactor simulation codes, such as MELCOR [G4], ASTEC [C5] and MAAP [E3]. The main inputs to these computer codes are *(a)* the events that are either known or are postulated to have occurred during the progression of the accident and *(b)* the characteristics of the reactors. The simulations are based on detailed modelling of the different parts of the reactor and its systems, and address all the physical and chemical phenomena involved in the course of a severe accident (for example, thermal-hydraulic conditions, the behaviour of the fuel as temperatures rise when cooling is reduced or lost, the release of radionuclides from the fuel into the reactor coolant as the fuel overheats, hydrogen production, the degradation of the reactor core as the fuel melts and how it interacts with the bottom of the reactor vessel, the retention of radionuclides in the containment and their release to the environment through any leakage paths, and so on). These computer codes were developed for, and are used extensively in, reactor safety assessments, in particular in relation to designing reactors to prevent and mitigate potential severe accidents. The uncertainty associated with the use of these codes for estimating the release of radionuclides following an actual accident is, however, much greater, not least because of the lack of specific information on key plant parameters as the accident progresses, the need to make major assumptions about the timing and nature of key events in the process, and the fact that the models still represent a considerable simplification of reality. The Fukushima Nuclear Accident Independent Investigation Commission of the National Diet of Japan [N2] expressed major reservations about the reliability of these methods, both now and in the future, because of the major uncertainties about what exactly occurred in the damaged reactors. The estimates so far published using these methods only considered releases during the first few days of the accident; this limited their usefulness for the Committee's purpose of estimating exposures, where account needed to be taken of all significant releases.

B9. The second approach is based on measurements of radioactive material in the environment and the use of reverse or inverse modelling:

(a) *Reverse modelling* evaluates the rates of release of radionuclides by comparing measurements of radioactive material or dose rates in the environment with estimates derived from simulations of dispersion of radionuclides in the atmosphere. Atmospheric transport, dispersion and deposition

models (ATDM) are used to estimate levels in the environment for unit release of a radionuclide. Each measurement location is considered independently and the estimate is compared with the measurement; the release is adjusted empirically to fit the measured levels. Comparisons can be made with a range of measurements of radionuclides in the environment, for example, time-dependent concentrations in air and deposition densities on the ground, dose rates, and dust samples. A weakness of this approach is that it does not take account of uncertainties or bias in the measurements, the dispersion model and the meteorological data.

(b) Inverse modelling involves a similar, but mathematically more sophisticated, approach in which the (matrix) equation relating the measured values (of concentration or deposition density of radionuclides, or dose rate) to the source term is solved by minimizing the function which includes all of the sources of technical error that contribute to differences between calculated values (derived generally by ATDM) and measured values. Technical errors are therefore explicitly taken into account.

B10. Estimates made using this second approach are also associated with much uncertainty; their quality is influenced by the availability and quality of measurements of radiation or radioactive material in the environment and of meteorological data of sufficient temporal and spatial resolution. The complexity of a release (for example, marked variation in its magnitude and characteristics such as its height, thermal energy, and chemical form with time) adds further to the uncertainty. In addition, where the source term had been estimated by reverse or inverse modelling, it was inextricably linked to and dependent on the measurement data, the meteorology and the ATDM used in its derivation; if different meteorology or ATDM had been used with the measurement data, then the resulting source term estimate could have been different. Strictly, therefore, source term estimates derived in this way would be best used to estimate environmental levels by employing the same meteorology and ATDM used in their derivation. If used with different meteorology and ATDM to predict concentrations of radionuclides in the environment, the fit with measurements could have been less good (at least at those measurement points used for the reverse or inverse modelling). The extent to which this matters in practice is the subject of ongoing scientific discussion.

3. Source term estimates

B11. Numerous estimates have been published of the release of radioactive material from FDNPS; these are summarized in table B2 in terms of the total release of two of the more radiologically important radionuclides, ^{131}I and ^{137}Cs. For each case, the method used and the date the estimate was made and/or the date of its publication are indicated. The earliest estimates were made in late March 2011, even while the accident was still progressing. Others followed in the subsequent months, with many being further refined over time as more information became available (relating to both the development of the accident and measurements in the environment), and as methods improved. This subject remains an active area for research and investigation and further improvements can be expected.

Table B2. Source terms estimated for the FDNPS accident

Strictly, the various estimates of total release are not all directly comparable[a]

Reference	*Date of publication*	*Total release[a] (PBq)*		*Approach used*	*Comments*
		^{131}I	*^{137}Cs*		
IRSN [I31]	22 March 2011	90	10	Accident progression	Based on limited information while the accident was still progressing. Estimates related to time period 12 to 22 March 2011
ZAMG [Z3]	22 March 2011	400	33	Reverse modelling	Based on limited information while the accident was still progressing. Estimates related to first 4 days of accident (12 to 15 March 2011 inclusive)
NISA [N13]	12 April 2011	130	6	Accident progression	Estimates made for purposes of INES assessment of accident severity
NISA [N14]	6 June 2011	160	15	Accident progression	Estimates related to time period 12 to 18 March 2011
Chino et al. [C6]	July 2011	150	13	Reverse modelling	Estimates for the period 12 to 31 March 2011 only. Based on limited data available at the time. Subsequently refined by Katata et al. [K1] and Terada et al. [T19]
NISA[b]	16 February 2012	150	8	Accident progression	Included releases only over a limited period
Stohl et al. [S11]	1 March 2012[c]	–	37	Inverse modelling	Based solely on CTBTO measurements in the northern hemisphere. Guided by a first estimate based on assumptions on the total release from the three reactors and from the spent fuel pool of Unit 4, analysed the accident sequence using MELCOR and on-site measurements of dose rate. Appeared to be an overestimate compared with most other estimates
Winiarek et al. [W15]	9 March 2012	190–380	12	Inverse modelling	Obtained similar results when using inverse modelling with and without a first estimate (used an IRSN-estimated source term as the first estimate). Source term estimate limited to releases that were partly or wholly dispersed over Japanese land mass
TEPCO [T13, T15]	24 May 2012	≈500	≈10	Reverse modelling	Based on dose rates measured by monitoring vehicles on site and considered most unlikely to be an underestimate. Estimates related to time period 12 to 31 March 2011
Terada et al. [T19]	19 June 2012	120	9	Reverse modelling	Further refinement of Chino et al. [C6] and Katata et al. [K1]. Releases over the ocean estimated by interpolation of those over the land
Mathieu et al. [M6]	June 2012	197	20.6	Forward and reverse modelling	Based on dose-rate measurements on- and off-site using IRSN codes. Source term estimate limited to releases that were partly or wholly dispersed over Japanese land mass
Katata et al. [K1]	July 2012	130	11	Reverse modelling	Refinement of Chino et al. [C6] using more extensive monitoring data during the early stages of the accident. The releases tabulated were the sums of the estimates made by Katata et al. for the period up to 17 March 2011 and by Chino et al. for the period after 17 March. For the period up to 17 March, Katata et al. estimated releases of ^{131}I and ^{137}Cs of 44 and 3.9 PBq, respectively
Hoshi and Hirano [H9]	17 September 2012	250–340	7.3–13	Accident progression	Estimates relate to period 11 to 17 March 2011

Reference	*Date of publication*	*Total release[a] (PBq)*		*Approach used*	*Comments*
		^{131}I	*^{137}Cs*		
Achim et al. [A2]	September 2012	400	10	Reverse modelling	Based solely on CTBTO measurements in the northern hemisphere. Release of ^{131}I in particulate form estimated to be 100 PBq. Estimate of total release was more uncertain and relied on assumptions about gas–particulate conversion of iodine
Kobayashi et al. [K18]	15 March 2013	200	13	Reverse modelling	Further refinement of Terada et al. [T19] to provide a better estimate (i.e. not interpolated) of radionuclides dispersed directly over the ocean. Coupled atmospheric and oceanic dispersion simulations with observed concentrations of ^{134}Cs in the Pacific Ocean
Saunier et al. [S3]	25 November 2013[d]	106	15.5	Inverse modelling	Used an original approach (using IRSN codes) to inverse modelling based solely on dose-rate measurements from 57 monitoring stations in Japan. Source term estimate limited to releases that were partly or wholly dispersed over Japanese land mass

[a] *The various estimates of total release are not all directly comparable. Many of the estimates of total release do not actually represent the total and, where appropriate, this is indicated in the comments column. Some estimates were for releases over prescribed time periods. Estimates based on reverse or inverse modelling used different approaches in estimating the releases that were dispersed wholly over the ocean: in some cases these releases were estimated by interpolating between estimates of releases that were obtained by simulating dispersion over the Japanese land mass (i.e. where environmental measurements were made); in others the component of the total release that was dispersed wholly or partially over the Japanese land mass was simply not included in the total; and in one case, environmental measurements made on land were supplemented with measurements made in ocean water in order to estimate the total release.*

[b] *Quoted in [T13, T15].*

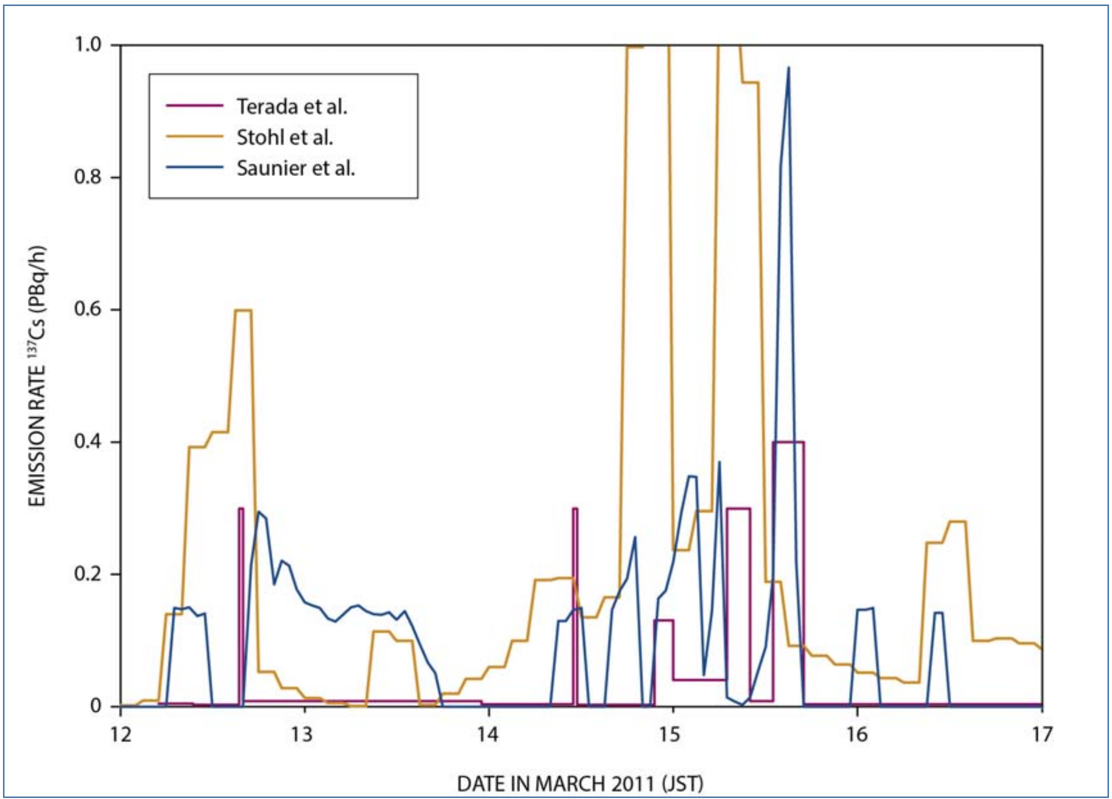
[c] *Published online as a discussion paper on 20 October 2011.*

[d] *Published online as a discussion paper on 12 June 2013.*

B12. Given their inherent uncertainties and the fact that not all of the estimates were directly comparable (that is, some early estimates covered only the first days after the accident, whereas others integrated the release over a much longer period; and some represented the total release to the atmosphere, whereas others represented only that fraction that was partly or wholly dispersed over the Japanese land mass—see table B2), the various estimates of the releases of the two principal radionuclides spanned relatively small ranges. For ^{131}I the estimates ranged from about 100 to 500 PBq; for ^{137}Cs they ranged, in general, from about 6 to 20 PBq (albeit with some estimates based on more limited information ranging up to 40 PBq). For perspective, the releases of ^{131}I and ^{137}Cs following the Chernobyl accident were estimated at 1,760 and 85 PBq, respectively [U12], that is about factors of 10 and 5 times higher than the averages of the estimates given in table B2 for the FDNPS accident.

B13. Much greater variation was, however, apparent in the estimated temporal patterns of release and this is exemplified in figure B-I for three of the published estimates. While all three show peaks in the estimated release rate of ^{137}Cs corresponding to the main events occurring at the three reactors, these peaks were assessed to have occurred at different times, to have been of different durations, and to have differed in magnitude at particular times by more than a factor of ten.

Figure B-I. Three estimates of the pattern of release rates of ^{137}Cs over time [S3, S11, T19]



B14. The various estimates have differing strengths and weaknesses reflecting when they were made and the methods used. In general, the Committee preferred those made later because they were often refinements of earlier estimates and/or had benefited from additional information. Further, the Committee preferred estimates derived using inverse or reverse modelling, as opposed to those from analyses of accident progression for three reasons: *(a)* the former are judged to be more reliable being based on measurements of radioactive material in the environment; *(b)* the Committee acknowledged the major reservations expressed in the report by the Fukushima Nuclear Accident Independent

Investigation Commission of the National Diet of Japan [N2] on the reliability of estimates based on accident progression; and *(c)* estimates based on accident progression only covered a limited period of the release.

B15. For its purposes, the Committee had to select a source term that was best able to provide a sound basis for estimating levels of radioactive material in the environment where no measurements existed; these levels were an essential input to the subsequent estimation of doses (see chapter IV of the main annex A, and appendix C). Estimates based on reverse or inverse modelling, as opposed to simulation of accident progression, were clearly preferable in this context consequent upon them having been derived from, and optimized to fit, measurements of radioactive material in the environment. The Committee chose to use the source term estimated by Terada et al. [T19] from among those derived on the basis of reverse or inverse modelling. This was the last but one refinement in a series of estimates made by a group of Japanese scientists at JAEA [C6, K1]. It was chosen in preference to the latest refinement by Kobayashi et al. [K18] that took account of measurements of radioactive material in the Pacific Ocean in addition to those over the Japanese land mass; by contrast, Terada et al. had estimated the magnitude of releases dispersed wholly over the ocean by interpolation between releases for which measurements were available over the Japanese land mass. Adoption of the Kobayashi et al. source term by the Committee would, however, have resulted in an overestimation of the levels of radioactive material in the terrestrial environment, which would have been inconsistent with the Committee's intent of making a realistic assessment. The Committee did not consider the source term estimated by Saunier et al. [S3] because it had not yet been published at the time the choice was made; it was, however, subsequently used to test the robustness of a number of assumptions made regarding the use of the source term of Terada et al. together with ATDM simulations for estimating levels of radionuclides in the environment (see section III.E of this appendix).

B16. The releases of ^{131}I and ^{137}Cs estimated by Terada et al. lay within the ranges of published source terms in table B2, albeit at the lower ends. While they provided a sound basis for estimating the levels of radioactive material in the terrestrial environment where measurements did not exist, there were indications that they may have been underestimates of the total amounts of these radionuclides released, perhaps by a factor of up to about two because of assumptions made about the magnitude of releases dispersed wholly over the ocean (see table B2). For its purposes, the Committee had to specify a source term to provide a sound basis for estimating levels of radioactive material in the terrestrial environment where no measurements existed. With one exception (that is, for evacuees during the early stages of the accident), the levels of radionuclides in the environment estimated on the basis of the assumed source term and its subsequent dispersion in the atmosphere were not used in any absolute sense; rather, they were used in a relative sense to scale measured deposition densities of radionuclides on the ground to infer concentrations of radionuclides in the air. When used in this relative way, the scaling (and the inferred concentration in air) is relatively insensitive to plausible choices of the source term (see section E of this appendix).

B17. Terada et al. provided estimates of the releases of ^{131}I and ^{137}Cs as a function of time. These two radionuclides, together with ^{134}Cs, make by far the largest contribution to the dose received by the population. A large number of other radionuclides would also have been released in the accident and some were measured in the environment; but very few were released in sufficient amounts to contribute significantly to doses. Those that could have contributed significantly were incorporated by the Committee into the source term used, and comprised other isotopes of iodine and caesium, ^{132}Te and ^{133}Xe.

B18. The significance of very short-lived radionuclides was greatly reduced by the delay between reactor shutdown and when the first release occurred (around 14 hours). The fractional release and significance of isotopes of elements such as strontium, barium and plutonium was much lower than those of iodine and caesium because of their much lower volatilities; this has been confirmed by measurements in the environment [N18][32].

B19. The releases of other isotopes of iodine and caesium were estimated from those of ^{131}I and ^{137}Cs by scaling with the ratio of their respective inventories in the three reactor units at shutdown and taking account of radioactive decay before the time of any release. This approach was justified because the behaviour of all isotopes of iodine (and likewise all isotopes of caesium) was the same within a given reactor and its containment system; consequently, their fractional releases (relative to their inventories at any given time) were identical. The ratios of other isotopes of iodine and caesium [N16] for each of the three units at the time of shutdown and for the three units taken as a whole are shown in table B3. The ratios differed slightly between the three units reflecting the different operating histories of the reactors; average values were assumed to apply throughout the release period when estimating the releases of these other radioisotopes. The ratio of ^{133}I to ^{131}I, corrected for radioactive decay back to the time of reactor shutdown (14:46 on 11 March 2011 JST), was derived from measurements of air samples taken between 14 and 20 March 2011 at various locations in Japan and also by the CTBTO network (figure B-II); the measured ratios are broadly in accord with the ^{133}I/^{131}I ratio averaged over the inventory of the three reactors. Iodine isotopes were assumed to be released in equal amounts in particulate and gaseous/elemental forms notwithstanding the wide variation over time in their relative components in measurements (contribution of particulates varying, in general, within a range of about 20% to 70%) [F7, O2]; ^{132}I produced by radioactive decay of the parent radionuclide ^{132}Te was, however, assumed to be in particulate form only (that is, the form assumed for its parent).

Table B3. Ratios of the quantities of other radionuclides to those of ^{131}I or ^{137}Cs in the three reactors at time of shutdown (14:46 on 11 March 2011 JST) [N16]

Reactor unit	*Radionuclide ratio*				
	^{132}I/^{131}I	*^{133}I/^{131}I*	*^{132}Te/^{137}Cs*	*^{134}Cs/^{137}Cs*	*^{136}Cs/^{137}Cs*
Unit 1	1.47	2.10	9.7	0.94	0.27
Unit 2	1.47	2.09	13.2	1.08	0.32
Unit 3	1.47	2.10	14.0	1.05	0.34
Average ratio (Units 1–3)	1.47	2.10	12.4	1.03	0.31

B20. For releases of isotopes of tellurium, however, there was no a priori reason why they should have been directly correlated with those of caesium or iodine; the chemistry, physical characteristics and behaviour in the reactors of these three elements were all different and would have influenced both the timing and magnitudes of their releases. Measured concentrations of ^{132}Te in air samples, relative to those of ^{137}Cs, are shown in figures B-III and B-IV. Figure B-III includes measurements made in Japan at different times by various research institutes; measurements from other sources were also available but showed greater variability in the ratio, raising some additional questions about their reliability. Figure B-IV contains measurements from the CTBTO network (see attachment B–1 for details); the line through the data is the ratio of the respective inventories of ^{132}Te and ^{137}Cs (corrected for radioactive decay to the time of shutdown). The measured ^{132}Te/^{137}Cs ratios varied considerably with time and space, typically from a value of a few to a few tens (corrected for radioactive decay to the time

[32] This situation differs markedly from that of the Chernobyl accident; less volatile elements (for example strontium and plutonium) were released, in relatively larger amounts, directly to the atmosphere as a result of the initial explosion and physical destruction of parts of the core. Such mechanisms did not occur in the accident at FDNPS, where the volatility of the elements, and the extent to which they were retained within the containment by other mechanisms (for example the suppression pool), were the principal determinants of the amounts released.

of shutdown). The data, however, were not sufficiently comprehensive or consistent to be used to estimate or model the time dependence of the release of ^{132}Te. In the absence of such data, the release of ^{132}Te relative to that of ^{137}Cs was assumed to be fixed and determined from their respective inventories in the three reactors at the time of shutdown, i.e. an average ratio of 12.4, as indicated in table B3. In broad terms this assumption was reasonable (see the comparisons between the lines and data in figures B-III and B-IV); however, this led to under- and overestimates of the release of ^{132}Te during particular release episodes, which may have had implications for the contribution of this radionuclide to estimated doses.

Figure B-II. Ratio of ^{133}I to ^{131}I in air samples taken between 14 and 20 March 2011 in Japan and by the CTBTO network (corrected for radioactive decay to time of reactor shutdown, 14:46 on 11 March 2011 JST, see attachment B–1)

The dashed line corresponds to a ratio of 2.1, the average ratio of the respective inventories of the two isotopes in the three units at shutdown [K5, O2, T7]; see attachment B–1 for CTBTO data. For Takasaki pre-detection: the data from the CTBTO station at Takasaki for the first 2 days when extraordinary preliminary signals were recorded; these data were considered to be valid for checking radionuclide ratios only

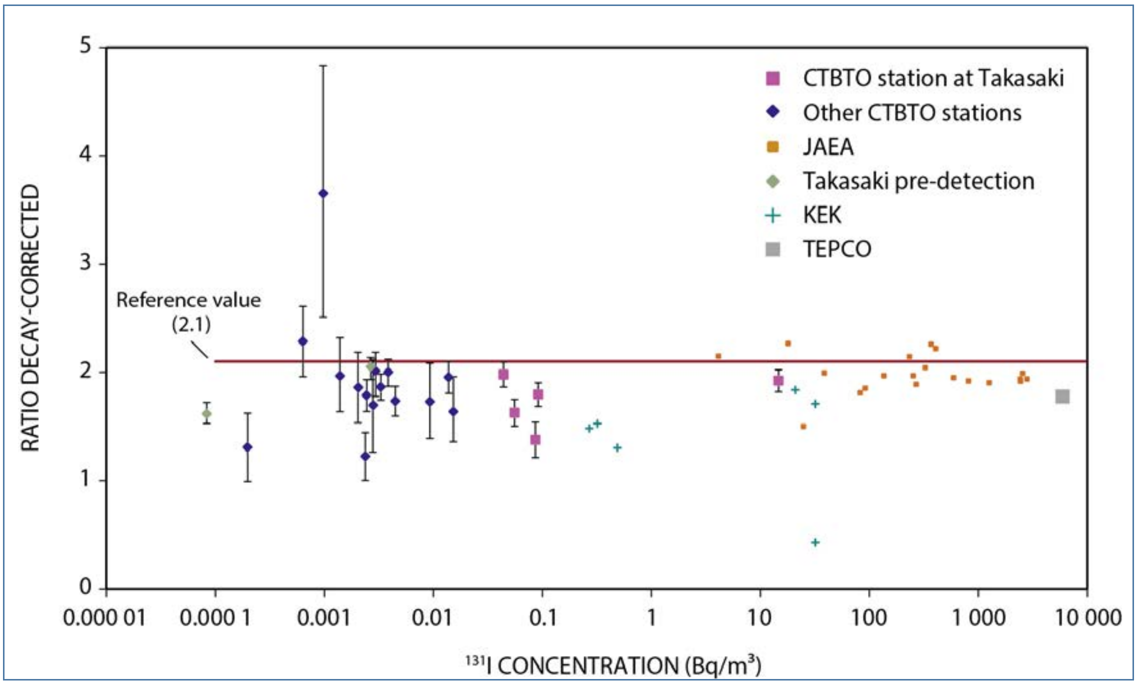


Figure B-III. Ratio of ^{132}Te to ^{137}Cs concentrations in air samples measured at various locations and times (JST) in Japan

The line represents how the ratio would vary as a function of time if the releases of ^{132}Te and ^{137}Cs had been in proportion to their respective inventories in the three units [A9, F7, J6, K5, O2]

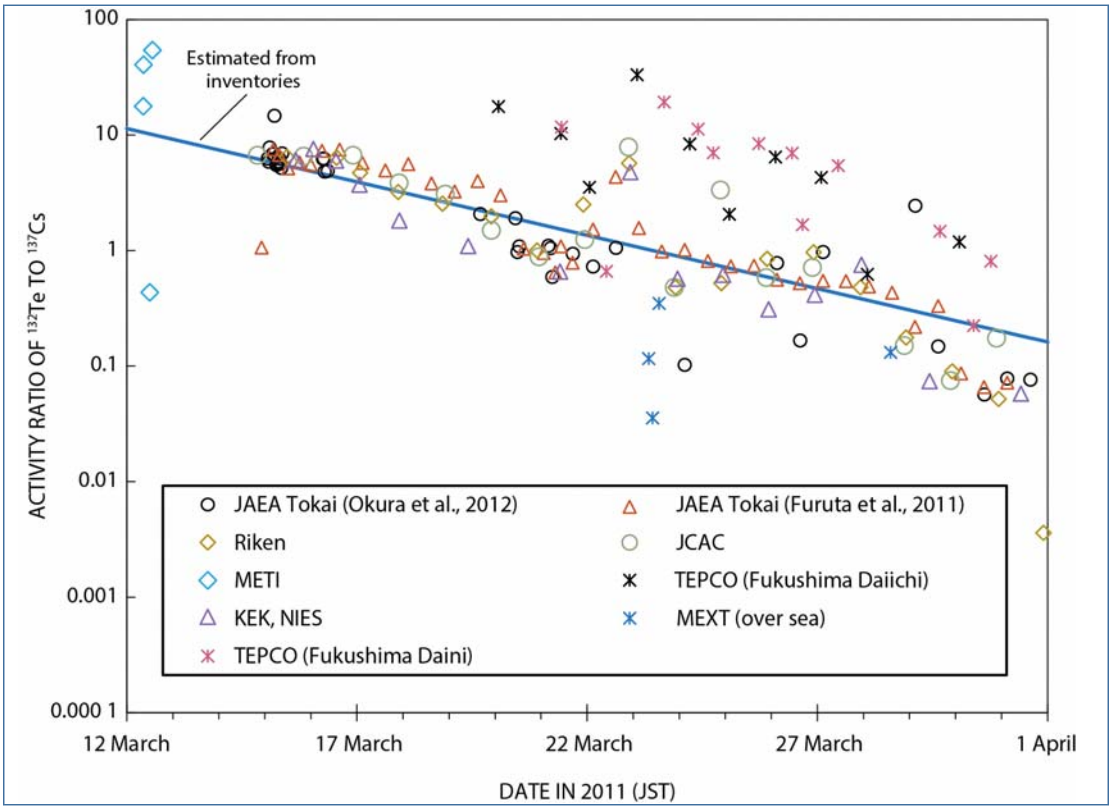
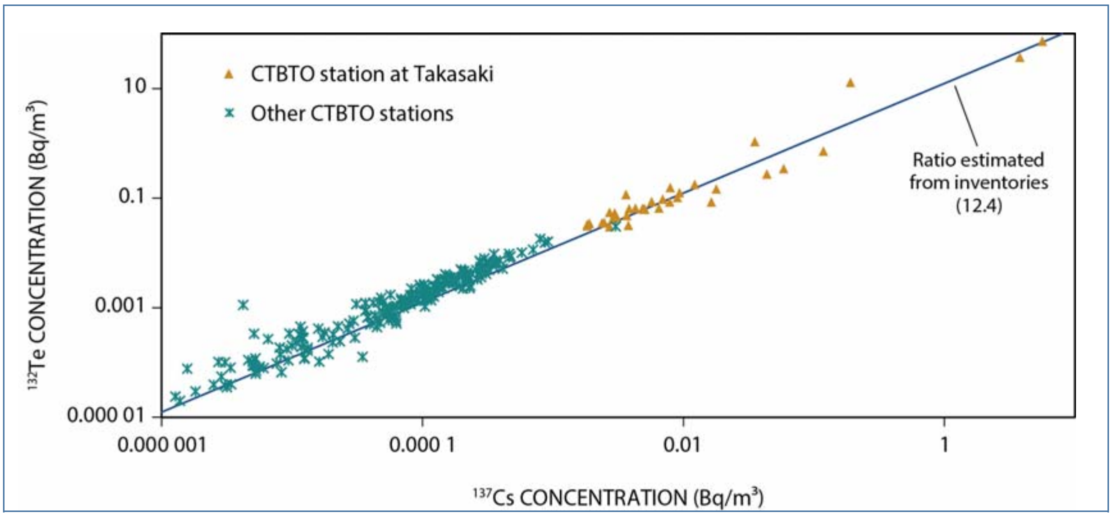


Figure B-IV. Comparison of measured concentrations of ^{132}Te and ^{137}Cs in air samples measured by the CTBTO network (corrected for radioactive decay to the time of reactor shutdown, 14:46 on 11 March 2011 JST)

See attachment B-1 for measurement data



B21. For ^{133}Xe, the temporal pattern of release estimated by the updated simulation of [H10] was adopted together with the estimated inventory of this radionuclide in the three operating reactors taken from Nishihara et al. [N16]; this estimate was comparable with those of Le Petit et al. [L4] and Achim et al. [A2]. The total release of each radionuclide in the source term adopted for the purposes of this study is summarized in table B4; the time-dependent releases of the two most significant radionuclides, ^{131}I and ^{137}Cs, are shown in figures B-I and B-XVI.

B22. While most of the radioactive material was released in the period up to 17 March, releases continued for a considerable time thereafter. After the first week, the release rates gradually declined, albeit with some fluctuations over more limited periods of time (see table B5 and figure B-I). By the beginning of April, the rate of release had fallen to one thousandth or less of those during the first week; these much lower release rates persisted for many weeks afterwards, but were insignificant compared with what had gone before.

Table B4. Estimated total amounts of radiologically significant radionuclides released to atmosphere (based on [T19])

Radionuclides	*Total release to atmosphere (Bq)*	*Percentage of the inventory at reactor shutdown released (%)*
^{132}Te	2.85×10^{16}	0.33
^{131}I	1.24×10^{17}	2.1
^{132}I [a]	2.85×10^{16}	0.32
^{133}I	9.56×10^{15}	0.07
^{133}Xe	7.32×10^{18}	61
^{134}Cs	9.01×10^{15}	1.3
^{136}Cs	1.77×10^{15}	0.81
^{137}Cs	8.83×10^{15}	1.3

[a] *Direct release of ^{132}I was small compared to the ingrowth from radioactive decay of released ^{132}Te.*

Table B5. Estimated release rates to atmosphere of potentially significant radionuclides (based on [T19])

Time period in 2011 (JST)		*Duration (h)*	*Release rate (Bq/h)*							
Start	*End*		^{132}*Te*	^{131}*I*	^{132}*I*^{a}	^{133}*I*	^{133}*Xe*	^{134}*Cs*	^{136}*Cs*	^{137}*Cs*
12March 05:00	12 March 09:30	4.5	4.0×10^{13}	3.7×10^{13}	4.0×10^{13}	4.8×10^{13}	6.6×10^{15}	3.8×10^{12}	1.1×10^{12}	3.7×10^{12}
12 March 09:30	12 March 15:30	6	1.7×10^{13}	1.7×10^{13}	1.7×10^{13}	1.9×10^{13}	7.6×10^{16}	1.8×10^{12}	5.1×10^{11}	1.7×10^{12}
12 March 15:30	12 March 16:00	0.5	3.0×10^{15}	3.0×10^{15}	3.0×10^{15}	3.0×10^{15}	1.2×10^{16}	3.1×10^{14}	8.9×10^{13}	3.0×10^{14}
12 March 16:00	13 March 23:00	31	7.3×10^{13}	8.4×10^{13}	7.3×10^{13}	5.5×10^{13}	1.2×10^{17}	8.6×10^{12}	2.4×10^{12}	8.4×10^{12}
12 March 23:00	14 March 11:00	12	2.6×10^{13}	3.6×10^{13}	2.6×10^{13}	1.2×10^{13}	5.8×10^{15}	3.7×10^{12}	9.8×10^{11}	3.6×10^{12}
14 March 11:00	14 March 11:30	0.5	2.0×10^{15}	3.0×10^{15}	2.0×10^{15}	8.3×10^{14}	6.4×10^{15}	3.1×10^{14}	8.1×10^{13}	3.0×10^{14}
14 March 11:30	14 March 21:30	10	1.5×10^{13}	2.3×10^{13}	1.5×10^{13}	5.5×10^{12}	6.1×10^{15}	2.4×10^{12}	6.1×10^{11}	2.3×10^{12}
14 March 21:30	15 March 00:00	2.5	7.9×10^{14}	1.3×10^{15}	7.9×10^{14}	2.6×10^{14}	6.6×10^{15}	1.3×10^{14}	3.4×10^{13}	1.3×10^{14}
15 March 00:00	15 March 07:00	7	2.3×10^{14}	3.5×10^{14}	2.3×10^{14}	6.0×10^{13}	1.1×10^{17}	4.1×10^{13}	1.0×10^{13}	4.0×10^{13}
15 March 07:00	15 March 10:00	3	1.7×10^{15}	3.0×10^{15}	1.7×10^{15}	4.4×10^{14}	1.9×10^{17}	3.1×10^{14}	7.7×10^{13}	3.0×10^{14}
15 March 10:00	15 March 13:00	3	4.3×10^{13}	8.0×10^{13}	4.3×10^{13}	1.1×10^{13}	1.1×10^{17}	8.2×10^{12}	2.0×10^{12}	8.0×10^{12}
15 March 13:00	15 March 17:00	4	2.1×10^{15}	4.0×10^{15}	2.1×10^{15}	4.9×10^{14}	2.1×10^{17}	4.1×10^{14}	1.1×10^{14}	4.0×10^{14}
15 March 17:00	17 March 06:00	37	1.3×10^{13}	2.1×10^{14}	1.3×10^{13}	1.5×10^{13}	1.3×10^{16}	3.1×10^{12}	7.3×10^{11}	3.0×10^{12}
17 March 06:00	19 March 15:00	57	2.9×10^{13}	4.1×10^{14}	2.9×10^{13}	7.6×10^{12}		1.0×10^{13}	2.2×10^{12}	1.0×10^{13}
19 March 15:00	21 March 03:00	36	6.6×10^{13}	3.8×10^{14}	6.6×10^{13}	1.7×10^{12}		3.5×10^{13}	6.8×10^{12}	3.5×10^{13}
21 March 03:00	21 March 21:00	18	2.1×10^{13}	1.4×10^{14}	2.1×10^{13}	2.7×10^{11}		1.4×10^{13}	2.6×10^{12}	1.4×10^{13}
21 March 21:00	22 March 23:00	26	5.8×10^{12}	4.1×10^{14}	5.8×10^{12}	4.1×10^{11}		4.8×10^{12}	8.3×10^{11}	4.7×10^{12}
22 March 23:00	24 March 00:00	25	8.7×10^{12}	7.1×10^{14}	8.7×10^{12}	3.3×10^{11}		9.0×10^{12}	1.5×10^{12}	8.9×10^{12}
24 March 00:00	25 March 00:00	24	2.3×10^{12}	1.9×10^{14}	2.3×10^{12}	4.3×10^{10}		2.9×10^{12}	4.6×10^{11}	2.9×10^{12}
25 March 00:00	26 March 11:00	35	7.5×10^{11}	5.6×10^{13}	7.5×10^{11}	5.4×10^{9}		1.3×10^{12}	1.9×10^{11}	1.2×10^{12}
26 March 11:00	28 March 10:00	47	7.3×10^{10}	4.0×10^{12}	7.3×10^{10}	1.2×10^{8}		1.8×10^{11}	2.4×10^{10}	1.7×10^{11}
28 March 10:00	29 March 21:00	35	1.4×10^{12}	7.5×10^{12}	1.4×10^{12}	6.4×10^{7}		4.8×10^{12}	5.8×10^{11}	4.7×10^{12}
29 March 21:00	30 March 11:00	14	2.1×10^{12}	1.5×10^{13}	2.1×10^{12}	6.0×10^{7}		8.9×10^{12}	1.0×10^{12}	8.8×10^{12}
30 March 11:00	31 March 00:00	13	2.9×10^{13}	1.8×10^{14}	2.9×10^{13}	4.8×10^{8}		1.4×10^{14}	1.6×10^{13}	1.4×10^{14}

Time period in 2011 (JST)		*Duration (h)*	*Release rate (Bq/h)*							
Start	*End*		^{132}Te	^{131}I	^{132}I [a]	^{133}I	^{133}Xe	^{134}Cs	^{136}Cs	^{137}Cs
31 March 00:00	31 March 22:00	22	8.0×10^{11}	2.4×10^{13}	8.0×10^{11}	3.9×10^{7}		4.6×10^{12}	5.0×10^{11}	4.5×10^{12}
31 March 22:00	2 April 09:00	35	2.2×10^{11}	1.8×10^{12}	2.2×10^{11}	1.3×10^{6}		1.7×10^{12}	1.7×10^{11}	1.6×10^{12}
2 April 09:00	4 April 09:00	48	5.5×10^{10}	1.8×10^{12}	5.5×10^{10}	3.9×10^{5}		5.9×10^{11}	5.5×10^{10}	5.8×10^{11}
4 April 09:00	7 April 17:00	80	7.8×10^{9}	7.0×10^{11}	7.8×10^{9}	2.6×10^{4}		1.4×10^{11}	1.2×10^{10}	1.4×10^{11}
7 April 17:00	13 April 23:00	150	7.2×10^{9}	7.0×10^{11}	7.2×10^{9}	1.4×10^{3}		3.5×10^{11}	2.2×10^{10}	3.5×10^{11}
13 April 23:00	1 May 00:00	409	4.5×10^{8}	7.0×10^{11}	4.5×10^{8}	6.2×10^{0}		1.7×10^{11}	6.2×10^{9}	1.8×10^{11}

[a] *Direct release rate of ^{132}I is small compared to the ingrowth from radioactive decay of released ^{132}Te.*

B. Releases to the ocean

B23. Radioactive material from FDNPS entered the marine environment directly and indirectly.

– Direct release into the ocean was at least known to have resulted from leakage of highly-contaminated water from a trench outside Unit 2 (discovered on 2 April 2011), and the deliberate discharge of weakly contaminated radioactive liquid waste from storage tanks; the latter were emptied to create capacity for the storage of highly contaminated water remaining in the trench (see section III below). Further releases occurred subsequently (for example in May and December 2011) but, in general, these were insignificant compared with those that occurred in the first month after the accident. In addition, groundwater, contaminated by numerous sources of radioactive material on site (e.g. leaks from storage tanks, dispersal of contaminated reactor coolant, and deposition of radionuclides released to the atmosphere), represents a continuing source of release to the ocean.

– Radioactive material entered the ocean indirectly via two routes: *(a)* most importantly, from the deposition onto the ocean surface of material released to the atmosphere and dispersed over the ocean; and *(b)* from run-off into rivers of material deposited over the land mass and transported downstream into the ocean. This latter process would continue over an extended period. Further releases could not be excluded in the future, either inadvertently (e.g. from water continuing to be released from the reactor buildings into groundwater) or as part of the waste management strategy adopted in the remediation of the FDNPS site.

B24. At the end of 2013, releases of radionuclides to the marine environment continued to be reported [N19], apparently emanating from contaminated groundwater on the FDNPS site. Several tens of per cent of the inventories of the more volatile elements (i.e. hydrogen/tritium, iodine and caesium) in the cores of the three damaged reactors had been found in stagnant water, mainly in the basement of the turbine and reactor buildings but also in surrounding areas [N15]. Less volatile elements (e.g. strontium, barium and lanthanum) had also been found but at levels that were between about a tenth to one hundredth of those for the more volatile elements in terms of their relative inventories. Monitoring results published by the Nuclear Regulation Authority [N18] indicated that these continuing release rates during 2013 were much lower than of the major releases that occurred in the immediate aftermath of the accident. Furthermore, measures were being taken to attempt to control them (e.g. the building of a containment wall between the FDNPS site and the ocean). As at the end of 2013, it was considered that the ongoing releases were unlikely to significantly affect the Committee’s assessment of doses to the public. However, continued monitoring and assessment of the implications of the releases were warranted.

B25. Following the accident, numerous observations were carried out in the ocean in order to detect the presence of radionuclides released from FDNPS and have continued ever since. The operator of the station (TEPCO), the Japanese government agencies, and research laboratories from different countries (mainly Japan) collected and analysed numerous samples of water, suspended matter, sediment, and marine organisms. These measurement data are described in detail in section IV below. They were used by various authors to estimate the amounts of radionuclides released directly into the ocean. These estimates are summarized in table B6 together with estimates of the deposition on to the ocean surface from material released to atmosphere.

Table B6. Comparison of estimates of direct release to the ocean with those of deposition on the ocean surface from the atmosphere

Source of estimate (Period considered in 2011)	*Direct release to the ocean (PBq)*		*Deposition on ocean surface from the atmosphere (PBq)*	
	^{131}I	*^{137}Cs*	*^{131}I*	*^{137}Cs*
TEPCO [T15] (26 March–30 September)	11	3.6		
Kawamura et al. [K3] (12 March–30 April)	11[a]	4[a]	57	5
Tsumune et al. [T24] (26 March–31 May)		3.5 ± 0.7		
Bailly du Bois et al. [B2] (26 March–18 July)		27 ± 15		
Estournel et al. [E4]		0.81[b] 4.1–4.5[c] 5.5 (upper bound)		5.7–5.9 (northern Pacific Ocean)
Charette et al. [C4]		11–16		
Kobayashi et al. [K18] (12 March–1 May)	11	3.5[d]	99	7.6

[a] 21 March–30 April. [b] 1–6 April. [c] 12 March–30 June. [d] 26 March–30 June.

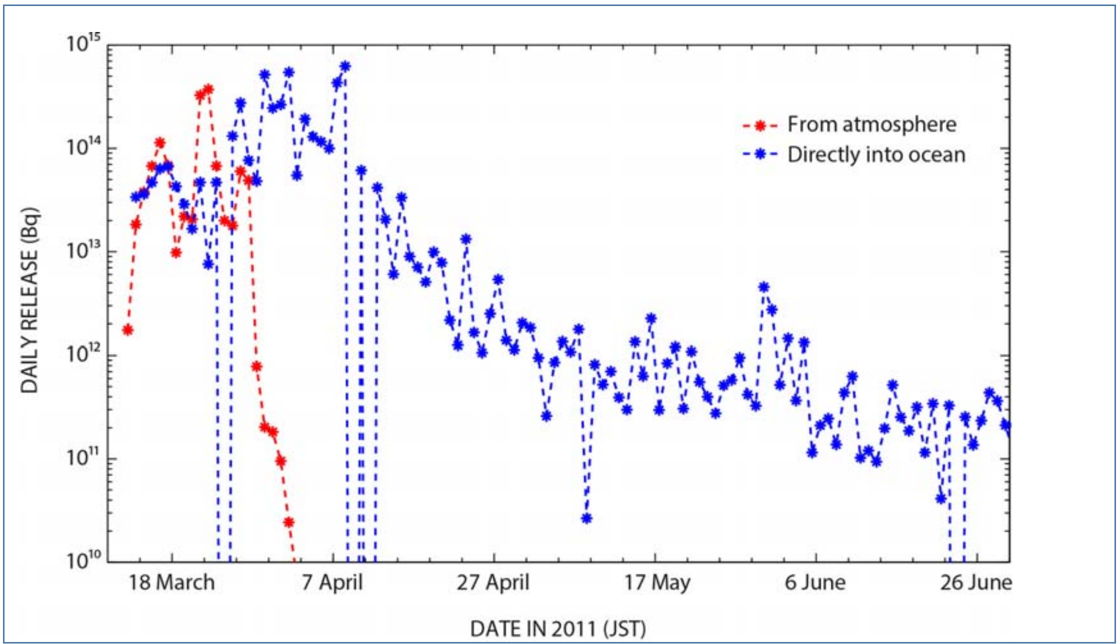
B26. Tsumune et al. [T24] indicated from an analysis of ^{131}I/^{137}Cs ratios that atmospheric inputs were responsible for concentrations in seawater measured before 26 March 2011. Atmospheric inputs would have been responsible for concentrations of ^{137}Cs ranging from 100 to 1,000 Bq/L in the vicinity of FDNPS, a few tens of becquerels per litre 10 km to the south and about 10 Bq/L at 30 km. It should be noted that this is an approximation because atmospheric deposition was not isotropic around FDNPS. The total amounts estimated by Kawamura et al. [K3] to have been deposited on the surface of the northern Pacific Ocean from the atmosphere were about 60 PBq and 5 PBq for ^{131}I and ^{137}Cs, respectively. Estournel et al. [E4] estimated that about 6 PBq of ^{137}Cs was deposited on the northern Pacific Ocean; only a small percentage (about 5%) of this amount, however, was estimated to have been deposited within a radius of 80 km of FDNPS. Kobayashi et al. [K18] estimated the deposition of ^{131}I and ^{137}Cs to be about 99 PBq and 7.6 PBq, respectively; these estimates were derived from coupling atmospheric and oceanic dispersion simulations with observed concentrations of ^{134}Cs in seawater collected from the Pacific Ocean.

B27. Several authors have used models of oceanic circulation and radionuclide dispersion in the ocean to estimate the magnitude of direct releases of radionuclides into the ocean from FDNPS. Kawamura et al. [K3] used the information published by TEPCO of the leak detected from 1 to 6 April 2011 to estimate this to be 4 PBq of ^{137}Cs and 11 PBq of ^{131}I. Tsumune et al. [T24] adjusted the release of ^{137}Cs in their model so that their estimate of average concentration between 26 March and 6 April fitted the average concentration measured at the southern outlet of FDNPS. This method resulted in a source term estimate of 3.5 ± 0.7 PBq of ^{137}Cs. The modelling work of Dietze and Kriest [D3] supported a source term in the range 1-4 PBq, rather than the much higher estimate reported in Bailly du Bois et al. [B2]; according to the analysis of Diest and Kriest [D3], the methodology used by Bailly du Bois et al. [B2] produced estimates of early releases (to mid-April) which were biased high and later releases (mid-April to July) which were biased low, and therefore total estimates from extrapolating backwards in time would be too high. Estournel et al. [E4] used a model with a relatively high resolution near the FDNPS site (600 m). The release of ^{137}Cs was calculated daily using an inverse method, constrained by fitting to the observed concentrations at the two outlets of the plant. The total ^{137}Cs release to the ocean was estimated to be around 4.1–4.5 PBq. Estournel et al. adjusted this to a maximum value of 5.5 PBq to account for the observed increase in concentration 30 km offshore in mid-April, which had not been reproduced by the dispersion model (see section IV below). Charette et al. [C4] extrapolated the inventory of ^{134}Cs in the ocean from June 2011 back to early April, the period of the peak release. They thus estimated a value of 11 PBq for the direct release of ^{134}Cs, and that of ^{137}Cs could be assumed to be the same.

B28. Both Kawamura et al. [K3] and Estournel et al. [E4] estimated the time distribution of the releases to the ocean, and both showed a similar pattern that indicated direct releases to the ocean dominated over inputs from deposition of radionuclides released to atmosphere from around the end of March 2011 onwards. The release rates of ^{137}Cs as estimated by Estournel et al. [E4] are shown in figure B-V; they estimated that about 99% of the total direct release to ocean occurred before 22 April 2011. Measurements of radionuclide concentrations in seawater were not available before 21 March. The estimations by Estournel et al. for the period 11 March to 30 June assumed that concentrations in seawater before 21/23 March were the same as the first measured values.

Figure B-V. Estimated daily release of ^{137}Cs into the ocean [E4]

(Red: deposition from the atmosphere on to the ocean surface integrated over the whole modelling domain; blue: direct release calculated by inverse method)



B29. Other radionuclides were also released to the ocean, both directly and indirectly. Isotopes of strontium and plutonium have been measured in seawater and sediments. Povinec et al. [P12] studied the measurements of concentrations of ^{89}Sr and ^{90}Sr in seawater. These generally showed strontium concentrations during the main period of the direct release to be one to two orders of magnitude lower than those of caesium. There was an exception to this general pattern around December 2011, when, following an accidental leakage of treated water from which caesium had been removed, measured concentrations of ^{89}Sr and ^{90}Sr, but not ^{137}Cs, rose [P12]. The concentrations of ^{90}Sr had fallen below those of ^{137}Cs again by January 2012. On the basis of different assumptions about the ratios of ^{90}Sr to ^{137}Cs and the range of estimates of total direct release of ^{137}Cs to the ocean, Povinec et al. estimated a direct release of ^{90}Sr of between 0.04 PBq and 6.5 PBq (although the latter was based on the high estimated release of ^{137}Cs of 27 PBq by Bailly du Bois et al. [B2]).

B30. All of the estimates of releases to the ocean were associated with much uncertainty. In reviewing these estimates, the Committee gave more weight to results based on three-dimensional modelling taking into account the high variability of the dispersion, rather than to those derived with extrapolation methods using constant dispersion rates. It concluded that the direct release to the ocean of ^{137}Cs was likely to have been in the range of about 3–6 PBq, with the direct release of ^{131}I likely to be about three times higher. The direct release of ^{90}Sr could be estimated to be in the range of about 0.04–1 PBq (based on ratios to the ^{137}Cs release). The estimated direct releases of ^{137}Cs (about 3-6 PBq) were of a similar order of magnitude to the estimated deposition on to the ocean from releases to the atmosphere (about 5–8 PBq). For ^{131}I, deposition on to the ocean from releases to atmosphere (about 60–100 PBq) was estimated to be about 5–10 times higher than the direct releases. However, because the inputs from deposition on to the ocean surface provided a diffuse source, whereas the direct releases were from a localized source, direct releases accounted for most of the observed elevated concentrations in seawater around FDNPS from 26 March onwards. The dispersion of radionuclides deposited from the atmosphere and released directly to the ocean is considered further in section IV below.

III. TRANSPORT AND DISPERSION IN THE ATMOSPHERE

A. Meteorological conditions

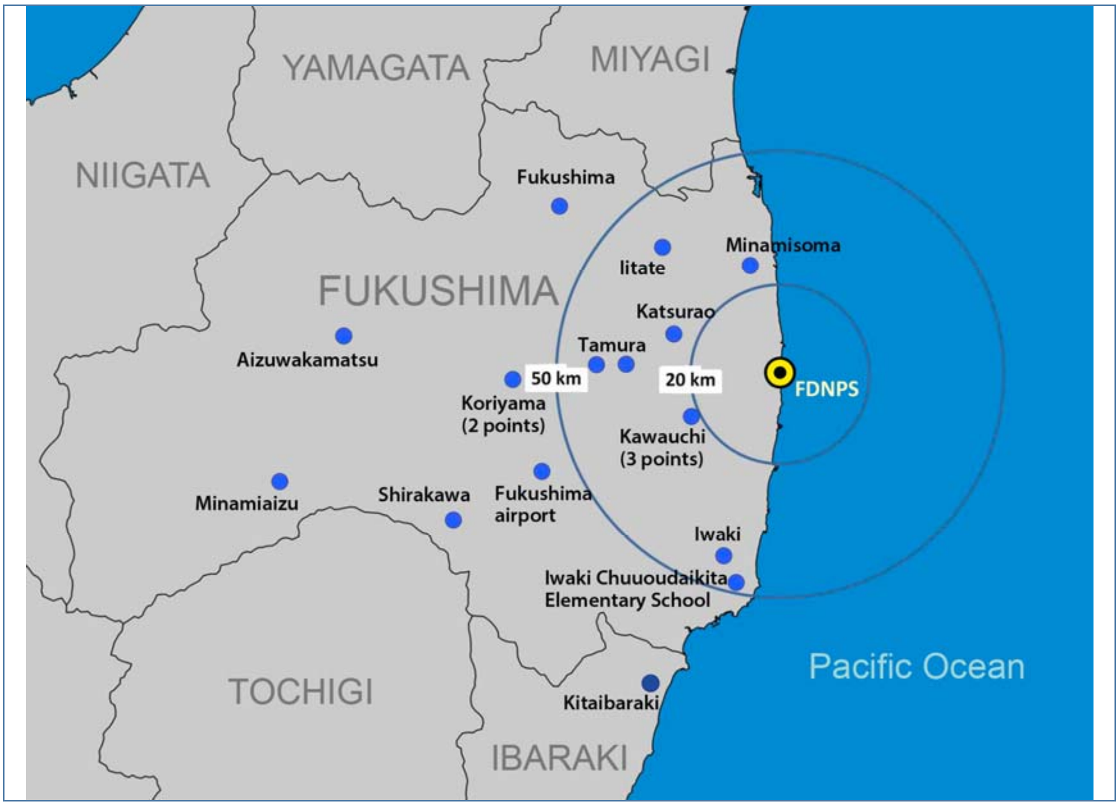
B31. The meteorological conditions observed during the key episodes in the release of radioactive material to the atmosphere have been described by many authors [K15, K20, M25, S11, S12, W16]. From 9 to 11 March 2011, a weak low pressure trough over eastern Japan caused the appearance of light rain until 12 March in the morning (JST). Then, a high pressure system moved eastward along the south coast of the main island from 12 to 13 March; the wind direction was from the south below 1 km, and from the west above 1 km in altitude in the afternoon of 12 March, at the time when the hydrogen explosion occurred in Unit 1. During the period 14 to 15 March, another weak low pressure trough moved eastward off the southern coast of the main island, then moved toward the north-east while developing rapidly after 15 March. Some light rain was observed from 15 to 17 March in the morning because of a weak low pressure system that moved north-eastward off the east coast. In particular, rain was observed in Fukushima Prefecture during the night, from 15 March at 17:00 to 16 March at 04:00 [K15], a time corresponding with significant releases of radioactive material to the atmosphere. The low-level winds were from the south-west during the morning of 14 March, the time when a hydrogen explosion occurred at Unit 3. The 950 hPa winds were from the west until 14 March, but changed to a direction from north-north-east in the morning of 15 March, the time when significant releases occurred from Unit 2. During the period 18 to 19 March, a high pressure system dominated and winds were generally blowing from the west. A low pressure system was then observed passing over the main island from 20 to 22 March with moderate rain until 23 March in the Kanto area (Ibaraki, Chiba, Tochigi, Saitama and in Tokyo).

B. Synthesis of observations

B32. Dose-rate measurements provided a useful basis for estimating the source term by inverse or reverse modelling (see section II.A above); furthermore, they provided a valuable basis for assessing the quality of estimates made by atmospheric transport models of the dispersion of released material. Most of the measured dose rates came from portable monitoring posts deployed by Fukushima Prefecture during the accident. This was because many of the automatic monitoring posts in the prefecture did not operate during much of the period when the largest release occurred because of damage caused by the earthquake and tsunami. MEXT also published extensive dose-rate measurements made in each prefecture [N18], and particularly in Fukushima Prefecture.

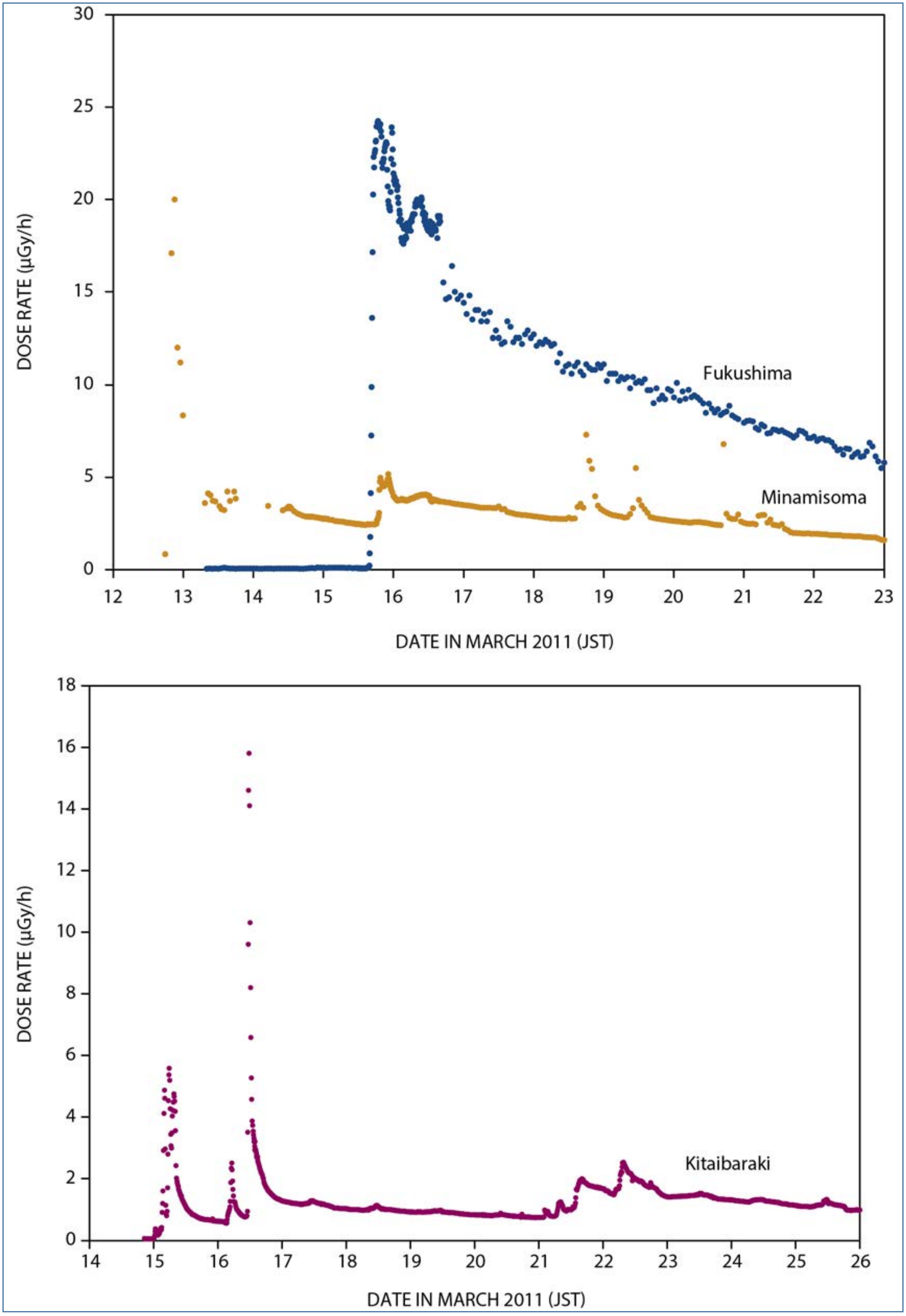
B33. There were also some automatic stations recording dose rates continuously during the course of the accident. The spatial distribution of dose-rate stations in the vicinity of FDNPS is shown in figure B-VI.

Figure B-VI. Spatial distribution of dose-rate stations in the vicinity of FDNPS [F5]



B34. Dose-rate measurements made at three locations, namely Fukushima, Minamisoma and Kitaibaraki, are shown in figure B-VII.

Figure B-VII. Dose-rate measurements at Fukushima, Minamisoma and Kitaibaraki [F4, I8]



B35. In comparison, very few extended or continuous measurements in Japan were made, or have been published, of the concentration of radionuclides in air during the release period[33]. The few measurements of particular interest, because they spanned the whole period of major releases, comprised the following:

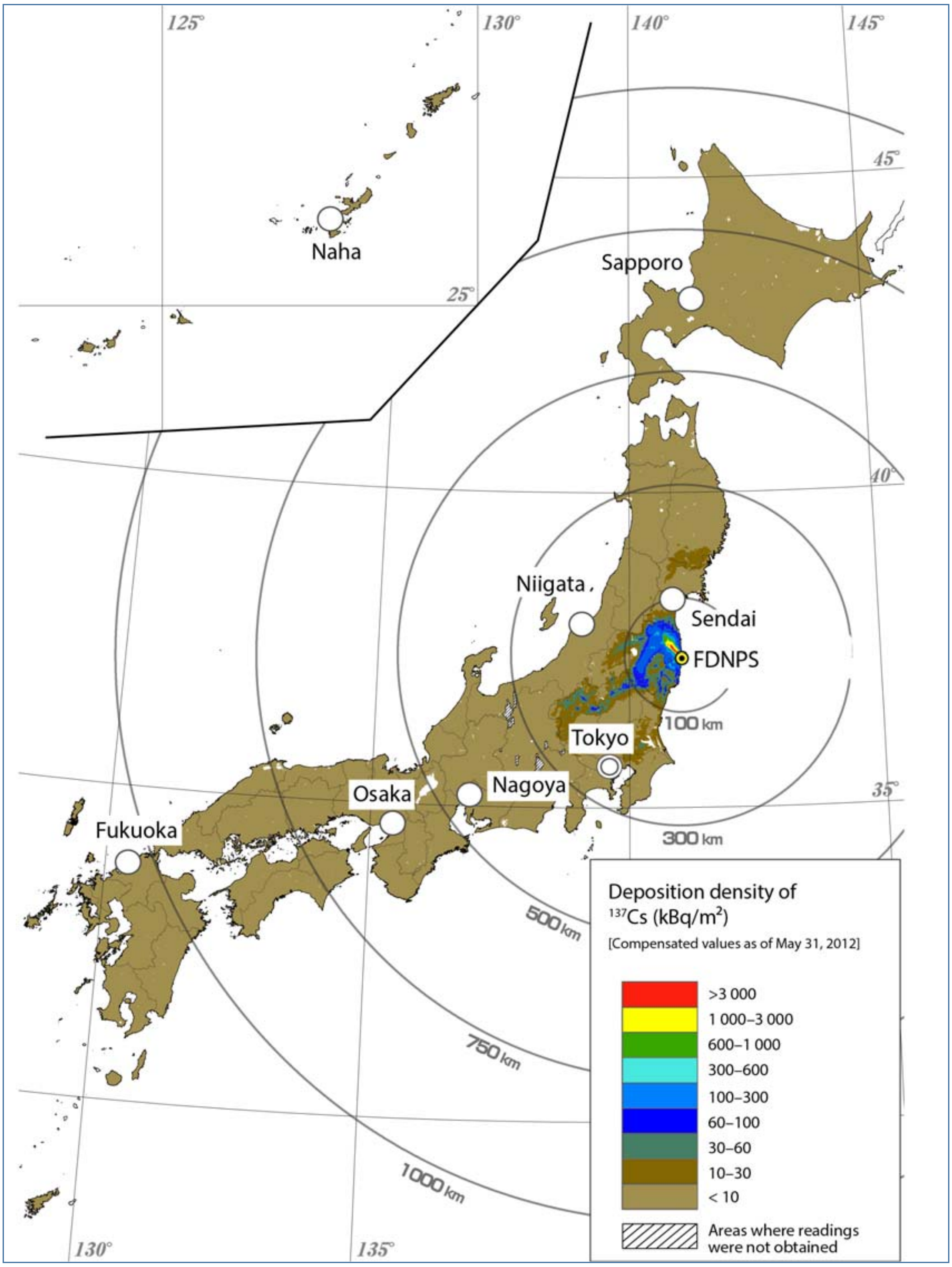
- Tokyo–Setagaya, located 250 km south-south-west of FDNPS;
- Tsukuba (Ibaraki Prefecture), located about 170 km from FDNPS in the direction of Tokyo;
- Takasaki (Gunma Prefecture) located 250 km south-west of FDNPS;
- Tokai-mura (JAEA office) located 100 km south-south-west of FDNPS.

The monitoring stations at Tokyo, Tsukuba, Takasaki and Tokai-mura were, however, all located in the Kanto area; consequently, their measurements were largely redundant; the exception is Takasaki where measurements were also made of the concentrations in air of noble gases.

B36. However, numerous and extensive measurements of the deposition densities of radionuclides were made. The United States Department of Energy measured deposition densities from aerial monitoring with fixed-wing aircraft from 17 March 2011 [U17] and ground measurements (in situ gamma spectrometry). MEXT subsequently, from June 2011, carried out a major campaign of aerial (helicopter) and ground measurements to cover the whole of the affected territory [N18]. The deposition density of ^{137}Cs on the ground surface is shown in figure B-VIII [N18].

[33] Outside of Japan, numerous measurements were made of concentrations of radionuclides in air when the released material passed overhead; these were used by many countries to assess doses to the public (see appendix C).

Figure B-VIII. Measurement results of the airborne monitoring surveys conducted by MEXT (deposition density of ^{137}Cs) [N18]



C. Atmospheric dispersion pattern

B37. Several events during the course of the accident led to major releases of radionuclides to the atmosphere (see table B1). Four periods were of particular interest in this respect.

B38. Venting and the hydrogen explosions in Units 1 and 3, during the period 12 to 14 March, were the origins of the initial and substantive releases of radioactive material to the atmosphere. The material released from Unit 1 spread mainly northwards along the eastern coast of the main island, then towards the north-east and east over the Pacific Ocean. This release was only detected by the Minamisoma station (see figure B-VI), located on the coast, about 25 km from FDNPS. No rainfall was recorded during this release episode. An increase in the dose rate during the night of 12 March was evident at the Minamisoma station (see figure B-VII) followed by a rapid decrease; this was characteristic of the passage of a radioactive plume in dry conditions. Simulations from one of the ATDMs used by a task team of the World Meteorological Organization (WMO) (see next section) of the ^{131}I concentration in air on 12 and 13 March, following the releases from Unit 1 and then Unit 3, are illustrated in figure B-IX. Owing to westerly winds, this plume travelled mostly towards the Pacific Ocean and had limited impact on the Japanese land mass.

B39. The material released from Unit 2 over the period 15 to 16 March was mainly due to the melting of the core and a breach of the reactor containment; this material was dispersed over eastern Japan because of rapidly changing weather conditions. This release episode could be better characterized than many others because it was monitored by many stations. It was the major contributor to the deposition of radioactive material on the Japanese land mass. The release took place in two quite distinct periods: firstly, during the night of 14 to 15 March; and, secondly, in the late morning and early afternoon of 15 March. From 00:00 to 05:00 JST on 15 March, the released material moved towards the south without encountering rain. An increase in the dose rate during the morning of 15 March was evident at the Kitaibaraki monitoring station (see figure B-VII). Radioactive material continued to be released throughout the rest of the day; this material moved towards the south then progressively towards the north-west and then to the south again on 16 March; these changes were reflected in the dose rates measured at the Kitaibaraki monitoring station (see figure B-VII) where two increases in the dose rate were recorded during 16 March. After 17:00 on 15 March, rainfall occurred until early morning of 16 March and this resulted in major deposition of radioactive material onto the ground; this was reflected in the large increase in the dose rate observed during the evening of 15 March at Fukushima (see figure B-VII). The relatively slow decrease in the dose rate at Fukushima is characteristic of radioactive material passing over a monitoring station in wet conditions (i.e. rainfall); the radionuclides deposited onto the ground by rain contribute to the dose rates measured by the monitoring station. Figure B-X shows simulations of the ^{131}I concentration in air at two times following the major releases that occurred from Unit 2; the simulated concentrations also include contributions due to continuing releases from Units 1 and 3.

B40. From the afternoon of 16 March onwards, subsequent releases, mainly from Units 2 and 3, spread easterly over the Pacific Ocean without any major impact for the Japanese territory. The simulated ^{131}I concentration in air during these releases is shown in figure B-XI.

B41. During the period from 20 to 23 March, releases from the three units were dispersed over the Japanese territory encountering rainfall on occasions. The simulated ^{131}I concentrations in air at particular times following these further releases from Units 1–3 are shown in figure B-XII.

B42. From 23 March, the release rates fell significantly and, compared with earlier releases, had minimal impact on the Japanese territory. The chronological patterns of atmospheric dispersion are seen as animations in attachments B-2 to B-3.

Figure B-IX. Simulated ^{131}I concentration in air during the initial releases from Units 1 and 3

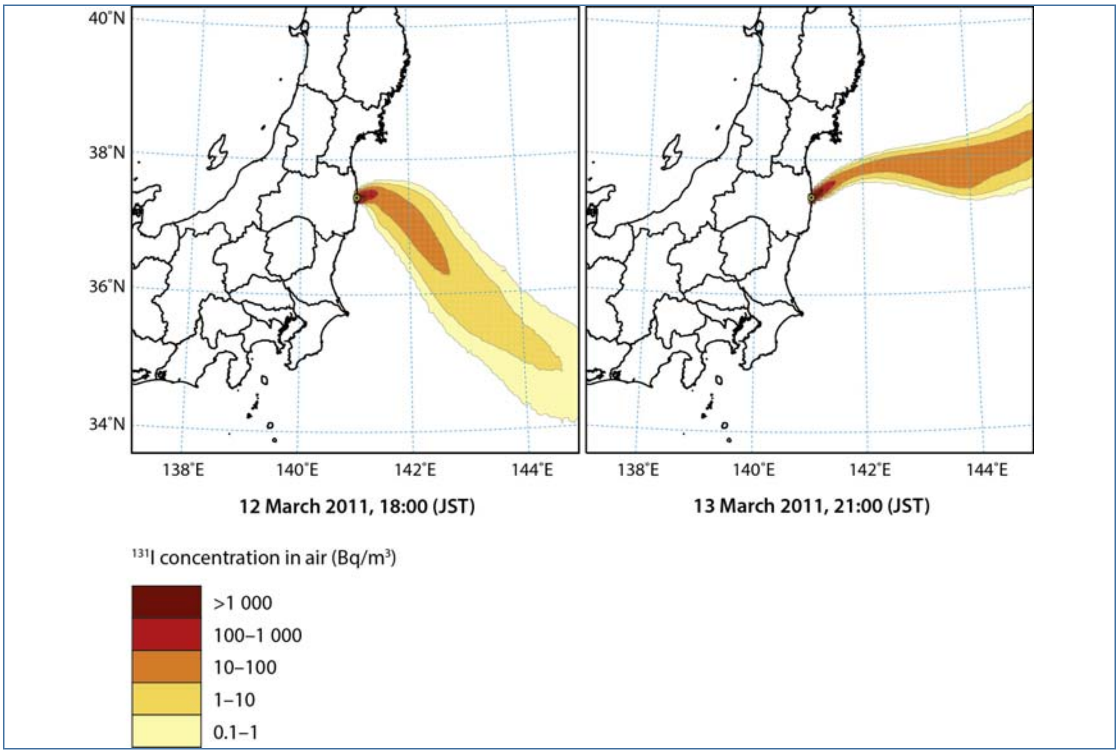


Figure B-X. Simulated ^{131}I concentration in air following the major releases from Unit 2 to the atmosphere

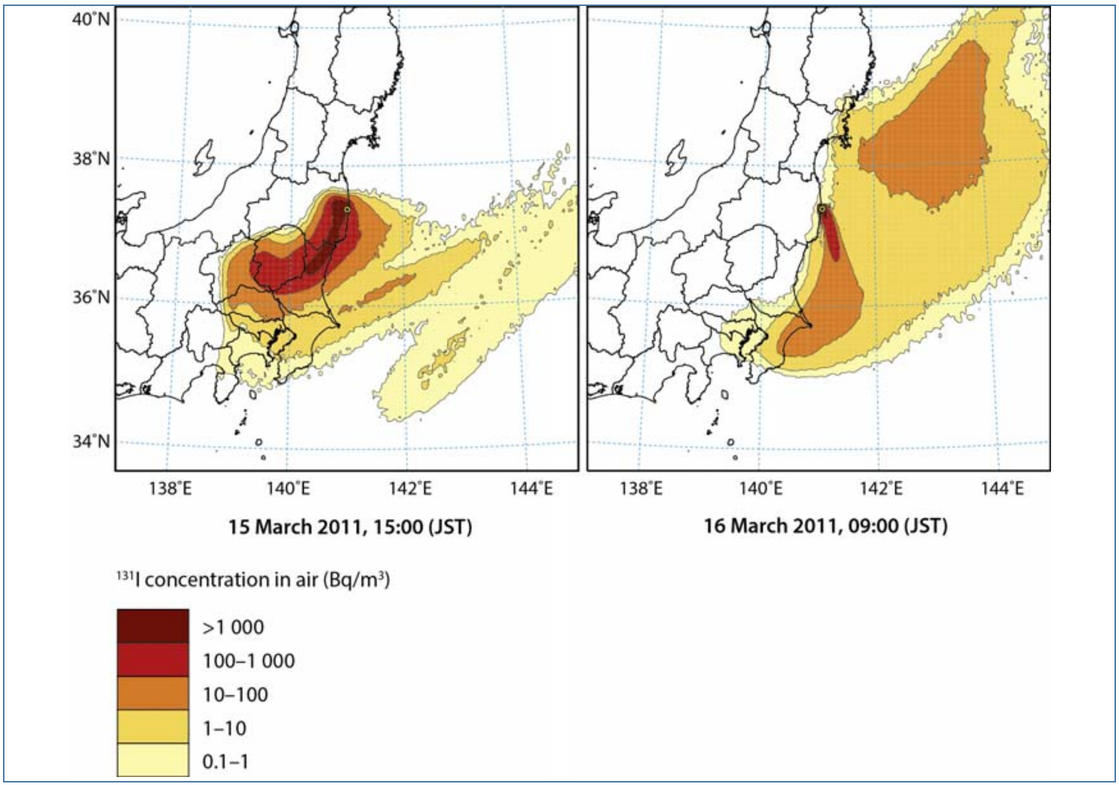


Figure B-XI. Simulated air concentration of ^{131}I during subsequent releases from FDNPS

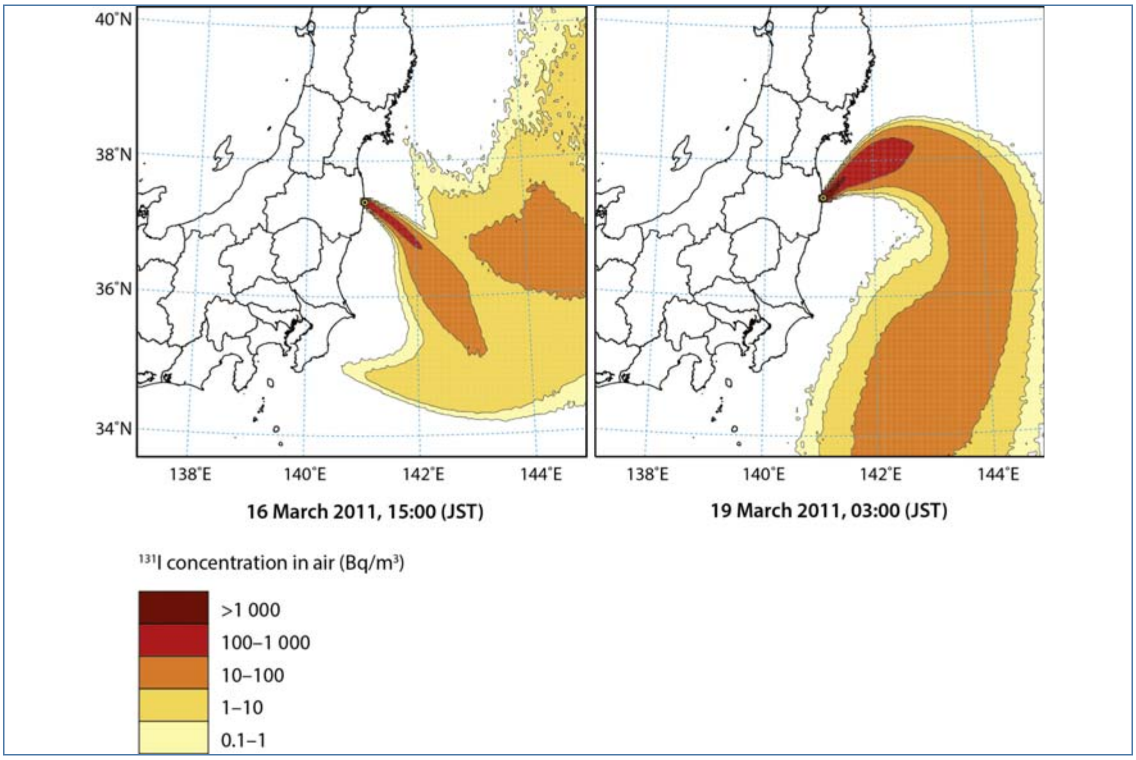
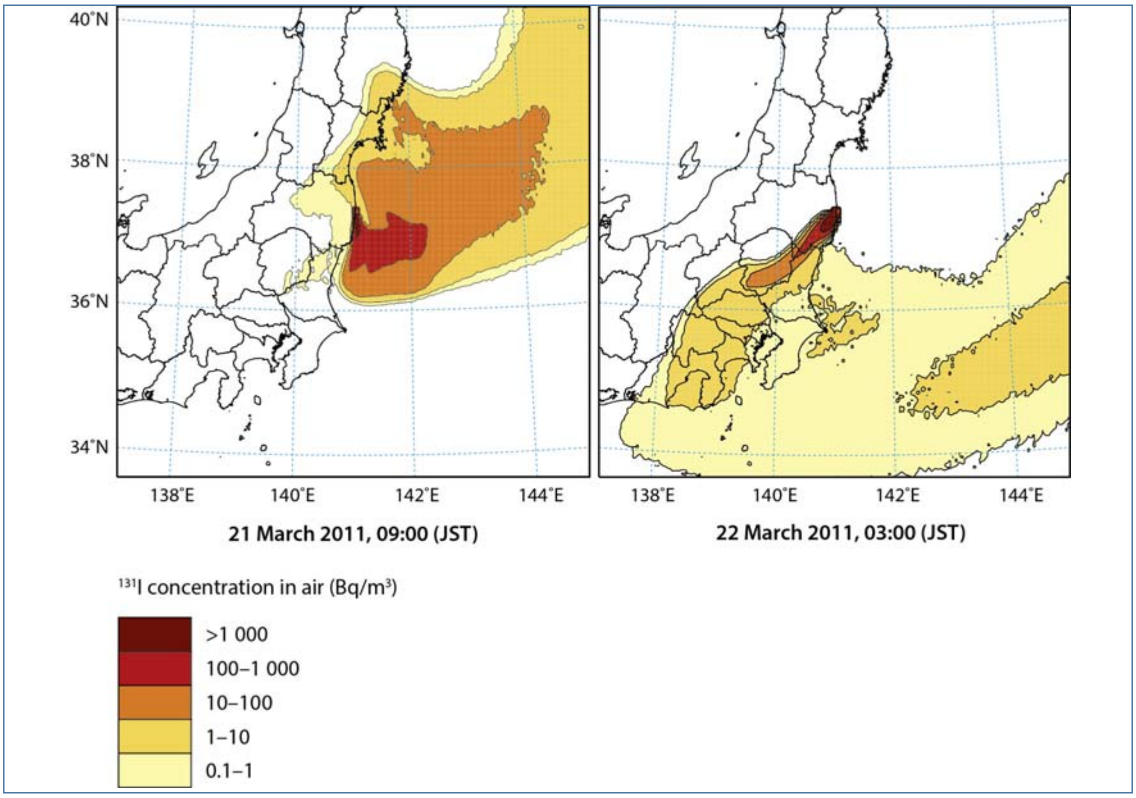


Figure B-XII. Simulated ^{131}I concentration in air during the releases from FDNPS in the period 20 to 23 March



D. Methodology and results of dispersion and deposition assessment

B43. The World Meteorological Organization (WMO) organized a task team to advise the Committee on the use of meteorological analyses and data in estimating concentrations of released radionuclides in the terrestrial environment using atmospheric transport and dispersion models (ATDM). The task team approached this by applying the meteorological data to ATDMs and comparing the results with the available measurement data. The task team consisted of participants from the Canadian Meteorological Centre (CMC), the United States National Oceanic and Atmospheric Administration (NOAA), the United Kingdom Met Office (UKMET), the Japan Meteorological Agency (JMA), and the Austrian Zentralanstalt für Meteorologie und Geodynamik (ZAMG). Each of these participants used their institute's own models, each with its unique treatment of the meteorological input data, dispersion, and deposition computations. Each participant also used the computed fields derived from meteorological data analysis that were already available to them, as well as the higher spatial and temporal resolution fields provided by JMA. The results provided a range of solutions because of variations in model parameterizations and the meteorological analysis data. Further information on the meteorological analyses and the models can be found in the task team's final report [W18].

B44. Dispersion and deposition calculations for a unit source using each model–meteorology combination were made available on a website [N17] for three generic species of material: *(a)* a gas with no wet or dry scavenging (to represent noble gases such as ^{133}Xe); *(b)* a gas with a relatively large dry deposition velocity (0.01 m/s) and wet removal (to represent released iodine in a gaseous form); and *(c)* a particle with wet removal and a small dry deposition velocity (0.001 m/s) (to represent all other released radionuclides, including iodine in a particulate form). These could be used to estimate concentrations in air and deposition densities of radionuclides on the ground for any postulated source term subject to specifying the time dependence of release rates for each released radionuclide.

B45. In order to evaluate the performance of the various ATDM–meteorology combinations, the WMO task team used a provisional source term estimate that had been developed prior to the Committee making a formal choice on what to use for its dose assessment. The provisional source term differed in a number of respects from that finally adopted by the Committee, but was sufficiently similar not to prejudice the main findings relating to the performance of different ATDM–meteorology combinations[34]. The results for each ATDM–meteorology combination can be found in [W18] where they were compared with the measurements of deposition densities of radionuclides and the more limited measurements of concentrations in the air. The outcome of the evaluation was inconclusive with respect to which ATDM–meteorology combination provided the best fit to the measured deposition densities and concentrations of radionuclides in air: the best fit for deposition density was not the same as that for concentration in air. To obtain better fits, the mean of the ten most representative ATDM–meteorology combinations was computed and compared with the measurement data. Statistical analysis showed that this "ensemble mean" provided a better fit than any individual ATDM–meteorology combination for both deposition density and radionuclide concentration in air. The performance of some ATDM–meteorology combinations was, however, not dissimilar to that of the ensemble mean [W18].

B46. In estimating the dispersion and deposition of radioactive material released from FDNPS, a number of simplifying assumptions had to be made to configure the ATDM simulations. Most of these

[34] Since this work was completed, task team members carried out further analyses using the Terada et al. source term [T19] (that is the source term adopted by the Committee for its assessment). The performance of the various ATDM–meteorology combinations for this source can be found in [D4].

concerned the characteristics of the source term as estimated by Terada et al. [T19] and were made as a compromise to accommodate the following potentially conflicting demands: *(a)* faithfully representing the varying radionuclide release rates; *(b)* the spatial and temporal resolution of the available meteorological data; and *(c)* the computational time and storage requirements of the subsequent simulations made using the ATDM in the WMO work. The main simplifications were the following: *(a)* release rates were specified in three-hourly time intervals as opposed to the finer resolution given by Terada et al. [T19] for particular release periods; *(b)* all releases were assumed to occur from, and be uniformly distributed over, a column from the ground to a height of 100 m, rather than characterizing the specific events leading to the releases (for example, hydrogen explosions and venting).

B47. For the assessment of exposures in the non-evacuated areas, the ATDM results were used to estimate the concentrations of radionuclides in air from measured deposition densities on the ground by scaling the measured deposition densities by the ratio of the concentration in air and deposition density estimated by one or other ATDM–meteorology combination. Despite the better performance of the ensemble mean (in terms of estimating measured levels in the terrestrial environment), the use of a single ATDM was judged to be more appropriate for most of the Committee's purposes.

B48. Estimates of the "bulk deposition velocity" for ^{137}Cs at selected locations (that is the ratio of the deposition density to the time integral of concentration in air) are given in table B7 for five of the best performing ATDM–meteorology combinations of the ten combinations that constituted the ensemble mean. The values for a given location varied within a range of about three to ten but, typically, by about five. This variability provided an indication of the uncertainty associated with inferring concentrations in air (and thus internal exposures via inhalation) from measured deposition densities. In general, the contribution of inhalation to the total exposure from all pathways was small; consequently, variability of the magnitude indicated above was unlikely to have had much impact on the overall precision of estimated doses.

Table B7. Comparison of "bulk deposition velocities" for ^{137}Cs estimated by different ATDM–meteorology combinations for selected locations

Location/Model	*Bulk deposition velocity (mm/s) for ^{137}Cs[a]*					
	NOAA-GDAS[b]	*UKMET-MESO[c]*	*UKMET-ECMWF[d]*	*NOAA-ECMWF*	*ZAMG-ECMWF*	*Average*
Okuma Town[e]	6.2	3.3	3.2	3.4	1.2	3.4
Iwaki City	6.8	3.2	6.1	7.6	8.8	6.4
Fukushima City	91	160	71	66	340	140
Iitate Village[e]	48	52	250	200	130	140
Namie Town[e]	48	24	240	87	80	97

[a] *The bulk deposition velocity is the ratio of the estimated deposition density on the ground and the estimated integrated radionuclide concentration in air; it was used to infer integrated concentrations in air from deposition density measurements for estimating internal exposures from inhalation of radioactive material (see appendix C).*

[b] *GDAS – Global Data Assimilation System*

[c] *MESO – Mesoscale Analysis provided by the Japan Meteorological Agency (JMA).*

[d] *ECMWF – European Centre for Medium range Weather Forecasting.*

[e] *Bulk deposition velocities were not used for assessing exposures in evacuated areas (Okuma Town, Namie Town and Iitate Village were all evacuated).*

B49. Given this limited sensitivity, the choice of which ATDM–meteorology combination to use had limited practical significance for the Committee's assessment of doses. The Committee chose the NOAA-GDAS ATDM–meteorology combination for the purposes of estimating ratios; this model was one of the higher ranked combinations[35], indeed even more highly ranked than the ensemble mean for deposition of ^{137}Cs. Compared with the average ratios of the five combinations at particular locations, the use of the NOAA-GDAS combination led to inferred concentrations in air that were typically within a factor of two lower or higher.

B50. The ^{137}Cs deposition pattern computed by NOAA-GDAS (figure B-XIII) was compared with the measured deposition pattern. The modelling results reproduced the observed deposition pattern quite well. The NOAA-GDAS calculations of the concentrations in air were compared to measured concentrations in air at the JAEA sampling site [F7, O2] (figure B-XIV); the comparison was not as good, capturing only three of the four main peaks and estimating the size of the peaks only within about a factor of ten. While the modelling results were able to capture the general pattern of radionuclide concentrations in the environment spatially and temporally, their ability to reproduce deposition density or concentration in air accurately at any particular time or location may have had considerable uncertainty; this is illustrated in figure B-XV where the NOAA-GDAS predictions are compared with the corresponding measurement of ^{137}Cs deposition density. The predictions showed little bias compared to the measured deposition densities. However, the uncertainty for specific locations varied by more than a factor of ten for the lowest deposition densities, but fell with higher deposition densities; at the highest deposition densities, the model predictions underestimated those measured by a small factor.

B51. The results of the ATDM simulations were used in a different way for estimating the concentrations in air and deposition densities of radionuclides to which the early evacuees were exposed. No data were available on the measured deposition densities before or during the evacuations; consequently, the method for estimating concentrations of radionuclides in air from deposition density measurements and a ratio derived from ATDM simulations could not be used. Instead, the time-dependent radionuclide concentrations in air and deposition densities estimated by the ATDM simulations were used directly. For reasons of consistency with the estimation of radionuclide concentrations in air for non-evacuees from the measured deposition densities, the NOAA-GDAS combination was also used here for estimating concentrations in air (and deposition densities) to which the early evacuees were assumed to be exposed. Given the inherent uncertainties in the estimates of these models for any given location, the choice of the NOAA-GDAS combination (relative to any other ATDM–meteorology combination or an average of several) was unlikely to be of great practical significance (see section E).

[35] Ranked in terms of a complex statistical measure related to how well a model was able to replicate measured levels in the environment (see [W18]).

Figure B-XIII. The calculated ^{137}Cs deposition density using the NOAA-GDAS combination

The contours show the terrain elevation at 250 m intervals

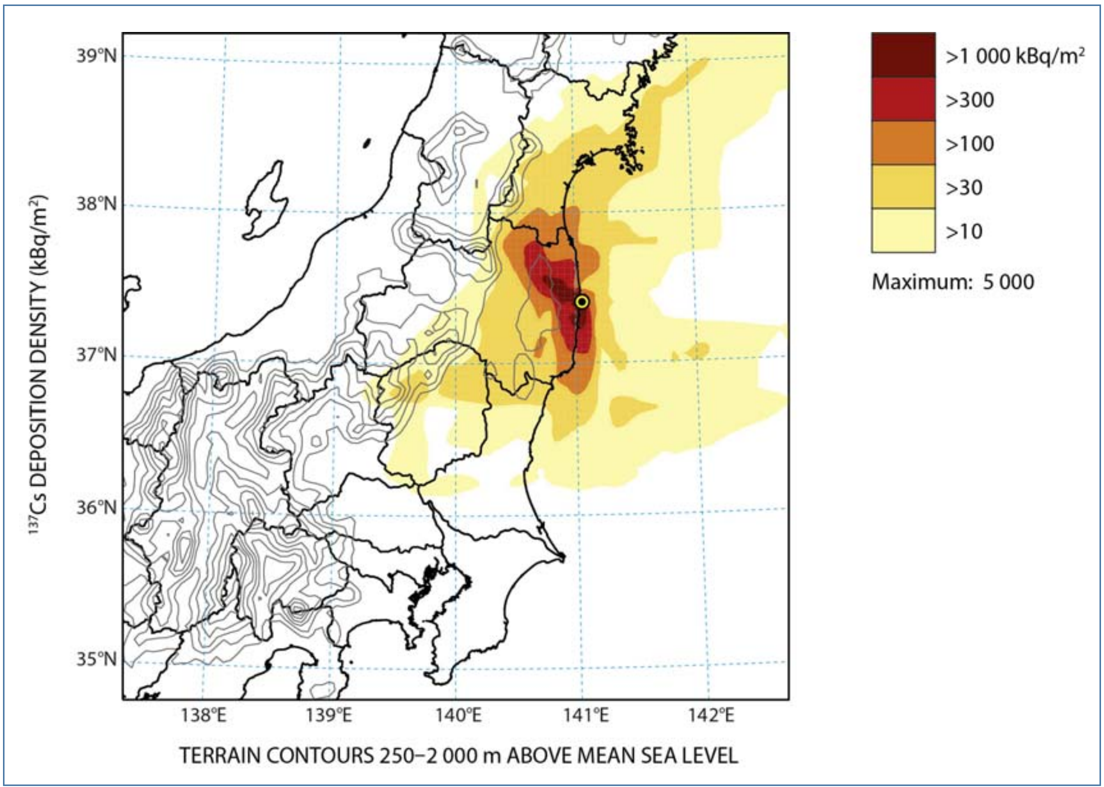


Figure B-XIV. The calculated ^{137}Cs concentrations in air (red +) using the NOAA-GDAS combination and measured data at Tokaimura, Ibaraki, Japan (black o) [F7, O2]

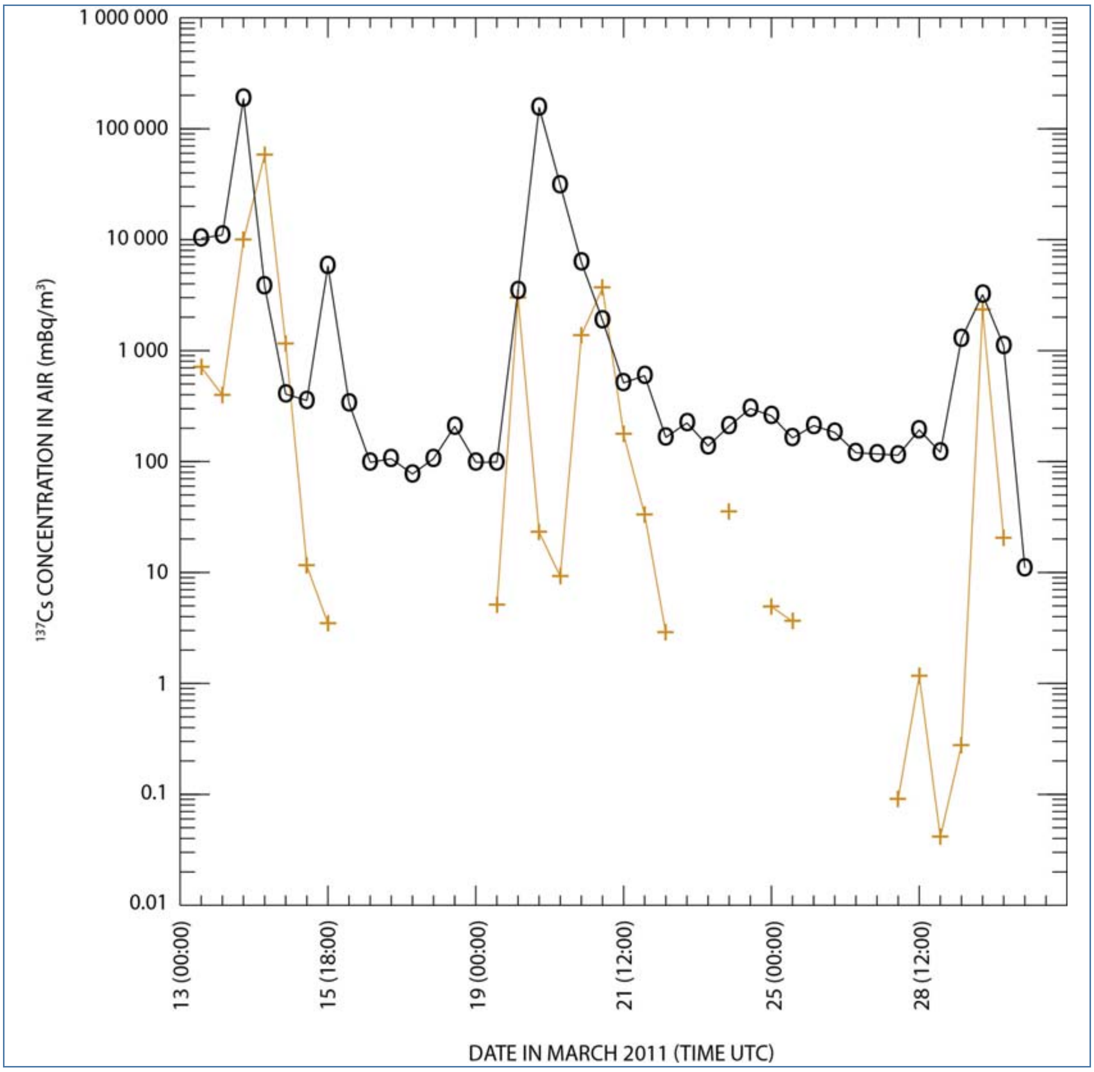
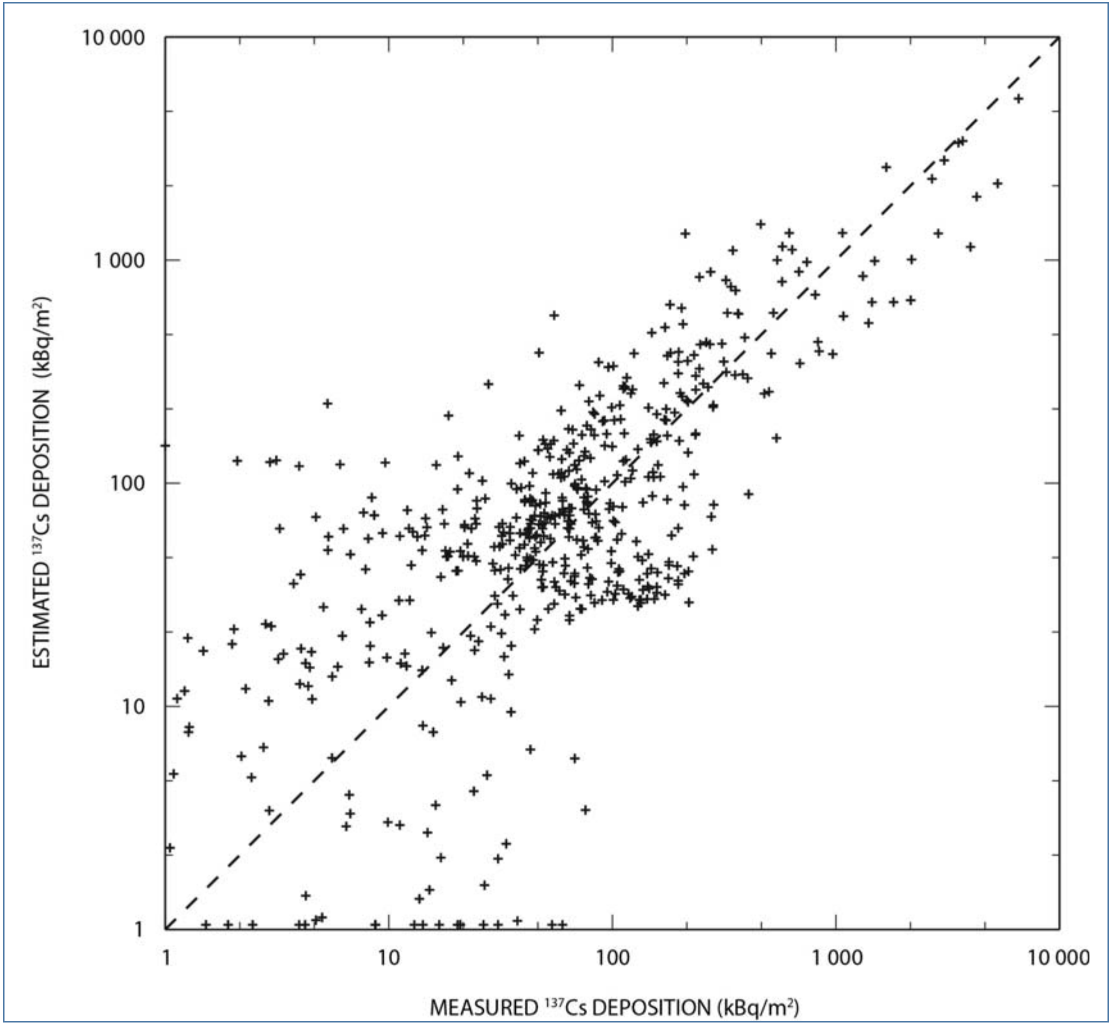


Figure B-XV. Scatter plot comparing NOAA-GDAS estimates and measurements of ^{137}Cs deposition density



E. Robustness of estimation of radionuclide levels in the environment where no measurements are available

B52. The ATDM estimates of the concentrations of radionuclides in air and deposition densities on the ground were associated with much uncertainty resulting from uncertainties in the source term and how material was dispersed in and deposited from the atmosphere. A rigorous analysis of these uncertainties was beyond the scope of this assessment. However, indications of the robustness of the estimates made in this assessment were made by conducting more limited scoping studies.

B53. For this purpose, separate estimates were made, using an independently derived and applied source term–ATDM–meteorology combination (that was not part of the WMO group), of the main quantities used to calculate doses to people; these quantities were time integrals (total and truncated) of concentrations of radionuclides in air and their deposition density on the ground, and ratios of these two quantities used to infer concentrations in air from measured deposition densities.

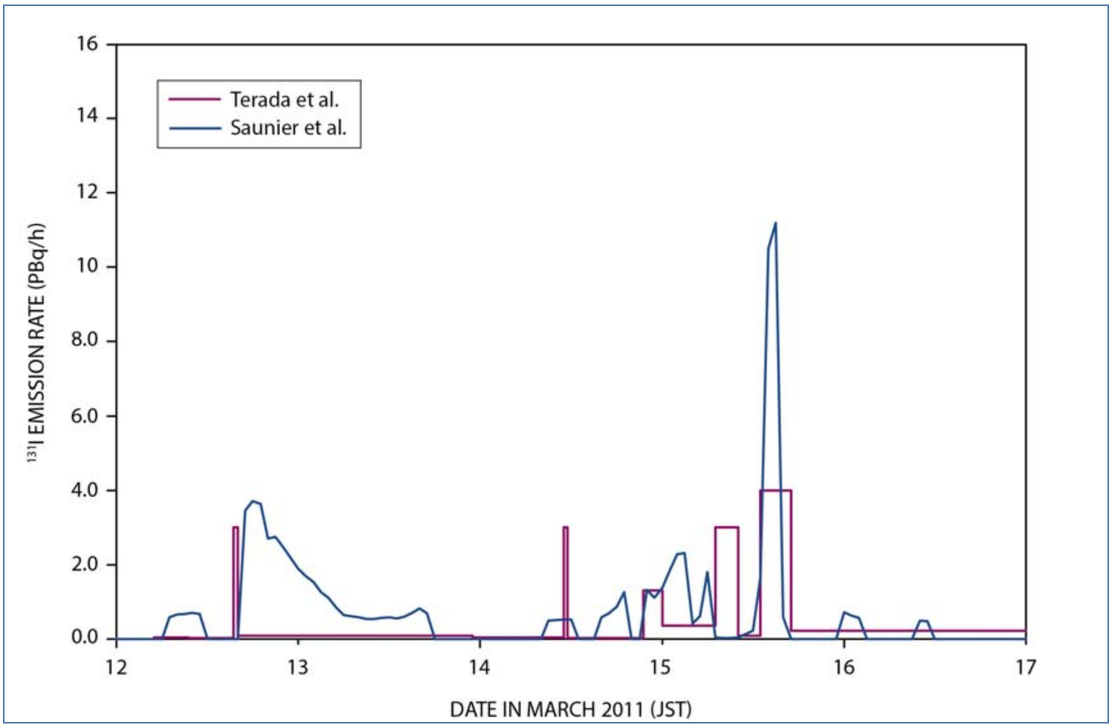
B54. The NOAA-GDAS ATDM results were compared with an IRSN ATDM–meteorology combination, namely an IRSN–ECMWF model using the source term of Saunier et al. [S3], which was derived using a different methodological approach, and measurements that were largely independent from those used by Terada et al. [T19] (the source term adopted by the Committee). The main features of, or assumptions adopted in, the two source term–ATDM–meteorology combinations are summarized in table B8. A comparison of the two source terms is also provided in figure B-XVI, where the time-dependent releases of ^{131}I are shown. A comparison of the time-dependent releases of ^{137}Cs is given in figure B-I, at least for the first few days when the releases were largest. Much greater temporal resolution was apparent in the Saunier et al. source term estimate consequent upon it being derived from numerous measurements of dose rate that were, in general, continuous throughout the release period.

Table B8. Comparison of the main features and assumptions in the two source term–ATDM–meteorology combinations

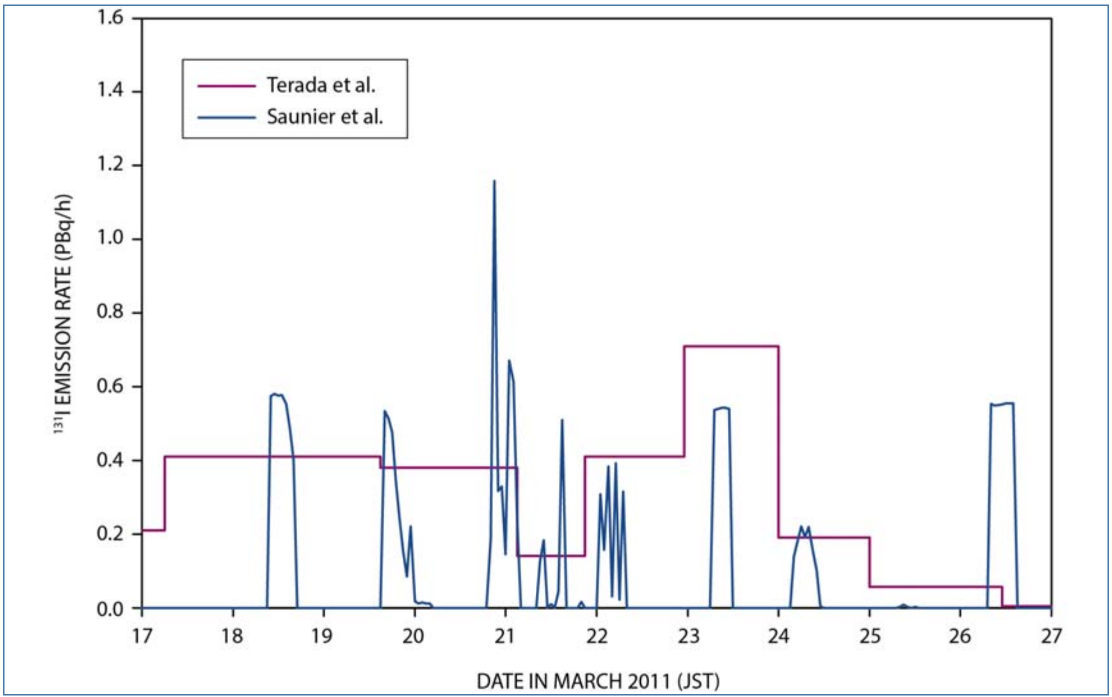
Characteristics of the source term–ATDM–meteorology combinations		*Terada–NOAA-GDAS*	*Saunier–IRSN-ECMWF*
Source term	Basis of derivation	Reverse modelling of environmental measurements (concentrations in air, deposition densities, dust samples, dose rates) Total releases: ^{131}I, 120 PBq; ^{137}Cs, 8.8 PBq	Inverse modelling of generally continuous dose-rate measurements from 57 monitoring stations in Japan Total releases: ^{131}I, 103 PBq; ^{137}Cs, 16 PBq
	Release heights	Assumed spread uniformly over a column from ground to height 100 m	Assumed spread uniformly over a column from ground to height 160 m
	Form of release	All nuclides released as particulates apart from noble gases, and iodine (assumed half released as particulate and half as elemental gaseous iodine)	Apart from noble gases, all nuclides released as particulates
Meteorology	Source	NOAA global analysis [W18]	ECMWF [W18]
	Time resolution	3 hourly	Hourly
	Spatial resolution	0.5° latitude and longitude	0.125° latitude and longitude
	Vertical resolution	56 layers; 10 within the lowest 1 km	11 layers between 0 and 3 400 m
Atmospheric dispersion and deposition	ATDM model	HYSPLIT [D5]	IdX [S3]
	Dry deposition	Particulates 10^{-3} m/s Elemental iodine 10^{-2} m/s	Particulates 2×10^{-3} m/s
	Wet deposition	Particulates in-cloud 4×10^{4} L/L Particulates below-cloud 5×10^{-6} s^{-1} Gaseous iodine 0.08 M/a solubility [D6]	$5 \times 10^{-5} p_0$ where p_0 is the precipitation rate (mm/h)

Figure B-XVI. Comparison of the time-dependent releases of ^{131}I estimated by Terada et al. [T19] and Saunier et al. [S3]

(a) Period of 12 to 17 March 2011



(b) Period 17 to 27 March 2011 (Note: different vertical scale to that used in (a))



B55. Table B9 shows the "bulk deposition velocities" estimated by the Terada–NOAA-GDAS combination and the Saunier–IRSN-ECMWF combination (referred to as "NOAA" and "IRSN" in the table) at selected locations for ^{131}I and ^{137}Cs. In addition, the ratio of the IRSN and NOAA ratios are also shown to indicate by how much the estimated concentrations in air (and thus the doses from inhalation) would have been different had the IRSN combination been used instead of the NOAA combination.

Table B9. Comparison of "bulk deposition velocities" for ^{131}I and ^{137}Cs estimated by different source term–ATDM–meteorology combinations for selected locations

Location/Model	*^{131}I*			*^{137}Cs*		
	NOAA (mm/s)	*IRSN (mm/s)*	*Ratio IRSN to NOAA*	*NOAA (mm/s)*	*IRSN (mm/s)*	*Ratio IRSN to NOAA*
DELIBERATE EVACUATION AREA						
Iitate Village	28	42	1.5	48	28	0.58
NON-EVACUATED LOCATIONS						
Iwaki City	8.5	5.6	0.65	6.8	4.9	0.71
Fukushima City	34	150	4.4	91	95	1.1

Note: The bulk deposition velocity is the ratio of radionuclide deposition density to the integrated concentration in air used to infer concentrations in air from measured deposition densities on the ground and thus estimate internal exposure from inhalation of radioactive material.

B56. For ^{137}Cs, the bulk deposition velocities estimated by the IRSN combination were, on average, about 20% lower than those estimated by the NOAA; at specific locations, they ranged from about 10% higher to a factor of about 1.5 lower, depending on the location. For the same value of measured deposition density, these differences would have translated into inferred concentrations in air (and thus doses from inhalation for the non-evacuated areas) ranging from about 10% lower to about a factor of 1.5 higher, depending on the location, compared with those estimated by the Committee using the NOAA combination.

B57. For ^{131}I, the bulk deposition velocities estimated by the IRSN combination ranged from about a factor of about 4 higher to a factor of about 30% lower—depending on the location—than those estimated by NOAA. These differences would have translated into inferred concentrations in air (and thus doses due to inhalation for the non-evacuated areas) ranging from about a factor of 30% higher to about a factor of 4 lower, depending on the location; on average, they would have been about 40% lower compared with those estimated by the Committee using the NOAA combination.

B58. The time integrals (truncated to when evacuation occurred) of the concentrations of ^{131}I in air and deposition densities estimated by the NOAA and the IRSN combinations are shown in table B10 at 14 selected locations and times relevant to the estimation of doses to early evacuees. The ratios of truncated concentrations in air estimated by the IRSN and NOAA combinations (and likewise the ratios of their respective estimates of deposition densities) are also shown in the table; the variation in these ratios was much greater than in the ratios of the two quantities (i.e. ratios of concentration in air and deposition density, see table B9).

B59. For 9 of the 14 locations, the IRSN estimates for ^{131}I concentration in air were within a factor of two of those for NOAA, and, for most locations, the ratios varied between about 0.5 and 12 (ignoring the value of zero for Futaba Town and 2,100 for Minamisoma City). For deposition, the IRSN estimates were within a factor of two of those for NOAA for 6 out of 14 locations, and for most locations (13 out of 14) the ratios varied between about 0.2 and 8 (ignoring the value of zero for Futaba Town). This level of variability was not unexpected and was typical of the uncertainty associated with the use of ATDM–meteorology combinations to estimate concentrations in air and deposition densities at specific locations; this variability was further compounded by the use of different source terms in the two cases. The implications of this variability for the estimation of doses to evacuees are further addressed in appendix C.

Table B10. Comparison of the time-integrated concentration of ^{131}I in air and deposition density estimated by two combinations of source term, ATDM and meteorology

Location	*Time period*		*NOAA*		*IRSN*		*Ratios (IRSN/NOAA)*	
	From	*To*	*Time-integrated concentration in air (Bq s/m³)*	*Deposition density (Bq/m²)*	*Time-integrated concentration in air (Bq s/m³)*	*Deposition density (Bq/m²)*	*Time-integrated concentration in air*	*Deposition density*
Kawauchi Village	2011-03-12 11:00	2011-03-16 08:00	3.4×10^7	4.1×10^5	4.0×10^8	2.9×10^6	11	7.0
Okuma Town	2011-03-11 21:23	2011-03-12 04:00	0	0	0	0	1	1
Kawamata elementary school	2011-03-12 08:00	2011-03-19 08:00	6.8×10^7	2.2×10^6	7.5×10^7	2.7×10^6	1.1	1.2
Futaba Town	2011-03-11 21:23	2011-03-12 21:00	8.4×10^7	5.6×10^5	0	0	0	0
Kawamata elementary school	2011-03-12 21:00	2011-03-19 17:00	6.8×10^7	2.2×10^6	7.5×10^7	2.7×10^6	1.1	1.2
Iwaki City	2011-03-12 13:00	2011-03-31 12:00	2.9×10^8	2.5×10^6	1.5×10^8	8.1×10^5	0.51	0.33
Iwaki City	2011-03-12 13:00	2011-03-16 15:00	2.2×10^8	1.2×10^6	1.1×10^8	2.5×10^5	0.50	0.21
Namie Town Tsushima activation centre	2011-03-12 15:00	2011-03-16 10:00	2.2×10^8	6.8×10^6	1.7×10^8	3.1×10^6	0.75	0.46
Tamura City, Denso Higashinihon	2011-03-12 08:00	2011-03-31 08:00	9.4×10^6	3.6×10^5	9.4×10^7	2.5×10^6	10	6.9
Minamisoma City	2011-03-11 00:00	2011-03-15 10:00	1.3×10^5	9.3×10^5	2.7×10^8	5.7×10^5	2100	0.61
Date City office	2011-03-15 16:00	2011-03-31 11:00	1.8×10^7	3.1×10^5	1.9×10^7	2.1×10^6	1.1	6.8
Kawauchi Mura elementary school	2011-03-13 11:00	2011-03-16 10:00	3.3×10^7	4.0×10^5	3.9×10^8	3.1×10^6	12	7.9
Namie Town Tsushima activation centre	2011-03-11 00:00	2011-03-23 14:00	2.8×10^8	7.4×10^6	1.8×10^8	3.9×10^6	0.64	0.53
Katsurao Village	2011-03-11 00:00	2011-03-21 12:00	2.4×10^8	5.5×10^6	2.4×10^8	4.0×10^6	0.99	0.74

IV. TRANSPORT AND DISPERSION IN THE OCEAN

A. Synthesis of observations

(a) *In the water column*

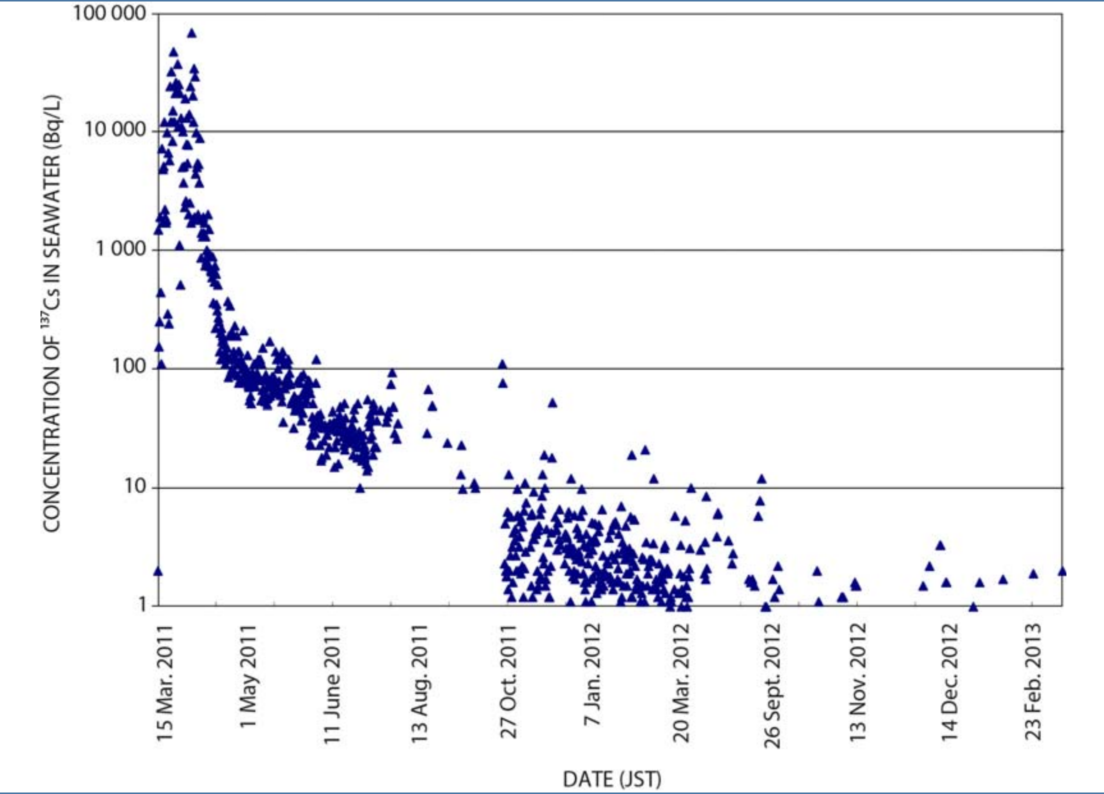
B60. Numerous observations of radionuclides were made in the northern Pacific Ocean over a wide range of distances from FDNPS, beginning one week after the accident [B25, H7, M11, T6]. Measurements were also made in the Sea of Japan to assess the radionuclide concentrations on the western side of the archipelago. These data provided a relatively good understanding of the spatial and temporal distribution in the ocean of ^{137}Cs and ^{134}Cs, the most radiologically significant radionuclides released.

B61. Isotopes of other elements were also measured, including: ^{131}I, which was measured at elevated concentrations but only over a limited time because of its relatively short half-life of 8 days; ^{129}I, which was detected near the Japanese coast; and ^{89}Sr and ^{90}Sr, which were detected near FDNPS in 2011 and 2012 and, for ^{90}Sr, over a larger area (30 to 600 km) in June 2011.

(b) *Observations of ^{131}I, ^{134}Cs and ^{137}Cs*

B62. On 21 March 2011—within ten days of the first release of radionuclides from FDNPS—the operator, TEPCO, began to conduct monitoring of seawater near one of the two outlets located on either side of the FDNPS port [T6]. Monitoring was also carried out inside the port. Three days later, the monitoring was extended to the second outlet. Monitoring for ^{131}I, ^{134}Cs and ^{137}Cs was then conducted at points near each of these outlets twice daily. The results for ^{137}Cs in seawater near FDNPS are shown in figure B-XVII [B23]. They indicated that concentrations of ^{137}Cs increased to a first peak at 47,000 Bq/L on 31 March, followed by a second peak at 68,000 Bq/L on 7 April, before declining rapidly to under 10,000 Bq/L by 9 April and generally below 200 Bq/L by the end of April. Thereafter, the decrease was much slower. The ratio of the concentrations in seawater of ^{134}Cs to those of ^{137}Cs was found to be very close to 1. In 2012, concentrations of ^{137}Cs measured near the two outlets were between 1 and 10 Bq/L. Measurements of concentrations in the port during 2012 ranged between 10 and 100 Bq/L, indicating that some releases were continuing, possibly from residual leaks, from underground water sources, from run-off into rivers from deposits on land, or from desorption of radionuclides from marine sediments.

Figure B-XVII. Measured concentrations of ^{137}Cs in seawater near the FDNPS site [B23]



B63. During the first days of monitoring, concentrations of ^{131}I in seawater 20 to 30 times higher than of ^{137}Cs were measured, reflecting the relative importance of atmospheric deposition at this time. Around 25 March, the ratio of the two radionuclides in the vicinity of FDNPS fell sharply to 10. By around mid-May, this ratio was close to 0.1, reflecting the comparatively short half-life of ^{131}I.

B64. TEPCO also conducted monitoring in coastal waters further away from FDNPS [T6], and increased the number of measurement stations over time. Two coastal stations south of FDNPS were monitored daily: the first 11 km to the south at the Fukushima Daini Nuclear Power Station; and the second 16 km to the south at Iwasawa beach. TEPCO progressively added other sites, both along the coast and on sections located 3 km, 8 km and 15 km offshore. In addition, MEXT [M11] performed regular measurements at different stations on a section located 30 km from the coast.

B65. During the period characterized by large direct liquid releases (between 26 March and 8 April), dispersion of the released radionuclides away from FDNPS was relatively limited. Concentrations at the monitoring site 11 km to the south, where they were the next highest after the FDNPS outlets, were approximately 20 times lower [T6]. Moreover, concentrations fell even more rapidly with distance over this period perpendicular to the shoreline. At 15 km offshore, concentrations were 100 times lower than at FDNPS and, at 30 km offshore, they were about 1,000 times smaller. After 8 April, when the concentrations measured in seawater at FDNPS peaked, concentrations at 30 km offshore increased significantly for a few days suggesting a mechanism of seaward dispersion. From the middle of May, samples collected 15 km offshore by TEPCO were most often below the relevant detection limit.

B66. Regarding the dispersion along the coast, a comparison of two sites to the north and to the south located at the same distance from FDNPS [T6] indicated that the coast south of FDNPS would have been more affected than the northern coast. However, this indication should be treated with caution because the northern coast was not monitored during the period of large direct releases.

B67. Various scientific cruises were made at distances farther from FDNPS between April and June 2011 [B25, H7]. In addition, ships voluntarily took measurements across the entire northern Pacific Ocean at least up until March 2012 [A12]. The detection limits for these measurements were lower than those of the regular monitoring discussed above.

B68. One month after the accident, a scientific cruise aimed at measuring ^{134}Cs and ^{137}Cs was organized several hundred kilometres from the Japanese coast with an additional extension to about 2,000 km towards the north-east [H7]. The concentrations of ^{137}Cs were found at up to 100 times higher than the pre-accident levels. The ratio of these two caesium radionuclides was found to be close to one, indicating that the source was FDNPS. The presence of these radionuclides in the north-east and south-east directions at such a large distance from FDNPS so shortly after the accident indicated that their presence was mainly because of atmospheric inputs.

B69. In June 2011, a cruise conducted measurements with a relatively high spatial density between 30 and 600 km from the Japanese coast of radionuclide concentrations in the surface and subsurface waters [B25]. The concentrations of ^{134}Cs were highest near the coast. At 600 km offshore, concentrations at the surface reached 0.1–0.3 Bq/L. A clear finding of this sampling work was that the concentrations to the south of the Kuroshio current were low, showing that this powerful current formed a southern boundary for liquid releases from FDNPS.

B70. Finally, for the period from March 2011 to March 2012, other ships sampled the northern Pacific Ocean between 20°N and 50°N [A12]. The results showed radiocaesium was moving towards the east at a rate close to 80 mm/s. The main body of the radioactive plume reached longitude 180°E (more than 3,000 km from the station) in March 2012, one year after the accident, with a maximum concentration of 10^{-2} Bq/L. This propagation was confined along the parallel of 40°N latitude.

B71. Generally, measurements where the detection limit was high (10 to 20 Bq/L) did not detect released radionuclides in seawater below the surface. More precise measurements with a lower detection limit indicated that ^{134}Cs concentrations decreased significantly with depth below the ocean surface. In June 2011, released radiocaesium in a dissolved form apparently had not penetrated below 100–200 m from the ocean surface [B25].

(c) *Other radionuclides*

B72. Radiostrontium (^{89}Sr and ^{90}Sr) was detected in measurements made regularly over a year at FDNPS [P12] and offshore during a cruise in June 2011 [C2]. At FDNPS, ^{90}Sr concentrations were up to 4 orders of magnitude higher than those that preceded the accident, but were generally at least one order of magnitude lower than those of ^{137}Cs (except for the short period following the direct release to the ocean in December 2011—see section II.B above). Further offshore, in June 2011, the ratio of the concentration of ^{90}Sr in seawater to that of ^{137}Cs was about 0.02. This concentration ratio was much higher in seawater than in ground deposition, indicating direct liquid releases to the ocean were the dominant source, rather than deposition from the atmosphere.

B73. TEPCO [T6] and NRA [N20] conducted—and at the end of 2013 continue to conduct—seawater monitoring; they detected the presence of plutonium radioisotopes in seawater samples, but levels were near or below the detection limit.

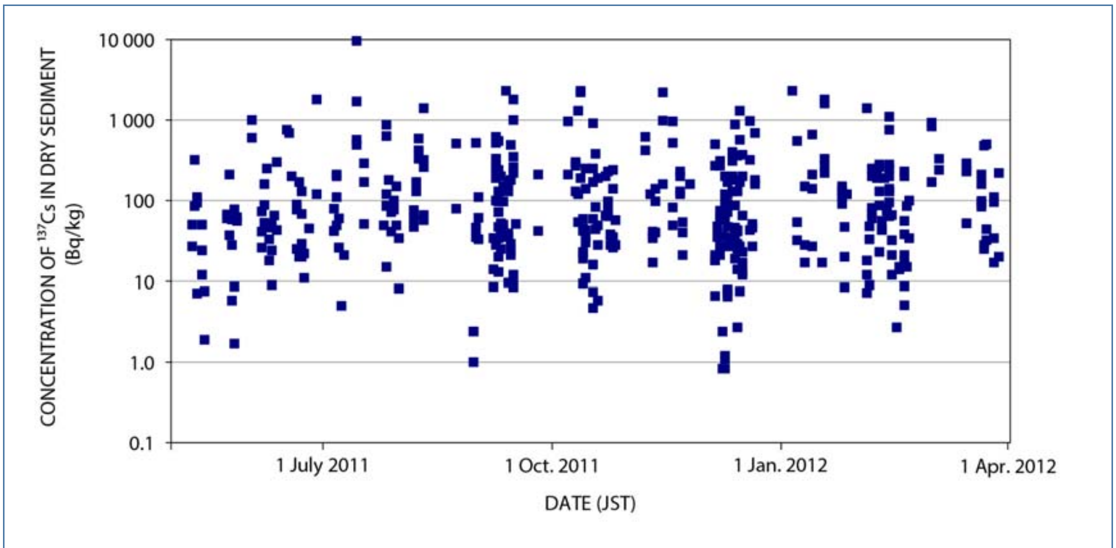
(d) *Concentrations of ^{134}Cs and ^{137}Cs in sediments*

B74. Almost 1,000 samples of sediment from the surface (30 mm) of the seabed taken between the end of April 2011 and the end of 2012 off Fukushima Prefecture and neighbouring prefectures have been analysed [M11]. The radionuclides most frequently detected were ^{134}Cs and ^{137}Cs. The highest concentration of ^{137}Cs, of the order of 10^5 Bq/kg in dry sediment, was measured in the port of the FDNPS site. Levels decreased significantly with distance from the FDNPS site, with ^{137}Cs concentrations generally lying between 10 and 1,000 Bq/kg in dry sediment, compared to values of 1 Bq/kg before the accident (see figure B-XVIII). The initial $^{134}Cs/^{137}Cs$ ratio was close to 1, in line with ratios found in seawater. The higher concentrations were associated with fine sediments. Measurements performed on the 30–100 mm layer showed significant concentrations that could have resulted from bioturbation [O7]. The Committee considered how the distribution of ^{137}Cs in sediment developed with time, but it was difficult to draw conclusions, owing to the high spatial heterogeneity of concentrations. However, it was clear that concentrations of ^{137}Cs in sediment had changed much less over time compared to concentrations in water (compare figures B-XVII and B-XVIII).

B75. The resuspension of fine sediments in coastal areas is a process that recurs when currents and waves are sufficiently energetic. Transport of turbid layers generated by resuspension along the bottom can then redistribute radionuclides for several years before they are permanently buried under new layers of sediment. Moreover, sediment represents a source of radionuclides for marine species living or feeding on the ocean floor.

Figure B-XVIII. Concentrations of ^{137}Cs in sediment

Taken from [M11]. Higher values observed in the FDNPS port have not been plotted



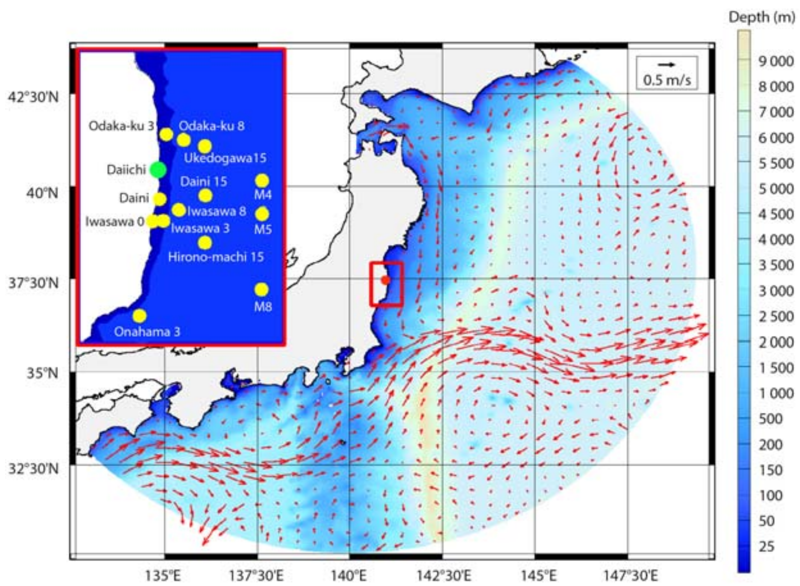
B. Marine dispersion models and validity checks

B76. The numerous observations available enabled an understanding of some of the characteristics of the dispersion of released radionuclides in the marine environment. Modelling of dispersion could supplement this understanding provided that models had been reasonably well-validated by observations. To understand how this dispersion occurred at the regional level, the modelled surface currents for the month of April 2011 are presented (as arrows) in figure B-XIX [E4]. This shows, in particular, the influence of the Kuroshio current that transports warm and salty waters along the southern coast of Japan and then eastwards to the central Pacific Ocean north of the 35°N parallel. This current flows from about one hundred kilometres south of FDNPS and creates a boundary between the warm waters to the south and the cold waters to the north, into which the direct liquid releases of radionuclides were made. Periáñez et al. [P3] conducted similar modelling studies.

B77. Off the coast of FDNPS, the continental shelf (where the water is less than about 200 m deep—corresponding to the darker blue colours in figure B-XIX) is about 40 km wide. Currents on the continental shelf vary in response to forcing by the wind, tides and freshwater inputs from rivers. Wind seems to be the main driver of the currents in this coastal region. The coast induces a blockage which channels the currents within the first few kilometres. When the wind is favourable for southward transport, surface water and associated contaminants can reach the Kuroshio current within a few days, and then be dispersed eastwards towards the centre of the Pacific Ocean.

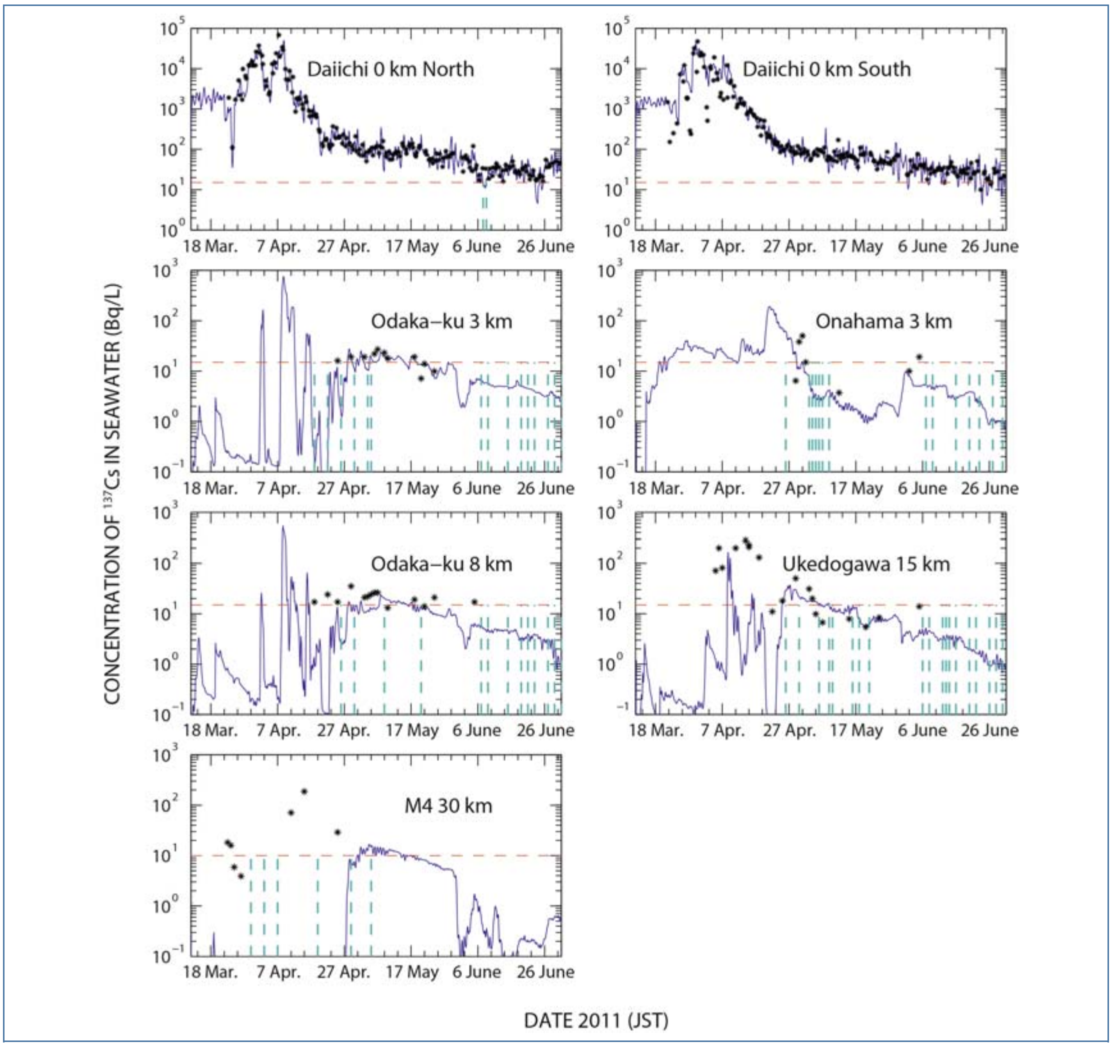
B78. To be confident in an analysis of the dispersion, the results of models had to be validated against available observations. The results of different models mentioned in section II.B of this appendix [E4, K3, T24] and those from the analysis of Periáñez et al. [P3] (which incorporated a dynamic model of the interactions between seawater and sediments) were compared with observations at different points. Masumoto et al. [M5] presented an intercomparison of the results of some of these models with others. The models sometimes related to winds used to force the hydrodynamic models, to oceanic currents, and to time series of concentrations at different points. Estournel et al. [E4], using the daily source term discussed in section II.B above, simulated the ^{137}Cs dispersion and then compared simulated and observed concentrations at 13 sites along the coast and at 3, 8, 15 and 30 km offshore (see position in the insert of figure B-XIX). The results are shown in figure B-XX. The variations of concentration with time were generally well reproduced, apart from the early observed increase in concentrations at 30 km offshore (discussed in section II.B of this appendix). This simulation was used to provide insight into how direct releases to the ocean and deposition from the atmosphere were dispersed in the ocean.

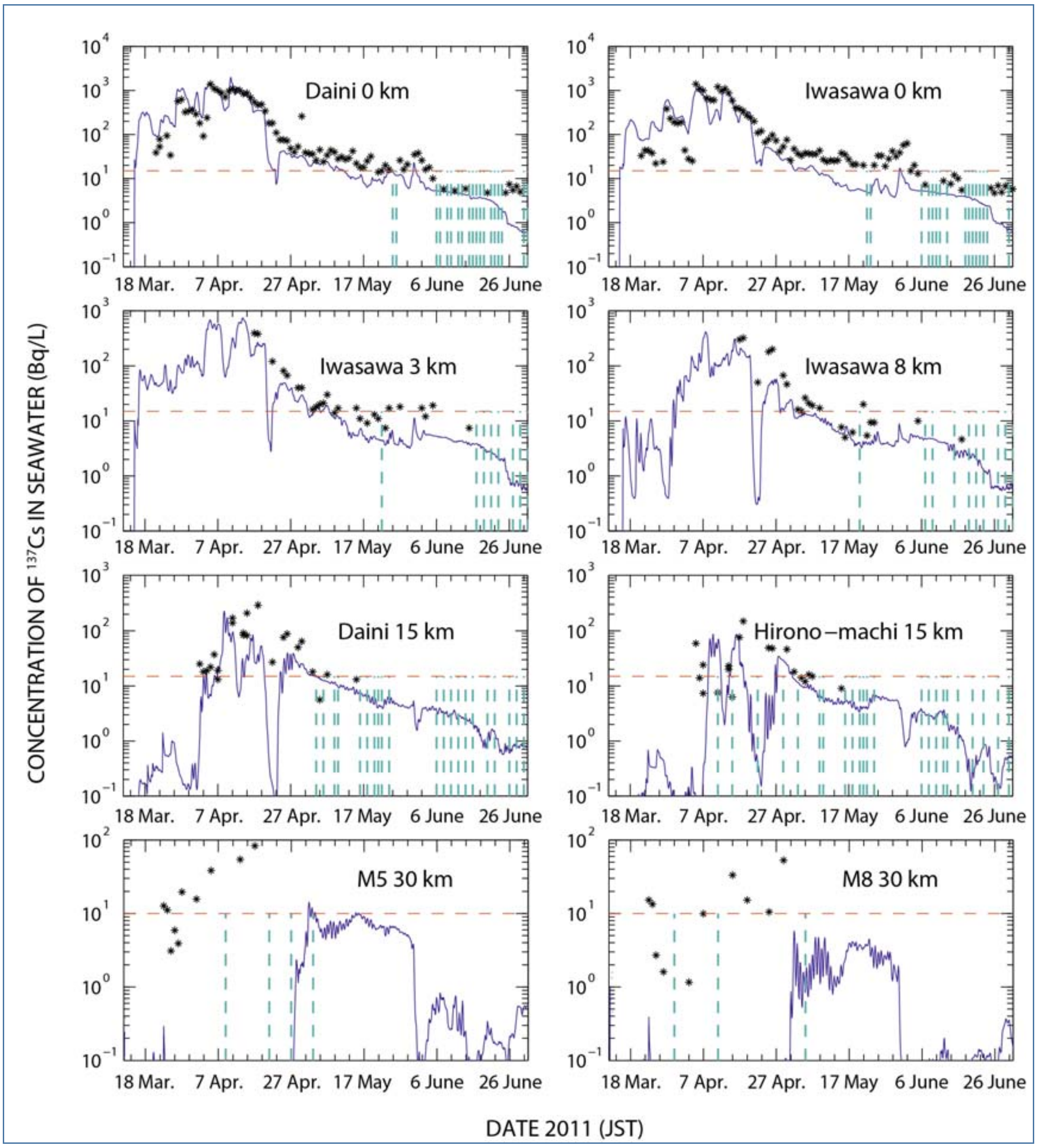
Figure B-XIX. Surface current simulated for April 2011 superimposed on the sub-marine topography (from [E4])[a]



[a] *The red dot indicates the Fukushima Daiichi Nuclear Power Station (FDNPS). The top left insert is a close-up around FDNPS indicating the position of the points used to validate the dispersion model (see figure B-XX).*

Figure B-XX. Comparison of ^{137}Cs concentrations (Bq/L) observed (dots) and simulated (solid line) at different points indicated in the frames (from [E4])[a]





[a] *See map on figure B-XIX for site locations. The red dashed line indicates the detection limit while vertical cyan dashed lines indicate observations below the detection limit.*

C. Results of dispersion assessment

(a) *Dispersion of direct releases to the ocean*

B79. The wind blew mainly southwards during the first month after the accident, when the direct releases from FDNPS to the ocean were highest. Such wind conditions produced transport to the south and confinement against the coast (see figure B-XXI), owing to the Coriolis effect. This situation is typical of coastal downwelling. It is the origin of the high concentrations observed south of FDNPS (at Fukushima Daini Nuclear Power Station and Iwasawa beach) [T6]. This southward transport then led to an interaction between the coastal waters carrying the released radionuclides and the Kuroshio current, and subsequently to an eastward transport.

B80. After mid-April, the wind blew mainly northwards inducing a northward and eastward surface current. This situation was favourable to disperse radionuclides in the entire coastal area, including to the north of FDNPS (see figure B-XXII). Radionuclide concentrations then decreased sharply near to the coast, while they increased 30 km offshore. An analysis of observations of ^{137}Cs and temperature and salinity profiles at 30 km offshore in mid-April indicated that radiocaesium was associated with a 10–20 m thick low-salinity layer. The presence of this river-influenced coastal water pushed by the wind over denser oceanic water promoted the offshore transport of radionuclides, limited their dispersion into the underlying waters and thereby increased the residence time of radionuclides in surface waters.

Figure B-XXI. Mean concentration of ^{137}Cs in surface waters (Bq/L) during the first month after the accident (from [E4])

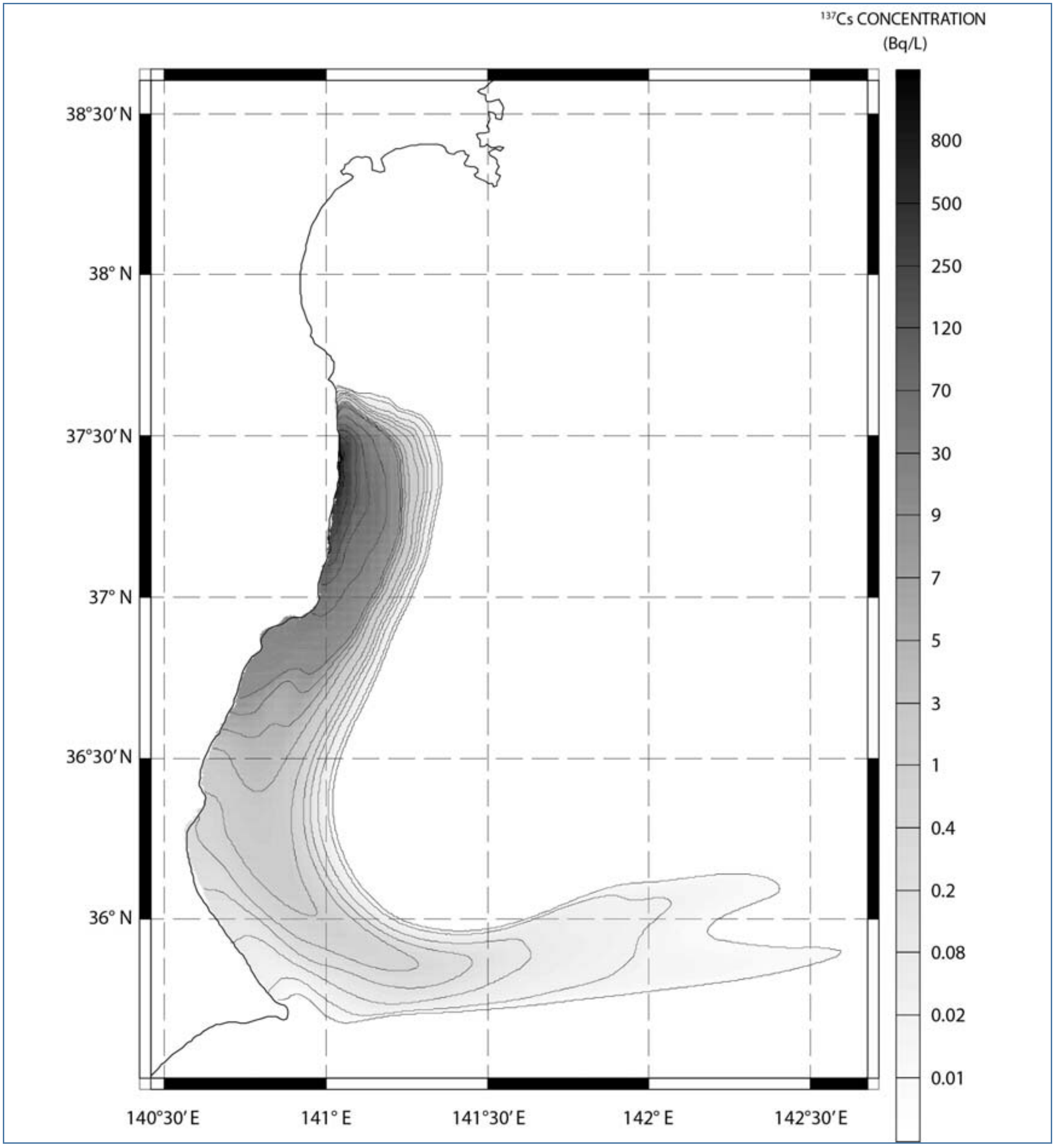
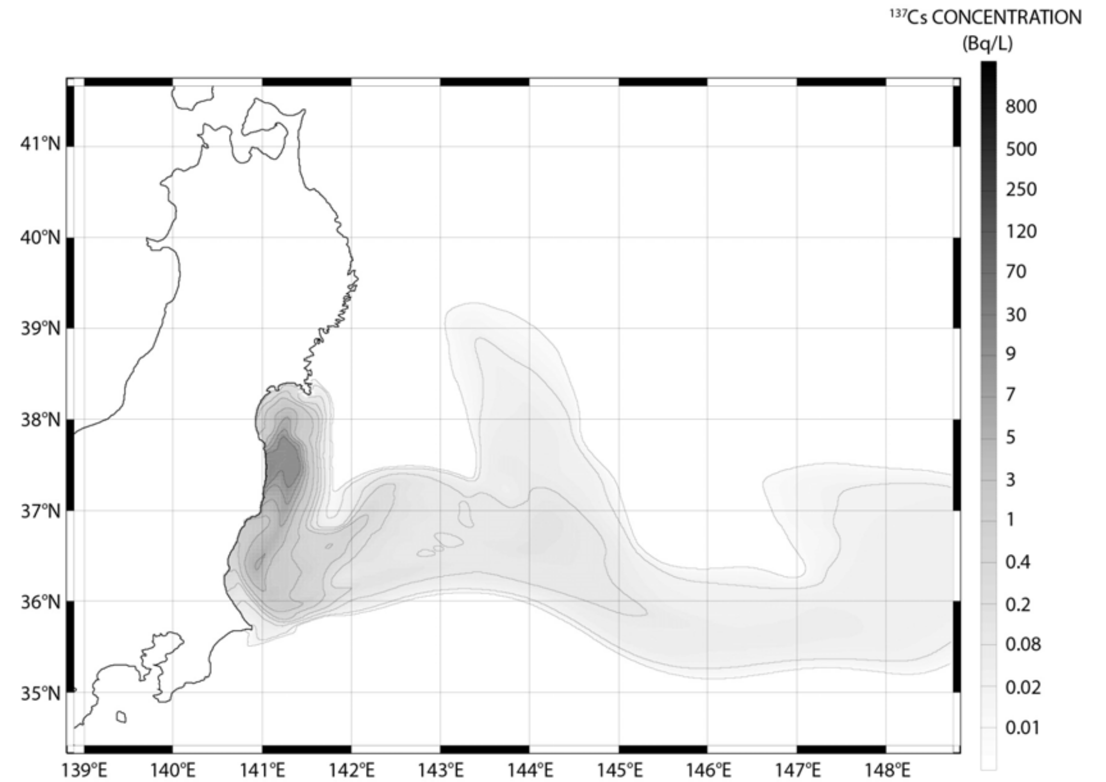


Figure B-XXII. Mean concentration of ^{137}Cs in surface waters (Bq/L) in May 2011 (from [E4])[a]



[a] *Note that the horizontal scale differs from the one used in figure B-XXI.*

(b) *Dispersion of radionuclides deposited from the atmosphere*

B81. Radionuclides released to atmosphere were deposited on to the ocean over a wide region. Deposition density was highest in the coastal area near FDNPS. According to different authors [E4, K3], the magnitude of the accumulated deposition density would have been of the order of 10^4 Bq/m^2 close to the coast and around 10^2–10^3 Bq/m^2 500 km away from FDNPS, depending on the wind direction at the time of the releases. Oceanic dispersion models have been used to simulate the fate of these deposits.

B82. The contribution to concentrations in surface waters due to these deposits from atmosphere was much lower than that due to the direct releases into the ocean (except perhaps during the first days, when direct releases were not detected). At large distances during the first month, atmospheric deposition was responsible for the observed concentrations, which were low (less than 0.05 Bq/L at a few hundred kilometres [E4]). These results were within an order of magnitude of the average observations reported by Honda et al. [H7], although some values around 0.3 Bq/L were measured in a relatively small area.

B83. Regarding ^{131}I, Kawamura et al. [K3] simulated concentrations along the coast south of FDNPS that reached a few hundreds of becquerels per litre in March, decreasing offshore to about 10 Bq/L also within March, and to 1 Bq/L in April.

(c) *Long-term global transport*

B84. Simulations of the ^{137}Cs dispersion across the Pacific Ocean over the first 30 years after the accident have been published [N3]. These simulations indicated that radionuclides released directly would reach the Californian coast of the United States 4–5 years after the accident, but this timescale was likely to have been overestimated because the low-resolution ocean model used in this study underestimated the strength of currents. This has been confirmed by observations reported by Aoyama et al. [A12] and discussed in section III.A of this appendix. However, the simulated concentrations for 2012 were of the same order of magnitude as Aoyama’s observations. The model indicated that ^{137}Cs released directly from FDNPS would be distributed throughout the northern Pacific Ocean within ten years of the accident at concentrations below 10^{-3} Bq/L; these are less than concentrations of ^{137}Cs in the Pacific Ocean of $1-2 \times 10^{-3}$ Bq/L that existed before the accident [B25].

(d) *Uptake onto, and release from, sediments*

B85. Periáñez et al. modelled the interactions between seawater and sediments [P3] using a three-dimensional advection/diffusion model with terms describing the adsorption/desorption reactions between the deepest water layer and seabed sediments in a dynamic way using both one-step and two-step kinetic models. They estimated concentrations of ^{137}Cs in seawater and sediment for comparison with measurements. The model provided a fit to the measurements of ^{137}Cs concentrations in surface water similar to that illustrated in figure B-XX; it also was able to reproduce the general pattern of ^{137}Cs concentrations measured in sediments. The authors estimated a half-time for the ^{137}Cs content in the sediment of 167 days.

APPENDIX C. ASSESSMENT OF DOSES TO THE PUBLIC

I. INTRODUCTION

C1. This appendix provides more detailed information on the assessment of radiation exposures of the public. Knowledge about the distribution of radioactive material in the environment was used to make estimates of the doses to members of the public in Japan. This study also took account of the preliminary dose estimation carried out by the World Health Organization (WHO) [W11] and the large amount of information that had become available since the WHO preliminary dose estimation was completed. A review of relevant published scientific papers and information formed part of this study.

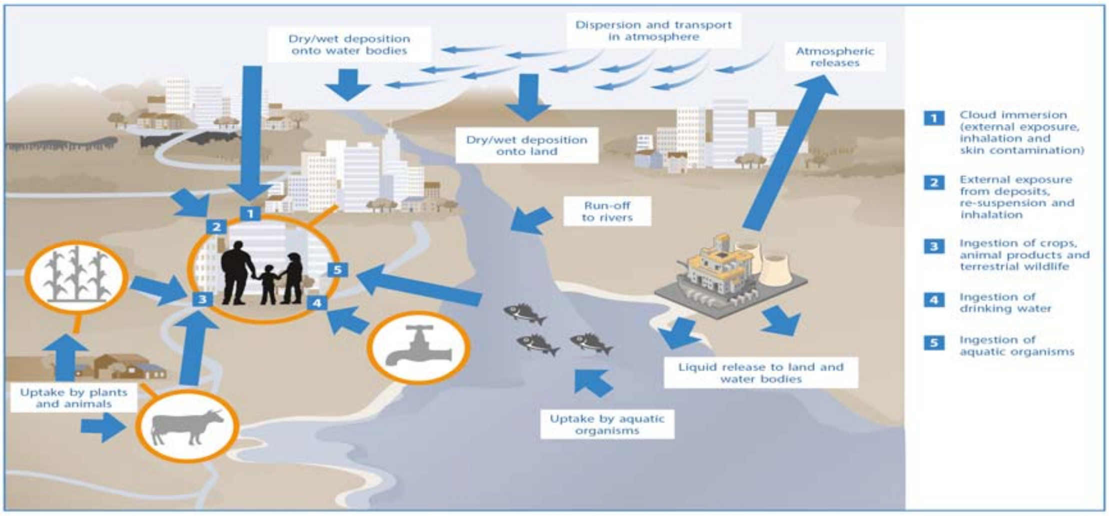
C2. The assessment considered the more important pathways by which people were exposed to radiation following the accident, with the main focus being on estimating exposures of individuals considered to be representative (i.e. having typical habits, such as food intake and behaviour) of the different subsets of the Japanese population. Three main age groups at the time of the releases were considered: 20-year-old adults, 10-year-old children and 1-year-old infants. For some exposure pathways, people were only exposed for a short period of time—during and just after the releases. Other pathways can continue to cause exposure for many years into the future, albeit at rates that reduce with time. The assessment, therefore, included exposures in the first year following the accident, exposures integrated over the first 10 years and exposures up to age 80 years, taking into account the ageing of the three age groups considered. An integration period of 80 years was used rather than the 70-year value that is standard for radiation protection; this was to reflect the longer lifespans common in Japan. Particular attention was paid to the exposures of people living in the more affected areas of Fukushima Prefecture and some neighbouring or nearby prefectures in eastern Japan. It is important to recognize that there was significant variability in the deposition density of radionuclides deposited on soil across Japan and that very few measurements of radionuclides in air were made for the most affected areas following the accident.

A. Exposure pathways

C3. A broad range of radionuclides was released from Fukushima Daiichi Nuclear Power Station (FDNPS) over a prolonged period of time (see appendix B). The main endpoints of the Committee’s dose assessment were the absorbed doses to selected critical organs (in grays, Gy), most importantly the thyroid, but also the red bone marrow and female breast, and the effective doses (in sieverts, Sv). The Committee focused on estimating absorbed doses to the thyroid because radioiodine, if ingested or inhaled, concentrates in the thyroid, and this is particularly important for infants and children. The effective doses estimated in the Committee’s study were the sum of the effective doses due to external exposure received over the period of interest and the committed effective doses due to internal exposure from intakes of radionuclides by ingestion and inhalation over the same period.

C4. As detailed in appendix B, the major releases following the accident were to the atmosphere and the ocean. The radionuclides in these releases subsequently moved through the environment. Figure C-I illustrates the more important exposure pathways.

Figure C-I. Exposure pathways following releases of radioactive material to the environment



C5. The major exposure pathways following the releases to atmosphere were:

(a) External exposure from radionuclides in the radioactive plumes;

(b) Internal exposure from inhalation of radionuclides in the radioactive plumes;

(c) External exposure from radionuclides deposited on the ground;

(d) Internal exposure from ingestion of radionuclides in food and water.

C6. The first two exposure pathways were only relevant during the passage of the radioactive plumes. The third and fourth exposure pathways persist until the deposited radionuclides have decayed or been removed by physico-chemical processes. Other possible exposure pathways, such as the inhalation of resuspended radionuclides or exposure via contamination of the skin, were not major contributors to exposure for the releases from FDNPS and were not considered further.

C7. For radionuclides released to the ocean or deposited onto the ocean from the atmosphere, transfer to fish and other seafood that may be eaten by people is of particular importance. Other exposure pathways could have resulted from radionuclides in sediments and sand (external irradiation plus internal irradiation following inadvertent ingestion); however, these could only have been relevant for the coast outside of the 20-km evacuation zone established around the FDNPS site because of the restrictions placed on public access. At this distance from the plant, they were not expected to be significant contributors to human exposure, and were not included in the Committee’s assessment.

B. Data for dose assessment

C8. Appendix A catalogues the extensive body of data available as input to the assessment, and sets out the processes that were used to ensure that the quality of the data was sufficient for the purposes of the assessment. Measurements were largely focused on the radionuclides ^{131}I, ^{134}Cs and ^{137}Cs, because these were considered to be the most significant contributors to exposure. The radionuclide, ^{131}I, largely determined absorbed doses to the thyroid, which were delivered over a relatively short period after the accident (via inhalation and ingestion). The radionuclides, ^{137}Cs and, to a lesser extent, ^{134}Cs, determine the continuing longer-term exposure of the population, in particular from radioactive material deposited on the ground. Only limited data were available for ^{133}Xe, the radionuclide with the largest estimated release of activity (see appendix B), because this is an unreactive (noble) gas which cannot be collected by air filter sampling. (These data were obtained by the monitoring station of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) at Takasaki, Gunma Prefecture.) However, the contribution of ^{133}Xe to exposures was very small.

C9. In vivo measurements of radionuclides in people provide a direct source of information to assess their internal exposures. Two main sets of data were available to the Committee: the first was from measurements of ^{131}I in the thyroid, particularly of children; and the second was from whole-body monitoring for ^{134}Cs and ^{137}Cs. Such measurements can only indicate what activities of radionuclides are in the person at the time of monitoring. The available measurements covered only a limited number of people and locations and were insufficient to directly estimate internal exposure of people in either Fukushima Prefecture or the remainder of Japan. Therefore, the estimates of internal exposure were based on measurements of radioactive material in the environment, combined with models describing how people were exposed to this material.

C10. The data were used in one of two ways in this study: either as direct input into the exposure assessment, or to check the validity of the assessment. Data used as direct input included those from the measurements of deposition density of radionuclides on the ground. The Committee used these data as the primary basis for estimating external exposure. In addition, an extensive database of measurements of activity concentrations of radionuclides in food in Japan was used for the estimation of doses from ingestion. The data used as a check on the dose assessment included the results of numerous dose-rate measurements, a limited number of measurements of concentrations of radionuclides in air at particular locations and times, and the limited number of in vivo measurements of radionuclides in people (whole-body and thyroid measurements). The Committee used the results from atmospheric transport, dispersion and deposition modelling (ATDM) described in appendix B to supplement the available measurements of the levels of radionuclides deposited on to the ground or in the air.

1. Radiation measurements within Japan

C11. Although the main source of data was the official information provided by the Japanese authorities, data from other sources were also used. These included data provided by Member States of the United Nations (such as those obtained by personnel of the United States of America in Japan), and published information (such as that obtained by IAEA field teams [I6]). The Committee made extensive checks to determine whether the measurements were consistent or not, and whether or not they had been carried out using established methodologies whose quality had been assured.

C12. An extensive monitoring programme was conducted under the direction of the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) with the cooperation of the Japan Atomic Energy Agency (JAEA), various universities and research institutes. The dataset of the initial MEXT ground survey provided the most comprehensive measurements of deposition density comprising approximately 2,200 results derived from measurements of soil samples conducted over the period from 6 June to 8 July 2011, in areas within a distance of 80 km of FDNPS. The dataset provided information on ambient dose equivalent rates and deposition densities of the gamma-emitting radionuclides, ^{110m}Ag, ^{129m}Te, ^{131}I, ^{134}Cs and ^{137}Cs, on soil. The higher values for deposition density were found for sampling locations within the evacuated areas. The highest measured value for ^{137}Cs was 15 MBq/m^2 for a location in Okuma Town, where the corresponding ambient dose rate at the time of measurement was 55 μSv/h.

C13. The MEXT dataset also included the results of measurements of deposition density for ^{89}Sr, ^{90}Sr, ^{238}Pu and $^{239+240}Pu$ on soil at a limited number (100) of the sampling points. The highest values of deposition density for ^{89}Sr and ^{90}Sr were 22,000 Bq/m^2 and 5,700 Bq/m^2, respectively, at locations within the 20-km evacuation zone. Only 6 samples gave measured values of ^{238}Pu above the detection limits; the highest value measured was 4 Bq/m^2. The results of the measurements of $^{239+240}Pu$ for 50% of the samples were below the detection limits; the highest value was 14 Bq/m^2. The detailed measurement results for the initial 2,200 measurements are provided in attachments C-1 to C-5 and maps for all radionuclides measured are provided in attachment C-6.

C14. In late 2011, MEXT conducted an additional series of in situ measurements and/or soil sampling and measurements of ^{134}Cs and ^{137}Cs in 11 prefectures of eastern Japan. The results of the later MEXT survey were combined with the initial 2,200 measurements and provided the primary input data for the estimation of external exposure at district level within Fukushima Prefecture and the prefectures of Miyagi, Tochigi, Gunma, Ibaraki, Iwate and Chiba. Concurrent with the MEXT surveys, the Japanese Ministry of Agriculture, Forestry and Fisheries (MAFF) conducted measurements of ^{134}Cs and ^{137}Cs in cultivated soils in 15 prefectures of eastern Japan from April 2011 to February 2012. The results of these surveys were also used in the assessment.

C15. For the Committee’s assessment of doses to the public, the measurement results of the ground survey were combined with data on the Japanese population. The Japanese Government divided Japan into a grid for the purposes of reporting relevant geospatial information. The primary, first-order grid used 1 degree of longitude (east and west), and 40 minutes of latitude (north and south). The second-order grid split each first-order grid cell into 8 by 8 cells, each corresponding to 0.125 degrees of longitude and 0.083 degrees of latitude. The dimensions of these grid cells were approximately 10 km by 10 km. A third-order grid was obtained by equally dividing the second-order grid cells into further 10 by 10 cells. The horizontal and vertical distances of the third-order grid cells were approximately 1 km by 1 km. Each of the results of the measurements made by MEXT was assigned to the corresponding grid cell of approximately 1-km squares to allow combination with the population data.

C16. Once combined, the Committee produced dose rates and deposition densities of radionuclides for each district covered by the surveys. A map of the deposition density of ^{137}Cs in Fukushima Prefecture and some neighbouring prefectures, referenced to the 14 June 2011, is shown in figure C-II. The derived measurement datasets are provided in attachment C-7.

C17. The United States Department of Energy (USDOE) performed airborne surveys in areas within a distance of 80 km of FDNPS. Data were collected from 2 April to 9 May 2011, with the reported dose rates and deposition densities of ^{134}Cs and ^{137}Cs adjusted to 30 June 2011. This dataset was used to refine the interpretation of the ATDM results (appendix B), and to quantify the variability of the deposition density within each district or prefecture. The measured values of dose rate and deposition density from the USDOE airborne survey were averaged within each grid cell of approximately 1-km squares and compared with the measurement data from the MEXT ground survey. Figure C-III shows the deposition densities of ^{137}Cs derived from the USDOE airborne survey for the eastern part of Fukushima Prefecture, and indicates that the areas of highest deposition density were in an area to the north-west of FDNPS.

Figure C-II. Deposition density of ^{137}Cs averaged by district within Fukushima Prefecture and some districts in neighbouring prefectures, based on data from the MEXT ground survey adjusted to 14 June 2011

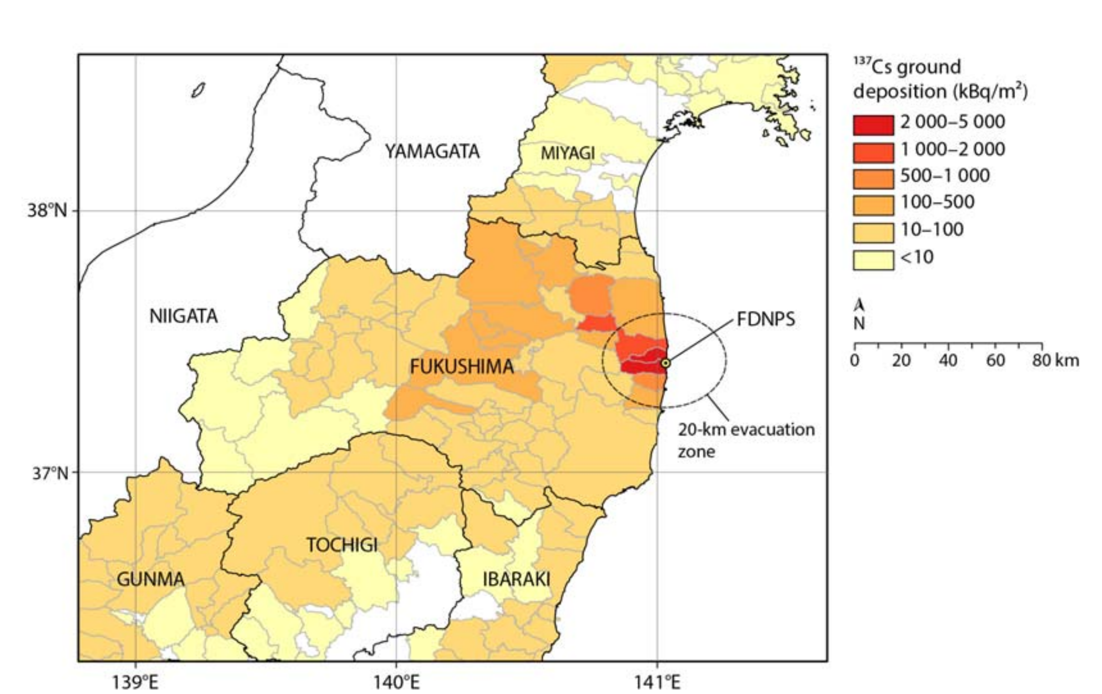
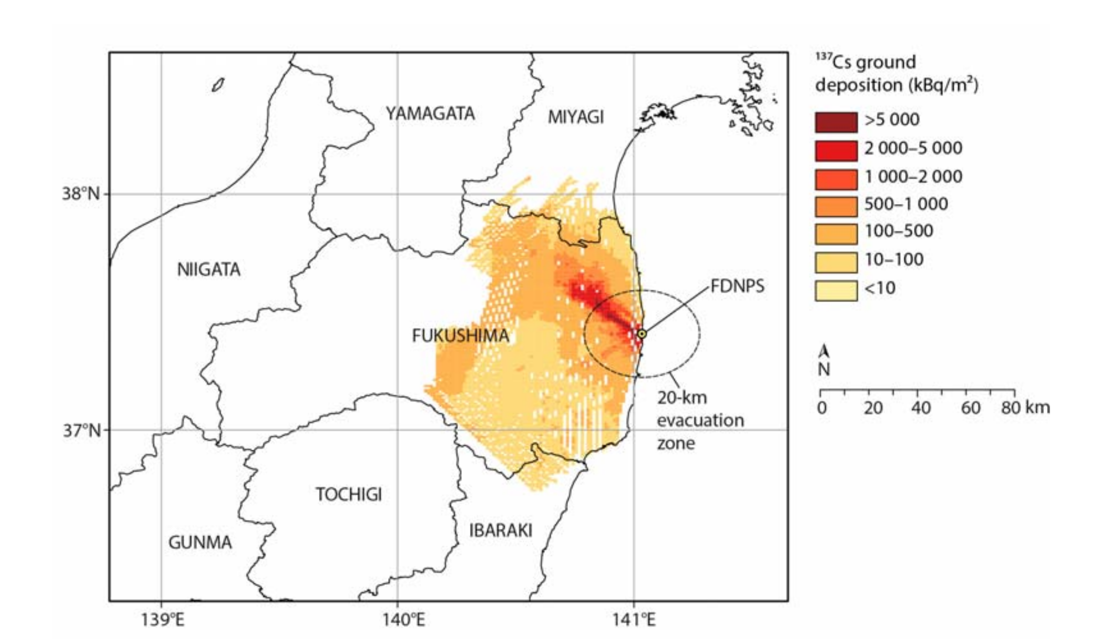


Figure C-III. Deposition density of ^{137}Cs in Fukushima Prefecture based on measurement data from the airborne radiometric surveys adjusted to 30 June 2011 [U17]



C18. There was only limited information available on the concentrations of radionuclides in air following the releases from FDNPS. The data provided by the Japanese Government and by the USDOE are summarized in appendix A. There were insufficient data during the first weeks on concentrations of ^{131}I in air to provide direct estimates of the exposure from inhalation during the passage of the radioactive plumes.

C19. Measurements of ^{131}I, ^{134}Cs and ^{137}Cs were made in a wide variety of foods in Japan following the accident. Since March 2011, a database has been compiled on radionuclide concentrations in foodstuffs under the guidance of the Food and Agriculture Organization of the United Nations (FAO) and the International Atomic Energy Agency (IAEA) in collaboration with the Japanese authorities, including the MAFF and the Japanese Ministry of Health, Labour and Welfare (MHLW). This FAO/IAEA food database includes data for over 500 types of foodstuffs sampled in all 47 prefectures in Japan. These data were provided through the FAO/WHO International Food Safety Authorities Network (INFOSAN) based on information published or provided by MHLW and compiled by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The FAO/IAEA food database was validated before use by the Committee as outlined in attachment C-8.

C20. Data on concentrations of radionuclides in drinking water were provided by MHLW. The first sample of drinking water was collected in Fukushima Prefecture on 16 March 2011. Some districts did not begin sampling water until late March or early April 2011. Outside of Fukushima Prefecture, data were only available for ^{131}I, ^{134}Cs and ^{137}Cs in drinking water. For districts within Fukushima Prefecture, data were also available for ^{132}I.

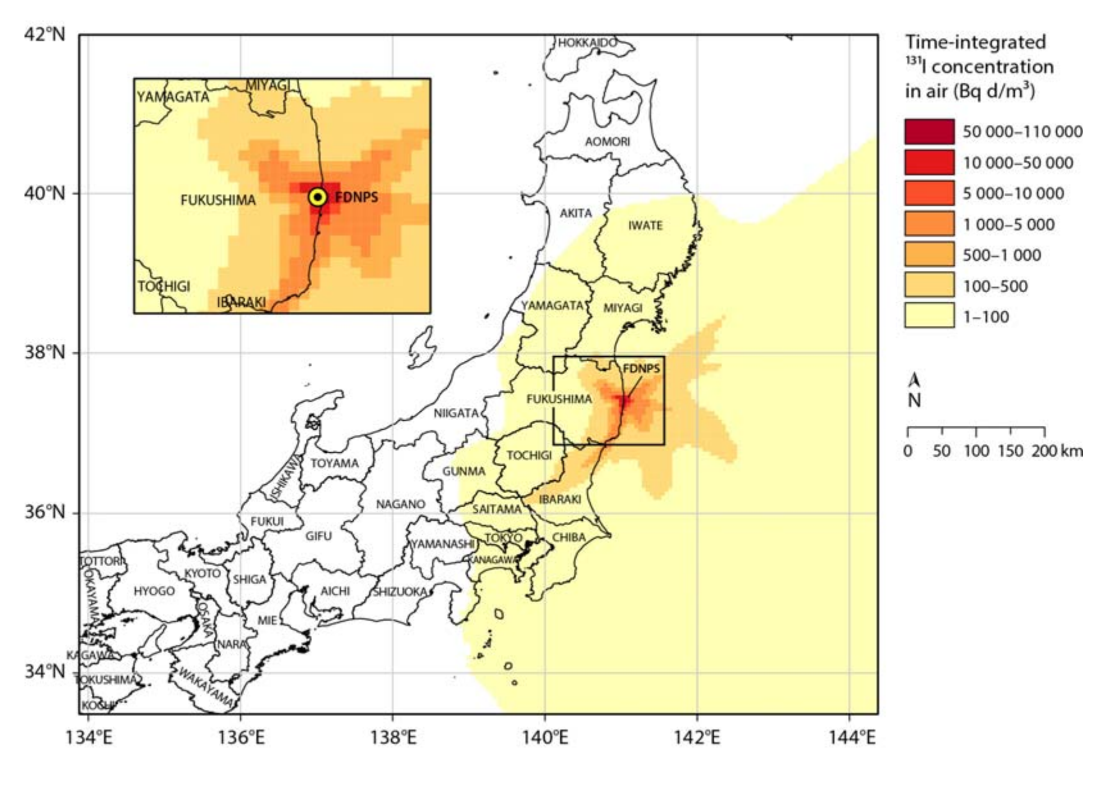
2. Atmospheric transport, dispersion and deposition modelling for Japan

C21. Since there was much less information available on the concentrations of radionuclides in air, the exposures from the plume at specific times and locations were estimated from the assumed time sequence of the release of the more significant radionuclides and their transport through the atmosphere using NOAA–GDAS ATDM as described in appendix B. While the estimates of radionuclide concentrations in air and deposition densities of radionuclides provided by the assumed source term and ATDM analyses at any specific location are uncertain, the ratios of these two estimates are much less so. In particular, the ratios are relatively insensitive to the absolute magnitude and temporal pattern of the estimated release of the radioactive material, which is associated with much uncertainty. The main uncertainties in these ratios result from uncertainties in the parameters that describe wet and dry deposition. The Committee used such location-dependent ratios, derived from the ATDM analyses, to infer time-integrated radionuclide concentrations in air from the measured deposition densities of radionuclides. It then used these inferred concentrations to assess the exposures from radionuclides in air in all regions of Japan except in the evacuated areas.

C22. For the evacuated areas, where only a limited number of measurements of radionuclide concentration in air and deposition density were made during the periods of the evacuations, the Committee relied on estimates of these quantities provided by the assumed pattern of release of the more significant radionuclides and the ATDM analyses. The ATDM results provided the time-dependent activity concentrations in air of the radionuclides, ^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{133}Xe, ^{134}Cs, ^{136}Cs and ^{137}Cs. While the ATDM results were based on the available source-term data and the NOAA–GDAS model included detailed information on the meteorological conditions, there were significant uncertainties in the ATDM results for specific locations and times (see appendix B). The ATDM results were also used in the calculation of dose from ingestion of radionuclides in future years to communities within Fukushima Prefecture and elsewhere in Japan.

C23. The ATDM results were provided as points on a grid of 5-km squares and these values were assigned to the corresponding cells of the measurement dataset of the MEXT ground survey. The ATDM analyses provided estimates for both the particulate and the non-particulate forms of ^{131}I. Figure C-IV shows the estimated time-integrated concentrations of particulate ^{131}I in air for the period from 13 March to 1 April 2011, based on the ATDM analyses. The map of the ATDM results demonstrates that a significant proportion of the releases of radionuclides to atmosphere were dispersed over the ocean. The derived datasets and maps for ^{131}I and ^{137}Cs from the ATDM analyses are provided in attachments C-9 to C-10.

Figure C-IV. Time-integrated (13 March–1 April 2011) concentration of particulate ^{131}I in air over Japan based on the results from the NOAA–GDAS atmospheric transport, dispersion and deposition modelling analyses (appendix B)



3. Radiation measurements outside of Japan

C24. Twenty-five Member States of the United Nations provided, on request, relevant data directly to the Committee (Argentina, Australia, Belarus, Belgium, Brazil, Canada, China, Finland, France, Germany, India, Indonesia, Malaysia, Mexico, Pakistan, the Philippines, Poland, the Republic of Korea, the Russian Federation, Slovakia, Singapore, Spain, Sweden, the United Kingdom of Great Britain and Northern Ireland, and the United States of America). The data included information on: radionuclides detected in air samples, and in imported and locally produced foods; in vivo (such as whole-body counting and thyroid measurements) and in vitro (such as urine analyses) measurements of citizens of these States who were in Japan at the time of the accident; and analyses of environmental samples. A summary of the data provided is given in attachment C-11.

C25. A number of publications reported radionuclide concentrations in air, rainwater, soils, plants and dairy products, and deposition densities. These cover locations within south-east Asia [K10, K12, L13], the Russian Federation [B14], North America [B10, B15, D1, M2, S10, W8, Y3], Europe [B1, B3, B7, B11, C1, C7, C8, E5, I30, K21, L9, L14, M3, M4, P4, P7, P9, P10, P13, T22], the Arctic [P1] and Cuba [A8].

C26. Detection of ^{131}I, ^{134}Cs and ^{137}Cs in air samples was reported in most of these publications, peaking from late March to early April 2011. Across the European monitoring network, rising levels of these radionuclides were recorded up to 30 March 2011 for western and central Europe, and up to 3 April 2011 for eastern Europe. In general terms, the levels were extremely low and by the end of April 2011, measurements of particulate ^{131}I were again below the limit of detection. A summary of the data is provided in [M4].

4. Protective actions

C27. Extensive measures were put in place by the Japanese authorities to protect people from the radioactive releases [A6]. These included the initial evacuation over the period 11–15 March 2011 out to a distance of 20 km from the site, and the implementation of the so-called "deliberate evacuation area" (from 22 April 2011). Further evacuation was carried out, based on environmental measurements, in districts to the north-west of FDNPS between March and June 2011. For its assessment, the Committee took account of when and where these protective measures were implemented. In November 2011, the government of Fukushima Prefecture reported the results of a questionnaire issued to all residents of Fukushima Prefecture regarding their activities over the four-month period from 11 March to 11 July 2011. Based on the results, 18 scenarios representative of the movements of residents evacuated following the accident at FDNPS were developed. These scenarios are discussed in the next section. Additional information describing the status of the protective measures in the evacuated localities was provided by the Japanese Government.

C28. Early measurements made on samples of vegetables grown in the most affected area showed concentrations of ^{131}I above the provisional regulation values. Restrictions on food supplies were introduced from 17 March 2011. Many people took their own protective actions, in addition to those recommended by the authorities. For example, some people evacuated on their own accord, avoided fresh foods or avoided foods produced in Fukushima Prefecture. The Committee only took into account the likely impact of the official protective actions. Nevertheless, it gave consideration to the effect that different dietary intakes would have made on individual exposures.

C29. The long-term process of remediation of contaminated areas, which has started, will reduce future exposures from the deposited radionuclides and the transfer of radionuclides to food. The possible impact is discussed in later sections of this appendix.

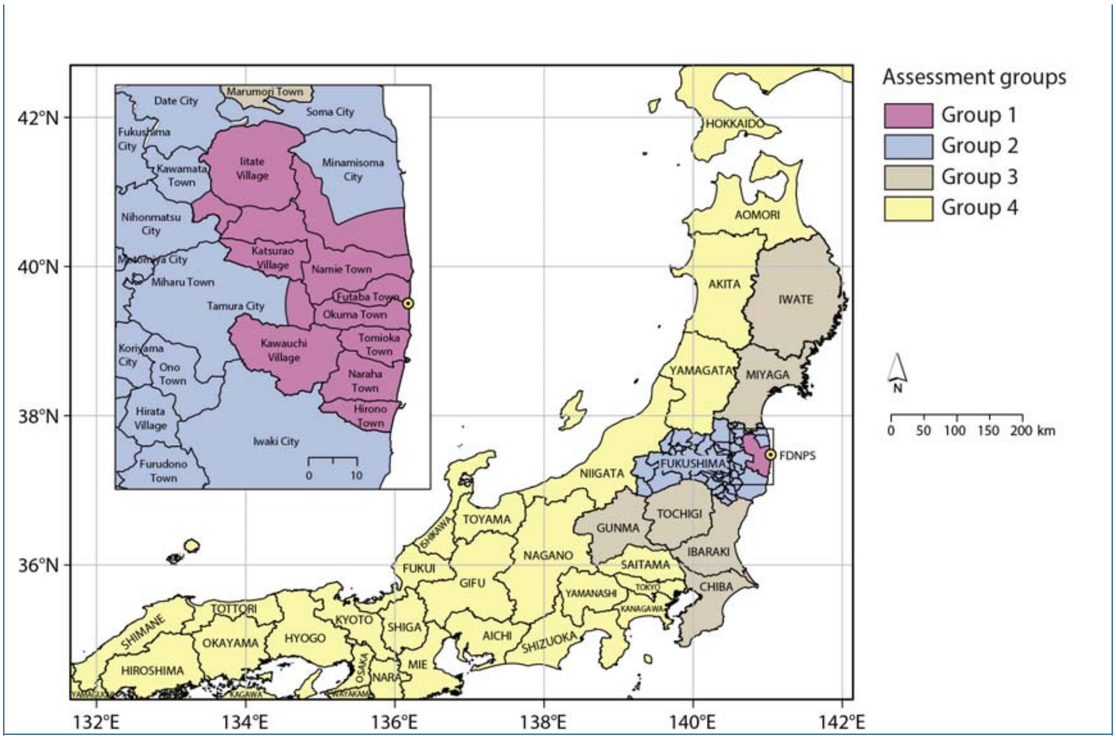
II. METHODOLOGY

A. Regions considered for dose estimation

C30. In order to estimate doses to the members of the public in Japan, the Committee focused on four groups of geographical areas (see figure C-V). Group 1 included settlements in Fukushima Prefecture from which members of the public were evacuated in the days to months after the accident according to 18 evacuation scenarios, with each scenario applying to a settlement. Group 2 included all non-evacuated districts of Fukushima Prefecture. Group 3 included selected prefectures in eastern Japan that were neighbouring (prefectures of Miyagi, Tochigi, Gunma and Ibaraki) or nearby (prefectures of Iwate and Chiba) Fukushima Prefecture. Group 4 included all the remaining prefectures of Japan.

C31. The spatial resolution adopted for assessing the doses in each of these groups was dependent on the available data. Estimates for Group 2 were made at the district level for the external exposure and inhalation pathways and at the prefecture level for the ingestion pathway. The selection of the six prefectures included in Group 3 was based on the number of measurements taken and the measured levels of deposition density of ^{137}Cs. Estimates of dose for Group 3 were made at the district level for a number of districts for the external exposure and inhalation pathways. The dose from ingestion for five of the six prefectures was based on an average for the five prefectures. Iwate Prefecture was the exception and the estimated average dose for this prefecture was the same as that for Group 4. Doses for all Group 4 prefectures were assessed at prefecture level for the external exposure and inhalation pathways, and on the basis of an average for the Group 4 prefectures together for the ingestion pathway.

Figure C-V. Geographic regions for estimation of doses to representative members of the public in Japan



Group 1. Members of the public who were evacuated in the days to months after the accident, based on the 18 scenarios reported by NIRS, were included in this group.

Group 2. Members of the public living in the non-evacuated districts of Fukushima Prefecture.

Group 3. Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate.

Group 4. Members of the public living in the remaining prefectures of Japan.

C32. For this assessment, estimates of the radiation exposures of representative members of the public with typical habits were made using a number of different methods. The methodologies outlined in this section are described in detail in attachments C-12 and C-13. The Committee did not explicitly estimate doses to the foetus or breast-fed infants because they would have been similar to those to other age groups for both external and internal radiation exposure. For example, doses to the foetus and breast-fed infant due to external exposure would have been approximately the same as those to adults and 1-year-old infants, respectively.

C33. The assessment of doses for countries outside of Japan was based on a review of estimates published in the literature, including the results of the WHO preliminary dose estimation, supported by the extensive measurements, and dose assessments carried out by Member States of the United Nations. The Committee did not undertake a comprehensive assessment based on a modelling approach to estimate doses to members of the public in the rest of the world.

B. Assessment of external exposure in non-evacuated areas

C34. External exposure was a major contributor to the doses to the public from the releases of radionuclides into the environment (for example, see [W11]). There were two components of the external exposure: *(a)* exposure from radionuclides in the air; and *(b)* exposure from radionuclides deposited on the ground. The exposure from radionuclides in the air would have been relatively short-term and only would have persisted while the radionuclides were present in the air, but the exposure from deposited radionuclides would persist until they have decayed or been removed by physico-chemical processes or remedial action.

C35. The measured ambient equivalent dose rates (or air kerma rates) included those from released radionuclides (in the air and on the ground) and a background component from naturally occurring sources of radiation [U12]. It was not possible to directly use the measurements of dose rate owing to a lack of detailed information about the background component and the contribution from particular radionuclides. For this reason, the dose rates as a function of time and location due to the deposited radionuclides were estimated from the measurements of the deposition densities of these radionuclides on the ground. This also allowed for the estimation of dose rates into the future, with account being taken of the radioactive decay and migration into the ground of each radionuclide.

C36. The assessment of absorbed dose to organs or effective dose from external exposure required information on the gamma-radiation field, information relating to human behaviour in the radiation field over time and conversion coefficients that relate the radiation field to absorbed or effective dose, as appropriate. These conversion coefficients depend on the irradiation geometry and therefore whether the radionuclides were in the air or deposited on the ground. For external exposure from deposited radionuclides, the kerma rate in air at a height of 1 m above the ground surface was used as the reference measure for the radiation field. Its value is influenced both by the deposition density of radionuclides on the ground surface and by natural factors such as the initial attenuation of radiation in soil, radioactive decay, migration of long-lived radionuclides into soil, and the presence of snow cover. Account was taken of the change of these factors with time. So-called "location factors" were used to express the effects of these factors as the ratio of the dose rate in a given location to that in a reference location. Occupancy factors were used to take account of the fraction of time spent by different groups of people in different locations. The detailed methodology is provided in attachment C-12.

1. External exposure from deposited material

C37. For the assessment of external exposures of people within the areas of Japan that were not evacuated, the main approach was to use the measurements of deposition density of radionuclides on the ground. The measurement datasets are summarized in the previous section and appendix A. The computational model (see [G6, G8, G9, J3]) consists of four submodels: *(a)* the estimation of the kerma rate in free air at a reference site in the settlement; *(b)* the estimation of the location factors; *(c)* the estimation of occupancy factors for different population groups at various types of locations; and *(d)* the estimation—for different population groups—of coefficients to convert kerma rate in air to absorbed dose rate to the particular organ or effective dose rate. The models, parameters and assumptions are described in detail in the attachment C-12 and outlined below.

C38. The external exposure of members of the public depends on the amount of time spent outdoors and indoors, the shielding properties of the indoor location, and the size of the individual (taken to be related to age). The three age groups used for the assessment were considered to be representative of particular social groups; 20-year-old adults (representative of people aged 16 years and older in 2011), 10-year-old children (representative of school children aged 6 to 15 years in 2011) and 1-year-old infants (representative of preschool children up to 5-years old in 2011). The group of adults was subdivided into those working mostly outdoors and those working mostly indoors. The group of indoor workers also included students and pensioners because their behaviour in this respect—as reported in Japanese demographic data—was similar.

C39. For these population groups, shielding properties of three types of house typical of Japan were considered: *(a)* a wooden house with one to three storeys; *(b)* a wooden fireproof (plastered) house with one to three storeys; and *(c)* a concrete multi-storey apartments. Location factors are time-dependent and their values decline with time because of radionuclide migration in the environment owing to weathering, cleaning and other factors. The initial values of location factors for these three types of dwellings were 0.4, 0.2 and 0.1, respectively (see attachment C-12). In total, 12 combinations of social/age groups and house types were considered. The main results are presented for two typical population groups: *(a)* adults living in wooden houses and working indoors; and *(b)* infants living in wooden houses. The choice of these two groups was based on statistical data that showed that the majority of the population of Fukushima Prefecture and the Group 3 prefectures reside in wooden or wooden fireproof one-to-two-storey houses.

C40. For the assessment of dose in the first year following the accident, the dose conversion coefficients based on the computational phantom for adults specified by the International Commission on Radiological Protection (ICRP) [I24] and other voxel phantoms for the age groups [G7, P6] were applied. For the long-term exposure assessments, the growth of 1-year-old infants and 10-year-old children was taken into account. The group of 1-year-old infants (as of 2011) had the same dose conversion coefficients applied for the first five years (up to 5-years old, preschool). For the 10-year period from March 2016, the dose conversion coefficients for 10-year-old children were applied; and from March 2026, the dose conversion coefficients for adults were used. A similar approach was used for the children aged 10 years in 2011: appropriate dose conversion coefficients were applied for the first five years after the accident; and for March 2016 onwards, dose conversion coefficients for adults were applied.

C41. Occupancy factors (i.e. the amounts of time spent by different population groups in different types of location) were based on data from Japanese national surveys [N18]. The values used are given in table C1. These occupancy factors were used in combination with the 12 combinations of social/age groups and house types. It was assumed that typical adults spend 60% of their time in wooden one-to-two-storey houses and 30% of their time at work in multi-storey buildings. Typical preschool children were assumed to spend all of their indoor time (80%) in wooden houses.

Table C1. The occupancy factors used to assess doses due to external exposure to members of the public in Japan

Type of location	*Occupancy factor (dimensionless)*			
	Adults		*10-year old*	*1-year old*
	Outdoor worker	*Indoor worker or pensioner*		
Indoors	0.7	0.9	0.85	0.8
Outdoors including:	0.3	0.1	0.15	0.2
Paved environment	0.2	0.05	0.05	0.1
Unpaved environment	0.1	0.05	0.1	0.1

C42. The MEXT ground-survey dataset was used to provide data on the deposition density of radionuclides. From this dataset, values were available as follows: ^{134}Cs and ^{137}Cs in all the soil samples; ^{110m}Ag in 343 samples; ^{129m}Te in 799 samples and ^{131}I in 419 samples. In many samples, ^{129m}Te (half-life 33.6 d), ^{131}I (half-life 8.02 d) and ^{110m}Ag (half-life 250 d) were not detected because of radioactive decay and/or low deposition levels. In the absence of measurable levels of these radionuclides, the deposition densities were estimated from the ^{137}Cs concentrations in soil using average values for the ratios of the radionuclide concentrations derived from locations where these radionuclides were detected. Table C2 summarizes the average values of the ratios of the concentrations of ^{110m}Ag, ^{129m}Te, ^{131}I and ^{134}Cs, to those of ^{137}Cs. For most of the locations, the ratios were relatively consistent.

C43. However, the measurement data showed that there was a narrow region along the coast to the south of FDNPS (the so-called “south trace”) where the ratios for ^{129m}Te and ^{131}I were significantly elevated, although their concentrations were still strongly correlated with those of ^{137}Cs. The Committee used these elevated ratios to assess doses for the towns of Tomioka, Naraha and Hirono and for Iwaki City.

C44. There was a statistically significant correlation between the concentrations in soil samples of ^{110m}Ag with respect to those of ^{137}Cs. The correlation coefficient was however smaller than those for ^{129m}Te and ^{131}I. Nevertheless, the uncertainty in using the concentration ratio for ^{110m}Ag from table C2 to estimate the concentrations of this radionuclide in soil where no measurement data were available did not substantially influence the dose estimates, because the contribution of this radionuclide to exposure in the first year following the accident was of the order of 0.1%.

Table C2. Ratio of the concentrations of radionuclides in soil to those of ^{137}Cs (adjusted to 00:00 15 March 2011)

Area	*Characteristic*	*Radionuclide (half-life)*						
		^{110m}Ag (250 d)	*^{129m}Te (33.6 d)*	*^{132}Te+^{132}I (3.2 d)*	*^{131}I (8.02 d)*	*^{134}Cs (2.06 a)*	*^{136}Cs (13.2 d)*	*^{137}Cs+^{137m}Ba (30.2 a)*
All of Japan except for the south trace	Ratio to ^{137}Cs concentration	0.0028	1.1	8	11.5	1.0	0.17	1.0
	Standard deviation (*n*)[a]					0.07 (2 181)	0.02 (56)	
	Correlation coefficient (*n*)[a]	0.47 (343)	0.97 (689)		0.72 (339)			
South trace[b]	Ratio to ^{137}Cs concentration	0.0028	7.9	59	74	1.0	0.17	1.0
	Correlation coefficient (*n*)[a]		0.85 (110)		0.89 (73)			

[a] *n is the number of soil samples.*

[b] *The towns of Tomioka, Naraha and Hirono, and Iwaki City of Fukushima Prefecture.*

C45. The deposition densities of ^{136}Cs were inferred from the measured levels of ^{137}Cs. From the measurements of soil samples from various sites in Japan [E1, T1] the average isotopic ratio, $^{136}Cs/^{137}Cs$, was estimated to have been 0.17 ± 0.02 (n = 56) on 15 March 2011. Based on analysis of air samples (n = 565) from CTBTO (see attachment B-1) and in Europe [K16], the average isotopic ratio $^{136}Cs/^{137}Cs$ was estimated to be 0.21 ± 0.02 on 11 March 2011. These calculated ratios differ from the value of 0.31 derived from inventory calculations [N16] and used by the Committee in table B3. For consistency, the ratios derived from the soil sample measurements were used for this dose assessment.

C46. For the non-evacuated areas, the deposition densities of ^{132}Te on the ground were inferred from the measured levels of ^{129m}Te, using ratios for these radionuclides derived from other published measurement data. The ratio $^{132}Te/^{129m}Te$ varied substantially. It was estimated as 9.1 ± 1.6 (n = 14) from soil samples in Japan [T1] and 5.8 ± 0.1 (n = 14) from air samples collected over Europe [K16]. For the Committee’s assessment, a rounded value of 7 was used, based on environmental measurements, although the theoretical ratio calculated for Unit 2 of FDNPS gave higher, but diverse values of 22 [N16] and 13 [K16]. The decay corrected ratio $^{132}Te/^{137}Cs$ was essentially constant for about 80 days after the accident, which indicates that radiotellurium was retained in the surface soil like radiocaesium [T2]. For the evacuated areas, the deposition densities of ^{132}Te on the ground were derived from the ATDM results, which used a single value of 12.4 for the $^{132}Te/^{137}Cs$ ratio (see table B3), based on the reactor inventories.

2. External exposure from radionuclides in the air

C47. There were insufficient measurements of gamma dose rate and of radionuclides in air during the passage of the radioactive plumes for an assessment to be made of external exposure based on environmental measurements. Therefore, the radionuclide concentrations in air were estimated from the measurements of deposition density and the ATDM results. External exposures due to radionuclides in air were then calculated based on the assumption that the plume could be represented by a semi-infinite cloud. This assumption was considered appropriate where the distribution of radionuclides in air could be considered to be uniform over distances of hundreds of metres. Estimates of radionuclide concentrations in air were averages for the grid cells of approximately 5-km squares.

C48. Within Fukushima Prefecture (except the evacuation areas) and other prefectures of Japan where there were measurements of the deposition densities of radionuclides, the concentrations of ^{131}I, ^{134}Cs and ^{137}Cs in air were estimated from these using the ratios of estimates from ATDM of the time-integrated activity concentrations in air to the deposition density for each radionuclide as a function of location.

C49. The duration of the radioactive plume passing overhead was short (a few hours) and the contribution of this exposure pathway to the total dose was minor compared with that from deposited radionuclides. It was assumed that people were mostly outdoors during the passage of the plume. This would have overestimated the actual exposure because it ignores the effect of the shielding of buildings when people were indoors. Full details of the methods of calculation of external exposures from radionuclides in air and related parameter values are given in attachment C-12.

C. Assessment of doses in non-evacuated areas from inhalation of radionuclides

C50. The assessment of internal exposures in the non-evacuated areas from the inhalation of radionuclides required information on the concentrations of radionuclides in air, the age-dependent breathing rates and the dose conversion coefficients for intake via inhalation. As outlined in the previous section on assessing external exposure from radionuclides in the air, the radionuclide concentrations in air were estimated from the measurements of deposition density of radionuclides on the ground and the ATDM results using the methods described in detail in attachment C-12.

C51. The Committee used standard values of the age-dependent breathing rates and dose conversion coefficients for absorbed doses to the thyroid and red bone marrow, and for effective dose [I15, I25]. These dose conversion coefficients were based on a default particle size of 1 µm. The inhalation rates applied were the average rates over a day from the ICRP model of the respiratory tract. The dose conversion coefficients for inhalation were based on the inhalation rates for males [I18]. No allowance was made for any possible reduction in activity concentrations in air indoors over those outdoors.

C52. The ICRP dose conversion coefficients are based on generic anatomical and physiological human data and, as such, may not be entirely appropriate for the assessment of absorbed doses to the thyroid of Japanese individuals because of the high iodine content of the Japanese diet. This factor may have meant that both the uptake of radioiodine by the thyroid [Z4] and the thyroid mass [L5, Z6] were smaller.

D. Assessment of doses from ingestion of radionuclides

1. Internal exposure from the ingestion of radionuclides in food in the first year

C53. The assessment of exposure from the ingestion of radionuclides required information on their concentrations in foodstuffs and drinking water over the period of interest, the appropriate age-dependent intake rates and dose conversion coefficients for intake via ingestion of the radionuclides. Full details of the methodologies used to estimate the doses from ingestion are given in attachment C-13.

C54. The dose conversion coefficients used were those published by ICRP [I25]. Within Japan, extensive measurements were made of the activity concentrations of radionuclides in different foodstuffs (terrestrial and aquatic) starting in parts of Fukushima Prefecture a few days after the accident. These measurements were mainly intended to identify where restrictions on food supplies were required rather than to assess the doses to different population groups. In time, the monitoring was extended to the whole of Japan and became more systematic. The FAO/IAEA food database only included measurement data for ^{131}I, ^{134}Cs and ^{137}Cs and so only these radionuclides were considered in the assessment of doses from ingestion. However, these assessed doses would only have increased marginally if additional radionuclides had been explicitly considered, owing to their short half-lives or the very small quantities released.

C55. The FAO/IAEA food database included measured concentrations of radionuclides in immature crops or in areas where restrictions were in place but these data were not used in the assessment. The measurement data used were for foodstuffs as marketed (see attachment C-8). Many of the measurements were at or below the limits of detection and in these cases, it was generally assumed that the concentrations of each of the radionuclides considered (^{131}I, ^{134}Cs and ^{137}Cs) was 10 Bq/kg in each type of foodstuff, the nominal limit of detection. This was considered to be more appropriate than assuming that all of the values were zero but may have led to some overestimation of the doses from ingestion. However, in view of the short half-life of ^{131}I (8.02 days), all values for this radionuclide were assumed to be zero beyond four months after the accident. Furthermore, the activity concentrations of the radionuclides in rice were assumed to be zero until six months after the accident when rice was expected to be harvested.

C56. There were insufficient data in the first months following the accident to adopt a fine spatial resolution for the assessment of the doses from ingestion of radionuclides. It was assumed that the majority of people in Japan obtain their food from supermarkets where food is sourced from the whole of the country. It was therefore considered appropriate to base the assessment on the average concentrations of radionuclides in foodstuffs over wide areas in order to estimate the average exposures of groups within the population. Therefore, the mean concentrations measured in groups of foodstuffs in Fukushima Prefecture, five surrounding prefectures (Miyagi, Tochigi, Gunma, Ibaraki and Chiba), and the rest of Japan formed the basis of the main assessment of doses. For Iwate Prefecture, the dose to people was taken to be the same as that to the rest of the Japanese population.

C57. Information on how much of particular foodstuffs were consumed per capita of the population, based on surveys carried out in Japan, were provided by the Government of Japan for use in the assessment. The most extensive data were available for adults but there were also data for infants and children. Table C3 below summarizes the food intakes used in this study based on the groups of foodstuffs considered.

Table C3. Data on food intake by age group used in the dose assessment

These age ranges are from the reports of the surveys provided by the Government of Japan and were adopted by the Committee without amendment for age

Food category	*Per capita food intake by age group (g/d)*		
	Adults (≥20 years)	*Children (7–14 years)*	*Infants (1–6 years)*
Leafy vegetables	71.3	60.4	35.7
Root vegetables	75.1	77.7	52.7
Other vegetables	193.0	161.8	96.7
Soya and soya products	57.5	38.1	25.9
Rice and rice products	342.2	312.1	190.1
Wheat and wheat products	96.4	88.8	65.1
Other cereals	8.3	7.6	4.8
Fresh and processed fruits	86.0	81.9	76.8
Juices	22.4	20.0	16.3
Marine and migratory fish	37.1	25.3	14.9
Crustaceans and molluscs	42.8	29.2	17.2
Eggs	34.3	33.6	23.8
Beef/cattle	13.6	17.6	9.5
Pork (excluding wild boar)	43.1	55.9	30.1
Poultry	21.4	27.7	15.0
Other meat	1.7	2.2	1.2
Milk	83.2	259.7	174.8
Milk and dairy products	7.8	24.4	16.4
Mushrooms	16.5	13.2	8.6
Algae	10.9	8.7	5.8

2. Internal exposures from ingestion of radionuclides in food beyond the first year

C58. For the assessment of doses from ingestion beyond the first year after the accident, a modelling approach was used to estimate the concentrations of radionuclides in foodstuffs as a function of time. Information was obtained on the agricultural practices in Japan, such as the times when different crops are planted and harvested, and crop yields, and on any Japanese-specific data on the transfer of radionuclides to specific foodstuffs. In the absence of a Japanese-specific model, these data were then used in a modified version of the FARMLAND model [B21] for predicting the transfer of radionuclides through terrestrial food chains. Foods of particular importance were green vegetables, rice and milk but a range of different food groups were considered. Following an accidental release, the transfer of radionuclides to foodstuffs is very dependent on the time of year that the release occurs. The levels of radionuclides would be much higher in the first year if a release were to occur when crops are close to harvest and animals are grazing outdoors, than if it were to occur before crops are planted and animals are being given stored feed and housed indoors. The accident at FDNPS occurred in March when only a few crops were being grown and animals were being given stored feed; this led to lower concentrations of radionuclides in foodstuffs than would have been the case if the accident had happened later in the year (as was the case for the Chernobyl accident in 1986).

C59. A modelling approach was also used to estimate doses from seafood consumption in subsequent years. As discussed in appendix B, there were significant difficulties in determining the releases of radionuclides to the ocean and therefore the dose estimates should be considered very uncertain. Nevertheless, estimates of the possible exposures beyond the first year were derived from the calculated levels of ^{137}Cs in seawater over the next 10 years based on the modelling of the marine environment carried out by [N3].

C60. The restrictions on food supplies were implicitly taken into account in the estimation of doses from ingestion in the first year from the database of measurements, because the measurements were for foodstuffs as marketed (measurements of foodstuffs with activity concentrations over the set levels, which were removed from sale, were not included). For the assessment of doses from ingestion based on the modelled concentrations of radionuclides in foodstuffs, it was assumed that no food at levels above those specified by the Japanese authorities was or would be consumed. From March 2011 until April 2012, the levels were those specified by MHLW [M15], and are reproduced in table C4. In April 2012, lower levels were introduced for radiocaesium and these were taken into account in the assessment of doses from ingestion after the first year.

Table C4. Concentrations of radionuclides in foodstuffs and drinking water above which restrictions on supplies were introduced in Japan from March 2011 until the end of March 2012, in accordance with the Japan Food Sanitation Act

Radionuclide	*Provisional regulation values of radioactive material in foodstuffs (Bq/kg)*	
Radioiodine (representative radionuclides among mixed radionuclides: ^{131}I)	Drinking water Milk, dairy products[a]	300
	Vegetables (except root vegetables and tubers) Fishery products	2 000
Radiocaesium	Drinking water Milk, dairy products	200
	Vegetables Grains Meat, eggs, fish etc.	500
Uranium isotopes	Infant foods Drinking water Milk, dairy products	20
	Vegetables Grains Meat, eggs, fish etc.	100
Alpha-emitting isotopes of plutonium and transuranic elements (total radioactive concentration of ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{241}Am, ^{242}Cm, ^{243}Cm, ^{244}Cm)	Infant foods Drinking water Milk, dairy products	1
	Vegetables Grains Meat, eggs, fish etc.	10

[a] *Guidance was provided so that materials with activity concentrations exceeding 100 Bq/kg were not used in milk supplied for direct consumption or used in making powdered milk for babies.*

3. Assessment of internal exposures from ingestion of radionuclides in drinking water

C61. Measurements of radionuclides in drinking water were made by the Japanese authorities and were provided to the Committee. The estimated exposures were based on these measurements with account being taken of any restrictions that had been introduced (see table C4). Levels were only elevated for a limited period in the months following the accident.

C62. Within Fukushima Prefecture, average effective doses to people living in each district were estimated. For the rest of Japan, average effective doses to people living in each prefecture were estimated. Doses were calculated as weekly or monthly averages. For the districts within Fukushima Prefecture, average weekly doses were calculated for the period from March 2011 to the end of May 2011. After this period, monthly averages were calculated because the concentrations of radionuclides in drinking water had fallen significantly and fewer measurements had been made. For prefectures other than Fukushima, monthly averages were calculated for the period from March 2011 to March 2012. All monthly averages were based on calendar months.

E. Assessment of doses to residents of evacuated communities

C63. As outlined in section I of this appendix, the Japanese authorities took extensive measures to reduce radiation exposures. There was widespread evacuation at different times following the accident and there were also restrictions on food supplies.

C64. People within a distance of 20 km of the FDNPS site were evacuated as a precaution between 11 and 15 March 2011. Most of the residents of the towns of Futaba, Hirono, Naraha, Okuma and Tomioka and Kawauchi Village, as well as those residents of the cities of Minamisoma and Tamura, Namie Town and Katsurao Village living within the 20-km area were evacuated on 12 March 2011. Most were therefore absent from the more affected areas when the later radionuclide releases occurred. Exposures of these residents were estimated based on the evacuation scenarios described below. However, the evacuation of patients in hospitals and nursing homes within the 20-km evacuation zone, together with a small number of residents, was not completed for some days after 12 March 2011 [T4].

C65. The Government of Japan subsequently initiated the additional deliberate evacuation based on environmental measurements, notably to the north-west of the FDNPS site. The residents of the whole of Iitate Village as well as parts of the towns of Namie, Kawamata and Katsurao Village were evacuated between March and June 2011. For the resident groups from these locations, doses were assessed for the period before, during and after the evacuation. For the external and inhalation exposure pathways, the assessment was based solely on the ATDM results; for the ingestion exposure pathway, the assessment was based on measurements of the activity concentrations of radionuclides in foodstuffs. After people reached the evacuation destinations, some of them stayed there but many, especially young families, moved to other areas of Japan. However, to provide an estimate of the doses to evacuees received during the first year, it was assumed that they remained in the evacuation destinations for the whole year.

C66. The dose assessment for the period before and during the evacuation was based on the results from a questionnaire survey issued by the local authorities to all residents within Fukushima Prefecture (two million people) to ascertain their activities and, specifically, their locations and movements. Approximately 21% of the population completed the questionnaires. The National Institute for Radiological Science (NIRS) used the results of this survey to define 18 scenarios representative of the movements of residents local to FDNPS, following the accident [A5]. All 18 scenarios are outlined in table C5. Information on the numbers of evacuees by settlement is provided in attachment C-12.

Table C5. Eighteen evacuation scenarios based on the NIRS survey

Scenario	*Location at 11 March 2011*	*Evacuation destinations*		
1	Tomioka Town	12 March: Kawauchi Village Office	16 March: Big Pallet Fukushima, (Koriyama City)	
2	Okuma Town	12 March: Funahiki Vocational Improvement Center, (Tamura City)		
3	Futaba Town	12 March: Kawamata Elementary School at 08:00	19 March: Saitama Super Arena	31 March: former Kisai Prefectural Senior High School, (Kazo City)
4	Futaba Town	12 March: Kawamata Elementary School at 21:00	19 March: Saitama Super Arena	31 March: former Kisai Prefectural Senior High School, (Kazo City)
5	Naraha Town	12 March: Iwaki City Office	31 March: Funahiki Vocational Improvement Center, (Tamura City)	
6	Naraha Town	12 March: Iwaki City Office	16 March: Aizu-Misato Town Office, (Aizumisato Town)	
7	Namie Town	12 March: Tsushima Center of Activation	16 March: Adachi Gymnasium, (Nihonmatsu City)	
8	Tamura City	12 March: Denso Higashinihon	31 March: Big Pallet Fukushima, (Koriyama City)	
9	Minamisoma City	15 March: Date City Office	31 March: Azuma General Gymnasium, (Fukushima City)	
10	Hirono Town	12 March: Ono Town Office, (Ono Town)		
11	Kawauchi Village	13 March: Kawauchi Elementary School	16 March: Big Pallet Fukushima, (Koriyama City)	
12	Katsurao Village	14 March: Azuma General Gymnasium, (Fukushima City)		
13	Namie Town Tsushima Center of Activation	23 March: Adachi Gymnasium, (Nihonmatsu City)		
14	Katsurao Village	21 March: Azuma General Gymnasium, (Fukushima City)		
15	Iitate Village	29 May: Iino Branch Office of Fukushima City Office, (Fukushima City)		
16	Iitate Village	21 June: Iino Branch Office of Fukushima City Office, (Fukushima City)		

Scenario	*Location at 11 March 2011*	*Evacuation destinations*		
17	Minamisoma City	20 May: Minamisoma City Office, (Minamisoma City)		
18	Kawamata Town Yamakiya Region	01 June: Kawamata Town Office, (Kawamata Town)		

C67. Within the 18 evacuation scenarios, four types of human activities were considered: normal living conditions; residents preparing for evacuation; evacuation; and sheltering. For the normal living conditions, the assumptions on human behaviour were the same as those used in the external and inhalation exposure calculations for the non-evacuated areas. For the evacuation preparation, evacuation, and sheltering activities, the Committee assumed occupancy factors and breathing rates that reflected the nature of activities undertaken (distinct from those considered for normal living conditions). The NIRS survey was used to identify the building types in each location, and temporal and spatial movements of residents local to FDNPS. The assessments for the 18 evacuation scenarios used the deposition density and air concentration results from NOAA–GDAS ATDM. Otherwise, the same input parameters and methods as detailed in the previous sections for the assessment for external exposure and dose from inhalation for the non-evacuated areas were applied.

C68. At present, detailed information about the scale and effectiveness of the environmental remediation is not available and therefore assessments of doses allowing for the effectiveness of these measures were not possible. Estimates were made of the doses that would be received by the residents of evacuated settlements if they were to return to their homes and regular lifestyle one, two or three years after the accident, without the implementation of remediation (see table C19 below).

F. Assessment of collective doses

C69. The collective dose to the general public is an instrument primarily for optimization of protection or comparing radiological technologies or protection measures. The aggregation of very low individual doses over extended time periods is inappropriate. Comparisons have been made of the collective dose integrated over a defined time period with those from other events associated with radionuclide releases to the environment (such as global fallout following the testing of nuclear weapons in the atmosphere and the Chernobyl accident). The Committee has estimated the collective effective dose and the collective absorbed dose to the thyroid for the population of Japan. The main contributors to the collective effective dose to the public were the long-term exposure pathways: external exposure from ^{134}Cs and ^{137}Cs deposited on the ground and internal exposure from ingestion of the same radionuclides in foods.

C70. The collective dose due to external exposure for a particular area depends on the population size, radionuclide deposition densities, dwelling type and occupation of the local population. Based on national statistical data, it was assumed that about 30% of the Japanese population live in wooden one-to-three-storey houses, another 30% live in wooden fireproof one-to-three-storey houses, and about 40% live in concrete multi-storey apartments. Also, it was assumed that about 10% of the adult population are outdoor workers.

C71. The collective doses from the ingestion of terrestrial foods were estimated from the total production of foods, taking into account food wastage, in different regions of the country. In estimating collective doses, it was assumed that any foods with activity concentrations above the levels recommended by the Japanese authorities were not eaten. The activity concentrations in most of the food produced in Japan following the accident were below the set levels and the restrictions are known to have been widely implemented. If there had been a limited consumption of some food with activity concentrations above the restriction levels, the impact on the assessed collective dose is likely to have been small.

C72. The estimated collective effective dose and collective absorbed dose to the thyroid were based on the age and social composition of the population of Japan and the population distribution by district and prefecture as provided by the Japan 2010 Census [M20]. The collective doses were assessed for populations residing in all localities of Fukushima Prefecture and the other prefectures of Japan. A detailed description of the methodology is provided in attachment C-12.

III. RESULTS

C73. The methodologies described in section II were used to derive detailed estimates of the doses by age group (20-year-old adults, 10-year-old children and 1-year-old infants) for the settlements in Fukushima Prefecture that were evacuated according to the 18 evacuation scenarios (Group 1), the non-evacuated districts within Fukushima Prefecture (Group 2), the Group 3 prefectures, and the rest of Japan (Group 4). A detailed dose assessment was conducted for all districts in Fukushima Prefecture and some districts of the Group 3 prefectures of Iwate, Miyagi, Tochigi, Gunma, Ibaraki and Chiba. Additional estimates of dose were made for those districts that were in the evacuation zones and for those districts that were partially evacuated (the cities of Minamisoma and Tamura and Kawamata Town). The uncertainties associated with the measurement data and the additional modelling approach are discussed in the next section.

C74. The datasets and ATDM did not provide sufficient information for the estimation of doses to members of the public in neighbouring countries and elsewhere in the world. The Committee has relied on the estimates of these doses published in the literature, including the WHO preliminary dose estimation [W11], or provided by Member States of the United Nations.

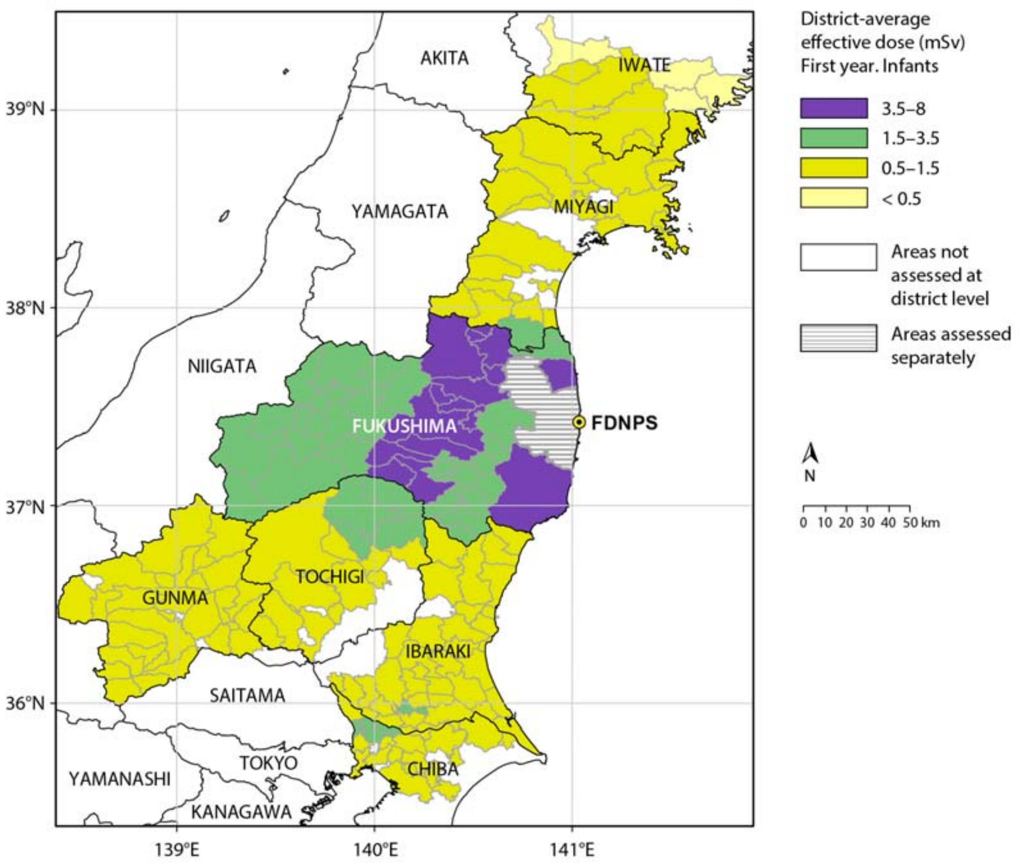
A. Estimates of doses in Japan in the first year

1. Effective dose

C75. Table C6 summarizes the estimated district- or prefecture-average effective doses received in the first year following the accident, for 20-year-old adults, 10-year-old children and 1-year-old infants residing in the non-evacuated districts of Fukushima Prefecture (Group 2), the Group 3 prefectures and the remaining prefectures in Japan (Group 4). The doses are summed over the main exposure pathways and are intended to be characteristic of the district- or prefecture-average doses received by people living in each location. The estimates in table C6 reflect the range of average doses across the districts within prefectures, not the ranges of doses received by individuals within the populations at these locations. The relative contribution of each main exposure pathway to the total estimated doses varied from location to location reflecting the levels of radionuclides in the environment and exposure conditions. Detailed results for each district and age group are provided in attachment C-14.

C76. Figure C-VI shows the district-average effective doses in the first year following the accident for 1-year-old infants living in districts of Fukushima Prefecture and some districts of the Group 3 prefectures that were not evacuated. The spatial distribution in the estimated doses shown in this figure reflects the pattern of the releases and depositions of radionuclides in the different settlements in the area.

Figure C-VI. The district-average effective doses in the first year following the accident for 1-year-old infants living in districts of Fukushima Prefecture and some districts of Group 3 prefectures that were not evacuated



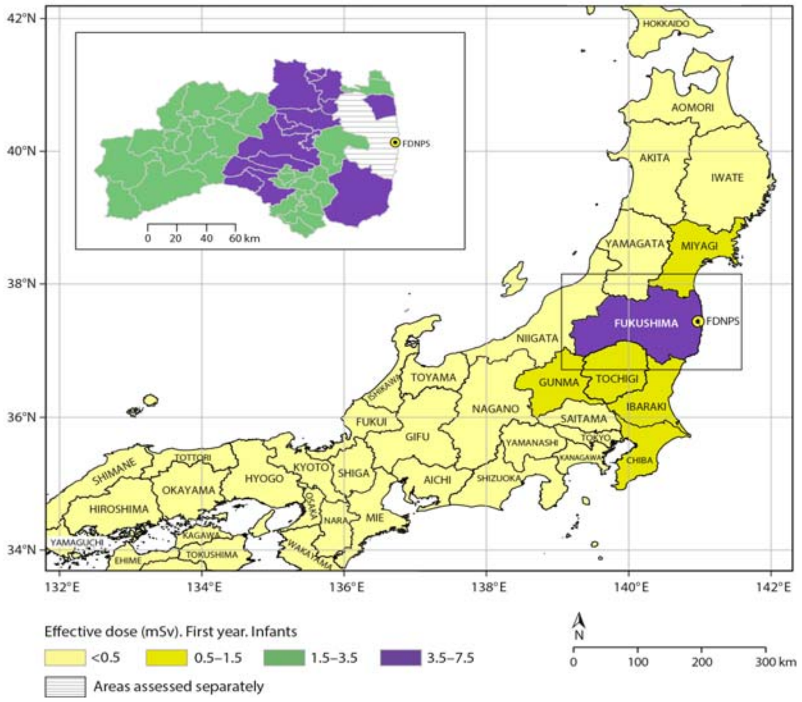
C77. The highest estimated doses were to those individuals who were not evacuated in Fukushima Prefecture, the districts that partly fall within the 20-km evacuation zone (Minamisoma City) and those with high levels of deposition density (the cities of Fukushima, Nihonmatsu, Date, Motomiya and Koriyama, Koori Town and Otama Village). The district-average total effective doses to adults in these areas were in the range of 2.5 to 4.3 mSv in the first year. The contribution of external exposure from deposited radionuclides to the total effective dose was dominant. One-year-old infants were estimated to have received average effective doses in the first year up to twice those received by adults.

C78. For the districts of the Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average total effective doses to adults were in the range of 0.2 to 1.4 mSv in the first year, with the contribution from ingestion of food in the prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi being 0.2 mSv. In Iwate Prefecture, the contribution to dose from ingestion of food was 0.1 mSv, the same as for the remainder of Japan. The prefecture-average total effective doses to adults for the prefectures in the remainder of Japan were in the range 0.1 to 0.3 mSv in the first year, with ingestion contributing 0.1 mSv, and generally being the dominant pathway.

C79. Figure C-VII shows the prefecture-average effective doses in the first year to 1-year-old infants in the rest of Japan. Prefecture-average doses in other prefectures were lower than those in Fukushima Prefecture and were considerably lower in the more distant prefectures, where the dose estimates were less than the variation in background doses from natural sources of radiation. Measurement results reported by a number of groups, including the online community group SafeCast [S1], also showed dose rates in most areas across Japan distant from Fukushima Prefecture to be at the background level.

Figure C-VII. Estimated total effective doses to 1-year-old infants in the first year following the accident

The main map shows the prefecture-average effective dose. Fukushima Prefecture average includes non-evacuated districts only. The inset map shows the district-average effective doses for non-evacuated districts of Fukushima Prefecture



C80. External exposures of the foetus and breast-fed infant from gamma radiation (mainly from ^{134}Cs and ^{137}Cs) would have been approximately the same as those to adults and infants, respectively. The doses from inhalation and ingestion would have been dominated by intakes of radiocaesium and radioiodine. For radiocaesium, the effective doses to the foetus and breast-fed infant would have been less than those to the mother [I19, I20, O1]. For radioiodine, including ^{131}I, the breast-fed infant may have received absorbed doses to the thyroid up to a factor of two higher than those to the thyroid of the mother. Overall, the doses received by the foetus and breast-fed infant would have been lower than or within the range of doses estimated for the three main age groups [O1].

C81. For districts within Fukushima Prefecture (Group 2) and Group 3 prefectures, the relative contribution of each exposure pathway varied from location to location, reflecting the levels and composition of radionuclides in the environment and foodstuffs. In the areas of higher deposition density, the greatest contribution to effective dose was from external exposure to deposited material. Inhalation of radionuclides in air was an important exposure pathway for the thyroid. The relative contribution to effective dose in the first year from the ingestion of food varied, depending on the contribution from other pathways. This variability in the contribution from the different pathways arose because doses from ingestion reflected concentrations of radionuclides averaged over much larger areas than the doses from other pathways. In areas of Japan far away from the FDNPS site, doses from ingestion predominated for most prefectures. The doses presented here are representative of the average doses to the different populations and, as discussed later, the actual doses to individuals would have varied about these averages depending on factors such as what foods were consumed and location within districts. The variability is such that the estimates of the effective dose to an individual could be up to about two to three times higher or lower in some locations than the average for the district.

Table C6. Estimated district- or prefecture-average effective doses in the first year following the accident for residents of Japan for locations that were not evacuated

The reported doses are the ranges of the district-average doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates of dose are intended to be characteristic of the average dose received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations

Residential area	*Effective dose by pathway (mSv)*								
	Adults			*10-year old*			*1-year old*		
	External + Inhalation	*Ingestion*[a]	*Total*	*External + inhalation*	*Ingestion*[a]	*Total*	*External + inhalation*	*Ingestion*[a]	*Total*
Group 2[b]—Fukushima Prefecture									
Districts not evacuated[c]	0.0–3.3	0.9	1.0–4.3	0.0–4.7	1.2	1.2–5.9	0.1–5.6	1.9	2.0–7.5
Group 3[d] prefectures									
Chiba Prefecture	0.1–0.8	0.2	0.3–1.1	0.1–1.0	0.3	0.4–1.3	0.1–1.1	0.5	0.6–1.7
Gunma Prefecture	0.1–0.6	0.2	0.3–0.8	0.1–0.8	0.3	0.4–1.1	0.1–0.9	0.5	0.6–1.5
Ibaraki Prefecture	0.1–0.6	0.2	0.3–0.8	0.1–0.9	0.3	0.4–1.2	0.1–1.0	0.5	0.6–1.5
Miyagi Prefecture	0.1–0.3	0.2	0.3–0.5	0.1–0.9	0.3	0.4–1.2	0.1–1.0	0.5	0.6–1.6
Tochigi Prefecture	0.1–1.2	0.2	0.3–1.4	0.1–1.7	0.3	0.4–2.0	0.2–2.0	0.5	0.7–2.5
Iwate Prefecture	0.1–0.3	0.1	0.2–0.5	0.1–0.5	0.1	0.2–0.6	0.1–0.6	0.2	0.3–0.8
Group 4[e]—rest of Japan									
40 remaining prefectures	0.0–0.2	0.1	0.1–0.3	0.0–0.2	0.1	0.1–0.4	0.0–0.3	0.2	0.2–0.5

[a] *The ingestion dose for Iwate Prefecture is the same as for the prefectures in the rest of Japan.*

[b] *Group 2: Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

[c] *Excluding specific areas that were evacuated within these districts.*

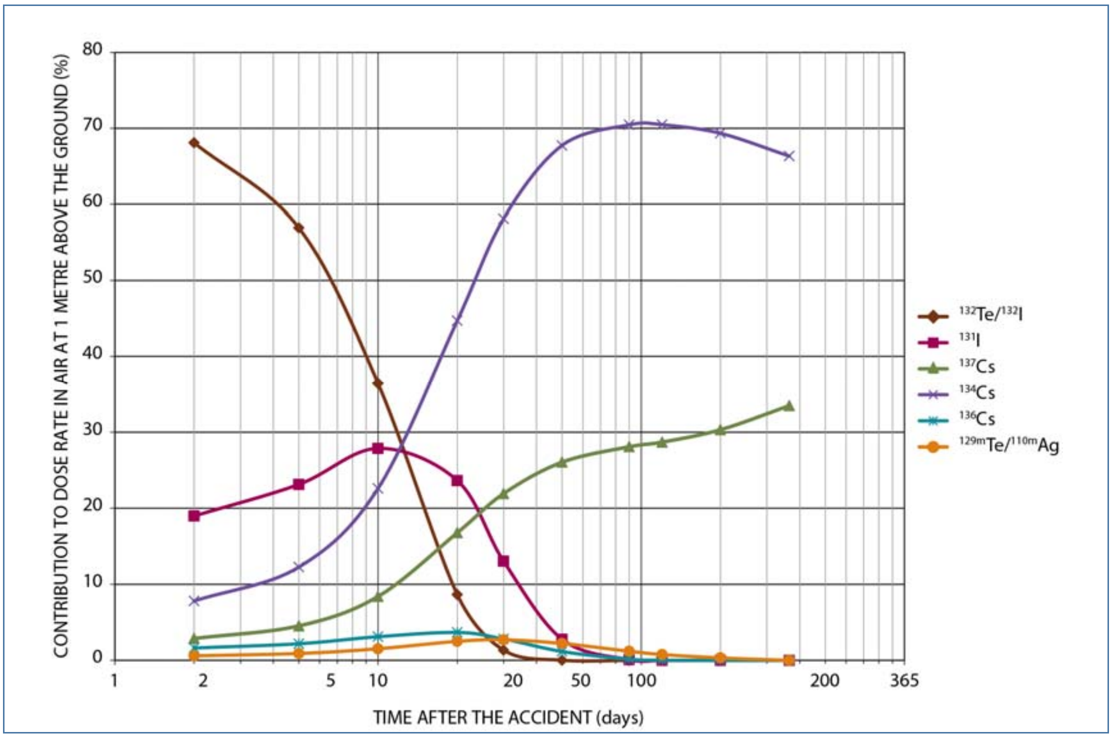
[d] *Group 3: Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate. The prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi were grouped together to calculate the dose from ingestion in these prefectures. For Iwate Prefecture, the dose from ingestion was assumed to be the same as that for the rest of Japan.*

[e] *Group 4: Members of the public living in the remaining prefectures of Japan.*

2. Contribution of external exposure to the total effective dose

C82. The gamma-radiation dose rates in air from the deposited radionuclides were estimated as a function of time and location from the measurements of the deposition density of radionuclides on the ground. Figure C-VIII shows the contributions of the main radionuclides to the dose rate. While the more important radionuclides contributing to the external exposure were ^{131}I, ^{134}Cs and ^{137}Cs in the first weeks following the release, there were also significant contributions from the short-lived radionuclides, in particular, ^{132}Te and ^{132}I. The dose rate due to deposited material fell by a factor of 10 in the first month and, after two months, the dose rate was predominantly due to ^{134}Cs and ^{137}Cs.

Figure C-VIII. Percentage contribution of different radionuclides to the dose rate in air at 1 m above the ground in the first months after the accident

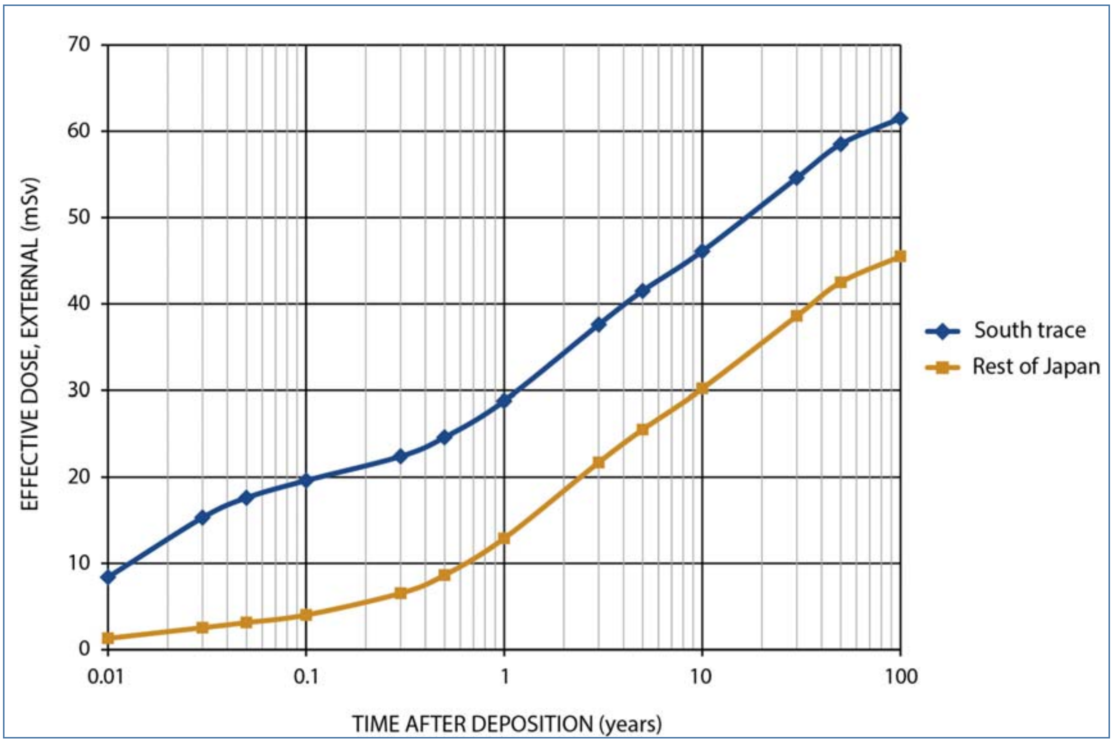


C83. The deposition of radionuclides on the ground at locations within the south trace (the towns of Tomioka, Naraha and Hirono and Iwaki City of Fukushima Prefecture) was significantly enhanced in ^{132}Te, ^{131}I and ^{132}I compared with the rest of Japan. As a consequence, for the assessment for the non-evacuated areas, the external exposure per unit deposition density of ^{137}Cs in the first year was larger by a factor of about two for Iwaki City than in the rest of Japan, as shown in figure C-IX.

C84. The estimated district- or prefecture-average effective doses to the various age and population groups in the first year for all the districts of Fukushima Prefecture, the Group 3 prefectures and the remaining prefectures in Japan (Group 4) are summarized in table C6. The contribution of external exposure was larger in the districts with the higher deposition densities of radionuclides on the ground. In the non-evacuated districts of Fukushima Prefecture, the district-average effective doses to infants in the first year from external exposure were not more than 5 mSv (Fukushima City) and for adults, not more than 3 mSv.

Figure C-IX. Accumulated effective doses per unit deposition density from external exposure of typical adults living on the south trace and in the rest of Japan

The doses are normalized to the deposition density on the ground of 1 MBq/m^2 of ^{137}Cs. A typical adult is defined as an adult living in a wooden house and working indoors in a concrete multi-storey building



C85. The estimated effective doses to the various age and population groups due to external exposure from deposited radionuclides varied depending on the dwelling type and people's occupation, especially, on the time spent outdoors, and on body size (which is correlated with age). Table C7 presents the ratios of the average effective dose to each of the various age/population groups in the first year to that of a typical adult (defined as an adult living in a wooden house and working indoors in a concrete multi-storey building). The effective doses to the most exposed group (preschool children living in wooden houses) and to the least exposed group (indoor workers living in apartment blocks) deviate from that to the typical adult by no more than a factor of two.

Table C7. Ratios of the effective dose to each of various age/population groups of the Japanese population to that to the typical adult from external exposure in the first year

A typical adult is defined as an adult living in a wooden house and working indoors in a concrete multi-storey building

Dwelling type	Ratio of effective doses			
	Adults		*10-year old*	*1-year old*
	Outdoor worker	*Indoor worker*		
Wooden one-to-three-storey house	1.4	1.3	1.4	1.7
Wooden fireproof one-to-three-storey house	1.0	0.7	0.9	1.1
Concrete multi-storey apartment	0.8	0.5	0.6	0.8

3. Contribution of internal exposure from ingestion to total dose

C86. Doses to a range of organs and for various age groups from ingestion were calculated from the monthly intakes of radionuclides in foods in the first year following the releases, using the database of activity concentrations in food. The estimates of effective dose and absorbed dose to the thyroid from ingestion in the first year are given in table C8.

C87. The doses from intakes of radionuclides via ingestion in the first month following the accident contributed the major part of the total doses received from ingestion during the first year. For example, intakes in the first month contributed over 80% of the effective dose to adults and over 90% of the effective dose to infants from the ingestion pathway. The doses from intakes via ingestion after the first month showed some fluctuation from month to month. The doses in months 2 to 4 and then in months 5 to 12 were essentially constant given the uncertainties in the dose assessment. This was partly as a result of the use of a constant value for the activity concentrations of radionuclides in foodstuffs when the measurements were below the limits of detection.

C88. In using the database of radionuclides in foods, the Committee assumed that the results were representative of the activity concentrations in food as consumed in the different prefectures. However, the measurements were taken to indicate where restrictions were required and so were likely to be biased towards the higher end of the range of actual activity concentrations in foods. If it had been assumed that only 25% of the food consumed was from the local prefecture and the remaining 75% from the rest of Japan then the estimated doses would have been lower. For example, for Fukushima Prefecture, the estimated effective dose to a 1-year-old infant in the first year would have been 0.6 mSv rather than 1.9 mSv and the absorbed dose to the thyroid would have been 10 mGy rather than 33 mGy. More detailed results of the assessment are provided in the attachment C-15.

Table C8. Estimated doses to adults, children and infants, living in different locations, from the ingestion of radionuclides in food in the first year

Location	*Effective dose (mSv)*			*Absorbed dose to thyroid (mGy)*		
	Adults	*10-year old*	*1-year old*	*Adults*	*10-year old*	*1-year old*
Group 2—Fukushima Prefecture	0.94	1.2	1.9	7.8	15	33
Group 3 prefectures	0.21	0.31	0.53	2.1	4.3	9.4
Group 4—rest of Japan	0.11	0.13	0.18	0.53	1.2	2.6

4. Estimates of doses from drinking water

C89. Table C9 summarizes the estimates of the district- or prefecture-average effective doses and absorbed doses to the thyroid from the ingestion of radionuclides in drinking water between March 2011 and March 2012. The maximum average doses were estimated for Iitate Village, with the intakes occurring before the deliberate evacuation. The detailed results of the assessment of doses from drinking water are provided in attachment C-15.

Table C9. Estimated district- or prefecture-average effective doses and absorbed doses to the thyroid from drinking water in Fukushima Prefecture and other locations in Japan

Location	*Effective dose (mSv)*			*Absorbed dose to thyroid (mGy)*		
	Adults	*10-year old*	*1-year old*	*Adults*	*10-year old*	*1-year old*
Group 2—Fukushima Prefecture[a]	0.02	0.02	0.06	0.38	0.44	1.1
Group 2—Iitate Village	0.16	0.19	0.48	3.2	3.7	9.6
Group 3 prefectures[b]	0.001–0.03	0.001–0.03	0.002–0.06	0.02–0.55	0.02–0.64	0.05–1.2
Group 4—rest of Japan[c]	0–0.010	0–0.011	0–0.027	0–0.18	0–0.21	0–0.54

[a] *Population-weighted average determined from doses for non-evacuated districts of Fukushima Prefecture.*

[b] *Range of doses for prefectures of Iwate, Gunma, Tochigi, Miyagi, Ibaraki and Chiba.*

[c] *For the majority of prefectures in Japan radionuclides were not detected in drinking water above detection limits. Only the prefectures of Akita, Kanagawa, Niigata, Saitama, Shizuoka, Tokyo, Yamagata and Yamanashi detected radionuclides above detection limits. Tokyo reported the highest results for prefectures in the rest of Japan.*

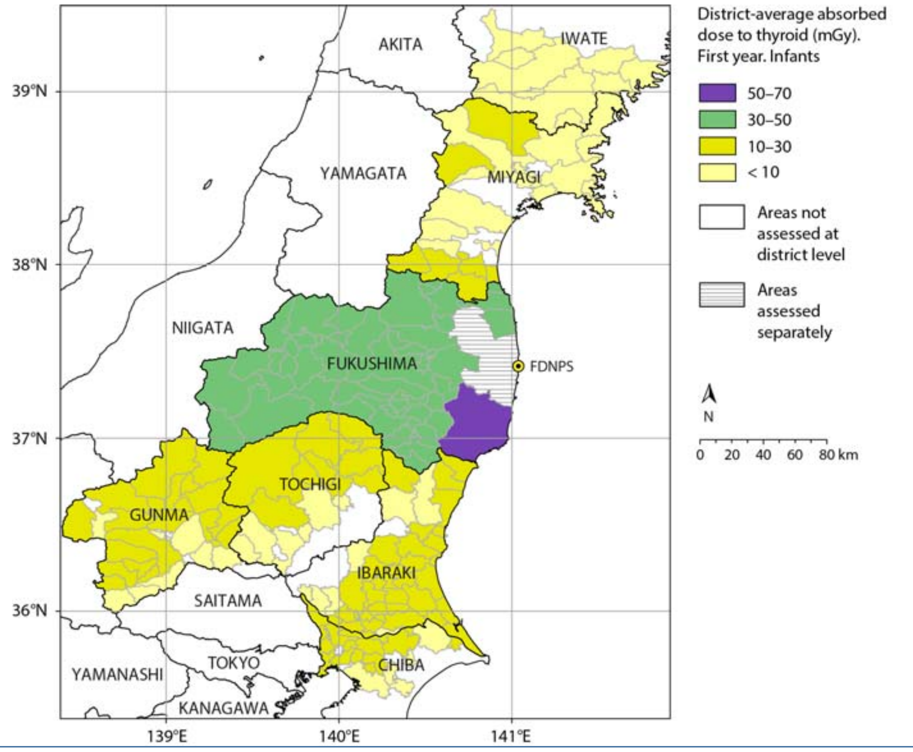
C90. Two papers have reported estimates of average doses from drinking water to Japanese citizens. Murakami and Oki [M26] estimated absorbed doses to the thyroid from a number of pathways including ingestion of drinking water for citizens of Tokyo for the first year following the accident. Amano et al. [A9] estimated committed effective doses due to ingestion of tap water in the two months directly following the accident for Chiba residents. The estimated doses to adults and infants in both papers show very good agreement, within 10% of those estimated here. Differences of factors of about two for the doses to children could be attributed to the use of dose conversion coefficients for different age groups.

5. Estimates of absorbed doses to the thyroid, red bone marrow and female breast from exposure in the first year

C91. It is particularly important to consider the absorbed doses to the thyroid of infants from intakes of radioiodine because of the radiosensitivity of their thyroids. The first-year absorbed doses to the thyroid of various age groups for all the districts of Fukushima Prefecture, most districts of the Group 3 prefectures and for the rest of Japan (Group 4) are presented in detail in attachment C-16 and summarized in table C10. Most of the absorbed dose to the thyroid was received by the public over the first month after the accident.

C92. Figure C-X shows the estimated absorbed doses to the thyroid of 1-year-old infants in the first year by district for the different locations in Fukushima Prefecture and districts of some neighbouring prefectures. Again, districts where the communities were evacuated are not included in these estimates, but are discussed in the following section. The highest district-average doses to the thyroid were to individuals in the cities of Iwaki and Fukushima. The highest district-average absorbed dose to the thyroid was estimated to have been 52 mGy for a 1-year-old infant living in Iwaki City, with approximately one third of this due to inhalation and two thirds to ingestion. The contribution of inhalation to the absorbed dose to the thyroid was higher in districts with the higher deposition density of radionuclides on soil. Within each district, there was also a marked spatial variability in the concentration of ^{131}I in air and the estimates of the absorbed dose to the thyroid of an individual from inhalation could be up to about two to three times higher or lower in some locations within districts than the average dose for the district. The estimated absorbed doses to the thyroid for adults and 10-year-old children in the first year were about 30% and 50%, respectively, of those for 1-year-old infants.

Figure C-X. The district- average absorbed doses to the thyroid in the first year following the accident for 1-year-old infants living in districts of Fukushima Prefecture and some districts of Group 3 prefectures that were not evacuated



C93. For Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average absorbed doses to the thyroid of infants were estimated to be in the range of 3 to 15 mGy, with the dominating exposure pathway being ingestion; the contribution of the inhalation pathway ranged from a few to about thirty per cent. In the remaining 40 prefectures of Japan, the prefecture-average absorbed doses to the thyroid of infants were estimated to have been about 3 mGy, with between 75% and 100% of the dose from the ingestion of food.

C94. For the non-evacuated districts within Fukushima Prefecture, the district-average absorbed doses to the red bone marrow and the female breast of adults, children and infants in the first year were estimated to be in the range of 0.6 to 3.6 mGy, 0.4 to 4.6 mGy and 0.3 to 5.3 mGy, respectively. For Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average absorbed doses to the red bone marrow and the female breast of adults, children and infants in the first year were estimated to be in the range of 0.1 to 1.2 mGy, 0.1 to 1.6 mGy and 0.1 to 1.9 mGy, respectively. In the remaining 40 prefectures of Japan, the prefecture-average absorbed doses to the red bone marrow and the female breast in the first year were estimated to have been less than 0.3 mGy for adults, children and infants. The absorbed doses to the red bone marrow of various age groups in the first year following the accident for all the districts of Fukushima Prefecture, most of districts of the Group 3 prefectures and for the rest of Japan (Group 4) are presented in detail in attachment C–17.

Table C10. Estimated district- or prefecture-average absorbed doses to the thyroid in the first year following the accident for residents of Japan for locations that were not evacuated

Residential area	*Absorbed dose to thyroid[a] (mGy)*								
	Adults			*10-year old*			*1-year old*		
	External + inhalation	*Ingestion[b]*	*Total*	*External + inhalation*	*Ingestion[b]*	*Total*	*External + inhalation*	*Ingestion[b]*	*Total*
Group 2[c]—Fukushima Prefecture									
Districts not evacuated[d]	0.1–9.6	7.8	7.8–17	0–16	15	15–31	0.2–19	33	33–52
Group 3[e] prefectures									
Chiba Prefecture	0.2–2.1	2.1	2.3–4.2	0.2–3.3	4.3	4.6–7.7	0.3–4.0	9.4	9.7–13
Gunma Prefecture	0.2–1.4	2.1	2.3–3.5	0.3–2.2	4.3	4.6–6.5	0.3–2.6	9.4	9.7–12
Ibaraki Prefecture	0.2–1.5	2.1	2.3–3.6	0.3–2.4	4.3	4.6–6.7	0.3–2.9	9.4	9.7–12
Miyagi Prefecture	0.1–1.5	2.1	2.2–3.6	0.2–2.4	4.3	4.6–6.8	0.2–3.0	9.4	9.6–12
Tochigi Prefecture	0.2–3.0	2.1	2.3–5.1	0.3–4.8	4.3	4.6–9.1	0.4–5.8	9.4	9.7–15
Iwate Prefecture[b]	0.1–0.9	0.5	0.6–1.4	0.2–1.4	1.2	1.3–2.5	0.2–1.7	2.6	2.7–4.2
Group 4[f]—rest of Japan									
40 remaining prefectures	0–0.4	0.5	0.5–0.9	0–0.6	1.2	1.2–1.8	0–0.8	2.6	2.6–3.3

[a] *The reported doses are the ranges of the district-average doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates of dose are intended to be characteristic of the average doses received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations.*

[b] *The dose from ingestion for Iwate Prefecture is the same as for the prefectures in the rest of Japan.*

[c] *Group 2: Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

[d] *Excluding specific areas that were evacuated within these districts.*

[e] *Group 3: Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate. Chiba, Gunma, Ibaraki, Miyagi, and Tochigi were grouped together to calculate the dose from ingestion in these prefectures. For Iwate Prefecture, the dose from ingestion was the same as that for the rest of Japan.*

[f] *Group 4: Members of the public living in the remaining prefectures of Japan.*

6. Estimates of doses to residents of evacuated communities

C95. The evacuations undertaken to protect the public from the releases from FDNPS reduced the radiation exposures that would otherwise have been received. Doses were estimated for the 18 groups of people in the NIRS scenarios who were evacuated at different times and moved to different locations (see table C5). The doses were assessed for the period before and during the evacuation. The last evacuation occurred on 21 June 2011. These dose estimates were based on the ATDM results for radionuclide concentration in air and deposition density in the days following the accident.

C96. The estimated settlement-average effective doses to adults in these groups from external irradiation from deposited radionuclides and from the plumes and internal irradiation following inhalation of radionuclides in air and ingestion of foods are summarized in table C11. The estimates of settlement-average total effective dose over the periods of these evacuations were less than 3 mSv for those evacuated by 15 March 2011, and less than 10 mSv for those evacuated at later times. These values are consistent with those obtained in a previous assessment of external doses to evacuees by NIRS that used a similar methodology but a different dispersion model and source term [A4].

C97. The estimated effective doses in the first year to those who were residents of the evacuated districts are the sum of the doses received before and during evacuation and during the remainder of the year at the location to which they were evacuated. These doses are also summarized in table C11. The settlement-average effective doses to adults who were evacuated in March 2011 were estimated to be less than 6 mSv in the first year and to those evacuated in April to June 2011 less than 10 mSv in the first year. Ten-year-old children and 1-year-old infants were estimated to have received average effective doses in the first year up to twice those for adults. Detailed results of the estimates of effective doses to the evacuees are provided in attachment C-18. Doses to the foetus and breast-fed infants were not explicitly estimated but would have been approximately the same as those to adults and 1-year-old infants, respectively.

C98. The estimates of settlement-average absorbed doses to the thyroid of a 1-year-old infant are shown in table C12. The settlement-average absorbed doses to the thyroid of 1-year-old infants before and during the evacuations were estimated to be up to about 50 mGy for those evacuated by 15 March 2011 and up to about 70 mGy for those evacuated at later times. These doses were principally from inhalation during the passage of the airborne radioactive material through the affected areas in the early days of the accident and from ingestion over the subsequent period. The absorbed doses to the thyroid for the first year for the 1-year-old infants who were evacuated ranged from 15 up to about 80 mGy. Detailed results of the estimates of absorbed dose to the thyroid of the evacuees are provided in attachment C-18. The protective effect of iodine blocking possibly implemented by some residents was not taken into account in the assessment.

C99. For the precautionary evacuated settlements (scenarios 1−12), the settlement-average absorbed doses to the red bone marrow in the first year were estimated to be in the range of 0.6 to 7 mGy and for the deliberately evacuated settlements (scenarios 13−18), in the range of 4 to 10 mGy, for all age groups. The first-year absorbed doses to the red bone marrow of various age groups for all the evacuated settlements of Fukushima Prefecture are presented in detail in attachment C–18. For evacuated girls and women, the settlement-average absorbed doses to the breast were estimated to be up to about 10 mGy for all age groups.

Table C11. Estimated settlement-average effective doses to adults evacuated from localities of Fukushima Prefecture

The doses calculated are settlement-average effective doses for each evacuation scenario, before and during evacuation, and for the first year following the accident. The dose estimates are intended to be characteristic of the average effective doses received by people evacuated from each settlement. Scenarios 1 to 12 correspond to the precautionary evacuated settlements; scenarios 13 to 18 correspond to the deliberately evacuated settlements

Locality	*NIRS scenario no.*	*Destination*	*Effective dose to adult (mSv)*				
			Evacuation[a]	*Destination*[b]	*Total first year*[c]	*Projected*[d]	*Averted*[e]
Tomioka Town	1	Koriyama City	0.2	3.1	3.3	51	48
Okuma Town	2	Tamura City	0.0	1.5	1.5	47	45
Futaba Town	3	Saitama	0.9	0.2	1.1	38	37
Futaba Town	4	Saitama	0.9	0.2	1.1	38	37
Naraha Town	5	Tamura City	2.2	1.5	3.7	7	3
Naraha Town	6	Aizimisato Town	1.3	1.2	2.5	7	4
Namie Town	7	Nihonmatsu City	1.3	3.7	5.0	25	20
Tamura City	8	Koriyama City	0.4	3.1	3.5	1.5	-
Minamisoma City	9	Fukushima City	1.4	4.3	5.7	4	-
Hirono Town	10	Ono Town	0.0	1.3	1.3	4	3
Kawauchi Village	11	Koriyama City	0.2	3.1	3.3	2	-
Katsurao Village	12	Fukushima City	0.0	4.3	4.3	6	2
Tsushima Activation Center, Namie Town	13	Nihonmatsu City	4.3	2.7	7.0	25	18
Katsurao Village	14	Fukushima City	2.7	3.3	6.0	6	-
Iitate Village	15	Fukushima City	5.7	2.1	7.8	11	3
Iitate Village	16	Fukushima City	6.2	1.8	8.0	11	3
Minamisoma City	17	Minamisoma City	3.8	1.0	4.8	4	-
Yamakiya Region, Kawamata Town	18	Kawamata Town	8.5	0.8	9.3	2	-

[a] *Estimate of the dose that people received before and during evacuation.*

[b] *Estimate of the dose that people received for the rest of the first year following evacuation.*

[c] *Estimate of the dose in the first year that people received before and during evacuation and at destination for remainder of year.*

[d] *Estimate of the dose that people would have received in the first year if they had not been evacuated.*

[e] *Estimate of the dose that people avoided by being evacuated.*

Table C12. Estimated settlement-average absorbed doses to the thyroid of 1-year-old infants evacuated from localities of Fukushima Prefecture

The doses calculated are settlement-average absorbed doses to the thyroid for each evacuation scenario, before and during evacuation, and for the first year following the accident. The dose estimates are intended to be characteristic of the average absorbed doses to the thyroid received by people evacuated from each settlement. Scenarios 1 to 12 correspond to the precautionary evacuated settlements; scenarios 13 to 18 correspond to the deliberately evacuated settlements

Locality	*NIRS scenario no.*	*Destination*	*Absorbed dose to thyroid of 1-year-old infant (mGy)*				
			Evacuation[a]	*Destination*[b]	*Total first year*[c]	*Projected*[d]	*Averted*[e]
Tomioka Town	1	Koriyama City	5.2	42	47	795	750
Okuma Town	2	Tamura City	0.0	36	36	507	470
Futaba Town	3	Saitama	12	3	15	288	270
Futaba Town	4	Saitama	16	3	19	288	270
Naraha Town	5	Tamura City	46	36	82	138	60
Naraha Town	6	Aizimisato Town	35	34	69	138	70
Namie Town	7	Nihonmatsu City	37	44	81	145	60
Tamura City	8	Koriyama City	1.9	42	44	36	-
Minamisoma City	9	Fukushima City	6.4	47	53	39	-
Hirono Town	10	Ono Town	0.0	34	34	76	40
Kawauchi Village	11	Koriyama City	5.0	42	47	40	-
Katsurao Village	12	Fukushima City	0.0	49	49	61	12
Tsushima Activation Center, Namie Town	13	Nihonmatsu City	59	24	83	145	60
Katsurao Village	14	Fukushima City	46	27	73	61	-
Iitate Village	15	Fukushima City	52	3.8	56	80	24
Iitate Village	16	Fukushima City	53	2.7	56	80	24
Minamisoma City	17	Minamisoma City	45	2.3	47	39	-
Yamakiya Region, Kawamata Town	18	Kawamata Town	63	1.9	65	45	-

[a] *Estimate of the dose that people received before and during evacuation.*

[b] *Estimate of the dose that people received for the remainder of the first year following evacuation.*

[c] *Estimate of the dose in the first year that people received before and during evacuation and at destination for rest of year.*

[d] *Estimate of the dose that people would have received in the first year if they had not been evacuated.*

[e] *Estimate of the dose that people avoided by being evacuated.*

C100. The evacuation of settlements within the 20-km zone was estimated to have averted effective doses to adults of up to about 50 mSv and absorbed doses to the thyroid of 1-year-old infants of up to about 750 mGy. In some areas, the doses received by the evacuees were similar to those that would have been received had they stayed in place. The estimated doses are averages for the various age groups and communities, and while some individual doses may have been higher, it was not possible to quantify the range of doses from the data available at the time. For the small number of hospital and nursing-home patients, residents and other individuals in the 20-km zone for whom the 18 evacuation scenarios were not applicable, higher doses could not be ruled out. The doses that were averted, when added to the estimates of dose received before and during the evacuation, can be used as estimates of the doses to people who might have stayed in the evacuation zone, and as an upper bound for any individual who might have gained access to the zone.

B. Estimation of doses in Japan from exposure over future years

C101. Estimates have also been made of district- and prefecture-average doses accumulated over the first 10 years after the accident and up to age 80 years. The doses from external exposure were assessed with similar methods as for the first year, but taking account of the reduction in dose rate due to radioactive decay and the removal of radionuclides by physico-chemical processes over the period of the exposure. The detailed methodology is presented in attachment C-12. Table C13 shows the dependence of doses from external exposure on the exposure duration and location for various age groups of the Japanese population. Because of a lack of detailed information on the implementation and effectiveness of remediation at specific locations, no account was taken of the possible reduction in exposure as a consequence of remediation.

Table C13. Dependence of the effective dose from external exposure normalized by deposition density of ^{137}Cs on the exposure duration

Exposure duration	*Effective dose from external exposure per unit deposition density[a] (mSv per 0.1 MBq/m² as of June 2011)*			
	Age/population group (as of 2011)			
	Adults		*10-year old*	*1-year old*
	Outdoor worker	*Indoor worker*		
Entire Japan except south trace[b]				
1 year	1.8	1.6	1.8	2.1
10 years	3.9	3.8	4.2	4.9
Up to age 80 years	5.6	5.6	6.0	6.7
South trace[b]				
1 year	4.0	3.7	4.1	4.9
10 years	6.2	5.9	6.5	7.6
Up to age 80 years	7.9	7.7	8.3	9.4

[a] *Because of a lack of detailed information on the implementation and effectiveness of remediation at specific locations, no account was taken of the possible reduction in exposure as a consequence of remediation.*

[b] *Towns of Tomioka, Naraha and Hirono and Iwaki City of Fukushima Prefecture.*

C102. The doses from the ingestion of radionuclides were estimated using the FARMLAND model, [B21] taking account of radioactive decay. The estimated effective doses and absorbed doses to the thyroid for adults, 10-year-old children and 1-year-old infants, integrated over 10 years after the accident and up to age 80 years are available in attachment C–19. The total doses from external and internal exposures are summarized in table C14.

Table C14. Estimated district- or prefecture-average effective doses to adults, 10-year-old children and 1-year-old infants (as of 2011) over the first year and first ten years and to age 80 years

Age group	*District- or prefecture-average effective dose[a] (mSv)*		
	Group 2—Fukushima Prefecture[b]	*Group 3[c] prefectures*	*Group 4[d]—rest of Japan*
1-year exposure			
Adults	1.0–4.3	0.2–1.4	0.1–0.3
10-year old	1.2–5.9	0.2–2.0	0.1–0.4
1-year old	2.0–7.5	0.3–2.5	0.2–0.5
10-year exposure			
Adults	1.1–8.3	0.2–2.8	0.1–0.5
10-year old	1.3–12	0.3–4.0	0.1–0.6
1-year old	2.1–14	0.3–6.4	0.2–0.9
Exposure to age 80 years			
Adults	1.1–11	0.2–4.0	0.1–0.6
10-year old	1.4–16	0.3–5.5	0.1–0.8
1-year old	2.1–18	0.4–6.4	0.2–0.9

[a] *The reported doses are the ranges of the district-average doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates of dose are intended to be characteristic of the average doses received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations.*

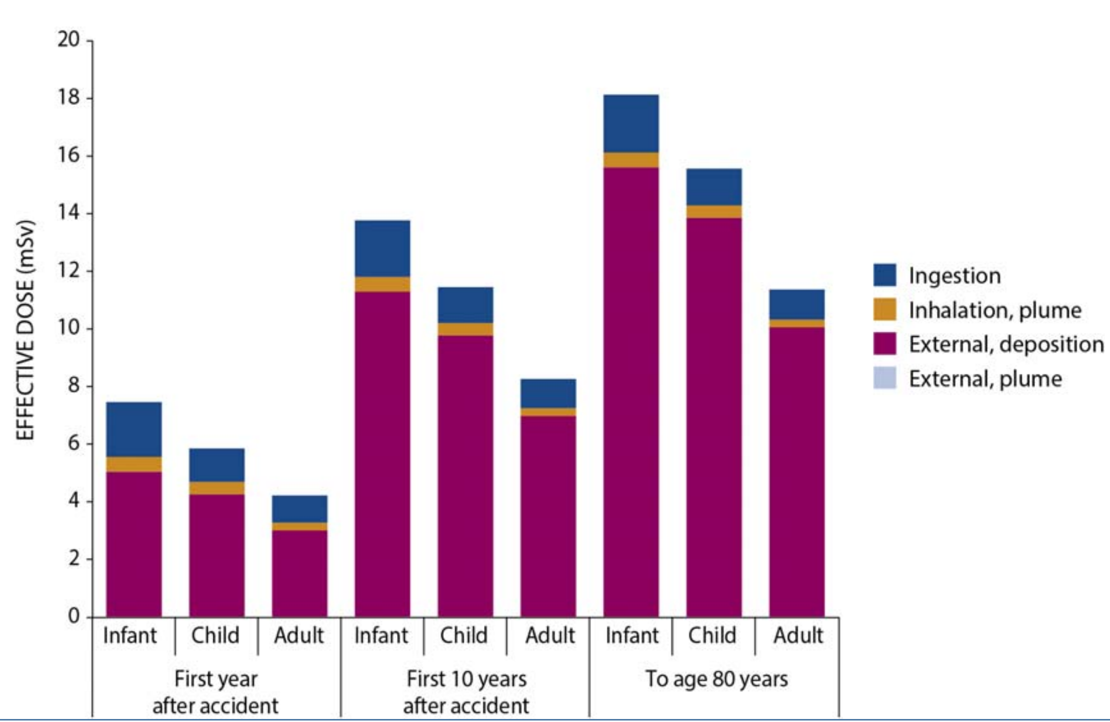
[b] *Group 2: Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

[c] *Group 3: Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate. The prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi were grouped together to calculate the dose from ingestion in these prefectures. For Iwate Prefecture, the dose from ingestion was the same as that for the rest of Japan.*

[d] *Group 4: Members of the public living in the remaining prefectures of Japan.*

C103. Figure C-XI shows the estimated district-average effective dose as a function of age group for the different integration times for people living in Fukushima City. Infants aged 1 year at the time of the accident had the highest estimated doses, followed by 10-year-old children and then those adults who spent more time outdoors (see also tables C7 and C13). Adults who spent more time indoors had the lowest estimated doses. However, the differences in the effective doses estimated for the same exposure periods were not large, being less than a factor of two.

Figure C-XI. Estimated district-average effective doses to typical adults, children and infants (as of 2011) living in Fukushima City



C104. The estimated average effective doses incurred over the 10-year-exposure period and the effective doses up to age 80 years are larger by factors of up to two and three, respectively, than those received in the first year. The greatest increases in dose were in the areas with the highest deposition densities.

C105. Most of the absorbed dose to the thyroid of the residents of Japan was received during the first year from inhalation of ^{131}I and ingestion of food containing this radionuclide. Continued exposure from the longer-lived radioisotopes of caesium is estimated to result in an absorbed dose to the thyroid up to age 80 years less than 50% higher than that received in the first year.

C. Radiation exposure outside of Japan

1. Countries neighbouring Japan

C106. When WHO undertook its preliminary dose estimation in 2011 [W11], very few measurement data were available for countries outside of Japan. In the absence of measured data, WHO applied a modelling approach to estimate doses received by people in these countries. The countries and regions considered were the far-eastern part of the Russian Federation, Indonesia, the Philippines, the Republic of Korea and South-East Asia. The effective doses and the equivalent doses to the thyroid for these places were all less than 0.01 mSv in the first year following the accident and the key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway.

C107. Following the FDNPS accident, Keum et al. also estimated the radiation doses to people in the Republic of Korea [K10]. These were based on measured levels of activity concentration and deposition density of radionuclides. Estimates of effective doses and equivalent doses to the thyroid in five age groups (infants, 5-year olds, 10-year olds, 15-year olds and adults) were made. The doses estimated for the Republic of Korea and in the WHO report are summarized in table C15.

2. Rest of the world

C108. The assessment of doses for countries outside of Japan was based on a review of estimates published in the literature, including the results of the WHO preliminary dose estimation [W11], supported by the extensive measurements, and dose assessments carried out by Member States of the United Nations. These dose estimates are summarized in table C15. Based on an analysis of this body of information, the Committee concluded that the total effective doses to individuals living outside of Japan were less than 0.01 mSv in the first year following the accident.

Table C15. Estimated doses in the first year following the accident reported for regions outside of Japan

Geographic location	*Estimated effective dose (mSv)*			*Comments*
	Adults	*10-year old*	*1-year old*	
Neighbouring countries				
The Republic of Korea, Indonesia, the Philippines, far-eastern part of the Russian Federation and South-East Asia [W11]	<0.01	<0.01	<0.01	WHO applied a modelling approach to doses received by people outside of Japan. The key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway. An estimate of equivalent doses to the thyroid was also made and these were also less than 0.01 mSv
The Republic of Korea [K10]	1.4×10^{-4}	1.9×10^{-4}	5.7×10^{-5}	Estimated the effective doses and equivalent doses to the thyroid for five age groups (infants, 5-year olds, 10-year olds, 15-year olds and adults) for the first year and up to age 70 years. Equivalent doses to the thyroid ranged from 5.0×10^{-4} for infants to 1.2×10^{-3} mSv for adults in the first year. Estimates were made using measured levels of airborne activity concentration and deposition density
Rest of the world				
Rest of the world [W11]	<0.01	<0.01	<0.01	WHO applied a modelling approach to doses received by people outside of Japan. The key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway. Estimates of equivalent dose to the thyroid were made and these were also less than 0.01 mSv
Belarus [K6]				Estimated the equivalent doses to the thyroid of children aged 1 to 2 years from inhalation of radioiodine. These ranged from 5×10^{-7} to 7×10^{-5} mSv. The maximum values were registered 24 days after the accident
Cuba [A8]	2×10^{-3}			Estimated the effective doses from the inhalation of ^{131}I and ^{137}Cs using measured concentrations in aerosols
France [I32]	2×10^{-4}			Estimated the maximum potential exposures (effective doses in adults and equivalent doses to the thyroid of 1-year-old infants) by inhalation and ingestion of ^{131}I. Based on measurements from mid-March 2011 to May 2011. The reported equivalent dose to the thyroid of 1-year olds in France was 4.5×10^{-2} mSv
Germany [B9]	3×10^{-5}		5×10^{-5}	Estimated the effective doses for the first year after the accident from inhalation and external exposure for ^{131}I, ^{134}Cs and ^{137}Cs from measurements of air samples and deposition density from late March to end of April 2011 in the south-west of Germany
Greece [K21]	1.1×10^{-6}	1.9×10^{-6}		Estimated the effective doses from the inhalation of ^{131}I using measured concentrations in aerosols; no doses from ingestion were calculated
Italy [I30]	3.5×10^{-2}		1.8×10^{-1}	Estimated the effective doses from external exposure, inhalation and ingestion of ^{131}I, ^{134}Cs, ^{137}Cs in milk and water. Ingestion of radionuclides in water was the major contributor of dose. Very conservative assumptions were applied as the highest concentration values measured for each radionuclide in rainwater were used to calculate the dose from ingested water

Geographic location	*Estimated effective dose (mSv)*			*Comments*
	Adults	*10-year old*	*1-year old*	
Netherlands [K17]	$<1 \times 10^{-5}$			Estimated the total effective doses from inhalation pathway using the measured airborne concentration of ^{131}I
Portugal [C1]	4.6×10^{-5}			Estimated the total effective doses from inhalation and ingestion pathways for ^{132}Te, ^{131}I, ^{134}Cs and ^{137}Cs from measured concentrations in aerosol samples and deposition densities from late March to mid-April 2011
Romania [C8]	8.5×10^{-5}			Estimated the total monthly effective doses from ingestion of ^{131}I in sheep milk and meat in Romania for the first year after the accident
Serbia [B11]	7.2×10^{-3}			Estimated the effective doses from ^{131}I concentrations in food, milk, air and rainwater. Doses were from inhalation and ingestion of food during one month. Ingestion of radionuclides in milk was the major pathway

D. Estimates of collective doses

C109. The collective effective doses and the collective absorbed doses to the thyroid from the major exposure pathways (external exposure, inhalation and ingestion) were estimated for the first year, 10 years and to age 80 years following the accident for Fukushima Prefecture, neighbouring prefectures and the rest of Japan, and are summarized in table C16.

Table C16. Collective effective doses and absorbed doses to the thyroid for the population of Japan (128 million in 2010)

Exposure pathway	*Exposure duration*		
	First year	*10 years*	*Up to age 80 years*
Collective effective dose (thousand man-sieverts)			
Inhalation	1.2	1.2	1.2
External	10	25	36
Ingestion	6.5	10	11
Total	18	36	48
Collective absorbed doses to thyroid (thousand man-grays)			
Inhalation	22	22	22
External	10	25	36
Ingestion	50	53	54
Total	82	100	110

C110. The main contributor to the collective effective dose in the first year was external exposure from deposited radionuclides; the ingestion of radionuclides in food was the next most important contributor. The collective effective dose will increase over the first 10 years owing to the continued external exposure and the ingestion of residual radionuclides in foods. After the first 10 years, the increase in the collective effective dose will continue predominantly due to external exposure.

C111. Most of the collective absorbed dose to the thyroid in the first year was caused by ingestion and inhalation of ^{131}I in the spring of 2011, with a smaller contribution from external exposure over the whole year. The collective absorbed dose to the thyroid will slowly increase over the first 10 years owing to the continued external exposure and the ingestion of radionuclides in foods. After the first 10 years, the slow increase will continue because of external exposure.

C112. These collective doses to the population of Japan due to the FDNPS accident can be compared to those to the populations of European countries exposed to radiation following the Chernobyl accident in the former Soviet Union in 1986. The collective effective dose and collective absorbed dose to the thyroid from the Chernobyl accident determined for the 20-year period (1986–2005) by the Committee from the results of both environmental and human measurements were about 360,000[36] man Sv and 2,300,000 man Gy, respectively. The lifetime doses would be about 400,000 man Sv and

[36] About 260,000 man Sv without the contribution of the dose to the thyroid (see annex D [U12]).

2,400,000 man Gy, respectively. The estimated collective effective dose to the population of Japan due to a lifetime exposure following the FDNPS accident is approximately 10–15% of the corresponding value for European populations exposed to radiation following the Chernobyl accident. The estimated collective absorbed dose to the thyroid for the Japanese population is approximately 5% of that for European populations due to the Chernobyl accident.

IV. UNCERTAINTIES

C113. The doses presented are settlement-, district- or prefecture-averages for representative members of the public. The estimated doses were based on the best available models and input data at the time of the study. However, there are uncertainties associated with the results of any assessment of this type because of incomplete knowledge or information, and the assumptions that were made. The main sources of uncertainty are discussed here.

A. Assessment of dose from external irradiation and inhalation

C114. The estimated doses for external exposure in the non-evacuated areas were largely based on measured levels of deposition density of radionuclides on the ground. The uncertainties associated with individual measurements of ^{134}Cs and ^{137}Cs are relatively small but those for ^{131}I are larger because of the significant amount of radioactive decay that occurred before the measurements were made.

C115. There are also uncertainties in how well the measurements represented the spatial distribution of the radionuclides for each district or prefecture when estimating district- or prefecture-average doses. For Fukushima Prefecture, there are extensive measurements with adequate spatial information. Comparisons were made between the measurements of deposition density from the MEXT ground surveys, the USDOE airborne radiometric survey and the NOAA–GDAS ATDM results for total ground deposition. These data were analysed over the grid cells of approximately 1-km squares, with all data corrected for radioactive decay to 1 April 2011. The resultant spreadsheets and maps are provided in attachments C-20 and C-21. The analysis shows good agreement between the measured deposition densities of ^{137}Cs on the ground from the MEXT and USDOE surveys. The marked spatial variability is consistent with the spatial variability seen in other datasets. Based on a comparison of the measured values, uncertainties associated with spatial variability in deposition density contribute an uncertainty of about a factor of two to the uncertainties in the estimated district-average doses. For the Group 4 prefectures, comparatively fewer measurements were made and the uncertainties in prefecture-average doses are likely to be larger.

C116. For external irradiation from deposited radionuclides, a further source of uncertainty is from the reduction in exposures from being indoors and the shielding effects of the building materials. The doses presented in previous sections are for the wooden houses which are the most common type of houses in Fukushima Prefecture. For people who live in wooden fireproof houses or concrete multi-storey apartments, the doses were estimated to be about factors of two and four lower, respectively, than those presented in the tables above. However, these factors were based mostly on European data obtained following the Chernobyl accident and not on measurements conducted in Japan. A further factor directly influencing the estimation of dose from external exposure is the indoor occupancy for the various age and social groups of the Japanese population.

C117. The estimates of exposure of the communities evacuated in March were based on the source term and NOAA–GDAS ATDM results directly. The agreement between the NOAA–GDAS ATDM results and the measured data for the deposition density of ^{137}Cs is good for many areas but for some locations, the ATDM results under- or overestimated the levels by up to a factor of ten. On average, the district-average deposition densities of ^{137}Cs obtained from NOAA–GDAS ATDM are about a factor of two higher than the values from the MEXT surveys. For ^{131}I, the district-average values obtained from NOAA–GDAS ATDM range from overestimates by up to a factor of two, to underestimates by up to a factor of 10, with an average of about one.

C118. A source of uncertainty in the estimation of doses to evacuees from inhalation derives from incomplete knowledge about the release rates of radionuclides over time and the weather conditions during the releases. The ATDM results have large uncertainties when used to estimate doses at specific locations. These uncertainties are discussed in section III.E in appendix B where the NOAA–GDAS ATDM results are compared with the ATDM results obtained by the French Institute for Radiation and Nuclear Safety (IRSN) [S3]. The ratios of the IRSN ATDM estimates for air concentrations of ^{131}I to those of the NOAA–GDAS ATDM results varied from about 0.5 and 12. These ratios reflect the uncertainty in the settlement-average doses from inhalation for these populations for specific locations and times. For deposition density, the ratio of the IRSN ATDM estimates to those of the NOAA–GDAS ATDM results varied between about 0.2 and 8. Again, these ratios reflect the uncertainty in the settlement-average doses from external exposure. The uncertainties in the total doses in the first year across all exposure pathways for the evacuated settlements are smaller than these ranges because of the contributions to the total doses from the other pathways and at other locations.

C119. Similar uncertainties with the NOAA–GDAS ATDM results are relevant to the assessment of doses from external exposure and inhalation of radionuclides from the passing plume outside of the evacuated areas. For this assessment, the impact of these uncertainties were partially reduced by the application of a scaling method based on the measured deposition densities of radionuclides on the ground and the ratio of air concentration to deposition density derived from NOAA–GDAS ATDM. As detailed in section III of appendix B, the ratio of the bulk deposition velocities for ^{131}I estimated by IRSN ATDM to those estimated by NOAA–GDAS ATDM ranged from a factor of about 4 higher to a factor of about 30% lower, depending on the location. These factors imply concentrations in air (and consequently doses from inhalation for the non-evacuated population) ranging from a factor of about 30% higher to a factor of about 4 lower, depending on the location. In addition, the doses from external exposure and inhalation from the passing plume usually contributed less than half of the total dose and the uncertainties introduced by the uncertainties in the NOAA–GDAS ATDM results are less important than for the evacuated population.

C120. The weather conditions during the passage of the plumes following the accident and the nature of the deposition (such as dry or wet deposition, amount of precipitation) significantly influenced the radionuclide distribution in the urban and forest environments. Lack of detailed information on these factors can cause significant uncertainty in the estimation of the dose from external exposure. Future work to provide a more detailed reconstruction of the dispersion and deposition conditions in March 2011 may allow for better estimates of early doses from external exposure and inhalation, particularly in the evacuated areas.

C121. An additional factor that affects the estimation of absorbed dose to the thyroid from inhalation is the ratio of particulate to gaseous forms of ^{131}I in the air. Measurement data were limited and available mostly at substantial distances from the release site. For Fukushima Prefecture, where absorbed doses to the thyroid could be more significant, there were no measurement data for the relative amounts of particulate and gaseous forms of ^{131}I in air; this ratio was therefore estimated from the modelling of the reactor releases and the ATDM results. The estimated value for this ratio has an uncertainty of up to a factor of two.

B. Assessment of dose from ingestion

C122. Using the FAO/IAEA food database of concentrations of radionuclides in foodstuffs, the Committee estimated doses from ingestion as a function of time in the first year following the releases for a range of organs and age groups. The full results are given in attachment C-15 and were all based on the food marketed at the location of interest, thereby allowing for the proportion of each food type that was imported into Japan. Some uncertainties in these dose estimates can be expected, reflecting the uncertainties in the measurement data and the types of foods that were available at different times. The doses in the first year were based on measurements made on food that was not randomly sampled, because priority was given to the identification of foods with the highest radionuclide concentrations. It is therefore, likely that the mean concentrations used in the Committee's assessment are overestimates of the true means, particularly in the first months after the accident when relatively few measurements were made.

C123. As discussed in section III.A of this appendix, if it is assumed that only 25% of food was from the local prefecture then the estimated doses would have been about a factor of three lower than those presented in this study. For doses beyond the first year, the uncertainties in the modelled values of radionuclide concentrations in foods would be reflected in uncertainties in the estimated doses. It was difficult to quantify the uncertainties in these modelled values as there was insufficient information on the transfer of radionuclides to food as a function of time for foods produced in Japan.

C124. The use of a constant activity concentration of 10 Bq/kg for foods when the measurements results were below the limits of detection also contributed to the uncertainty in the doses from intakes in the first year. This value was used for ^{131}I, ^{134}Cs and ^{137}Cs for the first four months following the accident, but only for ^{134}Cs and ^{137}Cs after four months. This is the reason for an apparent marked reduction in estimated doses from intakes in the fifth and subsequent months, particularly for the thyroid. The results also reflect the impact of the restrictions on food supplies, because products from the areas more affected by the accident were excluded from the market. Further information on the possible impact of this assumption is given in the compilation of information on doses from ingestion provided in attachment C-15. Sato et al. [S2] have shown the cautious nature of this assumption, particularly after the first few months. A duplicate-diet study conducted with a large number of volunteers in Fukushima Prefecture showed that many people were likely to have had lower doses from radiocaesium than those estimated by the Committee. However, the study could not consider the first few months after the accident when levels in food were higher and it did not consider intakes of ^{131}I, which contribute most to the doses in the first year. They also noted that the study group was not a random sample and that participants had a high degree of concern about their exposures, so they may not have been representative of the population as a whole.

C125. There were significant differences in the levels of radionuclides in different foodstuffs depending on where they were grown, reflecting differences in the deposition densities of radionuclides on the ground as well as local factors, such as the time of planting of the crop and the soil type. A key factor is where people obtain their food. In Japan, the majority of people use supermarkets to obtain their food and that food could have come from anywhere in the country, with a fraction being imported.

However, some people may grow their own vegetables and also provide these to neighbours, and farmers may consume their own produce. If individuals living in the areas of higher deposition density had eaten locally produced food even though restrictions had been introduced following the accident, then they could have received exposures significantly higher than those presented here. The impact of this can only be quantified using the modelled results, based on deposition data. Further information is provided in the compilation of doses from ingestion given in attachment C-15. This shows that the impact of the restrictions was to reduce doses by up to two orders of magnitude in Fukushima Prefecture, depending on age group and location.

C126. The Committee’s estimates of doses beyond the first year from ingestion were obtained using the modelling approach based on deposition data. It was assumed that 25% of food was from the prefecture where the individual lived and 75% from elsewhere in Japan, with allowance made for foods being imported into Japan. In order to assess the uncertainties associated with these assumptions, estimates were made for Fukushima Prefecture assuming that 100% of the local food consumed was from the prefecture, both with and without allowing for imported food. The effect of this is seen in table C17.

Table C17. Influence on effective doses to adults in Fukushima Prefecture of assuming that 100% of local food consumed was from the prefecture

Time (years)	*Effective dose (mSv) with food restrictions; values without restrictions shown in parentheses*		
	25% local, standard result	*100% local, but allowing for imports*	*100% local, no allowance for imports*
1	0.06 (2.0)	0.20 (7.9)	0.27
10	0.14 (2.1)	0.50 (8.3)	1.4
up to age 80	0.17 (2.1)	0.62 (8.4)	1.5

C127. The effect of assuming that 100% of local food consumed were from the prefecture is particularly marked when restrictions on food supplies were taken into account. Because the vast majority of people in Japan eat food from supermarkets, the above dose estimates do not apply to many individuals. It is very unlikely that anyone would have eaten only locally produced food and so the doses presented above should be viewed as the upper bound of possible doses from ingestion. Conversely, it should be recognized that following the accident, many people avoided produce from Fukushima Prefecture or even from Japan, and the settlement-average doses from ingestion would have been lower than those given above.

C128. It took some days for the food restrictions to be introduced in Japan and it is possible that some people ate food with activity concentrations of radionuclides above the restriction levels during this time. For most communities, this was unlikely to have resulted in a significant exposure relative to the exposure received over a full year. However, in the case of Iitate Village, there was a period of a number of weeks when the residents were living in the area and potentially eating local produce and drinking the locally sourced water. The estimates of dose from ingestion for Iitate Village are included in the evacuation scenarios using the standard parameters for ingestion, but an adult living in Iitate Village and eating only locally produced vegetables could have received an additional effective dose of about 10 mSv in the first week following the accident. This assumption is unlikely given the time of year and the limited availability of green vegetables growing in the open, but cannot be excluded as a possibility.

C129. Standard models have been used to determine the radiation doses following intakes of radionuclides into the body. These are based on a standard-sized person with particular metabolic characteristics. It has not been possible to generally consider the effect of the variability between people on the doses from intakes or the uncertainty in the models and data used. However, one aspect that has been briefly considered is that the Japanese diet is relatively high in stable iodine and this could have led to less transfer of radioiodine to the thyroid than in the standard model. There are indications that the transfer of iodine from blood to the thyroid is 20% [Y8] rather than the value of 30% used in the standard ICRP model [I25]. This could lead to slightly lower doses from intakes of ^{131}I, but the effect overall would be small (less than a 30% reduction in dose), compared with the other uncertainties associated with the dose assessment.

C130. The doses in the first year from ingestion of radionuclides in seafood were based on the measurement data contained in the database. Information on the contribution of ingestion of seafood to the total dose from ingestion was only available for individual radionuclides and for each month separately; these show that their contribution to the total dose was not greater than 10% overall. This reflects the restrictions put in place on the consumption of seafood from Fukushima Prefecture.

C131. Table C18 shows the estimates of future radiation doses from the ingestion of seafood. These estimates were based on the calculated levels of ^{137}Cs in seawater over the next 10 years from modelling the marine environment, based on work carried out by [N3]. The modelling of the changes in concentrations of radionuclides in seawater with time beyond 10 years is based on results from measurements of fallout from the testing of nuclear weapons in the atmosphere. These estimated effective doses are all very low and are less than those from the ingestion of terrestrial foods, even two years after the accident. This is because of the significant dilution of radiocaesium in the water and therefore the very low concentrations in seafood away from the FDNPS site. It is assumed that monitoring and restrictions on seafood will continue so that any products above the levels specified by the Japanese authorities will not be consumed.

Table C18. Estimated effective doses to different age groups from the consumption of radionuclides in seafood at various times after the accident

Time after the accident (years)	*Annual effective dose to different age groups (mSv in a year)*		
	Adults	*10-year old*	*1-year old*
2	3.9×10^{-5}	2.1×10^{-5}	1.4×10^{-5}
5	8.2×10^{-6}	4.3×10^{-6}	3.1×10^{-6}
10	3.2×10^{-6}	1.7×10^{-6}	1.2×10^{-6}
20	2.3×10^{-6}	1.2×10^{-6}	8.6×10^{-7}
50	8.1×10^{-7}	4.3×10^{-7}	3.1×10^{-7}

C132. There are two published papers that used a probabilistic approach for estimating doses from ingestion [K19, Y2]. The paper by Yamaguchi estimated a range of doses from ingestion that are consistent with those given here and which do not show a significant variation. The range of doses estimated by Koizumi et al. were lower than those given here but were based on a very limited set of measurements.

C. Future remediation and protective measures

C133. Since mid-2011, extensive remediation work has been underway or is being planned in the regions of Japan with the higher deposition densities, to reduce the dose rate and concentrations of radionuclides in areas where people live or grow food [S6]. This work includes the use of technologies for decontamination of inhabited areas, and of countermeasures in agriculture (such as phytoremediation) and in forestry. The experimental studies and tests in Fukushima Prefecture were planned to be completed by the first half of 2012. At that time, a large-scale environmental remediation programme was planned to be launched in the affected areas of Fukushima Prefecture. In some affected areas beyond the restricted area, local authorities initiated decontamination activities, mostly focused on public areas and especially on children's facilities (kindergartens, schools, hospitals and so on). Similar work, although in the temperate European environment, was intensively conducted in the Chernobyl-affected areas two decades ago, and the conclusions and recommendations from this work were summarized by the Chernobyl Forum [I1] and UNSCEAR [U12].

C134. It was not possible to include consideration of remediation in the dose assessment at this stage, because the effectiveness of the different measures to be applied in Japan was not known. Estimates of the effective doses from external irradiation that would be received by those who were evacuated if they were to return to their homes and regular lifestyles without any environmental remediation having been implemented are however shown in table C19. These estimates provide an upper bound to the doses that might be received in the future.

Table C19. Effective doses from external exposure of adults who were evacuated from localities of Fukushima Prefecture, if they were to return to their homes

Municipality	*Effective dose from external exposure (mSv in period indicated)*[a]		
	11 March 2012–11 March 2013	*11 March 2013–11 March 2014*	*11 March 2014–11 March 2015*
Futaba Town	11	6.7	4.5
Hirono Town	0.42	0.25	0.17
Iitate Village	4.1	2.5	1.7
Katsurao Village	2.0	1.2	0.83
Kawamata Town	0.50	0.30	0.20
Kawauchi Village	0.37	0.22	0.15
Minamisoma City	0.61	0.37	0.25
Namie Machi	9.8	6.0	4.0
Naraha Town	0.66	0.40	0.27
Okuma Town	12	7.3	4.9
Tamura City	0.19	0.12	0.08
Tomioka Town	5.3	3.2	2.2

[a] *External exposure from deposited radionuclides.*

C135. Although remediation may result in reduction in the activity concentrations of radionuclides in crops and animal products, if it is assumed that the restriction criteria for foodstuffs given above would continue to apply, the estimated doses from ingestion would not be affected. In future, more detailed studies could be carried out to investigate the impact of remediation on ingestion doses but this is beyond the scope of this assessment.

C136. The annual external doses to adults are already substantially below the Japanese criteria for evacuation (20 mSv). Decontamination of settlements with techniques that from past experience reduce the doses by about 1.5 would further reduce external doses for all the population groups [I1, U3]. The results in table C19 indicate that, after March 2014, the settlement-average effective doses to adults from external exposure were estimated to be less than 1 mSv in a year in seven of the evacuated localities.

V. COMPARISON WITH OTHER ASSESSMENTS

A. Direct measurements of radionuclides in people

C137. Measurements of radionuclides in people provide a direct source of information on their exposure. Two main sets of data were available to the Committee, the first from in vivo measurements of ^{131}I in the thyroid, particularly of children, and the second from in vivo whole-body monitoring for ^{134}Cs and ^{137}Cs. Such measurements can only indicate the levels of these radionuclides that are in individuals at the time that they were monitored. Assumptions have to be made to estimate total radiation exposures (such as when the intakes took place and how much was by inhalation or ingestion).

C138. Only a limited number of in vivo measurements of ^{131}I activity in the thyroid were reported for the weeks following the accident. Thyroid monitoring was carried out by local authorities on 1,080 children aged between 1 and 15 years in Iwaki City, Kawamata Town and Iitate Village over the period from 26 to 30 March 2011 using hand-held dose-rate instruments [K13]. The absorbed doses to the thyroid from internal exposure were calculated assuming exposure was continuous over the period from 12 to 24 March 2011. The results of the Committee’s analysis of the measurement data for infants and children were consistent with the assessment by the Japanese authorities. In its analysis, the Committee assumed a single exposure on 15 March 2011. The Committee's estimates of settlement-average absorbed doses to the thyroid from internal exposure were two to five times higher than the corresponding values derived from the direct monitoring of these children.

C139. Tokonami et al. [T20] reported the results of measurements made on the thyroid from 12 to 16 April 2011 on 62 evacuees from Tsushima District of Namie Town and the coastal area of Minamisoma City. They detected ^{131}I in 46 people and, for the adults in this group, estimated that the absorbed doses to the thyroid were in the range of 2 to 35 mGy. While three quarters of their estimates of absorbed dose to the thyroid were below 10 mGy, a quarter of the estimates were in the range 15 to 35 mGy. The estimates in this higher range are consistent with the estimates of absorbed doses to the thyroid for adults made by the Committee, but the lower range is lower by a factor of up to four. There is likely some overestimation introduced by the overall chain of models (i.e. in the assumed magnitude and pattern of the releases, the assumed protective measures, and the dosimetric and other factors) adopted by the Committee to estimate absorbed doses to the thyroid for the evacuees.

C140. As part of the Health Examination for Citizens in Fukushima Prefecture programme, whole-body counting of more than 106,000 residents of Fukushima Prefecture and neighbouring prefectures was conducted by the end of January 2013 [H5, M24].

C141. The paper of Momose et al. [M24] details a series of whole-body measurements on about 10,000 evacuees made from July 2011 to January 2012. The presence of ^{134}Cs and ^{137}Cs could be detected in the body in only 20% of the evacuees (minimum detectable activity was about 300 Bq). The Committee estimated the average effective dose from the intake of ^{134}Cs and ^{137}Cs since March 2011 from these measurements to be about 0.05 mSv to adults and about 0.03 mSv to adolescents. For almost all of the evacuees, the effective dose was estimated to have been below 1 mSv; an effective dose to just one person in about 5,000 adults and adolescents was estimated to have been about 1 mSv.

C142. According to Hayano et al. [H5], 33,000 residents of Fukushima Prefecture and neighbouring prefectures were examined by whole-body monitoring at Hirata Central Hospital located south-west of FDNPS in Fukushima Prefecture between October 2011 and February 2012. Only 12% of those monitored had an activity of ^{134}Cs and ^{137}Cs in the body above the minimum detectable level of about 300 Bq. Between March and November 2012, this proportion fell to 1%. This confirms that most of the radionuclide intake occurred soon after the accident. Based on the whole-body measurements conducted on adults between October 2011 and February 2012, the Committee estimated the average effective doses from the intake of ^{134}Cs and ^{137}Cs since March 2011 to be in the range of about 0.02 to 0.07 mSv, respectively.

C143. Both estimates, based on the large number of measurements [H5, M24], are substantially lower than the doses estimated in this study from the inhalation and ingestion of ^{134}Cs and ^{137}Cs. Although the aim of this study was to provide as realistic as possible an assessment of the doses to the Japanese population, these results would indicate that some of the assumptions made were still cautious, an inevitable consequence of the incompleteness of the information available to the Committee.

B. WHO study

C144. The preliminary exposure assessment by WHO [W11] and the related health risk assessment [W12] used data available up to September 2011. Although the assessments were intended to be realistic, given the limited information available at the time, some of the assumptions made by WHO were likely to lead to overestimation of doses.

C145. In table C20, the WHO results for the effective dose to adults and the absorbed doses to the thyroid of 1-year-old infants are compared with the results obtained in this study. This assessment used more comprehensive data than were available for the WHO study and it was therefore possible to make more realistic assumptions in parts of the assessment. In general, the estimates from this study of the effective doses in the first year in districts of Fukushima Prefecture are within the dose ranges in the WHO preliminary dose estimation. There is also good agreement in the estimates of the absorbed doses to the thyroid. Table C20 shows that in some cases, the estimated doses for specific locations were lower in this assessment than in the WHO study. This reflects the additional information available, in particular, for the evacuated areas, where more detailed information on the patterns of movement of the evacuees was available than for the WHO preliminary dose estimation [W11]. However, there are also locations where the estimated doses in this study were higher than those in the WHO study.

Table C20. Comparison of estimates of the effective dose to adults and of the absorbed dose to the thyroid of 1-year-old infants

Location	*WHO assessment [W12]*		*Committee's assessment*	
	First year	*Lifetime*	*First year*	*Up to age 80 years*
	EFFECTIVE DOSE TO ADULTS (mSv)			
Namie Town	22	24	5.0[a]	[d]
Naraha Town	4	8	3.7[a]	[d]
Iitate Village	12	14	8.0[b]	[d]
Katsurao Village	5	6	6.0[b]	[d]
Minamisoma City	5	8	5.7	[d]
Iwaki City	1	2	2.2	4.2
Rest of Fukushima Prefecture	1–5	2–10	1.0–4.3	1.2–12
Neighbouring prefectures	~1	~1	0.2–1.4	0.2–4.1
	ABSORBED DOSE TO THYROID OF 1-YEAR-OLD (mGy)			
Namie Town	122	123	81[c]	[d]
Naraha Town	39	42	82[c]	[d]
Iitate Village	73	74	56[c]	[d]
Katsurao Village	48	48	73	[d]
Minamisoma City	43	46	53[c]	[d]
Iwaki City	31	32	52	[d]
Rest of Fukushima Prefecture	31–39 (or 30–40)	32–42	33–52	[d]
Neighbouring prefectures	≤9	≤10	3–15	[d]

[a] *Within restricted zone.*

[b] *Within deliberate evacuation zone.*

[c] *Assessed NIRS evacuation scenario.*

[d] *Not assessed by Committee.*

VI. CONCLUSIONS

C146. For the great majority of people in Japan, the additional radiation doses received in the first year following the radioactive releases from the accident at FDNPS were less than the background doses received each year from natural sources of radiation (about 2.1 mSv [N23]). This is particularly the case for people living in prefectures remote from Fukushima Prefecture where doses of 0.2 mSv or less were estimated to have been received.

C147. For those residents who were evacuated in the first days after 11 March 2011, the estimated settlement-average total effective doses to adults in the first year were on average less than 6 mSv. For those who were evacuated at later times, the estimated settlement-average total effective doses to adults in the first year were on average less than 10 mSv. These doses include those received before and during evacuation and for the remainder of the year at the evacuation destination. The estimated settlement-average absorbed doses to the thyroid of one-year-old infants in the first year ranged from about 15 up to about 80 mGy. This is significantly higher than absorbed doses to the thyroid from natural background radiation; the average annual absorbed dose to the thyroid from naturally occurring sources of radiation is typically of the order of 1 mGy. For a small number of hospital and nursing-home patients, residents and other individuals who may have remained in the 20-km zone for longer periods, higher exposures may have occurred.

C148. For those people who were not evacuated, the highest district-average doses were received by those living in Fukushima City, where the district-average total effective doses in the first year were 4.3 mSv for adults and 7.5 mSv for 1-year-old infants. If no remediation were undertaken, people who were infants at the time of the accident could receive effective doses up to about 20 mSv, in addition to those received from natural sources of radiation, over their lifetimes. People living in a number of settlements within the districts of Koori Town, Otama Village, and the cities of Date, Iwaki, Koriyama, Nihonmatsu and Minamisoma were estimated to have received average effective doses in the first year in the range of 2 to 4 mSv for adults and 5 to 7 mSv for infants. For the remaining districts within Fukushima Prefecture the district-average effective doses were in the range of 1 to 2 mSv for adults and 2 to 5 mSv for infants. To provide context, 80-year cumulative effective doses from background exposure to natural sources of radiation in Japan are on average about 170 mSv (i.e. 2.1 mSv annually for 80 years). The variability of the deposition density of radionuclides in the environment and variations in human behaviour and food habits are such that the estimates of the effective dose to an individual could be up to about two to three times higher or lower in some locations than the average effective dose for the district.

C149. The highest estimated absorbed doses to the thyroid of individuals in non-evacuated districts in the first year were in the cities of Iwaki and Fukushima, with the district-average absorbed dose to the thyroid of 1-year-old infants in the first year being about 50 mGy. The estimated doses to 10-year-old children and adults were lower than those of 1-year-old infants by factors of about two and about three to four, respectively. For the Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average absorbed doses to the thyroid of infants in the first year were assessed to be in the range of about 3 to 15 mGy. In the remainder of the 40 prefectures of Japan, the prefecture-average absorbed doses to the thyroid of infants in the first year were assessed to be about 3 mGy.

C150. There were only a limited number of direct in vivo measurements of ^{131}I in the thyroid reported for the weeks immediately following the accident. The estimates of absorbed dose to the thyroid from these measurements were up to two to five times lower than the settlement-average absorbed doses to the thyroid estimated in this study. There is likely some overestimation introduced by the overall chain of models (i.e. in the assumed magnitude and pattern of the releases, the assumed protective measures, and the dosimetric and other factors) adopted by the Committee to estimate absorbed doses to the thyroid for the evacuees. The estimates of dose from internal exposure by gamma-emitting radionuclides derived from whole-body monitoring are substantially lower than the doses estimated in this study and therefore reflect some caution in the assumptions used in assessing the doses from internal exposure in this study.

C151. The estimated doses to evacuees have the largest associated uncertainties for all of the estimates made by the Committee during this study, and in view of the absence of measurements of concentrations of radionuclides in air at the time of exposure, are likely to remain so. Doses had to be estimated from the ATDM results, and assumptions about the temporal pattern of the releases, the time-varying location of people during the evacuation and any protective measures that were applied, all of which have associated uncertainties. Further information will, in time, become available on the pattern and magnitude of the releases and this may lead to some reduction in the overall uncertainty in the estimation of doses to evacuees.

C152. For the locations with the highest estimated doses, the most important exposure pathway was external exposure from deposited material, although there may also have been a significant contribution from inhalation and ingestion of radionuclides. For the locations with lowest estimated doses, ingestion of radionuclides in food gave the most significant contribution.

C153. The estimated doses depend on the radionuclide concentrations in the environment and on the age/social group of the population. Infants aged 1 year at the time of the accident had the highest estimated doses, followed by 10-year-old children and then by those adults who spent more time outdoors. Adults who spent more time indoors had the lowest estimated doses. However, the differences in the estimated effective doses among the considered groups were not large, being less than a factor of two.

C154. Generally, the total effective doses that will be incurred over the 10-year period following the accident were estimated to be a factor of up to two larger than those received in the first year. Lifetime doses were estimated to be up to a factor of three greater than the doses received in the first year, with the greatest increases in dose being in the areas with the highest levels of deposition density of radionuclides. Most of the absorbed doses to the thyroid were received by the residents of Japan during the first year by the pathways of inhalation of ^{131}I in air and ingestion of food containing ^{131}I. The doses to the thyroid over a lifetime were estimated to be less than 50% higher than those received in the first year. Children born over the next decades will not receive any dose to the thyroid from ^{131}I since it will have totally decayed, but will receive some exposure from ^{134}Cs and ^{137}Cs.

C155. The doses presented here are considered to be typical of the average exposures for each group of people. Doses would be significantly lower for some people, particularly those living in concrete multi-storey apartments and who had avoided locally produced fresh food after the accident. Doses would be higher for those who spent a significant proportion of each day outdoors and who ate locally produced food.

C156. The actions taken to protect the public significantly reduced the radiation exposures that could have been received. This was particularly the case for settlements within the 20-km evacuation zone and the deliberate evacuation zones, where the protective measures reduced the potential exposures in the first year by up to a factor of 10. The Committee estimated that effective doses thus averted ranged up to 50 mSv for adults; the absorbed doses to the thyroid of 1-year-old infants averted by evacuation ranged up to about 750 mGy.

C157. Collective doses to the Japanese population were also estimated for comparative purposes. The estimated lifetime collective effective dose to the population of Japan following the FDNPS accident is approximately a factor of eight lower than the corresponding value for European populations exposed to radiation following the Chernobyl accident, while the collective absorbed dose to the thyroid is a factor of about 20 lower.

C158. Based on an analysis of doses reported for countries neighbouring Japan and for the rest of the world, the Committee concluded that the total effective doses to individuals in populations living outside of Japan were less than 0.01 mSv in the first year following the accident.

C159. While the Committee has aimed to make realistic estimate of dose to public based on the available information, it is likely that some overestimation has been introduced generally by the overall chain of models used by the Committee and the lack of information on individual protective measures.

APPENDIX D. ASSESSMENT OF DOSES TO WORKERS

I. INTRODUCTION

D1. Up until 31 October 2012, a total of 24,832 occupationally exposed workers ("radiation workers[37]") had been involved in mitigation and other activities at the Fukushima Daiichi Nuclear Power Station (FDNPS). In addition, a few hundred emergency workers were deployed on the FDNPS site: these included fire-fighters, police and Self-Defence Force workers. An assessment of risks to health for these workers would need to be based on assessments of absorbed dose to relevant organs for each worker; however the quantity "effective dose" is usually reported in a radiation protection context. In general, assessments of effective dose resulting from occupational exposures to external sources of radiation ("external exposure") are based on readings from alarm pocket dosimeters worn by the worker; whereas for occupational exposures to internal sources of radiation resulting from intakes of radionuclides ("internal exposure"), committed effective doses or committed doses to specific organs

[37] In Japan, occupationally exposed workers are called "radiation workers", a term which applies to personnel engaged in radiation-related work in a controlled area. These workers are engaged in the installation, operation, utilization or maintenance of nuclear reactors, or are engaged in the transport, storage, disposal or removal of nuclear fuel material or nuclear fuel contaminated material.

are assessed using biokinetic and dosimetric models to interpret the results of bioassay monitoring. The term "bioassay" refers to measurements of the activities of radionuclides in the body (in vivo measurements) or measurements of activities in excreta samples (in vitro measurements).

D2. During the normal operation of the reactors, a few thousand occupationally exposed workers were employed at the site. This number increased dramatically following the accident, with almost twenty five thousand occupationally exposed workers having been involved in recovery and related operations by October 2012. The majority of these (about twenty one thousand) were employed by contractors of the Tokyo Electric Power Company (TEPCO) or subcontractors, rather than by TEPCO itself.

D3. As a result of the tsunami, initial capabilities for monitoring radiological conditions, both on-site and off-site, were severely hampered. Few on-site monitoring systems remained. Most electronic personal dosimeters, computer systems for activating and recording doses measured by these devices, installed contamination monitors, and many portable survey instruments were lost in the flooding.

D4. One of the aims of the Committee's assessment of doses to workers was to judge the extent to which the individual doses reported in Japan (section II of this appendix) provided a true and reliable measure of the doses actually incurred, and therefore the extent to which the reported doses could be used to support a reliable assessment of potential effects on health. Here, the term "reliable" was applied to a measure or assessment to indicate that it could be considered with confidence to be of sound and consistent quality.

D5. Given the typical time and effort required to perform a single dose assessment, it would not have been possible for the Committee to review or reassess the individual assessments of dose for such a large number of workers. Therefore, a two-stage approach was adopted. First, the methodologies used in Japan for assessing doses were reviewed (section III of this appendix). Second, independent dose assessments were made for defined groups of workers, and comparisons made with the doses reported in Japan for these workers (section IV).

D6. Doses received by workers with the highest exposures were of particular interest for the assessment of potential effects on health, and so assessments were performed for twelve of the thirteen workers[38] with the highest reported doses from internal exposure (whose committed effective doses, $E(50)$, were more than 100 mSv), with the aim of judging the reliability of the doses reported for these individual workers. These thirteen workers were all TEPCO workers, the measurements of internally incorporated radionuclides were all performed at the same (or similar) facilities, and the methods for assessing doses due to internal exposure were also similar. Internal exposure made the dominant contribution to the effective dose for the twelve workers, and seven workers with the highest reported committed doses from internal exposure also had the highest reported effective doses.

D7. In contrast, the much larger number of workers who received lower doses had different types of employment status (such as TEPCO employee, contractor or subcontractor employee, or emergency services worker), and both the type of facilities used for measurements of radionuclide activities and the method used to assess doses could have depended on the level of the assessed dose. The Committee evaluated the reliability of the dose assessments for these groups of workers by performing independent dose assessments for samples of workers randomly selected from the various groups, as described in section IV of this appendix.

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[38] At the suggestion of the Committee, the Japanese organizations initiated a reassessment of the doses received by the workers which was completed only by July 2013. This reassessment showed there to be thirteen (rather than the original twelve) workers (all TEPCO workers) with committed effective doses higher than 100 mSv. However, this information came too late for the Committee to carry out an independent detailed assessment of the dose from internal exposure that this thirteenth worker received.

II. DOSE STATISTICS

D8. Tables presenting the numbers of occupationally exposed workers in specified effective dose bands (and showing contributions from external and internal exposure) for each month since the accident up to October 2011 have been published by TEPCO [T8]; these were subsequently updated by the Committee with results from a reassessment conducted by Japanese organizations in July 2013—the updated data are given in tables D1, D2 and D3. These tables show that the highest effective doses resulted mainly from intakes of radioactive material, and that monthly doses in excess of 100 mSv only occurred in March 2011. Since November 2011, TEPCO has presented data in terms of the number of workers with cumulative effective doses over defined periods in various dose bands; the data published in November 2012 (and subsequently updated by Japanese organizations) are produced in table D4. These show that the number of workers with cumulative effective doses exceeding 100 mSv increased by 65% between the end of March 2011 and the end of October 2012.

D9. The data presented in this section only take into account the number of workers involved in the mitigation operations conducted between 11 March 2011 and 31 October 2012. Given the turnover of staff on site, the number of workers involved in such operations was increasing and consequently the distribution of workers across the different dose bands was constantly evolving. For updated information, one source of publicly available information was the website of TEPCO [39] which published a monthly update of information on the numbers of workers and their doses.

D10. Although tables D1–D4[40] provide useful statistics on the numbers of workers in specified dose bands, they do not provide information on internal and external exposure for individual workers. For instance, it was not possible to determine from these tables whether the single worker who was recorded with a committed dose from internal exposure in the 150–200 mSv range (table D2) was one of the thirteen workers with a total effective dose in the same range, or one of the six workers with a total effective dose in the “over 250 mSv” range (table D3). However, the Japanese authorities separately provided data to the Committee in spreadsheet form on the individual monthly and cumulative doses from internal and external exposures reported for 21,776 TEPCO and contractors’ workers up to April 2012. Tables D5, D6 and D7 show reported cumulative effective doses up to April 2012 for the 20 workers with the highest effective doses, highest committed effective doses from internal exposure and highest effective doses from external exposure, respectively, extracted from this spreadsheet. The highest reported effective dose was 679 mSv, for the TEPCO worker who also had the highest reported committed effective dose due to internal exposure (590 mSv). The highest reported effective dose from external exposure was 199 mSv, for a contractors’ worker who had a reported total effective dose (from internal and external exposure) of 238 mSv.

D11. Tables such as tables D5–D7[40] can only show individual data for a limited number of workers. However, a contour plot was used to summarize the individual dosimetric data for all 21,776 TEPCO and contractors’ workers for whom individual doses were reported up until April 2012 (figures D-Ia,b). These contour plots show the number of workers reported with effective doses from internal and external exposure within specified intervals. For instance, it can be seen that two workers had a committed effective dose in the interval 80–90 mSv from internal exposure and an effective dose in the interval 0-10 mSv from external exposure. Figure D-Ia shows the effective doses from internal and external exposure for each of the thirteen individual workers who had doses from internal exposure greater than 100 mSv, and also shows that most workers had significantly lower doses. There was little correlation between individual recorded values of dose from internal and external exposure. For the great majority of workers, the major contribution to their recorded dose was from external exposure, with a smaller contribution from internal exposure, as demonstrated by the elevated numbers of

[39] http://www.tepco.co.jp/

[40] Tables D1, D2, D3, D4, D5, D6 and D7 were updated by the Committee with the results from the reassessment performed by the Japanese organizations in July 2013.

workers close to the y- (external exposure) axis (figure D-Ib). The arithmetic mean of the reported doses from external exposure was 10 mSv, while the arithmetic mean of the reported doses from internal exposure was 1.7 mSv. Comparison with versions of figures D-Ia and D-Ib generated before the reassessment of doses by the Japanese authorities showed that there were some changes in the distribution of individual doses from internal and external exposure, but that these changes were relatively minor.

D12. A comparison between the distributions of the cumulative effective doses for TEPCO and for contractors' workers (see figure D-II) shows that they shared common features: they were asymmetric with a rightward skewness. Although log-normal distributions are often observed within exposed populations, it appears that the dose distributions here were generally not described well by such a distribution. The reasons for this were unclear (there may have been different distributions for various subgroups or for different phases of the accident, but this was not analysed). The distributions did show some differences, with a wider range of values for TEPCO workers than for contractors' workers. The difference of the means, 25 mSv (standard deviation: 38 mSv) for TEPCO and 10 mSv (standard deviation: 13 mSv) for contractors, respectively, was statistically significant between the two groups (*t*-test and Fisher test both gave *p*-values less than 0.001). Regarding the dose from internal exposure, 82% of contractors and 68% of TEPCO workers had zero dose recorded from internal exposures. The difference between these two groups is statistically significant (chi-squared test, *p* less than 0.001).

Table D1. Numbers of occupationally exposed FDNPS workers with effective doses from external exposure in each dose band, by month (March to October 2011) [T8, T11, T16]

The precision used by TEPCO is also used here to reproduce literally the reported values. If the values for "average dose" were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Monthly effective dose (mSv)		*<10*	*10 – <20*	*20 – <50*	*50 – <100*	*100 – <150*	*150 – <200*	*200 – <250*	*>250*	*Total*	*Maximum*	*Average*
March	TEPCO	673	598	292	105	20	6	0	0	1 694	182.33	19.41
	Contractor	1 697	331	182	58	8	3	0	0	2 279	199.42	9.07
	Total	2 370	929	474	163	28	9	0	0	3 973	199.42	13.48
April	TEPCO	559	35	8	0	0	0	0	0	602	46.29	3.95
	Contractor	2 734	186	42	0	0	0	0	0	2 962	47.75	3.11
	Total	3 293	221	50	0	0	0	0	0	3 564	47.75	3.25
May	TEPCO	289	8	2	0	0	0	0	0	299	25.05	2.51
	Contractor	2 680	119	21	0	0	0	0	0	2 820	41.59	2.67
	Total	2 969	127	23	0	0	0	0	0	3 119	41.59	2.65
June	TEPCO	179	4	0	0	0	0	0	0	183	12.44	1.13
	Contractor	1 811	104	17	0	0	0	0	0	1 932	43.00	2.55
	Total	1 990	108	17	0	0	0	0	0	2 115	43.00	2.42
July	TEPCO	189	0	0	0	0	0	0	0	189	4.69	0.78
	Contractor	1 804	65	8	0	0	0	0	0	1 877	34.42	2.27
	Total	1 993	65	8	0	0	0	0	0	2 066	34.42	2.13
August	TEPCO	93	0	0	0	0	0	0	0	93	2.63	0.42
	Contractor	1 005	30	1	0	0	0	0	0	1 036	20.40	1.87
	Total	1 098	30	1	0	0	0	0	0	1 129	20.40	1.75
September	TEPCO	52	0	0	0	0	0	0	0	52	1.99	0.47
	Contractor	897	25	8	0	0	0	0	0	930	31.21	2.07
	Total	949	25	8	0	0	0	0	0	982	31.21	1.99
October	TEPCO	49	1	0	0	0	0	0	0	50	10.21	0.64
	Contractor	772	5	2	0	0	0	0	0	779	23.10	1.25
	Total	821	6	2	0	0	0	0	0	829	23.10	1.22

Table D2. Numbers of occupationally exposed FDNPS workers with committed effective doses from internal exposure in each dose band, by month (March to October 2011) [T8, T11, T16]

The precision used by TEPCO is also used here to reproduce literally the reported values. If the values for "average dose" were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Monthly committed effective dose (mSv)		*<10*	*10 – <20*	*20 – <50*	*50 – <100*	*100 – <150*	*150 – <200*	*200 – <250*	*>250*	*Total*	*Maximum*	*Average*
March	TEPCO	1 038	398	186	37	6	1	1	5	1 672	590.00	11.97
	Contractor	1 837	249	99	21	0	0	0	0	2 206	98.53	5.12
	Total	2 875	647	285	58	6	1	1	5	3 878	590.00	8.07
April	TEPCO	579	1	0	0	0	0	0	0	580	18.81	0.11
	Contractor	2 618	9	1	0	0	0	0	0	2 628	38.40	0.31
	Total	3 197	10	1	0	0	0	0	0	3 208	38.40	0.27
May	TEPCO	278	0	0	0	0	0	0	0	278	7.89	0.04
	Contractor	1 978	5	2	0	0	0	0	0	1 985	32.80	0.15
	Total	2 256	5	2	0	0	0	0	0	2 263	32.80	0.13
June	TEPCO	154	0	0	0	0	0	0	0	154	6.94	0.06
	Contractor	1 383	0	0	0	0	0	0	0	1 383	7.10	0.01
	Total	1 537	0	0	0	0	0	0	0	1 537	7.10	0.02
July	TEPCO	165	0	0	0	0	0	0	0	165	0.00	0.00
	Contractor	1 399	0	0	0	0	0	0	0	1 399	0.50	0.00
	Total	1 564	0	0	0	0	0	0	0	1 564	0.50	0.00
August	TEPCO	85	0	0	0	0	0	0	0	85	0.00	0.00
	Contractor	802	0	0	0	0	0	0	0	802	2.61	0.00
	Total	887	0	0	0	0	0	0	0	887	2.61	0.00
September	TEPCO	44	0	0	0	0	0	0	0	44	0.00	0.00
	Contractor	689	0	0	0	0	0	0	0	689	1.13	0.00
	Total	733	0	0	0	0	0	0	0	733	1.13	0.00
October	TEPCO	44	0	0	0	0	0	0	0	44	0.00	0.00
	Contractor	615	0	0	0	0	0	0	0	615	1.82	0.00
	Total	659	0	0	0	0	0	0	0	659	1.82	0.00

Table D3. Numbers of occupationally exposed FDNPS workers with effective doses (from both internal and external exposure) in each dose band, by month (March to October 2011) [T8, T11, T16]

The precision used by TEPCO is also used here to reproduce literally the reported values. If the values for "average dose" were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Monthly effective dose (mSv)		*<10*	*10 – <20*	*20 – <50*	*50 – <100*	*100 – <150*	*150 – <200*	*200 – <250*	*>250*	*Total*	*Maximum*	*Average*
March	TEPCO	346	530	539	195	63	15	0	6	1 694	670.36	31.23
	Contractor	1 337	461	361	99	17	2	2	0	2 279	238.42	14.03
	Total	1 683	991	900	294	80	17	2	6	3 973	670.36	21.36
April	TEPCO	555	38	9	0	0	0	0	0	602	49.11	4.05
	Contractor	2 709	203	50	0	0	0	0	0	2 962	49.61	3.38
	Total	3 264	241	59	0	0	0	0	0	3 564	49.61	3.49
May	TEPCO	289	8	2	0	0	0	0	0	299	25.05	2.54
	Contractor	2 659	137	24	0	0	0	0	0	2 820	41.61	2.77
	Total	2 948	145	26	0	0	0	0	0	3 119	41.61	2.75
June	TEPCO	179	4	0	0	0	0	0	0	183	12.44	1.18
	Contractor	1 811	103	18	0	0	0	0	0	1 932	43.00	2.55
	Total	1 990	107	18	0	0	0	0	0	2 115	43.00	2.44
July	TEPCO	189	0	0	0	0	0	0	0	189	4.69	0.78
	Contractor	1 804	65	8	0	0	0	0	0	1 877	34.44	2.27
	Total	1 993	65	8	0	0	0	0	0	2 066	34.44	2.13
August	TEPCO	93	0	0	0	0	0	0	0	93	2.63	0.42
	Contractor	1 004	31	1	0	0	0	0	0	1 036	20.40	1.87
	Total	1 097	31	1	0	0	0	0	0	1 129	20.40	1.75
September	TEPCO	52	0	0	0	0	0	0	0	52	1.99	0.47
	Contractor	897	25	8	0	0	0	0	0	930	31.21	2.07
	Total	949	25	8	0	0	0	0	0	982	31.21	1.99
October	TEPCO	49	1	0	0	0	0	0	0	50	10.21	0.64
	Contractor	772	5	2	0	0	0	0	0	779	23.10	1.26
	Total	821	6	2	0	0	0	0	0	829	23.10	1.22

Table D4. Numbers of occupationally exposed FDNPS workers with cumulative effective doses for the period from March 2011 to 31 October 2012 in each dose band

Cumulative dose (mSv)	*TEPCO*	*Contractor*	*Total*
Over 250	6	0	6
200–<250	1	2	3
150–<200	24	2	26
100–<150	118	20	138
50–<100	508	529	1 037
20–<50	610	3 216	3 826
10–<20	498	3 136	3 634
10 or less	1 883	14 279	16 162
Total	3 648	21 184	24 832
Maximum	678.80	238.42	678.80
Average	24.56	10.31	12.41

Table D5. External and internal exposures for the 20 workers with the highest cumulative effective doses for the period March 2011 to April 2012

The precision expressed in the data provided is used here to reproduce literally the reported values, and also to allow cross-referencing of individual entries among the tables. If these values were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Employer	*Cumulative effective dose (mSv)*		
	External exposure	*Internal exposure*	*Total*
TEPCO	88.80	590.00	678.80
TEPCO	105.54	540.00	645.54
TEPCO	43.96	433.05	477.01
TEPCO	32.95	327.90	360.85
TEPCO	110.27	241.81	352.08
TEPCO	51.31	259.66	310.97
TEPCO	73.18	166.06	239.24
Contractors	199.42	39.00	238.42
Contractors	191.90	35.00	226.90
TEPCO	184.92	13.13	198.05
TEPCO	188.14	9.19	197.33
TEPCO	106.75	90.21	196.96
TEPCO	67.06	119.96	187.02
TEPCO	48.81	137.27	186.08
TEPCO	153.33	29.87	183.20

Employer	*Cumulative effective dose (mSv)*		
	External exposure	*Internal exposure*	*Total*
TEPCO	165.51	17.41	182.92
TEPCO	122.39	60.01	182.40
TEPCO	83.42	97.01	180.44
TEPCO	162.01	14.07	176.08
Contractors	93.00	83.00	176.00

Table D6. External and internal exposures for the 20 workers with the highest cumulative committed effective doses from internal exposure for the period March 2011 to April 2012

The precision expressed in the data provided is used here to reproduce literally the reported values, and also to allow cross-referencing of individual entries among the tables. If these values were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Employer	*Cumulative effective dose (mSv)*		
	External exposure	*Internal exposure*	*Total*
TEPCO	88.80	590.00	678.80
TEPCO	105.54	540.00	645.54
TEPCO	43.96	433.05	477.01
TEPCO	32.95	327.90	360.85
TEPCO	51.31	259.66	310.97
TEPCO	110.27	241.81	352.08
TEPCO	73.18	166.06	239.24
TEPCO	48.81	137.27	186.08
TEPCO	67.06	119.96	187.02
TEPCO	34.24	119.59	153.83
TEPCO	23.64	117.33	140.97
TEPCO	38.87	109.91	148.78
TEPCO	42.03	101.27	143.30
Contractors	8.28	98.53	106.81
TEPCO	83.43	97.01	180.44
Contractors	11.35	96.84	108.19
TEPCO	52.88	95.85	148.73
TEPCO	46.10	92.96	139.06
Contractors	11.35	90.88	102.23
TEPCO	106.75	90.21	196.96

Table D7. External and internal exposures for the 20 workers with the highest cumulative effective doses from external exposure for the period March 2011 to April 2012

The precision expressed in the data provided is used here to reproduce literally the reported values, and also to allow cross-referencing of individual entries among the tables. If these values were to be reported elsewhere, it would be appropriate to round them to 2 significant figures in order not to imply spurious accuracy

Employer	*Cumulative effective dose (mSv)*		
	External exposure	*Internal exposure*	*Total*
Contractors	199.42	39.00	238.42
Contractors	191.90	35.00	226.90
TEPCO	188.14	9.19	197.33
TEPCO	184.92	13.13	198.05
Contractors	175.62	0.00	175.62
TEPCO	165.51	17.41	182.92
TEPCO	162.01	14.07	176.08
TEPCO	159.88	8.79	168.67
TEPCO	153.33	29.87	183.20
TEPCO	152.85	9.67	162.52
TEPCO	144.13	25.40	169.53
TEPCO	140.97	15.50	156.47
TEPCO	132.20	3.13	135.33
TEPCO	130.72	20.37	151.09
TEPCO	129.68	8.49	138.17
TEPCO	129.60	23.21	152.81
TEPCO	129.36	15.67	145.03
TEPCO	128.07	24.68	152.75
TEPCO	127.92	3.85	131.77
TEPCO	126.25	41.74	167.99

Figure D-Ia. Contour plot showing the numbers of workers with a specified combination of dose from internal exposure and dose from external exposure

Cumulative doses for the period March 2011–April 2012. The width of the interval for effective doses from both internal and external exposure is 10 mSv. The figures can be thought of as 3-dimensional plots, where the x- and y-coordinates represent effective dose from internal and external exposure, respectively, while the number of workers with doses within a particular internal or external exposure interval is plotted on the z-coordinate, and represented by the colour

(Diagram courtesy of A.L. Shutt, Centre for Radiation, Chemical and Environmental Hazards, Public Health England)

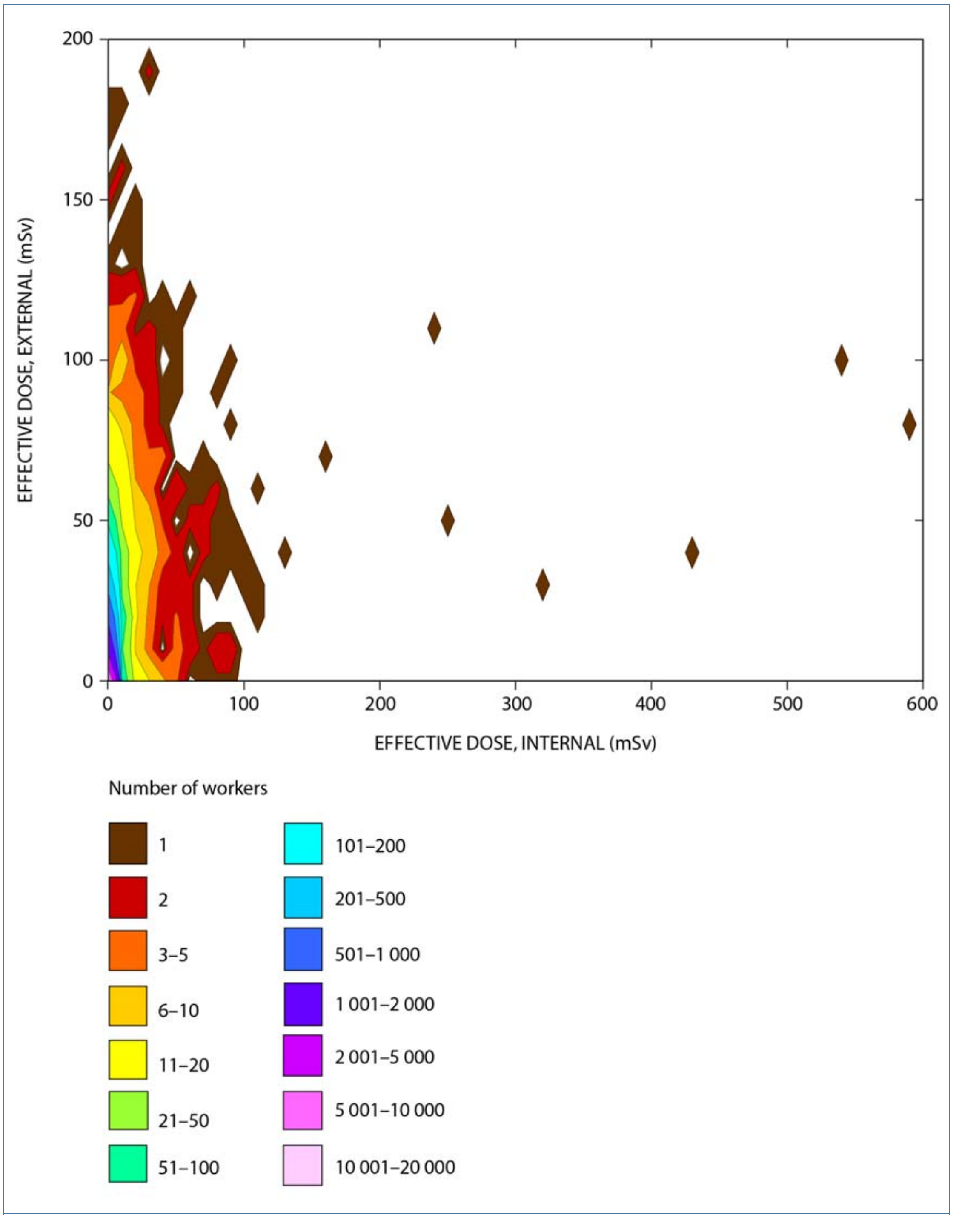
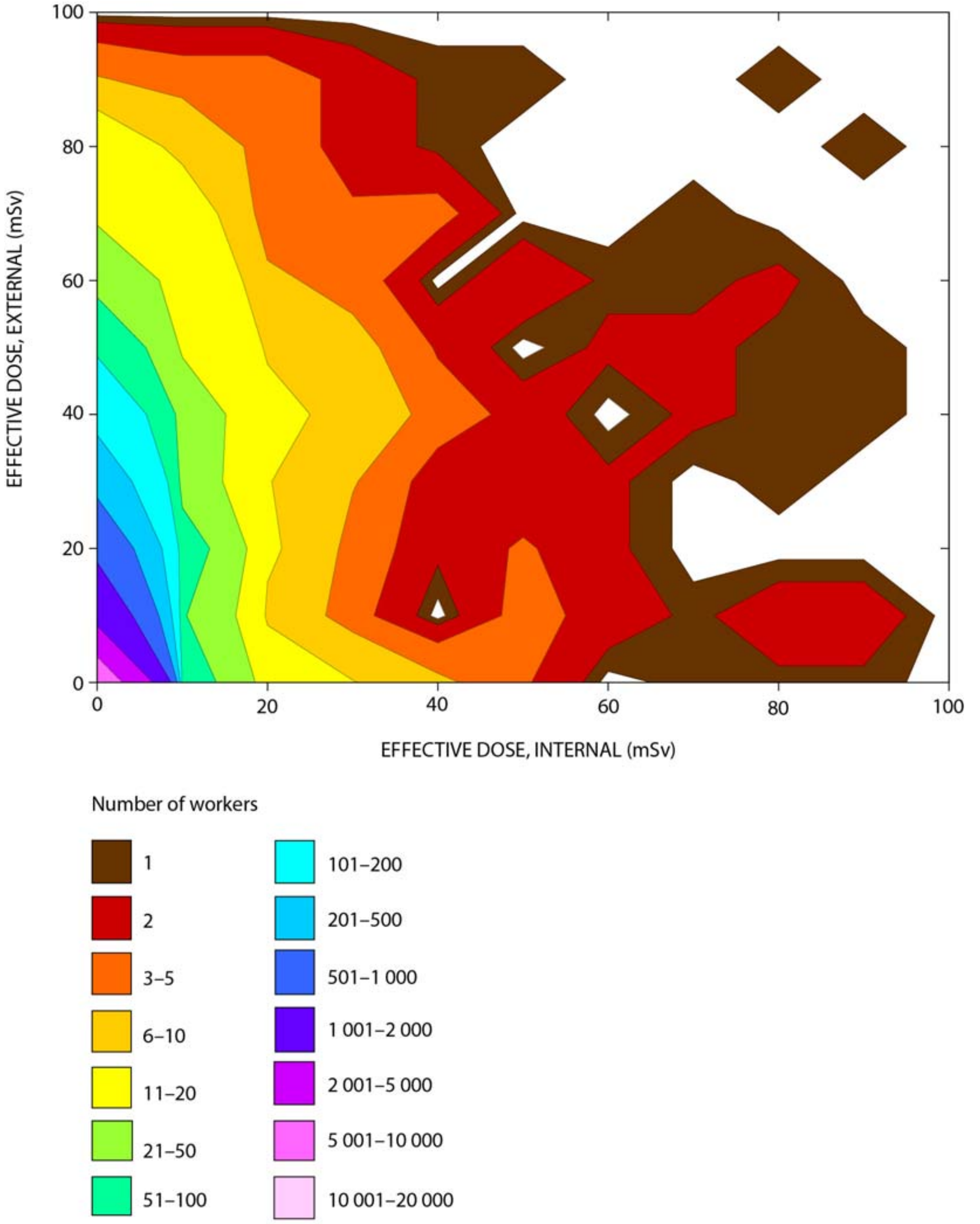


Figure D-Ib. Contour plot, expanded to show the numbers of workers in the 0–100 mSv dose range

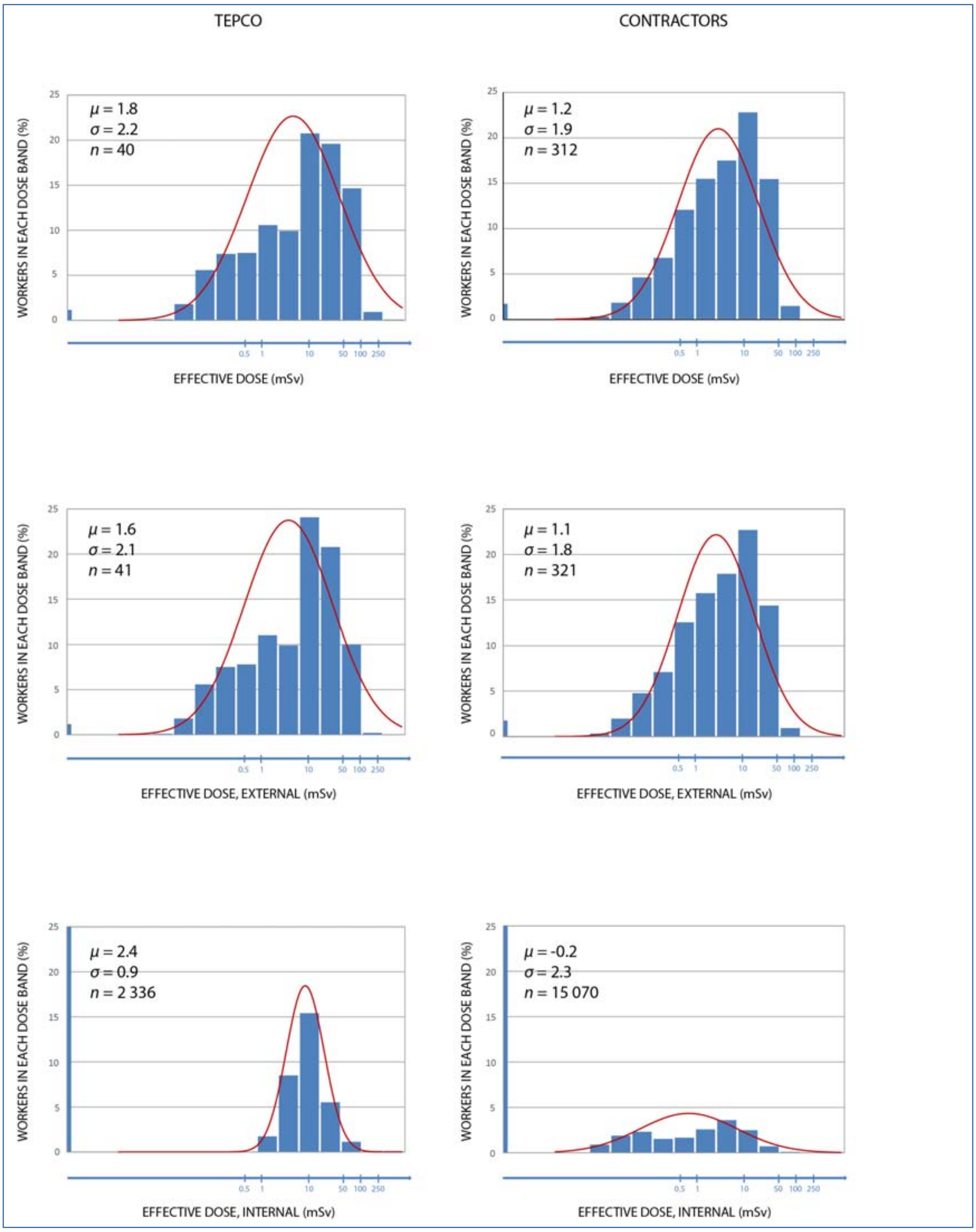
Cumulative doses for the period March 2011–April 2012. The width of the interval for effective doses from both internal and external exposure is 10 mSv. The figures can be thought of as 3-dimensional plots, where the x- and y-coordinates represent effective dose from internal and external exposure, respectively, while the number of workers with doses within a particular internal or external exposure interval is plotted on the z-coordinate, and represented by the colour

(Diagram courtesy of A.L. Shutt, Centre for Radiation, Chemical and Environmental Hazards, Public Health England)



Figures D-II. Distributions of effective doses from external and internal exposure combined, and from external and internal exposure separately, to FDNPS occupationally exposed workers in each cumulative dose band from March 2011 to April 2012

The red curve is the probability density of a log-normal distribution with the designated values of average (μ) and standard deviation (σ), fitted among the workers with measurable exposure for the period. The value n is the number of workers who were not measurably exposed during the period and who are represented by the small bar close to the origin



III. MONITORING AND DOSIMETRY

A. Monitoring of internally incorporated radionuclides

D13. TEPCO, the Japan Atomic Energy Agency (JAEA) and the National Institute of Radiological Sciences (NIRS) in Japan provided the Committee with detailed information on instruments, measurement systems, calibration phantoms and methodologies used for in vivo monitoring, together with monitoring data for selected workers. The following is a summary of the information received on monitoring systems and methods.

D14. At the request of TEPCO, JAEA started individual in vivo monitoring of workers who were responding to the emergency on 22 March 2011. The location chosen for conducting the monitoring was the town of Onahama, about 55 km south of the FDNPS site. Measurements were made with a simple mobile whole-body counter (WBC), the Canberra FASTSCAN™ system, which employs two thallium-activated sodium iodide (NaI(Tl)) detectors in a “shadow-shield” arrangement made of 10 cm thick steel. However, accurate quantification of radionuclide activities was difficult because of:

- The complexity of the gamma-ray spectrum. (NaI(Tl) detectors have relatively low energy resolution compared with semiconductor detectors and so cannot resolve complex spectra);
- Contamination on the ground and thus elevated background radiation levels affected the measurements at Onahama;
- The differences in the distribution of caesium and iodine radionuclides in the body (measurements were made of whole body activity but no measurements were made specifically of thyroid activity);
- The large number of workers to be measured, which exceeded the available capacity.

D15. Later, JAEA provided additional monitoring capabilities at the Nuclear Fuel Cycle Engineering Laboratories (JAEA-NFCEL). In addition to a FASTSCAN™ WBC, the JAEA facilities included: *(a)* a chair-type WBC that employed two semiconductor (high purity germanium (HPGe)) detectors in a shielded chamber made of 20 cm thick steel, with which both whole body and thyroid measurements could be made; and *(b)* an NaI(Tl) spectrometer used mainly for thyroid measurements. These facilities were used for workers whose committed effective dose from internal exposure as assessed from the results of monitoring at Onahama exceeded 20 mSv, and also for all female employees. Monitoring at JAEA was carried out for a total of 560 workers during the period 20 April 2011 to 5 August 2011. JAEA provided the monitoring results to TEPCO, but did not provide dose assessments. Further information is given in a report of the NIRS [N11].

D16. Where the assessed dose from internal exposure was in excess of 100 mSv, the worker was additionally monitored by NIRS. Measurements were performed using six HPGe detectors installed in a shielded chamber made of iron (200 mm), lead (3 mm), copper (0.1 mm) and acrylic (2 mm) [S13]. NIRS staff performed a dose assessment for each worker monitored, although TEPCO reassessed the dose for some of these workers.

D17. TEPCO made the final dose assessments reported for its workers using the results of the JAEA and NIRS measurements, where available. The Committee understood that those contractors with the ability to make the dose assessments reported these to TEPCO for their own workers, using results from the JAEA measurements, from a number of other monitoring locations, and information from a detailed interview. Contractors without the ability to make dose assessments used the doses assessed by TEPCO based on the results of the JAEA measurement, without considering other data or information.

D18. For most workers, the only radionuclides detected were ^{131}I, ^{137}Cs and ^{134}Cs, and reported doses due to internal exposure only took account of intakes of these radionuclides. For some of the workers with higher doses, ^{136}Cs and ^{129m}Te were also detected, but the contribution to the assessed dose from internal exposure due to intakes of these radionuclides was small. The delay in starting reliable in vivo monitoring meant that the shorter-lived radioisotopes which were likely to be present, including ^{132}Te, ^{132}I, ^{133}I and ^{136}Cs, would not have been detectable.

D19. In vitro monitoring was performed by NIRS on urine samples for seven among twelve of the thirteen workers with the highest internal exposure, although the results were not used for formal dose reporting. Each worker provided a single “spot” sample, mostly during June 2011, followed by two 24-hour samples during June or July 2011. Results were obtained for ^{131}I, ^{134}Cs and ^{137}Cs. No bioassay measurements were performed for tritium, ^{89}Sr, ^{90}Sr or transuranic radionuclides.

D20. The Committee was provided with information on personal status, employment status, details of individual monitoring performed and exposure conditions for each worker selected for independent assessment of dose from internal exposure, as follows:

- Age, sex and employment status (TEPCO employee, contractor employee, or emergency services worker);
- Work period(s) during which intakes could have taken place;
- Work activities during these periods;
- Date and time of any urine samples taken;
- Date, time and place of measurement;
- Type of measurement (whole body, thyroid or urine);
- The radionuclides for which measurements were performed;
- The activities measured for the radionuclides detected (in general, the radionuclides detected were ^{131}I, ^{134}Cs and ^{137}Cs; other radionuclides were detected in a small number of cases);
- Date(s) of intake assumed in the reported Japanese assessment;
- Results of the dose assessments that were performed, in particular the assessed effective dose;
- Details of any corrections made for short-lived radionuclides that may not have been measurable at the time of measurement;
- Brief descriptions of the dose assessment methodology used, including assumptions made about the physico-chemical form (including activity median aerodynamic diameter and lung clearance type).

B. Evaluation of information provided on monitoring of internally incorporated radionuclides

D21. The Committee evaluated information provided on the instruments, measurement systems, calibration phantoms and methodologies used for in vivo monitoring, with the following findings:

(a) Information provided on the in vivo measurement systems used at Onahama, JAEA and NIRS was deemed adequate for the Committee's purposes, and the measurement systems were judged to have been adequate for the purpose of assessing in vivo radionuclide levels, intakes and committed effective doses from internal exposure for workers during a radiation emergency;

(b) Sufficient information was provided on the calibration phantoms used for in vivo measurements at JAEA; the calibration phantoms were judged to be appropriate for the types of in vivo measurements needed and performed;

(c) Comprehensive calibration data and quality control data were provided relating to the in vivo measurements made by JAEA at its own laboratories, and by JAEA and TEPCO at Onahama; it was judged that adequate calibration methods and quality control procedures for in vivo measurements were in place.

D22. An important factor to be considered in both the Japanese and the Committee's independent dose assessments was the delay in performing reliable in vivo measurements of radioiodine in the thyroid. For most of the twelve workers with the highest committed effective doses from internal exposure (i.e. more than 100 mSv) for whom the Committee performed an independent assessment (out of thirteen workers), monitoring of ^{131}I in the thyroid did not start until mid- or late-May, although, for three workers, it started in mid-April. For most of the randomly-selected workers with lower committed effective doses from internal exposure, initial monitoring was not performed until mid-May to late June 2011, although a few workers were monitored during April 2011. For many of the selected workers, the first possible date of intake was in the period 12–22 March. Given that the radioactive half-life of ^{131}I is 8 days, this delay in starting thyroid monitoring was significant. As a result of the delay, ^{131}I was not measurable in the thyroid of many workers, and Japanese assessors had to make an estimate using one of two methods: *(a)* the "environmental ratio" method used environmental measurements to determine a time-dependent ^{131}I:^{137}Cs ratio, which was then used to estimate ^{131}I intake on a certain date from an intake of ^{137}Cs on that date determined from whole-body measurement data; and *(b)* the MDA (Minimum Detectable Activity) method assumed that the activity of ^{131}I present in the thyroid at the time of the measurement was equal to the detection limit of the ^{131}I measurement made. Japanese assessors chose the lower of the two intake estimates to derive subsequently a committed dose from internal exposure (see section IV.D below).

D23. Assessments of internal exposure for TEPCO workers were performed either by TEPCO or (in a few cases of high exposure) by NIRS, using the software packages MONDAL [N12] and IMBA [B12], respectively. Both were quality-assured software packages, and were judged by the Committee to be appropriate for the types of dose assessments needed and performed.

D24. The results of the Committee's independent assessments of doses from internal exposure are discussed in section IV of this appendix.

C. Monitoring of external exposure

D25. TEPCO provided detailed information to the Committee on the types of personal dosimeter used, the technical standards and calibration methods used, and the system used for allocating personal dosimeters to individuals during March 2011, for both TEPCO and contractors' employees. The Committee requested similar information for emergency services workers, but the information provided by the municipal authorities was rather sparse. The following is a summary of the information received from TEPCO.

D26. Two types of automated electronic personal dosimeter were used; the response characteristics are summarized in tables D8 and D9.

Table D8. Personal dosimeter response: gamma(X) ray

	Characteristics	*Gamma(X) ray*
1.	Energy range	50 keV to 6 MeV
2.	Detector	Silicon semiconductor
3.	Dose equivalent range	0.001 mSv to 999.999 mSv
4.	Indication range	0.01 mSv to 99.99 mSv (by 0.01 mSv) 100.0 mSv to 999.9 mSv (by 0.1 mSv) automatic changeover
5.	Accuracy of indication	±10% (0.1 mSv to 999.9 mSv, ^{137}Cs)
6.	Energy response	EP2 type ±20% (60 keV to 6 MeV, ^{137}Cs) ±30% (50 keV to 6 MeV, ^{137}Cs)
7.	Angular response	AP1 type ±20% (up to ±60 degree, vertical and horizontal, ^{137}Cs) ±50% (up to ±60 degree, vertical and horizontal, ^{241}Am)
8.	Linearity for wide range of dose rate	R1 type ±20% (0.1 mSv/h to 1 Sv/h: 1 mSv/h basis)

Table D9. Personal dosimeter response: beta particle

	Characteristics	*Beta particle*
1.	Energy range	300 keV to 2.3 MeV
2.	Detector	Silicon semiconductor
3.	Dose equivalent range	0.001 mSv to 999.999 mSv
4.	Indication range	0.01 mSv to 99.99 mSv (by 0.01 mSv) 100.0 mSv to 999.9 mSv (by 0.1 mSv) automatic changeover
5.	Accuracy of indication	±10% (0.1 mSv to 999.9 mSv, ^{90}Sr–^{90}Y)
6.	Energy response	EB1 type ±30% (500 keV to 2.3 MeV, ^{90}Sr–^{90}Y)
7.	Angular response	AB2 type ±50% (up to ±60 degree, vertical and horizontal, ^{90}Sr–^{90}Y)
8.	Linearity for wide range of dose rate	R1 type ±20% (0.1 mSv/h to 1 Sv/h: 1 mSv/h basis)

D27. Dosimeters were calibrated according to Japanese Industrial Standards JIS-Z-4312 [J4], for which the reference international standards were IEC 61525 [I27] and IEC 61526 [I28]; and JIS-Z-4511 [J5], for which the reference international standards were ISO 4037-1 [I34] and ISO 4037-3 [I35].

D28. When the power station was flooded, the Automatic Personal Dosimeter System became inoperable and about 5,000 personal dosimeters were rendered unusable, so that between 12 March 2011 and 1 April 2011, only 320 personal dosimeters were available for use. After 1 April, personal dosimeters were again provided to every worker. During the period when there were not enough personal dosimeters, those that were available were allocated to representatives of each working group [T11]. TEPCO stated that, for both its workers and contractors' workers, representative measurements were conducted when the following conditions were fulfilled:

- The effective dose for a job was not greater than 10 mSv;
- The workplace environmental dose rate was known;
- The gradient of ambient dose equivalent rates at the respective site was not large;
- All members of an operational group were always together at a work site.

D. Evaluation of information provided on monitoring external exposure

D29. The Committee's evaluation of the information provided found that the instrumentation, technical standards and calibration methods used appeared to meet generally accepted requirements for monitoring. The major factor potentially affecting the reliability of the monitoring performed was the use of shared personal dosimeters between 12 March and 1 April 2011. According to TEPCO [I6], the management system for individual dosimetry became inoperable immediately following the tsunami and associated damage, and it was not possible to gather access control information for "Radiation Controlled Areas" or personal dose data. Owing to the loss of personnel monitoring capabilities, emergency responders had to share dosimeters (with only one worker in a team wearing a dosimeter for many missions), and workers had to log their individual doses manually [I6]. Given the short supply of dosimeters during March 2011, and the absence of information on the extent to which the conditions described in paragraph D28 above were met for individual workers, some reservations remained about the reliability of the external dosimetry performed before 1 April 2011.

D30. An issue not considered by the Committee, but which should be mentioned, related to concerns raised in news reports published in July 2012 about the reliability of doses from external exposure (e.g. [A1]). These reports stated that some subcontractor workers had been told to cover their dosimeters with lead casings in order to falsify readings (i.e. to underplay exposures). According to a later press release from TEPCO [T14], the doses for five workers from external exposure were reassessed, and subsequently TEPCO took actions aimed at avoiding such problems in the future.

IV. DETAILED RESULTS OF THE COMMITTEE'S DOSE ASSESSMENT

A. Selection of workers for independent assessments of dose

D31. As explained in section I of this appendix, independent assessments of internal exposure were performed for twelve of the thirteen workers (all TEPCO employees) with the highest reported internal exposure (i.e. with committed effective doses, $E(50)$, greater than 100 mSv), and for a sample of workers with lower internal exposure who were randomly selected from various predefined groups. This random selection was intended to provide a reasonably representative sample from the 21,776 TEPCO and contractors' workers for whom individual doses were reported up to April 2012. In total, 42 workers were randomly selected, of whom 21 were TEPCO workers and 21 were contractors' workers. In addition, 13 emergency services workers (understood to be all from the police force) were selected. For the TEPCO and contractors' workers, equal numbers were randomly selected from each of the 0–5 mSv, 5-20 mSv and 20–100 mSv bands of committed dose from internal exposure as reported in Japan. It should be noted that no selection criterion was set for external exposure, and no information was provided on the doses from external exposure reported for the selected workers.

D32. A similar comparative approach could not be used to assess the reliability of reported dosimetric results for external exposure because they were obtained from personal dosimeter readings that could not be independently verified on an individual basis. Therefore, the assessment of the reliability of external exposure data was limited to reviewing and evaluating the information provided by TEPCO on personal dosimeters, technical standards, calibration methods and the system used for allocating personal dosimeters to individuals during March 2011 (see section III above of this appendix).

B. Methodology for assessing internal exposure

D33. The Committee identified seven assessors to make independent assessments, with each assessor using his/her own established procedures and expert judgement on issues such as choice of monitoring data and parameter values for biokinetic models. No single methodology is described here in detail; rather this section describes the general approach adopted.

D34. Retrospective assessments of internal exposure from the results of such monitoring data generally followed the steps below:

(a) The intake of a specified radionuclide was estimated from monitoring data using retention or excretion functions calculated on the basis of biokinetic models specified by the International Commission on Radiological Protection (ICRP) [I10, I11, I14, I15, I16, I17];

(b) Time-dependent retention of the radionuclide in source organs was then determined using organ retention functions calculated using the same biokinetic models;

(c) The projected number of radioactive disintegrations over a 50-year time period in each source organ was then determined;

(d) Values of "absorbed fractions" provided by an ICRP Task Group were then used to determine committed absorbed doses to target organs;

(e) Committed equivalent doses to organs were then determined using radiation weighting factors (w_R) specified by ICRP [I12];

(f) Committed effective dose were then determined using tissue weighting factors (w_T) specified by ICRP [I12].

D35. In practice, dosimetry services use various methods ranging in complexity from computer programs that implement the biokinetic models and calculate doses from internal exposure from first principles, to simple spreadsheets that make use of tabulated bioassay data and dose conversion coefficients provided by ICRP. Methods and software used by dosimetry services have generally been subject to formal quality assurance and/or accreditation procedures.

D36. For quality assurance purposes, every assessor who performed an assessment for workers with the highest internal exposures performed an assessment for worker A. Comparisons of these five independent assessments indicated good agreement. For each of the other 11 workers, at least two assessments were made, again with good agreement, with the possible exception of the results for worker K.

C. Results for workers with the highest internal exposure

D37. The Committee's independent dose assessments were made using the types of monitoring data and of information on exposure conditions described in section III of this appendix. For twelve of the thirteen workers with the highest internal exposures, the results of the Committee's independent dose assessments, the results of assessments by NIRS and TEPCO, and the results formally reported, are compared in tables D10, D11 and D12. These assessments were all based on in vivo measurements of radionuclide activities in the whole body and ^{131}I activity in the thyroid. The three tables show the committed effective dose from intakes of all the radionuclides for which monitoring results were reported, the contribution that intakes of ^{131}I made to that committed effective dose, and the absorbed dose to the thyroid from intakes of ^{131}I.

D38. The delay in starting in vivo monitoring with high energy resolution detectors meant that shorter-lived radionuclides other than ^{131}I (half-life = 8 d), specifically ^{132}Te, ^{132}I, ^{133}I and ^{136}Cs, would have been undetectable in the body at the time of measurement. Because of the short half-lives of these radionuclides, additional contributions to dose would have arisen mainly from intakes occurring during the days immediately following the shutdown of the reactors. The Committee assessed the implications in attachment D-1. A rigorous assessment was not possible because of incomplete knowledge of the work histories of individual workers during this period, incomplete knowledge of the time-varying levels of radionuclides in places where they worked and rested, and because of the lack of information on specific protective measures taken by individual workers. Nevertheless, the Committee made a number of plausible but simplifying assumptions about the time period(s) when intakes could have taken place, and the radionuclide composition of airborne activity to which the workers might have been exposed during these periods.

D39. The radionuclide composition of an intake would have been time-dependent, and was assumed to be similar to the time-dependent radionuclide composition of the releases on the FDNPS site, which varied considerably from day to day. The time period(s) of intake for an individual worker would have depended on three main factors: *(a)* the periods when the worker was exposed to radionuclides on the site (predominantly in the form of airborne activity); *(b)* the times and administered amounts of any stable iodine provided to individual workers for the purposes of "thyroid blocking"; and *(c)* the periods when items of personal protective equipment such as respirators or face masks were being used effectively by each worker.

Table D10. Assessed committed effective doses, *E*(50) (in millisieverts), for workers with the highest internal exposures from all measured radionuclides

	Working period		*Independent assessor*					*NIRS*	*TEPCO*	*Japanese final reported value*
			1	*2*	*3*	*4*	*5*			
Worker	*Start*	*End*	*IMBA*	*AIDE*	*MONDAL IMBA CALIN*	*IMBA*	*IMBA*	*IMBA*	*MONDAL*	*IMBA (A-B) MONDAL (C-L)*
A	2011-03-11	2011-04-16	616	580	596	643	495	590	ND	590
B	2011-03-11	2011-04-17	517	496	ND	ND	ND	540	ND	540
C	2011-03-11	2011-05-20	384	ND	ND	ND	383	380	433	433
D	2011-03-11	2011-05-17	322	ND	330	ND	ND	290	328	328
E	2011-03-11	2011-06-01	304	ND	ND	387	ND	270	260	260
F	2011-03-11	2011-04-10	ND	222	216	ND	ND	230	242	242
G	2011-03-11	2011-05-19	172	ND	ND	186	ND	160	166	166
H	2011-03-11	2011-05-22	ND	95	149	ND	ND	ND	137	137
I	2011-03-11	2011-05-27	ND	130	155	ND	ND	ND	120	120
J	2011-03-11	2011-06-01	125	ND	ND	117	ND	ND	120	120
K	2011-03-18	2011-05-12	ND	87	ND	ND	173	ND	117	117
L	2011-03-18	2011-05-10	ND	ND	ND	124	134	ND	101	101

ND: Not determined.

Owing to surface contamination and background radiation levels, TEPCO did not take into account measurements made at Onahama in their dose assessments.

With the exception of assessor 2, the assessors did take into account the Onahama measurements, but the effect on assessed doses was not large.

For workers C, D, E, F and G, measurements were made at NIRS, but the dose assessment was performed by TEPCO.

NIRS assumed a chronic exposure (11–12 March 2011); TEPCO assumed an acute exposure (12 March 2011); this explains why NIRS estimates were sometimes lower than TEPCO estimates.

IMBA – Integrated Modules for Bioassay Analysis [B12].

AIDE – Activity and Internal Dose Estimates [B8].

CALIN – Calcul d'Incorporation [A11].

MONDAL – Support System for Internal Dosimetry [N12].

D40. Work history information for 10 out of 12 of the workers with the higher reported internal exposures (i.e. committed effective doses greater than 100 mSv) indicated that there was reasonably good evidence that intakes commenced on 12 March 2011. However, the available evidence for this group of workers did not allow a clear conclusion to be drawn about whether intakes effectively ceased at some time during 12 March, or whether they continued for a few days. For all of the workers in this group for whom intakes probably commenced on 12 March, it was likely that significant intakes had ceased by 15 March. Indicatively, the additional contribution to effective dose due to internal exposure from the intakes of these short-lived radionuclides by those workers on site in the first few days of the accident may have been in the order of 20% relative to the contribution from ^{131}I; this contribution is likely to have varied considerably between individuals. However, the uncertainty on the time period of intake means that it was only possible to estimate ranges for the potential additional contributions to effective dose from intakes of short-lived radionuclides, rather than single values. Assuming that intakes took place only on 12 March provided an upper bound on the potential additional contribution to dose, while assuming that intakes could have taken place continuously between 12 and 15 March provided a lower bound. Thus, for this group of workers, the additional contribution to effective dose from internal exposure due to intakes of short-lived radionuclides could have been in the range 16−45% relative to the contribution due to ^{131}I intakes, depending on the time pattern of intake. The equivalent range for the additional contribution to absorbed dose to the thyroid was 6–28%.

Table D11. Assessed committed effective doses, *E*(50) (in millisieverts), for workers with the highest internal exposures (contribution from ^{131}I intake only)

	Working period		*Independent assessor*					*NIRS*	*TEPCO*	*Japanese final reported value*
			1	*2*	*3*	*4*	*5*			
Worker	*Start*	*End*	*IMBA*	*AIDE*	*MONDAL IMBA CALIN*	*IMBA*	*IMBA*	*IMBA*	*MONDAL*	*IMBA (A-B) MONDAL (C-L)*
A	2011-03-11	2011-04-16	610	573	588	635	488	580	ND	580
B	2011-03-11	2011-04-17	515	479	ND	ND	ND	540	ND	540
C	2011-03-11	2011-05-20	383	ND	ND	ND	383	380	433	433
D	2011-03-11	2011-05-17	322	ND	330	ND	ND	290	327	327
E	2011-03-11	2011-06-01	303	ND	ND	386	ND	270	259	259
F	2011-03-11	2011-04-10	ND	221	215	ND	ND	230	240	240
G	2011-03-11	2011-05-19	172	ND	ND	186	ND	160	166	166
H	2011-03-11	2011-05-22	ND	94	148	ND	ND	ND	136	136
I	2011-03-11	2011-05-27	ND	130	155	ND	ND	ND	120	120
J	2011-03-11	2011-06-01	124	ND	ND	117	ND	ND	119	119
K	2011-03-18	2011-05-12	ND	86	ND	ND	172	ND	116	116
L	2011-03-18	2011-05-10	ND	ND	ND	123	133	ND	100	100

ND: Not determined.

Owing to surface contamination and background radiation levels, TEPCO did not take into account measurements made at Onahama in their dose assessments.

With the exception of assessor 2, the assessors did take into account the Onahama measurements, but the effect on assessed doses was not large.

For workers C, D, E, F and G, measurements were made at NIRS, but the dose assessment was performed by TEPCO.

NIRS assumed a chronic exposure (11–12 March 2011); TEPCO assumed an acute exposure (12 March 2011); this explains why NIRS estimates were sometimes lower than TEPCO estimates.

IMBA – Integrated Modules for Bioassay Analysis [B12].

AIDE – Activity and Internal Dose Estimates [B8].

CALIN – Calcul d'Incorporation [A11].

MONDAL – Support System for Internal Dosimetry [N12].

Table D12. Assessed committed absorbed dose to the thyroid (in grays) for workers with the highest internal exposures (from ^{131}I intake only)

	Working period		*Independent assessor*					*NIRS*	*TEPCO*	*Japanese final reported value*
			1	*2*	*3*	*4*	*5*			
Worker	*Start*	*End*	*IMBA*	*AIDE*	*MONDAL IMBA CALIN*	*IMBA*	*IMBA*	*IMBA*	*MONDAL*	*IMBA (A-B) MONDAL (C-L)*
A	2011-03-11	2011-04-16	12.1	11.3	11.8	12.6	9.7	11.6	ND	11.6
B	2011-03-11	2011-04-17	10.3	9.5	ND	ND	ND	10.8	ND	10.8
C	2011-03-11	2011-05-20	7.6	ND	ND	ND	7.6	7.6	8.7	8.7
D	2011-03-11	2011-05-17	6.4	ND	6.8	ND	ND	5.8	6.5	6.5
E	2011-03-11	2011-06-01	6.0	ND	ND	7.7	ND	5.4	5.2	5.2
F	2011-03-11	2011-04-10	ND	4.4	4.3	ND	ND	4.6	4.8	4.8
G	2011-03-11	2011-05-19	3.4	ND	ND	3.7	ND	3.2	3.3	3.3
H	2011-03-11	2011-05-22	ND	1.9	3.0	ND	ND	ND	2.7	2.7
I	2011-03-11	2011-05-27	ND	2.6	3.1	ND	ND	ND	2.4	2.4
J	2011-03-11	2011-06-01	2.5	ND	ND	2.3	ND	ND	2.4	2.4
K	2011-03-18	2011-05-12	ND	1.7	ND	ND	3.4	ND	2.3	2.3
L	2011-03-18	2011-05-10	ND	ND	ND	2.4	2.6		2.0	2.0

ND: Not determined.

Owing to surface contamination and background radiation levels, TEPCO did not take into account measurements made at Onahama in their dose assessments.

With the exception of assessor 2, the assessors did take into account the Onahama measurements, but the effect on assessed doses was not large.

For workers C, D, E, F and G, measurements were made at NIRS, but the dose assessment was performed by TEPCO.

NIRS assumed a chronic exposure (11–12 March 2011); TEPCO assumed an acute exposure (12 March 2011); this explains why NIRS estimates were sometimes lower than TEPCO estimates.

IMBA – Integrated Modules for Bioassay Analysis [B12].

AIDE – Activity and Internal Dose Estimates [B8].

CALIN – Calcul d'Incorporation [A11].

MONDAL – Support System for Internal Dosimetry [N12].

D41. Based on information provided on work periods and dates of administration of stable iodine for the worker with the highest dose (worker A), the assumption that there was a single intake of radioiodine on 12 March was considered to provide the best estimate of absorbed dose to the thyroid of worker A of approximately 12 Gy. An investigation to determine the effect of the assumed period of intake on the assessed absorbed dose to the thyroid found that making alternative but reasonable assumptions about periods of intake for worker A could result in a reduction in the assessed absorbed dose to the thyroid by up to perhaps 30%.

D42. As noted in section III of this appendix, in vitro monitoring (including for beta–gamma emitters) of urine samples was performed for seven of the twelve workers. An investigation of the consistency between intakes assessed from in vitro data and from in vivo data was carried out for six of these workers. For two workers, the intake assessed from the in vitro data was about a factor of 2 less than that assessed from in vivo data, while for two other workers, the in vitro assessments were factors of 2 and 4 greater. For the remaining two workers, the in vitro measurements were all below the detection limit. Probable reasons for the differences include the delay in initiating urine sampling and the use of spot sampling for the first of the three urine samples collected for each worker. Spot samples are known to provide a less reliable measure of daily excretion than samples collected and amalgamated over 24 hours.

D43. The following conclusions were drawn about the internal exposure assessments for twelve of the thirteen workers with the highest internal exposures:

(a) There was good agreement between the Committee's independent assessments of committed effective dose from internal exposure and the assessments reported in Japan.

(b) For all twelve workers, the independently assessed committed effective dose arose almost completely from the estimate of absorbed dose to the thyroid due to ^{131}I intake.

(c) The largest absorbed dose to the thyroid was assessed for worker A; the independent assessments of absorbed dose to the thyroid for this worker ranged from 9.7 to 12.6 Gy, with an arithmetic mean (rounded to two significant figures) of 12 Gy.

(d) The delay in starting monitoring of ^{131}I in the thyroid increased the uncertainty in the dose assessments over what would normally be achievable, because of uncertainties in the retention function for iodine in the thyroid for individual workers. Given the lack of repeated measurements soon after intake, it was not possible to quantify this increase in uncertainty.

(e) The delay in starting in vivo monitoring meant that the shorter-lived isotopes of tellurium, iodine and caesium, in particular ^{132}Te and ^{133}I, were not detected. Indicatively, the additional contribution to effective dose due to internal exposure from the intakes of these short-lived radionuclides by those workers on site in the first few days of the accident may have been in the order of 20% relative to the contribution from ^{131}I; this contribution is likely to have varied considerably between individuals.

(f) The absence of adequate urine monitoring data meant that it was not possible to confirm the reliability of doses assessed from thyroid activity measurements using results obtained independently with a different monitoring method.

D. Results for the 55 randomly selected workers with lower internal exposure

D44. The method used to randomly select the workers for assessment is described at the beginning of this section. A single independent dose assessment was performed for each of these cases. Assessments were made using the types of monitoring data and the types of information on exposure conditions described in section III of this appendix. While the information provided for TEPCO workers was reasonably comprehensive, that for contractors' workers was less so. In particular, for 7 cases out of 21, the only data provided that clearly related to the formally reported dose assessment were the assessed values of committed effective dose, *E*(50). For the remaining 14 cases, data were additionally provided on *(a)* the work period (only in some cases); *(b)* the place of measurement (only in some cases); and *(c)* the assumed date of intake (only in some cases). Monitoring data were provided for all 21 cases, but it was unclear which monitoring data (from Onahama, JAEA or a number of other locations) were used for the formally reported dose assessment. New information was provided too late (in July 2013) to be taken into consideration by the Committee.

D45. Comparisons between the independent dose assessment and the formally reported doses are shown in table D13. The formally reported doses were those reported by the employer of each worker, that is, TEPCO or its contractors (or subcontractors).

D46. These assessments were all based on in vivo measurements of radionuclide activities in the body. The table shows the committed effective dose from intakes of all the radionuclides for which monitoring results were reported, and the contribution to committed effective dose from ^{131}I intakes. Assessments of absorbed doses to the thyroid from ^{131}I intakes were also made by the Committee's assessors, but are not reported here. Approximate values (within 2% of the assessed values) could be determined by dividing the ^{131}I contribution to E(50) given in table D13 by the value of the thyroid tissue weighting factor (w_T) used in the definition of effective dose, 0.05 [I12].

D47. For most workers, initial monitoring was not performed until the period mid-May to end of June 2011. A few of the selected workers were monitored during April, but none during March 2011. For many of the workers, the first possible date of intake was between 12 and 22 March 2011. As a result of this delay, ^{131}I was not measurable in the thyroid of many workers. For these workers, Japanese assessors had to make an estimate, using either an "environmental ratio" method or an "MDA" method (described in section III of this appendix).

D48. Because initial monitoring was not performed until the period mid-May to end of June 2011, ^{131}I was not detected in the thyroid by any of the measurement methods performed, for a significant fraction of the 42 TEPCO and contractors' workers selected (tables D13 and D14). For three TEPCO workers and two contractors' workers with committed effective doses in the 0–5 mSv dose band (worker IDs: 101, 105, 107, 122 and 126), inspection of the monitoring results for other radionuclides indicated that any ^{131}I present could have been at levels low enough to be undetectable even if monitoring had been carried out promptly. However, for the other 17 cases (that is, about 40%), the absence of an ^{131}I measurement result above the detection limit is attributed to the delay in initiating monitoring.

Table D13. Assessed committed effective doses, *E*(50), for 42 randomly selected TEPCO and contractors' workers, and 13 emergency services workers

Note: "-": no value recorded, or "not applicable"; "Method": the method used to assess ^{131}I intake when ^{131}I was not detected in the thyroid. The results of the final and reported Japanese assessments are presented with the precision with which they were reported

Worker ID	*Working period*		*^{131}I measurement above detection limit?*	*Committee's assessment*				*Japanese final reported assessment*				
				Committed effective dose, E(50) (mSv)				*Committed effective dose, E(50) (mSv)*				
	Start	*End*	*(Yes/No)*	*From ^{131}I*	*Method*		*Total E(50)*	*From ^{131}I*	*Method*		*Total E(50)*	*Alternative assessment[a]*
					Ratio	*MDA*			*Ratio*	*MDA*		
TEPCO WORKERS												
Cases selected in the *E*(50) committed effective dose band: 0–5 mSv												
101	2011-04-07	2011-04-07	N	0.0	-	-	0.0	0.0	-	-	0	
102	2011-03-11	2011-06-01	N	1.7	Y	N	1.7	2.2	Y	N	2.2	
103	2011-03-11	2011-04-21	Y	3.1	N	N	3.2	2.9	N	N	3.0	
104	2011-04-19	2011-04-23	Y	0.3	N	N	0.3	0.3	N	N	0.3	
105	2011-04-27	2011-04-27	N	0.0	-	-	0.0	0.0	-	-	0.0	
106	2011-03-15	2011-03-18	N	-	Y	N	-	4.8	Y	N	4.8	
107	2011-05-13	2011-05-17	N	0.0	-	-	0.0	0.0	-	-	0.0	
Cases selected in the *E*(50) committed effective dose band: 5–20 mSv												
108	2011-03-21	2011-05-13	Y	15	N	N	15	13.5	N	N	13.6	
109	2011-03-11	2011-05-06	Y	11	N	N	11	9.1	N	N	9.2	
110	2011-03-22	2011-05-25	Y	13	N	N	13	14.1	N	N	14.1	
111	2011-04-06	2011-05-29	Y	22	N	N	22	18.8	N	N	18.8	
112	2011-03-11	2011-05-18	N	7.8	Y	N	7.8	7.8	Y	N	7.9	
113	2011-03-12	2011-05-11	N	-	Y	N	-	6.6	Y	N	6.6	
114	2011-03-18	2011-04-21	Y	15	N	N	16	13.3	N	N	14.7	

Worker ID	*Working period*		*^{131}I measurement above detection limit?*	*Committee's assessment*				*Japanese final reported assessment*				
				Committed effective dose, E(50) (mSv)				*Committed effective dose, E(50) (mSv)*				
	Start	*End*	*(Yes/No)*	*From ^{131}I*	*Method*		*Total E(50)*	*From ^{131}I*	*Method*		*Total E(50)*	*Alternative assessment[a]*
					Ratio	*MDA*			*Ratio*	*MDA*		
Cases selected in the *E*(50) committed effective dose band: 20–100 mSv												
115	2011-03-11	2011-04-23	Y	28	N	N	28	30.5	N	N	30.6	
116	2011-03-12	2011-04-16	Y	21	N	N	22	21.3	N	N	22.2	
117	2011-03-18	2011-05-10	Y	23	N	N	25	18.0	N	Y	20.0	
118	2011-03-11	2011-05-17	N	30	N	Y	31	30.1	N	Y	31.9	
119	2011-03-11	2011-05-23	N	186	Y	N	187	25.3	N	Y	27.1	
120	2011-03-13	2011-03-30	Y	50	N	N	50	32.0	N	N	32.7	
121	2011-03-11	2011-05-21	Y	66	N	N	66	66.9	N	N	67.0	
CONTRACTORS' WORKERS[b]												
Cases selected in the *E*(50) committed effective dose band: 0–5 mSv												
122	2011-06-12	2011-06-23	N	0.0	-	N	0.0	-	Y	N	0.00	0.00
123	No values reported by contractor[c]		N	0.1	Y	N	0.1	-	Y	N	0.06	0.06
124	No values reported by contractor		N	0	N	N	<0.1		N	N	0.00	0.02
125	2011-04-06	2011-05-20	N	1.2	Y	N	1.3	-	Y	N	1.30	1.31
126	2011-06-16	2011-06-26	N	0.0	-	-	0.0	-	Y	N	0.00	0.00
127	No values reported by contractor		N	-	-	-	-		Y	N	0.00	0.42
128	2011-03-16	2011-06-10	N	0.0	N	N	0.1	-	Y	N	0.40	0.43
Cases selected in the *E*(50) committed effective dose band: 5–20 mSv												
129	2011-03-24	2011-04-27	N	10	Y	N	10	-	Y	N	2.90	9.92
130	2011-03-30	2011-06-14	N	6.9	Y	N	7.1	-	Y	N	1.70	3.12
131	No values reported by contractor		Y	6.9	N	N	7.1	-	N	N	0.00	7.16
132	2011-03-29	2011-04-21	N	16	Y	N	17	-	Y	N	1.30	2.52
133	2011-03-17	2011-03-20	N	6.8	Y	N	6.8	-	Y	N	6.83	6.83
134	2011-03-18	2011-04-09	N	-	-	-	-	-	N	Y	7.20	7.20
135	2011-03-23	2011-05-21	Y	7.5	N	N	7.6	-	N	N	6.60	6.65

Worker ID	Working period		^{131}I measurement above detection limit?	Committee's assessment				Japanese final reported assessment				
				Committed effective dose, E(50) (mSv)				Committed effective dose, E(50) (mSv)				
	Start	End		From ^{131}I	Method		Total E(50)	From ^{131}I	Method		Total E(50)	Alternative assessment[a]
			(Yes/No)		Ratio	MDA			Ratio	MDA		
Cases selected in the *E*(50) committed effective dose band: 20–100 mSv												
136	2011-03-17	2011-03-19	Y	83	N	N	83	-	N	N	0.00	0.76
137	2011-03-12	2011-03-23	Y	29	N	N	30	-	N	N	37.10	38.48
138	No values reported by contractor		Y	85	N	N	85	-	N	N	13.80	14.21
139	No values reported by contractor		Y	117	N	N	117	-	N	N	60.10	66.28
140	No values reported by contractor		N	109	Y	N	110	-	N	Y	27.2	27.27
141	2011-03-16	2011-03-31	Y	22	N	N	23	-	N	N	18.20	20.45
142	2011-03-11	2011-05-30	Y	35	N	N	35	-	N	N	35.6	35.65
EMERGENCY SERVICES WORKERS												
143	2011-03-17	-	N	0.012	N	N	0.026	0.012	N	N	0.042	
144	2011-03-17	-	N	0.0075	N	N	0.022	0.008	N	N	0.037	
145	2011-03-17	-	N	0.0026	N	N	-	0.004	N	N	0.018	
146	2011-03-17	-	N	0.004	N	N	0.0094	0.004	N	N	0.016	
147	2011-03-17	-	N	0.004	N	N	0.014	0.005	N	N	0.022	
148	2011-03-17	-	N	-	-	-	-	0.006	N	N	0.021	
149	2011-03-17	-	N	0.004	N	N	0.030	0.004	N	N	0.029	
150	2011-03-17	-	N	0.003	N	N	0.008	0.004	N	N	0.014	
151	2011-03-17	-	N	0.003	N	N	0.018	0.004	N	N	0.034	
152	2011-03-17	-	N	0.004	N	N	-	0.006	N	N	0.016	
153	2011-03-17	-	N	0.004	N	N	0.0087	0.004	N	N	0.014	
154	2011-03-17	-	N	0.005	N	N	-	0.006	N	N	-	
155	2011-03-17	-	N	-	-	-	-	0.006	N	N	-	

[a] *In July 2013, TEPCO conducted a reassessment of doses for contractors' employees, reported here as alternative assessment.*

[b] *Independent assessment doesn't take into account new information that Japanese organizations provided too late to the Committee. Japanese final reported assessment and alternative assessment take into account the results of reassessment that the Japanese organizations performed in July 2013. Differences between independent and Japanese assessments are presented in table D15.*

[c] *The Committee performed its own assessment for this worker. Information on the working period was provided more recently.*

Table D14. Numbers of selected TEPCO and contractors' workers for whom ^{131}I was not detected in the thyroid

Employer		*TEPCO*			*Contractor*			*Total*
Reported committed dose, *E*(50) (mSv)		0–5	5–20	20–100	0–5	5–20	20–100	
Number of workers	selected	7	7	7	7	7	7	42
	of those, ^{131}I not detected	5	2	2	7	5	1	22

D49. For 12 of the 17 cases, the independent assessor chose to use the environmental ratio method, while the MDA method was used for one case (table D13). For the remaining four cases (worker IDs: 124, 127, 128 and 134), the assessor judged that the quality of the information provided did not justify the use of either method. Where sufficient information to make a comparison was available, the choice of alternative estimation method for the final reported value could be seen to be broadly similar for the independent assessments and for the Japanese final reported assessments (table D13). The exceptions were for workers with IDs 117 and 119, where the MDA method was used to give the Japanese final reported assessment.

D50. Two of the independent assessors performed checks on the reliability of the environmental ratio method. For eight cases where ^{131}I activity measurements above the detection limit were available and had been used to make an assessment of the contribution to *E*(50) from ^{131}I intakes, the environmental ratio method was used to make a second estimate. (The cases selected were workers with IDs: 104, 108, 109, 115, 116, 136, 137 and 139.) Values for *E*(50) estimated by the environmental ratio method and expressed as a fraction of the *E*(50) assessed from the measurements of ^{131}I activity, were: 0.03, 0.05, 0.27, 0.45, 0.84, 2.7, 4.6 and 5.1 (geometric mean = 0.56). This distribution of values indicated the large variability in doses estimated using the environmental ratio method, and therefore the large uncertainty associated with the method, although the small sample size meant that the uncertainty could not be reliably quantified. The Committee judged that precise information on the timing of intakes would be needed in order to confirm the reliability of the *E*(50) estimates using the environmental ratio method.

D51. The independent assessors gave no specific consideration to the reliability of the MDA method, because it depended on the detection limits computed for the measurement system and measurement conditions (for example, the length of the counting period) used for each individual measurement. Because the methodologies used for in vivo monitoring were judged to be adequate (section III of this appendix), the calculations of detection limits were expected to be reliable; the method was therefore considered to be valid for assessing the upper limit for the activity in the thyroid at the time of the measurement. However, the method could not be taken to provide a reliable estimate of the true activity in the thyroid. Taking these considerations into account, together with the large uncertainty associated with the environmental ratio method, the Committee considered the Japanese assessors' practice of adopting the lower of the two estimates to be the best available course of action.

D52. The effect of this choice on the magnitude of under- or overestimates of the ^{131}I intake was considered. Where the method using the environmental ratio gave an anomalously high estimated intake (owing to the large uncertainty in the method) that should have yielded a measurement of activity in the thyroid above the detection limit, the estimate using the MDA method would have been reported instead. On the other hand, anomalously low intakes estimated using the environmental ratio method would have been reported in preference to those estimated using the MDA method. Furthermore, anomalously high intakes estimated using the environmental ratio method were less likely to have been replaced by the estimate using the MDA method where the true ^{131}I intake was relatively low, because the estimate could still have fallen below the estimate using the MDA method. Over the whole population of workers for whom the alternative estimation methods had to be used, the magnitude of the overestimates of ^{131}I would have been less than the magnitude of the underestimates, but the extent of this asymmetry could not be evaluated from the information that was available at the time.

Table D15. Comparison of committed effective doses, *E*(50), for 21 randomly selected contractors' workers assessed by the Committee with those from the Japanese final reported assessment, initial alternative assessment and alternative reassessment

Worker ID	*Committed effective dose E(50) (mSv)*			
	Committee's assessment	*Japanese final reported assessment*	*Initial alternative assessment (TEPCO)*	*Alternative reassessment (TEPCO)*
122	0.0	0.00	0.00	0.00
123	0.1	0.06	0.06	0.06
124	<0.1	0.00	0.02	0.02
125	1.3	1.30	1.31	1.31
126	0.0	0.00	0.00	0.00
127	–	0.00	0.42	0.42
128	0.1	0.40	0.14	0.43
129	10	2.90	13.46	9.92
130	7.1	1.70	9.19	3.12
131	7.1	0.00	7.16	7.16
132	17	1.30	16.77	2.52
133	6.8	6.83	6.83	6.83
134	–	7.20	7.20	7.20
135	7.6	6.60	6.65	6.65
136	83	0.00	88.05	0.76
137	30	37.10	30.33	38.48
138	85	13.80	47.70	14.21
139	117	60.10	87.77	66.28
140	110	27.2	27.27	27.27
141	23	18.20	24.78	20.45
142	35	35.6	35.65	35.65

D53. Where available, the results of alternative dose assessments for contractors' workers performed by TEPCO are presented in table D13, as well as alternative reassessments performed by TEPCO in July 2013. (It should be noted that these alternative estimates were not routinely reported, but were provided to the Committee for the selected contractors' workers.) Where the results of the contractor assessment and of the initial TEPCO assessment were significantly different, reasons were given in the information provided to the Committee. The reasons listed were: "Discrepancy in record level", "Discrepancy in measurement data", "Discrepancy in assumed intake date" or "Discrepancy in essential figure". The meaning of the latter comment is unclear. By the end of 2013, the Committee had not elucidated the reasons for these differences. The results of the reassessment that TEPCO performed were provided too late for the Committee to reassess independently the 21 contractors' workers using the new information. Table D15 compares the Committee's assessments with the Japanese final reported assessment, TEPCO's initial alternative assessment, and TEPCO's alternative reassessment. This table compares the Japanese final reported assessment and TEPCO's alternative reassessment for workers with IDs: 129, 130, 131, 132, 139 and 141.

D54. The following general conclusions were drawn about the internal exposure assessments for the 42 TEPCO and contractors' workers:

- For all of the workers with assessed committed effective doses from internal exposure above 0.1 mSv, the dose to the thyroid resulting from ^{131}I intake made the dominant contribution to the committed effective dose, *E*(50).

- For workers with assessed internal exposure to ^{131}I, on average 98% of the committed effective dose was due to the absorbed dose to the thyroid resulting from ^{131}I intake (according to the Committee's independent assessment).

- A high degree of uncertainty was associated with committed doses estimated for ^{131}I using the environmental ratio method in those cases where ^{131}I was not measured in the thyroid. The *E*(50) could have been underestimated by a factor of up to about 30, or overestimated by a factor of up to about 5.

- For four out of the 21 TEPCO cases, the TEPCO final reported assessment used the environmental ratio method; information on which contractors' assessments used this method was not available. For three out of the 21 TEPCO cases, the TEPCO final reported assessment used the MDA method; again, this information was not available for contractors' assessments. It was difficult to make an accurate estimate of the percentage of the 21,776 TEPCO and contractors' workers with reported doses for whom dose estimates were made using either the environmental ratio or the MDA methods; it might have been in the region of 40%.

D55. The following conclusions were drawn about the internal exposure assessments for the 21 TEPCO workers:

- There was good agreement between the Committee's independent assessments of *E*(50) and the TEPCO assessments for those cases where measurements of ^{131}I activity in the body above the detection limit were available.

- Good agreement was also found for those cases where the independent assessment and the TEPCO assessment both used the environmental ratio method, as well as for the case where both used the MDA method. This agreement confirmed that both methods had been applied correctly. However, it could not be taken to confirm the reliability of the dose values assessed using the environmental ratio method because of the large uncertainties.

- The independent assessments of *E*(50), expressed as a fraction of the TEPCO-assessed *E*(50), lay in the range 0.76–1.24 (13 values, standard deviation = 0.12), with two outliers at 1.54 and 6.91. The arithmetic mean value including the outliers was 1.46, and without the outliers was 1.03. There was no obvious trend in this value with dose. (Note that the 6.91 value was for a case—worker ID: 119—where the Committee's independent assessment used the environmental ratio method. A re-examination indicated that use of the MDA method would have been justified, which would have resulted in a lower value close to the TEPCO value.)

D56. The following conclusions were drawn about the internal exposure assessments for the 21 contractors' workers:

- There were a number of significant differences between the Committee's independent assessments of *E*(50) and the contractors' assessments, as shown in table D13. There were also some significant differences between TEPCO assessments and the contractors' assessments, also shown in table D13 and table D15. In most, but not all, cases the independent assessment was in reasonable agreement with the TEPCO assessment.

- The most extreme discrepancy was for worker with ID 136. The values of *E*(50) assessed by the Committee and by TEPCO were 83 mSv, 88 mSv (TEPCO's initial alternative assessment), and 0.8 mSv (TEPCO's alternative reassessment), respectively, but the contractor reported 0 mSv. The Committee was not able to reanalyse the information used for TEPCO's alternative reassessment because it came too late. For worker with ID 138, *E*(50) assessments by the Committee and by TEPCO were 85 mSv, 48 mSv (TEPCO's initial alternative assessment) and 14 mSv (TEPCO's alternative reassessment), respectively, but the contractor reported 14 mSv. Similar differences at lower dose levels were found for workers with IDs: 129, 130, 131 and 132.

- In two cases, TEPCO and the contractor were in reasonable agreement, but the Committee's assessment was significantly higher (workers with IDs: 139 and 140), even when TEPCO's reassessment was taken into consideration. This may have arisen from the use in the independent assessment of whole-body monitoring data from Onahama. After the assessments were completed, information was provided to the Committee that Onahama data were known to give overestimates (because of levels of environmental contamination and elevated radiation background). These data were discarded in Japanese assessments for those cases where other in vivo data (from JAEA or NIRS in particular) were available.

D57. The following conclusions were drawn about the dose assessments for the 13 emergency services workers:

- Independent assessments of *E*(50) were low (10–30 µSv).

- The contribution to *E*(50) from dose to the thyroid resulting from ^{131}I intake was 33% (average value).

- Measurements of activity in the whole body were of total radiocaesium only (^{134}Cs and ^{137}Cs combined), and a 1:1 isotopic ratio for the measured amount was assumed in both the Committee's and Japanese assessments.

- The Committee's assessments and the values reported in Japan were in reasonable agreement for the contribution made to *E*(50) by the absorbed dose to the thyroid from ^{131}I intake.

- Doses from caesium intakes reported in Japan were overestimated by a factor of 2. Given that total doses were low, this was not a significant issue.

D58. The potential additional contribution to committed doses from intakes of short-lived radionuclides was discussed earlier for workers with the highest internal exposures. For that group of workers, intakes probably took place within the period 12–15 March 2011, although there was uncertainty about the exact periods of intake. For other groups of workers with lower reported doses (for whom individual work history information was not available), the period of intake may have extended to later dates and so the possible range on the additional contributions to dose extended to lower values. For these groups of workers, the additional contribution to effective dose from intakes of short-lived radionuclides could have been in the range 6−45% relative to the contribution from ^{131}I, depending on the time pattern of intake. The corresponding range for the additional contribution to absorbed dose to the thyroid was 2−28%. These estimates of the additional contributions to committed dose assumed that intakes commenced on 12 March. The additional contributions to committed dose from short-lived radionuclides would have been negligible for all workers who commenced work at FDNPS after about 19 March. For those members of the FDNPS workforce who were working during the period 12–19 March, the indicative additional contribution to effective dose from intakes of short-lived radionuclides may be in the order of 20% relative to the contribution from ^{131}I, although this value was likely to be subject to large variations between individuals, mainly because of variations in the time period of intake.

E. Summary of the conclusions of the Committee's dose assessment

D59. With respect to the information collected for 24,832 workers, 13 workers received a cumulative dose from internal exposure above 100 mSv and 173 workers received a total effective dose above 100 mSv. The highest reported effective dose was 679 mSv, for the TEPCO worker who also had the highest reported committed dose from internal exposure (590 mSv). The highest reported effective dose from external exposure was 199 mSv, for a contractor's worker who had a reported total effective dose of 238 mSv. The Committee's evaluations showed that the committed effective dose $E(50)$ arose almost completely from the committed absorbed dose to the thyroid resulting from ^{131}I intake. It was not possible to make a definitive judgement about potential exposures to neutrons and to nuclides other than ^{131}I, ^{134}Cs and ^{137}Cs, because those exposures were not evaluated sufficiently to make a reliable assessment.

1. Assessments of dose from internal exposure

D60. The Committee's independent assessments of committed effective dose agreed reasonably with the assessments reported by TEPCO for those workers for whom ^{131}I in the thyroid was measured, including for twelve of the thirteen workers with the highest internal exposures.

D61. For a significant fraction of the TEPCO and contractors' workers assessed (22 out of 42), ^{131}I was not detected in the body by any of the measurements performed because of the delay in initiating monitoring. For several of the cases, the "environmental ratio" method was used to estimate the ^{131}I intake. An evaluation of the method showed that it produced highly variable results; owing to the uncertainty in the assumed ratio of ^{131}I to ^{137}Cs intake, $E(50)$ could, in extreme, have been underestimated by a factor of up to about 30, or overestimated by a factor of up to about 5. The Committee judged that estimates derived using this method had very large uncertainties and that precise information on the timing of the intakes would be needed to confirm their reliability.

D62. For several other cases, the "MDA" method was used to estimate the ^{131}I intake. The method was judged to provide a reliable estimate of the upper limit on ^{131}I intake, but could not be taken to provide a reliable estimate of the true intake.

D63. The reliability of assessments reported by TEPCO for those of its workers where ^{131}I was measured in the body could be confirmed. The twelve workers (independently assessed by the Committee) of the thirteen workers with the highest internal exposures from ^{131}I are all in this category. The largest absorbed dose to the thyroid from ^{131}I was assessed as 12 Gy; the estimates from the independent assessments ranged from 9.7 to 12.6 Gy, depending on assumptions made in the simulation, including the timing of the main intakes of ^{131}I.

D64. The reliability of assessments reported for those workers for whom ^{131}I was not detected in the body cannot be confirmed. Neither of the methods available to estimate ^{131}I intake in these circumstances provided a reliable estimate of the true intake, and the resulting dose estimates were subject to a high degree of uncertainty. Although workers in this category could have comprised about 40% of the 21,776 TEPCO and contractors' workers for whom individual internal and external exposures were reported, they were, in general, more likely to have received lower doses.

D65. The delay in starting in vivo monitoring meant that shorter-lived radionuclides, specifically ^{132}Te, ^{132}I, ^{133}I and ^{136}Cs, would have been undetectable in the body at the time of measurement. For those members of the FDNPS workforce who were working during the period 12–19 March, the indicative additional contribution to effective dose from intakes of short-lived radionuclides may have been of the order of 20% relative to the contribution from ^{131}I intake, although this value was likely to be subject to large variations between individuals (see attachment D-1 for details). For workers who commenced work after 19 March, the contribution of short-lived radionuclides would not have been significant.

D66. An assessment of health risk would need to make use of estimates of absorbed doses to organs. The Committee made indicative estimates of absorbed doses to selected critical organs, specifically thyroid, red bone marrow and colon using three scenarios (see attachment D-1). However, information on the timing of intakes was not yet available at the end of 2013 for the great majority of the 21,776 TEPCO and contractors' workers for whom individual internal and external exposures had been reported.

D67. Evidence from this investigation indicated that many of the dose estimates reported by contractors for their workers may have been significant underestimates. Based on the comparative assessments carried out, the Committee was therefore unable to confirm the reliability of assessments reported by contractors for their workers[41].

2. Assessments of doses from external exposure

D68. The evaluation of the information provided on dosimetric methods for external exposure indicated that the instrumentation, technical standards and calibration methods used appeared to meet generally-accepted requirements for monitoring. The major factor potentially affecting the reliability of the monitoring performed was the use of shared personal dosimeters during March 2011. Further work would be needed to quantify the resulting uncertainties in reported doses from external exposure.

[41] After the Committee drew this initial conclusion, doses for contractors' workers were reassessed in Japan [M17], and the Committee understands that at least some of the discrepancies have been resolved.

APPENDIX E. HEALTH IMPLICATIONS FOR THE PUBLIC AND WORKERS

I. INTRODUCTION

A. Objectives and structure

E1. The objectives of this appendix are to provide a commentary on the immediate and long term health implications of exposures to ionizing radiation resulting from the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS), and to consider the on-going health monitoring programmes.

E2. The phrase "health implications" is used here to express the Committee's interpretation of information on the consequences for health based on its assessment of radiation exposure from the FDNPS accident, specifically *(a)* to provide information on health effects that have been observed in exposed populations within the time frame considered by the Committee (generally about two years after the accident but in some cases longer); *(b)* to provide insight into the magnitude of risks of future health effects from the assessed radiation exposure of these populations; and *(c)* to provide information as to whether it was likely that risks would become manifest and discernible in the future disease statistics covering these populations. In addition to the interpretation of information on health implications of the radiation exposure, some contextual commentary is made on broader health implications, such as the impact on mental health, that are related to the accident and the response to it, as well as to the natural disaster itself.

E3. Section I.B briefly recapitulates current knowledge on the health effects and risks from exposure to ionizing radiation. Consideration is then given separately to the health implications for the public (section II) and for those exposed occupationally or in responding to the FDNPS accident (section III). The commentary on health implications for the public relied upon the Committee's assessment of exposures of different population groups in Japan, as outlined in appendix C. The commentary on health implications for workers was based on the exposures reported to—and to the extent possible independently assessed by—the Committee, and outlined in appendix D. The health risk assessment conducted by the World Health Organization (WHO) based on its preliminary dose assessment was also reviewed. Health effects, irrespective of their cause, that were observed within about the first two years following the accident, and risks of future health effects are discussed. The Committee drew upon the experience from the Chernobyl accident and its implications for the health of the general public and of workers. The radiation exposure resulting from the FDNPS accident is also put into perspective by using some other sources of exposure as a frame of reference, to help provide some context for understanding the overall radiation exposure of the population of Japan.

B. Recapitulation of knowledge on health effects and risks from exposure to ionizing radiation

E4. Exposure of tissues or organs to ionizing radiation can induce the death of cells that can be extensive enough to impair the function of the exposed tissue or organ. Effects of this type, which are called "deterministic effects", are clinically observable in an individual if the absorbed dose to a tissue exceeds a threshold level specific to that tissue. Such effects include the acute radiation syndrome (ARS), skin burns, loss of hair, hypothyroidism and developmental damage to an unborn child. Above the relevant threshold level, the severity of such a deterministic effect increases with the absorbed dose. The International Commission on Radiological Protection (ICRP) has introduced the term, "tissue reaction", which encompasses deterministic effects, circulatory disease and cataracts [I26].

E5. Exposure to radiation can also induce non-lethal changes to cell constituents, including DNA lesions. Different consequences can occur following such an event: the cell is successfully repaired (i.e. it returns to normal); or the cell remains unrepaired or is misrepaired (i.e. it remains abnormal). The human body's immune system is very effective in detecting and destroying abnormal cells. However, any abnormal cells that escape the immune defence over time may proliferate and contribute to carcinogenesis or hereditary effects. Such effects are called "stochastic" effects and are characterized by an increased incidence with increased dose to an exposed population but are indistinguishable from similar effects that occur in the absence of exposure. The Committee has conducted extensive reviews on these effects, most recently in [U7, U8, U9], and has also considered some key issues in this area that require further scientific attention [U10, U15]. Findings from these past reviews related to the most relevant health consequences of radiation from the FDNPS accident are recapitulated below, updated as appropriate with more recent information.

E6. *Solid cancer.* The Committee previously estimated the increased risk of solid cancer for the general populations of China, Japan, Puerto Rico, the United States and the United Kingdom following exposure to low-LET radiation[42] [U9]. The estimated lifetime risk depended on the absorbed dose, the model assumed for describing the risk of cancer following radiation exposure, the baseline cancer rate (i.e. the prevailing cancer rate in the absence of radiation exposure) in the respective country/area, and mortality rates for specific causes of death.

E7. The lifetime baseline risk of solid cancer in the general population of Japan is about 35% on average (males about 41%; females about 29%) [W12]. Following a hypothetical exposure of a group from the same population corresponding to an acute uniform whole-body dose of 1 Sv (equivalent to an absorbed dose of 1 Gy of low-LET radiation to all organs and tissues of the body), the Committee previously estimated the additional lifetime risk of solid cancer due to that exposure to be approximately 13% on average (annex A, table 70 in the Committee's 2006 Report [U9]). Following doses of 0.1 Sv and 0.01 Sv, the additional lifetime risk due to the exposure was estimated to be smaller by factors of about 10 and 100, respectively.

E8. The Committee has evaluated the uncertainty associated with its estimates of risk due to radiation exposure [U14]. For a hypothetical group of male radiation workers in the United Kingdom, the Committee estimated the average additional lifetime risk of solid cancer due to a whole-body dose of 100 mSv to be about 1%, and the 95% subjective confidence interval on this value to be from a factor of 2.5 lower to a factor of 2 higher. These estimates are similar to those made by the United States Committee on the Biological Effects of Ionizing Radiation [N22] and imply that for a population incurring an acute exposure of 100 mSv, the lifetime risk of cancer would increase from about 41% to about 42%. For 10 mSv, the theoretical increase would be from about 41% to 41.1%.

E9. *Leukaemia.* In Japan, the lifetime baseline risk of leukaemia in the general population is about 0.5% on average [W12]. The Committee has previously assessed the risk of mortality from leukaemia due to radiation exposure for the general population of Japan [U9]. Depending on the model applied, the additional lifetime risk after an acute low-LET exposure with an absorbed dose of 1 Gy to the red bone marrow was estimated to be in the range from 0.05% to 0.47% for the general population, and in the range from 0.11% to 0.84% for children exposed between 0 and 9 years of age.

E10. *Exposure during childhood.* The increase in cancer risk due to radiation exposure during childhood is generally greater than that for exposures at older ages (annex A of [U9]). However, the radiosensitivity of children is not the same for all organs and tissues. In annex B to this report to the General Assembly, the Committee describes evidence for children being more likely than adults to develop, for example, breast cancer, thyroid cancer and leukaemia (other than chronic lymphocytic leukaemia, CLL) after radiation exposure [U16]. It also discusses those tumour types for which children have the same or less sensitivity than adults. The increased likelihood for development of certain cancers after exposure during childhood need special recognition in the context of the FDNPS accident.

E11. *Thyroid cancer.* The risk of thyroid cancer following radiation exposure is strongly modified by the age at exposure with young children under age 6 years being at highest risk and risk decreasing with increasing age at exposure [U9]. The Committee estimated lifetime additional absolute risk of thyroid cancer due to irradiation for a hypothetical group of Ukrainians who received an absorbed dose to the thyroid of 0.2 Gy low-LET radiation at age ten years [U14]. For males, the exposure was estimated to add 0.07% (95% confidence interval, CI: 0.01%, 0.21%) to the baseline risk of thyroid cancer of 0.14%. Corresponding values for females were 0.59% (95% CI: 0.11%, 2.1%) and 0.62%.

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[42] As radiation interacts with matter, it loses its energy through interactions with atoms. The Linear Energy Transfer (LET) is a measure of the average amount of energy lost over a defined distance. The same absorbed dose of low-LET radiation (such as beta particles and gamma rays) creates less biological damage than of high-LET radiation (such as alpha particles). The radiation exposure from the FDNPS accident was essentially all from low-LET radiation.

E12. *In utero exposure.* The large and comprehensive Oxford Survey of Childhood Cancers (OSCC) that studied children who had been exposed in utero because of obstetric use of X-rays found a statistically significant increased risk among children of leukaemia and all solid cancers of about 40% relative to the baseline (i.e. a relative risk of 1.4) [W2]. Although no individual dose estimates were available, doses to the foetus were likely to have been of the order of 10 mGy. Similar results have been obtained in a number of other, smaller studies of the effects of obstetric radiography [U7]. However, the causal nature of such low doses following in utero exposure has been debated. Analyses of the survivors of the atomic bombings in Japan who were exposed in utero have only shown a statistically significant increase in incidence of adult-onset cancers at doses higher than about 50 mGy or so [P16]. While the magnitude of the risk of cancer from in utero exposures to diagnostic X-rays remains a matter for discussion [N5], it is possible to estimate upper bounds for any risk.

E13. *Hereditary effects.* Radiation exposure has never been demonstrated to cause hereditary effects in humans, despite extensive studies of the children of survivors of the atomic bombings in Japan, and of the children of cancer survivors treated with radiotherapy throughout the world. However, experimental studies on plants and animals have demonstrated that radiation can induce hereditary effects, and humans are unlikely to be an exception in that regard. Based on animal experiments, the Committee estimated 3,000 to 4,700 cases of hereditary effects per gray of low-LET radiation per one million progeny of the first generation after the exposed generation [U8]. This is equivalent to an absolute risk of hereditary effects per unit dose of 0.3% to 0.5% per gray. Thus, for a given whole-body exposure, the estimated risk that an individual's offspring will have a hereditary disease is on average less than one tenth of the individual's own risk of cancer.

E14. *Non-cancer somatic effects.* In its 2006 review, the Committee considered the scientific data to be insufficient to derive a causal relationship between radiation exposures and non-cancer somatic diseases for absorbed doses of less than about 1–2 Gy [U9]. In 2012, the ICRP estimated that a dose of 0.5 Gy represented a threshold for developing circulatory diseases as a result of irradiation more than 10 years after exposure [I26]. However, at such a dose it cannot be excluded that the risk of circulatory disease per unit dose is lower [S5] or even non-existent, although the subject remains a matter of much debate [L8].

II. HEALTH IMPLICATIONS OF RADIATION EXPOSURE OF THE PUBLIC RESULTING FROM THE FDNPS ACCIDENT

A. Observed health effects

E15. *Effects of radiation exposure.* In the short term, no deterministic health effects due to radiation exposure after the FDNPS accident were observed among members of the public and none are expected in the long term because the doses were far below the threshold values for such effects [N1, U9, U12].

E16. *Effects from other causes.* The most important and manifest health effects of the nuclear accident in the short term would appear to be on mental and social well-being [B20]. This aspect was exacerbated by the enormous impact of the earthquake and tsunami, the uprooting of thousands of people as a consequence of the evacuation and their displacement to unfamiliar surroundings, and the fear and stigma related to radiation exposure. It is outside of the Committee's mandate to assess the occurrence and severity of such effects. However, they are part of the broad definition of health as used by WHO and such effects may also continue in the long term. Furthermore, the evacuation following the accident caused immediate aggravation of the condition of already vulnerable groups; for example, it was reported that more than 50 hospitalized patients died either during or soon after the evacuation, probably because of hypothermia, dehydration or deterioration of underlying medical problems [T4], and that upwards of 100 elderly people may have died in subsequent months because of a variety of conditions linked to the evacuation [Y6]. Understanding the full health impact of the accident forms an important context for the Committee's commentary on health implications directly related to radiation exposure.

B. Risk assessment conducted by WHO

E17. The WHO published in 2013 a health risk assessment of the FDNPS accident to estimate the potential public health impact so that future health needs could be anticipated and public health actions taken [W12]. It estimated risks based on preliminary estimates of radiation doses using data gathered up until September 2011 [W11]. In contrast, the Committee used more comprehensive and recent data for its scientific assessment of doses, and made more realistic assumptions where data were sparse, particularly for the evacuated areas. Nevertheless, the Committee's dose estimates and the doses estimated by WHO were generally consistent; the ranges of estimates presented by WHO (see appendix C) encompassed the results of the Committee's dose assessment, although the WHO estimates were higher for a number of the evacuated settlements.

E18. The WHO did not expect any deterministic effects in any of the various groups it considered [W12]. It did not expect prenatal exposure to increase "... *the incidence of spontaneous abortion, miscarriages, perinatal mortality, congenital effects or cognitive impairment*." WHO considered the"... *hereditary risk in the offspring of an exposed person* ... [to] *be much lower ... than the additional cancer risk of that exposed person."* These statements are consistent with the views of the Committee for exposures typical of those estimated to have been incurred by the public as a result of the FDNPS accident.

E19. The WHO made the following main assumptions in its estimation of cancer risks [W12] (the Committee's remarks on those assumptions follow each one below):

(a) A linear non-threshold (LNT) dose–response model for solid cancer and a linear-quadratic non-threshold dose–response model for leukaemia. While the Committee noted that these models had been used for radiation protection purposes [I21], it also noted that the current state of knowledge on the risk of cancer from doses of the order of 100 mSv or less was quite limited, although some but not all data were compatible with the risks of cancer from such doses not being seriously underestimated by the LNT model. The Committee has previously decided not to use models to project absolute numbers of health effects among populations exposed at such levels, because of large and unavoidable uncertainties in the predictions (annex D to [U12]).

(b) A dose-and-dose-rate effectiveness factor (DDREF) of one. This is not incompatible with the Committee's estimates of cancer risks after doses of 0.01, 0.1 and 1.0 Sv delivered acutely [U9, U11], with recent results for solid cancer in the Life Span Study (LSS) of Japanese survivors exposed as a result of the atomic bombings at Hiroshima and Nagasaki [O8], or with a meta-analysis of low-dose-rate, moderate-dose exposures [J2]. In contrast, experimental evidence indicates values of DDREF greater than one for high-dose exposures at low dose rate [I21, U5].

(c) An onset of increased cancer risk from irradiation after minimum latency periods of 2 years for leukaemia, 3 years for thyroid cancer, and 5 years for breast cancer and all solid cancers combined. WHO assumed values for minimum latency period that are shorter than those from previous reviews of the literature by the Committee [U9] and represent a cautious assumption. Because radiation risks are not expected to be fully expressed already at the presumed minimum

latency period, the WHO assumption, in general, leads to a slight overestimation of the cancer risk for the first decade after exposure. For longer time periods the impact is negligible.

(d) Risk models derived from the LSS cohort of survivors of the atomic bombings in Japan. The WHO justified its choice of risk model by the general consistency of LSS risk estimates (which are themselves based on a Japanese population) with those found in populations exposed to protracted exposures, and with populations exposed during childhood or adolescence to radioiodine released after the Chernobyl accident, although there is inevitably some uncertainty about the level of consistency.

(e) Weights assigned to additive and multiplicative models in the transfer of LSS risk functions to the populations in Fukushima Prefecture. For leukaemia and all solid cancers, WHO gave equal weight to these two models of transfer, because the true interaction of radiation exposure with other causes of cancer is not generally known. For breast cancer, the WHO used an additive model because a pooled study had shown a smaller variability of excess absolute risk estimates than excess relative risk estimates [P14]. The choices made for all solid cancers and breast cancer were broadly consistent with assumptions made by ICRP, BEIR VII and USEPA, although there is less consensus for leukaemia [E2, I21, N22]. However, these organizations have proposed a multiplicative risk transfer model for thyroid cancer. WHO justified their choice of assigning equal weight for additive and multiplicative models by comparing the LSS results with data from studies after the Chernobyl accident. In past reviews, the Committee had applied additive and multiplicative models separately in order to assess the implications of the mode of transfer [U9]. The choice of model, although relevant because the population of Fukushima Prefecture has some different characteristics from the population exposed to radiation from the atomic bombings, was less important because the transfer was from one exposed Japanese population to another, rather than to another population of different ethnicity.

E20. According to WHO's preliminary dose estimation, average lifetime doses due to the accident to the colon, breast and bone marrow of people in the areas with the highest deposition densities of radionuclides (namely Namie Town in Futaba District and Iitate Village in Soma District) were estimated to be up to about 20 mSv [W12]. WHO estimated absorbed doses to the thyroids of adults and young children (delivered mainly within the first year) to be about 50 mGy and 100 mGy, respectively. They estimated that populations in other areas with high deposition densities received doses lower by a factor of at least two.

E21. WHO [W12] estimated, for the areas with the highest deposition densities of radionuclides, the mean lifetime risk of all solid cancer due to radiation exposure during infancy to be about 0.6% and 1.2% for males and females, respectively (table E1). This would be in addition to a baseline risk expected in the absence of radiation exposure from the accident of 41% and 29% of males and females, respectively. This estimated increase in risk due to radiation exposure was small compared with the temporal and regional variability of cancer incidence [C3]. For females, about 20% of the increase in cancer risk was estimated to be due to the risk of breast cancer. For exposure during infancy, nearly 40% of the estimated increase in risk of cancer for females was due to the risk of thyroid cancer; this was because the absorbed dose to the thyroid was significantly higher than that to other organs, and the excess relative risk of thyroid cancer per unit dose for this population group was high. However, because of the very low baseline lifetime incidence of thyroid cancer, WHO expected the additional absolute lifetime thyroid cancer risk due to radiation exposure to be small. The WHO estimates of risk per unit dose were compatible with estimates of the Committee in its earlier reports (see section I.B of this appendix).

Table E1. WHO's estimates of lifetime baseline risk, LBR, and lifetime attributable risk, LAR for areas within Fukushima Prefecture with effective doses of 12–25 mSv in the first year [W12]

The calculations were based on absorbed doses to the colon, bone marrow and breast of 20 mGy for the whole population, and absorbed doses to the thyroid of about 100, 75 and 50 mGy for an age at exposure of 1, 10 and 20, respectively The values calculated by WHO were quoted to two significant figures and have been reproduced here. The use of such precision should not imply that the numbers are accurately known. For example, consideration of the uncertainty associated with the LAR estimates would suggest that the actual values likely lie within bounds that are perhaps 2–3 times higher or lower. The LBR are also associated with uncertainty and variability between different years

Age at exposure (y)	*Sex*	*Risk quantity*	*All solid cancer*[a]	*Leukaemia*	*Breast cancer*	*Thyroid cancer*
1	Male	LAR LBR	0.6% 41%	0.03% 0.60%	–	0.10% 0.21%
	Female	LAR LBR	1.2% 29%	0.02% 0.43%	0.26% 5.5%	0.43% 0.77%
10	Male	LAR LBR	0.5% 41%	0.02% 0.58%	–	0.04% 0.21%
	Female	LAR LBR	0.8% 29%	0.01% 0.41%	0.17% 5.5%	0.19% 0.77%
20	Male	LAR LBR	0.3% 41%	0.01% 0.57%	–	0.01% 0.21%
	Female	LAR LBR	0.5% 29%	0.01% 0.40%	0.11% 5.6%	0.07% 0.76%

[a] *Includes the risk of thyroid cancer taking into account the relatively high absorbed dose to the thyroid, while the WHO report calculated the risk of all solid cancer assuming that the absorbed dose to all organs was equal to the dose to the colon.*

E22. The WHO remarked that the "ultrasound screening for thyroid disease is likely to lead to an increase in the [reported] incidence of thyroid diseases due to earlier detection of non-symptomatic cases (screening effect)" (see section D below). In its calculations, WHO did not consider explicitly the effect that the ultrasound screening programme in Fukushima Prefecture would have on detection rates and therefore on the observed/reported prevalence and incidence rates of thyroid disease. Nevertheless, the survey was expected to lead to an increase in the detection of cases of thyroid cancer, both of baseline ones and those that may be related to radiation exposure, which are currently indistinguishable.

C. The Committee's commentary on health implications for the public

E23. The Committee based its commentary on *(a)* its own dose estimates for subsets of the Japanese population as reported in appendix C and relevant attachments; *(b)* its estimates of disease risks from exposures to ionizing radiation including new estimates of the risk of thyroid cancer as summarized in section I.B; and *(c)* results of the WHO report [W12] as reviewed in section II.B (but modified by considering the risk of solid cancer including the full risk of thyroid cancer, whereas the WHO estimates for the risk of solid cancer were based on doses to the colon not taking into account that doses to the thyroid were in general higher). The Committee's commentary considers quantitative and qualitative estimates of potential disease outcomes among the exposed populations that may or may not be observable in future disease statistics. For the purpose of this study, the Committee has used the phrase "no discernible increase" where, although a disease risk in the longer term can be theoretically inferred on the basis of existing risk models, an increased incidence of effects is unlikely in practice to be observed in future disease statistics using currently available methods, because of the combination of the limited size of population exposed and low exposures, i.e. consequences that are small relative to the baseline risk and their uncertainties. To gain insight as to whether increased incidence might be discernible, the Committee considered some indicative numbers of individuals within doses bands, based on the population and dose information in appendix C and associated attachments.

1. Population of Japan and of Fukushima Prefecture

E24. For the general public of Japan, inhabiting areas where exposures from the FDNPS accident in the first year were of the order of or below annual background exposure to natural sources of radiation (and lifetime exposures are expected to be much below those incurred from background radiation), the Committee estimated that risks over their lifetimes were so low that no discernible increase in the future incidence of health effects due to radiation exposure would be expected among the population or their descendants. Disease risks for people who were evacuated and for people in districts of Fukushima Prefecture that were not evacuated (who received, in the first year, doses from the accident that exceeded the annual background exposure to natural sources) are discussed in detail below.

E25. The radiation exposure of the population resulting from the FDNPS accident had two main components: *(a)* doses due to external exposure and to internal exposure from incorporated radiocaesium, both of which are relatively homogeneous in the body. For such homogeneous whole-body exposures of adults with effective doses spanning up to about 100 mSv, the value of effective dose could be used to estimate absorbed doses to particular organs and qualitatively evaluate the exposure to explore whether a more sophisticated risk analysis was necessary; and *(b)* absorbed doses to the thyroid due to incorporation of radioiodine, which is discussed separately below.

E26. The quantity effective dose is itself not suited for quantitative risk estimations, having been developed for radiation protection and for demonstrating compliance with regulatory limits. It does allow partial body exposures as well as exposures due to intakes of radionuclides to be combined into an aggregate quantity that is useful in radiation protection, but not quantitative risk assessment. It includes judgements on values for tissue weighting and radiation weighting factors, and averages over all ages and both sexes. It thus does not represent risk to an individual or groups of similar individuals with the same characteristics, and is not useful for quantitative risk estimation. Therefore, the Committee based its estimates of risk from exposure during childhood on estimates of absorbed doses to specific organs.

E27. *All cancer.* The Committee estimated settlement averages of effective doses to adult evacuees to be less than 10 mSv in the first year after the accident (table C11). In the most affected districts of the areas that were not evacuated, average lifetime effective doses to adults were up to just over 10 mSv above natural background (table C14). Individual doses could be lower or higher by a factor of about 2 to 3. The Committee estimated that perhaps 15,000 people in the highest dose bands might have received average lifetime effective doses of about 25 mSv.

E28. Definite evidence for an increase in the incidence of some cancers from acute (weighted colon) doses of 100 mSv or more has been reported for population groups such as the survivors of the atomic bombings in Hiroshima and Nagasaki (see section I.B in this appendix and [U9]). While there is little or no direct evidence for an increase in the incidence of cancer as a whole in adult populations from homogeneous whole-body exposures with effective doses of 100 mSv or less, risks can be inferred at such levels (e.g. using a linear dose–response model). However the values of inferred risks are so small that in general no discernible radiation-related increase of overall cancer incidence would be expected among exposed members of the general public. However, separate consideration of certain malignancies has been made for particular groups (see below).

E29. *Thyroid cancer.* During the first year, incorporated radioiodine from the accident led to higher absorbed doses to the thyroid than to other organs and tissues. For adults in areas that were not evacuated, the district-average absorbed doses to the thyroid were less than 20 mGy in the first year after the accident (table C10). Available evidence indicates that the thyroid is not particularly sensitive to such doses during adulthood.

E30. In contrast, for 1-year-old infants who were evacuated after the accident, the Committee estimated settlement-average absorbed doses to the thyroid to be up to about 80 mGy (table C12). In the areas that were not evacuated, district-average doses to the thyroid were up to about 50 mGy (table C10). For example, the Committee estimated that about 35,000 children in the age range of 0−5 years lived in districts where the average absorbed dose to the thyroid was between 45 and 55 mGy.

E31. The Committee previously evaluated the risk of thyroid cancer from an absorbed dose to the thyroid of 200 mGy at age of ten years [U14]: the lifetime risk of thyroid cancer was estimated to be approximately doubled by the exposure. However, even for a hypothetical exposure of 10,000 children with such a dose to the thyroid, the uncertainty of the risk estimate is large, ranging from a relative risk of about 1.15 to about 4.0. The WHO estimates of the risk of thyroid cancer due to radiation exposure [W12] were consistent with those of the Committee, if the risk dependence on dose to the thyroid were assumed to be linear from several hundred milligrays down to the levels of dose received after the accident.

E32. From an estimate of absorbed dose of 50 mGy to the thyroid of infants, and assuming that the risk of thyroid cancer could be extrapolated down to these dose ranges using a linear dose–response function, a relative lifetime risk of thyroid cancer due to the exposure over the baseline risk could be inferred to be about 1.3. Such an increase in principle ought to be discernible if the effect of increased detection rate due to sensitive screening and other factors could be isolated, although most of the increased incidence would be expected to appear several decades after the exposure. Furthermore, direct measurements of radioiodine content in the thyroid have suggested that actual doses to the thyroid for some individuals might be lower than the average doses estimated by the Committee using environmental measurements and modelling, although there are some questions about how representative the thyroid measurements generally were. A detailed re-evaluation of the absorbed doses to the thyroid taking into account all available information relevant to thyroid exposure including the thyroid measurements, their quality assurance and information on individual protective measures is highly desirable.

E33. The Committee estimated that the doses to the thyroid varied considerably among individuals, indicatively from about 2 to 3 times higher or lower than the average for a district. It considered that fewer than a thousand children might have received absorbed doses to the thyroid that exceeded 100 mGy and ranged up to about 150 mGy. The risk of thyroid cancer for this group could be expected to be increased. However, it would be difficult, if not impossible, to identify precisely those individuals with the highest exposure, and risks at these low doses have not been convincingly demonstrated; moreover, as noted above, the lower dose values suggested by direct thyroid measurements on some populations should be reviewed, as well as their associated uncertainties. Information on dose distribution and uncertainties was not sufficient for the Committee to draw firm conclusions as to whether any potential increased incidence of thyroid cancer would be discernible among those exposed to higher thyroid doses during infancy and childhood.

E34. *Leukaemia.* The Committee estimated settlement-average absorbed doses to the red bone marrow of 1-year-old evacuees before and during their evacuation to be up to 10 mGy (appendix C, section III.A.6). In the areas not evacuated, district-average doses in the first year were estimated to be up to about 5 mGy (appendix C, section III.A.5). For example, about 18,000 children in the age range of 0−5 years were estimated to live in districts where the average absorbed doses to the red bone marrow were 4 to 6 mGy. The Committee has previously assessed the risk of mortality from leukaemia due to radiation exposure for the general population of Japan [U9]. Depending on the model applied, the lifetime risk from an absorbed dose of 1 Gy to the red bone marrow in children aged 0 to 9 years at exposure was estimated to be in the range from 0.11% to 0.84%. The risk estimates were mainly based on the LSS. In the past, (e.g. at the time when childhood leukaemia could be observed in the LSS), mortality rates of the disease were very high. Therefore, the risk function for mortality from childhood leukaemia is now often used to represent the risk function for incidence of childhood leukaemia as well. For the accident at FDNPS, the WHO estimates of the risks of leukaemia due to radiation exposure [W12] were consistent with those of the Committee.

E35. Most of the radiation-induced leukaemia risk after exposure during infancy would be expressed during childhood. WHO estimated the risk of leukaemia for the first 15 years after exposure during infancy. An absorbed dose of 26 mGy to the red bone marrow was estimated to increase the risk from a baseline of 0.03% to 0.05% [W12]. This is slightly lower but broadly consistent with some recent studies of childhood leukaemia after radiation exposure [W5]. The Committee’s estimates of exposure were lower than those of WHO. Considering the exposures and risks, and the size of the exposed group, any increase in childhood leukaemia is not expected to be discernible.

E36. *Breast cancer.* The Committee estimated settlement-average absorbed doses to the breast of girls before and during their evacuation to be up to 10 mGy. In areas that were not evacuated, district-averages of lifetime doses to the breast were up to 20 mGy. The Committee previously calculated a lifetime risk of breast cancer of about 0.3% for the general female population of Japan from an absorbed dose to the breast of 100 mGy [U9]. The difference in risk due to exposure as a child compared to as an adult depends on the assessment model used [U16]. However, in some studies the risk of breast cancer from exposure as a child was estimated to be higher by a factor of three to five than the risk from exposure as an adult [U16]. Compared to a baseline risk for breast cancer of about 5.5% [W12], the Committee does not expect that any increase in future incidence of breast cancer due to radiation exposure would be discernible.

E37. *Childhood cancer after exposure in utero.* Absorbed doses in utero may increase the relative risk of childhood cancer including leukaemia [U7] (see section I.B above). The Committee estimated settlement-average doses to the uterus of pregnant women who were evacuated to districts with high deposition densities to be up to 9 mGy. It could not exclude the possibility that a small number of pregnant women may have received absorbed doses to the uterus of up to about 20 mGy. However, because of the small numbers of pregnant women and foetuses exposed at such levels, it is not expected that any increase in the incidence of childhood leukaemia or other childhood cancers would be discernible. Further, low-dose prenatal exposure at these levels would not be expected to increase the incidence of spontaneous abortion, miscarriages, perinatal mortality, congenital effects or cognitive impairment.

2. Experience from the Chernobyl accident and comparison with other sources of exposure

(a) *Experience from the Chernobyl accident relevant to the public health implications of the accident at FDNPS*

E38. The doses received by the public due to the March 2011 FDNPS accident are in general much less than those received by the population residing near Chernobyl due to the April 1986 accident. There were no deterministic effects reported among the general population after the Chernobyl accident, and accordingly none are expected after the Fukushima accident, where the doses were considerably lower. The highest doses from the Chernobyl accident were to the thyroid as a result of the intake of ^{131}I into the body [U12]. The largest doses resulted from the failure to restrict the consumption of foodstuffs containing high concentrations of ^{131}I, in particular of milk; millions of children were exposed through ingestion with tens of thousands of them receiving doses to the thyroid exceeding 1,000 mGy [U12]. After the FDNPS accident, transfer to foodstuffs was more limited because the accident occurred earlier in the growing season. Moreover, restrictions on the sale of foodstuffs with radionuclide concentrations exceeding regulatory levels were implemented relatively promptly (the first instructions on restrictions were introduced on 17 March); this greatly reduced and constrained exposures from ingestion [N1].

E39. An increase in the incidence of thyroid cancer associated with the Chernobyl accident was first identified about four years after the accident [K4]. By 2005, approximately 6,000 people, under age 18 years at the time of the accident, had been diagnosed with thyroid cancer [I2, U9, U12, W3]. It has been estimated that about 30% in Ukraine and about 60% in Belarus of the incidence of diagnosed thyroid cancer could be attributed to the radiation exposure [J1]. In comparison, doses to the thyroid for the general public following the FDNPS accident were lower.

E40. No convincing increase in the incidence of childhood leukaemia or of solid cancer (except cancer of the thyroid) was reported as a result of exposures received from the Chernobyl accident, which is not unexpected given the levels of exposure that occurred [B13, U12]. No significant increases in the incidence of birth anomalies or foetal deaths were identified that could be attributed to radiation exposure resulting from the accident [W9].

E41. Reports about survivors of the atomic bombings of Hiroshima and Nagasaki indicated a psychological aftermath that included stigma, economic and social discrimination, anxiety, depression, and post-traumatic stresses that were long term [H8, K14, L6]; these were independent of any resulting physical sicknesses [Y1] and were associated with perceptions of disease risks [K14, O4]. The psychological impact of the accidents at Three Mile Island and Chernobyl followed a similar pattern as that of the atomic bombings [B19, B20, H4]. Two studies, conducted 6–7 years after the Chernobyl accident [H3, V2], found that the exposed population had significantly poorer mental health than controls. In Gomel Oblast, mothers with young children were found to be a particularly high risk group. Both studies found that the perception of harmful levels of exposure to radiation, as opposed to the actual levels of exposure, was the key risk factor. Similarly, an increase in the incidence of psychological effects has already been observed among the general population after the FDNPS accident [Y4, Y5]. Such long-term psychological effects can be expected to occur in the population of Fukushima Prefecture.

E42. In summary, the radiation exposures resulting from the FDNPS accident are substantially lower than those after the Chernobyl accident. This suggests that any increase in the incidence of health effects among the general public resulting from radiation exposure from the FDNPS accident will likely not be discernible.

(b) *Comparison with other sources of exposure*

E43. Background exposure to natural sources of radiation results in a global average effective dose of about 2.4 mSv annually, with wide variation about this value depending on geographical location (indicatively in a range of about 1–13 mSv) [U11]. The average annual effective dose in Japan is about 2.1 mSv [N23]. The effective dose over a lifetime from naturally-occurring sources of radiation in Japan (about 170 mSv) is significantly higher than that estimated as a result of the accident for an average person living in Fukushima Prefecture (see appendix C). In contrast, the annual absorbed dose to the thyroid from natural sources of radiation is about 1 mGy, and thus the lifetime dose to the thyroid is about 80 mGy.

D. Long-term medical monitoring

E44. The Fukushima Health Management Survey [A4, Y4, Y5] was launched to “evaluate radiation doses of citizens and [record] their health conditions, with the intention of utilizing the results for prevention, early detection and treatment of possible illness”. It includes a basic survey to estimate doses from external exposure to radiation of all 2.05 million residents of Fukushima Prefecture at the time of the accident, and the following detailed surveys for selected population groups: a thyroid ultrasound examination of children, a health check, a mental health and lifestyle survey, and a pregnancies and birth survey. The investigation is planned to continue for 30 years [Y5].

E45. The basic survey started in June 2011. A questionnaire was distributed to collect information on the activities and locations of residents during the period 11 March to 11 July 2011. The response rate to the questionnaire was low, less than 30% [Y5]. Individual doses from external exposure were estimated based on a respondent’s location, using a system for assessing external doses developed by NIRS in Japan [N10]. Doses from internal exposure were measured using whole-body counting. Many measurements were performed a considerable time after the accident, making it difficult to estimate doses from internal exposure for those radionuclides with short physical or biological half-lives.

E46. Improvements in the sensitivity of diagnostic techniques for thyroid cancer, such as the advent of ultrasound and fine-needle aspiration, have enabled the detection of subclinical disease. To ensure the early identification and treatment of any thyroid cancer in the child population, and their lifelong follow-up, ultrasound examinations of the thyroid were being performed on all individuals in Fukushima Prefecture who were aged 18 years or younger on 11 March 2011. Assessment of the current thyroid status of some 360,000 eligible subjects was expected to be completed within 3 years (by March 2014). Thereafter, individuals would undergo thyroid examinations every 2 years until age 20 and every 5 years thereafter [Y5]. As of 31 July 2013, in total 41,296 children living in 13 municipalities were selected for ultrasound examinations of the thyroid before April 2012, and 135,586 children in another 13 municipalities were selected for the period April 2012 to March 2013 (table E2) [F3]. The remaining 34 municipalities of Fukushima Prefecture were selected for ultrasonographic examinations in the period April 2013 to March 2014. The participation rate was about 82%. Nodules were detected in about 1% of the surveyed persons. The rate of cysts increased from 36% among persons from the municipalities examined in 2011/2012 to 45% among persons from the municipalities examined in 2012/2013. It should be noted that these examinations were made with modern, sensitive ultrasound equipment which could detect very small cysts and nodules. Similar equipment was used from November 2012 to January 2013 in an ultrasound survey of 4,365 children and adolescents (aged between 3 and 18 years) in the prefectures of Aomori, Nagasaki and Yamanashi [T5]. These prefectures were far from FDNPS and were not significantly affected by the accident. Thyroid nodules were detected in 1.6% of the children and cysts in about 57%, rates that were even higher than those found in Fukushima Prefecture. The Committee considered that the detected prevalence in the more distant prefectures represented the normal baseline risks under intensive screening conditions and were not related to radiation exposure.

E47. Children and adolescents with cysts with a diameter larger than 20 mm or with nodules larger than 5 mm were selected for secondary examination. About 0.5% of the children surveyed in the municipalities of Fukushima Prefecture before April 2012 met these criteria (table E2) [F3]. Again, this rate was somewhat higher for children of the municipalities examined in the period April 2012 to March 2013. In the unaffected prefectures of Aomori, Yamanashi and Nagasaki, the rate was slightly higher at 1.0%, which might be due to regional variability [T5].

Table E2. Numbers of persons participating in thyroid examinations, or having a specified diagnosis

Districts of Fukushima Prefecture were selected targeted for the first ultrasonography examinations in three time periods. Results for the first two groups given here are as of 31 July 2013 [F3]. Districts of Fukushima Prefecture with very low deposition densities were to be targeted for 2013/2014. Data for three prefectures with insignificant deposition densities were as of May 2013 [T5]

Examination / diagnosis	*Municipalities in Fukushima Prefecture targeted before April 2012[a]*	*Municipalities in Fukushima Prefecture targeted April 2012 to March 2013[b]*	*Prefectures of Aomori, Nagasaki and Yamanashi*
Ultrasonography	41 296	135 586	4 365
With nodules	438 (1.0%)	1 623 (1.2%)	72 (1.6%)
With cysts	14 728 (36%)	60 382 (45%)	2 483 (57%)
Required secondary examination	214 (0.5%)	953 (0.7%)	44 (1%)

[a] *Date, Futaba, Hirono, Iitate, Katsurao, Kawamata, Kawauchi, Minamisoma, Namie, Naraha, Okuma, Tamura, and Tomioka.*

[b] *Fukushima, Hisanohama of Iwaki, Izumizaki, Kori, Koriyama, Kunimi, Miharu, Motomiya, Nihomatsu, Nishigo, Otama, Shirakawa, and Tenei.*

E48. In the municipalities of Fukushima Prefecture with examinations before April 2012, 76% (165 persons) of those selected for secondary examination had been examined by 31 July 2013 (table E3). This enabled a preliminary estimation to be made of the frequency of malignancies in this population group. Cytological analysis of thyroid tissue taken from biopsies by fine-needle aspiration classified fourteen of the nodules to be malignant. Surgery had been performed for ten of these patients. In nine cases papillary carcinoma had been confirmed. One nodule turned out to be benign; the remaining thirteen cases of suspected or confirmed malignancy corresponded to a prevalence of 13/41,296, or about 0.03%. The increased prevalence of thyroid cancer may reflect the identification of previously undetected disease with these improved diagnostic techniques and increased screening rates, rather than a true increase in the prevalence of thyroid cancer [J8]. The prevalence of clinically occult small papillary thyroid cancers (i.e. asymptomatic tumours that would remain latent, but detectable) could be as high as 35% in many parts of the world, according to findings from autopsies of young people from the general population [R4]. A fraction of these would be detected by any ultrasound screening programme. Following treatment, the 10-year survival from those types of cancer that are radiation-induced is high (about 90%) [H14].

Table E3. Persons in areas of Fukushima Prefecture participating in thyroid examinations, or having a specified diagnosis, as of 31 July 2013 [F3]

Examination	*Persons in municipalities examined before April 2012[a]*	*Persons in municipalities examined from April 2012 to March 2013[b]*
Primary ultrasonography	41 296	135 586
Required secondary examination	214 (0.5%)	953 (0.7%)
Completed secondary examination	165	431
Malignancy according to biopsy cytology	14	30
Surgery	10	9
Confirmation of papillary carcinoma	9	9

[a] *Date, Futaba, Hirono, Iitate, Katsurao, Kawamata, Kawauchi, Minamisoma, Namie, Naraha, Okuma, Tamura, Tomioka.*

[b] *Fukushima, Hisanohama of Iwaki, Izumizaki, Kori, Koriyama, Kunimi, Miharu, Motomiya, Nihomatsu, Nishigo, Otama, Shirakawa, Tenei.*

E49. This is consistent with results from a study of a cohort of Ukrainians (the “UkrAm cohort”) who had been exposed during childhood or adolescence to ^{131}I from the Chernobyl accident, where an ultrasound screening programme detected higher prevalence and incidence rates of thyroid cancer than previously reported [T23]. During the first screening of the cohort between 1998 and 2000, forty-five cases of thyroid cancer were observed among 13,127 individuals. Part of the apparent increase could be attributed to the increased detection rate due to the programme of ultrasound screening of the cohort. It was estimated that about eleven of these cases would have been detected even if there had been no radiation exposure from the accident. The component of the incidence observed after the screening but not associated with radiation exposure was estimated to be considerably higher than the normal cancer rate for the whole of Ukraine [B16, F2]. The results corresponded to a prevalence of thyroid cancer cases not related to the accidental radiation exposure of about 0.09%, a value considerably larger than that observed in Fukushima Prefecture. (The difference between screenings of the UkrAm cohort and of people in Fukushima Prefecture could be explained, in part, by differences in the average age at first screening. The UkrAm cohort was first screened at an average age of about 21 years, which was older than the average age for the Fukushima screenings. Because the incidence rate of thyroid cancer increases strongly with increasing age during adolescence and early adulthood, the prevalence in the UkrAm cohort was higher than among those screened after the FDNPS accident.)

E50. A comprehensive health check (involving measurements of height, weight, body mass index, blood pressure, blood cell counts, blood chemistry, and urine testing) was being performed for people who lived in the precautionary evacuation areas (radius 20 km from FDNPS) and in Yamakiya District in Kawamata Town, Namie Town, and Iitate Village. A survey on mental health and lifestyle was asking parents to evaluate their children using the Strength and Difficulties Questionnaire [M7]. A self-administered questionnaire was provided to those 16 years or older [K9, W6]. Clinical psychologists and other mental health specialists offered telephone counselling and psychiatric referral based on answers to the questionnaires. The size of the selected population for the health check and the mental health and lifestyle survey was 210,189 people [Y5].

E51. The pregnancy and birth survey aimed to collect data on all pregnancies and births among all women in Fukushima Prefecture who were pregnant on 11 March 2011. Survey questionnaires included antenatal health, delivery records and mental health. Telephone and e-mail hotlines had been set up and midwives or public health nurses were providing consultation services and medical referral if necessary. The total number of women targeted was 15,954 [Y5].

III. HEALTH IMPLICATIONS OF RADIATION EXPOSURE OF WORKERS RESULTING FROM THE FDNPS ACCIDENT

A. Observed health effects

E52. As of November 2012, seven deaths had been reported since 11 March 2011 among FDNPS workers (i.e. workers of TEPCO and contractors) [T11]:

(a) Two workers, aged 21 and 24, died on 11 March 2011, directly as a result of the earthquake and tsunami. They were performing inspections in the turbine building of Unit 4 of FDNPS when the tsunami inundated the site and flooded the building [I29].

(b) Three contractors died from acute myocardial infarctions while at work on 14 May 2011, 9 January 2012, and 22 August 2012, respectively. All three workers had received effective doses

from external exposure of 0.7, 6.7 and 25 mSv, respectively. Whole-body counting of two of the workers carried out a few weeks prior to their deaths showed that they had received minimal doses from internal exposure. No effect attributable to radiation exposure on the mortality from myocardial infarction has been observed among the survivors of the atomic bombings of Hiroshima and Nagasaki, who received much higher doses [S9].

(c) On 16 August 2011, a contractor died from acute leukaemia. He received an effective dose from external exposure following the accident that was recorded as 0.5 mSv; whole-body counting carried out on 7 August 2011 showed minimal dose from internal exposure. Given the very low level of exposure and the minimal latency period of 2 years for leukaemia, this death could not be attributed to radiation exposure resulting from the accident.

(d) On 6 October 2011, a contractor died from septic shock owing to a retroperitoneal abscess. He received an effective dose of 5 mSv from external exposure following the accident. Whole-body counting carried out on 9 September 2011 showed that he had received minimal dose from internal exposure. The retroperitoneal abscess could not be attributed to radiation exposure resulting from the accident.

Acute radiation syndrome was neither reported nor expected because whole-body doses were below the threshold levels for such effects.

E53. On 24 March 2011, the feet of three contractors were reportedly exposed to radioactive water in a turbine building. The absorbed doses to the skin from the radioactive water were subsequently estimated to be about 450 mGy for two of the contractors and for the third essentially no dose to the skin from the radioactive water was estimated. However, in addition, during the same day the workers' skin was also exposed to gamma radiation in the air. Conservative estimates of the dose from this route of exposure were added to the dose to the skin from the radioactive water to give total absorbed doses to the skin of the feet, specifically about 650 mGy for two of the contractors and about 170 mGy for the third [T10]. After four days of hospitalization they were released with a prognosis of no likelihood of significant long-term harm [I6]. Assuming the dose estimates were correct, the Committee agreed with this prognosis. Further, no radiation-induced health effects were ever observed from this exposure; the estimated doses were far lower than the threshold values for skin damage [I13].

E54. On 29 October 2011, an accident occurred in which two workers were struck by the release of retaining wires on a crane. One worker had both of his legs broken and the other sustained injuries to his shoulders and other areas of his body. The worker with broken legs had surgery at Fukushima Medical University Hospital and was transferred to an Intensive Care Unit. The other worker was transported to Sogo Iwaki Kyoritsu Hospital after first receiving treatment at the medical unit at J-Village, which was a facility used as a base for FDNPS workers following the accident [I4].

E55. Approximately 17,500 stable iodine tablets (50 mg as potassium iodide) were distributed to about 2,000 workers involved in the emergency response [K11]. No immediate side effects, such as anaphylaxis with iodine hypersensitivity, were observed. Approximately 230 workers received health check-ups (from 13 March 2011 to 3 October 2011) because either they took stable iodine continually for more than 14 days, or received more than 20 tablets. Health check-ups were performed by J-Village Medical Centre or the Health Management Group of TEPCO Head Office. Blood tests were performed. Three workers had transient changes in the thyroid hormones TSH and FT_4. Four workers had TSH levels greater than 5.0 µIU/mL and normal FT_4 levels. This was not acknowledged as an increased rate of hypothyroidism attributable to distribution of stable iodine for thyroid blocking, because between 1% and 3.5% of males in the population normally has potential hypothyroidism.

B. Risk assessment conducted by WHO

E56. WHO conducted a health risk assessment [W12] that considered FDNPS workers employed by TEPCO and contractors exposed during the emergency phase. A preliminary dose estimation had been performed based on data provided by the Japanese government and TEPCO by mid-September 2011. The WHO assessment addressed 23,172 workers assigned to one or other of the following four exposure scenarios:

- Scenario 1: workers with very low doses to all tissues (absorbed doses to bone marrow, colon and thyroid: 5 mGy);

- Scenario 2: workers who received moderate doses to the thyroid and low doses to other tissues (dose to bone marrow and colon: 24 mGy; dose to thyroid: 140 mGy);

- Scenario 3: workers who received moderate doses to tissues (dose to bone marrow and colon: 200 mGy; dose to thyroid: 200 mGy);

- Scenario 4: twelve workers who received high doses to the thyroid and low to moderate doses to other tissues (dose to bone marrow and colon: 100 mGy; dose to thyroid: 11,800 mGy).

About 99% of the workforce involved with the emergency and subsequent mitigation were covered by Scenarios 1 and 2; the remaining 1% of workers assigned to Scenarios 3 and 4 comprised those at the upper bounds of internal and external exposure. These scenarios had been developed as part of the WHO study before individual dosimetric and bioassay data were available. They are, however, broadly consistent with the individual dosimetric data that were made available to the Committee (see section V and appendix D).

E57. More recent data have indicated that the doses from internal exposure for the majority of workers included in Scenario 1 were predominantly due to ^{131}I rather than $^{134/137}$Cs alone as assumed by WHO; this would have resulted in higher estimates of doses to the thyroid but lower estimates of effective doses. Data made available to the Committee also showed that there were 173 workers who had received effective doses greater than 100 mSv, rather than the 87 identified by WHO in specifying Scenarios 3 and 4.

E58. Lifetime attributable risk (LAR) of cancer occurring as a result of radiation exposure was calculated using the same method as was used for the general population (see section II.B of this appendix). According to the WHO report, about 50% of the workers were in the age range from 30 to 49 years at 31 January 2012. Estimated risks for workers exposed at age 40 are summarized in table E4; the LAR for exposure at age 20 was estimated to be higher by about 70%, and that at age 60 to be lower by about 50%.

E59. The WHO also assessed risks of effects other than cancer for the emergency and mitigation workers [W12]. They did not expect any deterministic effects, apart from possible thyroid disorders among the twelve workers of Scenario 4. They identified that there might be an increase in the risk of long-term circulatory disease among the workers of Scenario 3. They stated that any risk of hereditary effects among the offspring of workers involved in the emergency and subsequent mitigation would be much lower than the additional cancer risk for these workers.

Table E4. WHO estimates for FDNPS workers of lifetime attributable risks of leukaemia, thyroid cancer and all solid cancer, and percentage increase over lifetime baseline risk [W12]

Results are given for age 40 years at exposure and rounded

Exposure scenario	*Cancer type*	*Assumed dose (mGy or mSv)*[a]	*Lifetime risk (%) attributable to radiation exposure*	*Percentage increase over the lifetime baseline risk*
3	Leukaemia	200	0.12	23
	Thyroid cancer	200	0.02	8
	All solid cancer	200	2.0	5
4	Leukaemia	100	0.06	11
	Thyroid cancer	11 800	0.9	480
	All solid cancer[c]	100[b]	1.9	5

[a] *Dose to bone marrow for leukaemia, dose to thyroid for thyroid cancer, and dose to colon for all solid cancer combined.*

[b] *Dose to all organs except to the thyroid, which was assumed to be 11,800 mGy.*

[c] *Includes the risk of thyroid cancer taking into account the relatively high absorbed dose to the thyroid, while the WHO report calculated the risk of all solid cancer assuming that the absorbed dose to all organs except the thyroid was equal to the dose to the colon.*

C. The Committee's commentary on health implications for workers

E60. The Committee based its commentary on the same assumptions as for members of the public, modified as appropriate to match the worker population, and on the doses to workers reported in appendix D. Similar to its commentary on health implications for the public, qualitative estimates were made of disease outcomes, where the Committee has used the phrase "no discernible increase" where, although a disease risk in the longer term can be theoretically inferred on the basis of existing risk models, an increased incidence of effects is unlikely in practice to be observed in future disease statistics using currently available methods, because of the combination of the limited size of population exposed and low exposures, i.e. consequences that are small relative to the baseline risk and their uncertainties.

1. FDNPS workers

E61. The effective doses received by most of the FDNPS workers (99.3%) as a result of the accident were estimated to be less than 100 mSv with an average of about 10 mSv. The risk of these workers developing radiation-induced cancer is low (cf. the WHO estimates [W12]). There are distinct groups of more highly exposed workers; an assessment of the health implications for these groups is made below.

E62. *Cancer among workers receiving the highest effective doses.* A group of 160 workers received an effective dose equal to or in excess of 100 mSv, predominantly from external irradiation. The average effective dose in this group was about 130 mSv. If the group of 13 workers with high doses to the thyroid were included, the average effective dose would increase to about 140 mSv among a group of 173 workers (see below). Based on current understanding of risks, about two to three additional cases of cancer could on average occur in this group in addition to about seventy baseline cancers expected to occur in the absence of exposure (see table E1), although the uncertainties in such estimates are substantial. Such an increase occurring during the lifetime of the exposed individuals would not, however, be discernible because fluctuations of cancer incidence in groups of this size are considerably larger. The statistical power of detecting such an increase would be about 10%; for conducting a meaningful epidemiological study, a statistical power of 80% would usually be required.

E63. About one baseline leukaemia case would be expected to occur among a group of 173 male adult Japanese workers during their lifetime (noting the uncertainties associated with such estimates). A whole-body exposure of an adult male with an effective dose of about 140 mSv has been assessed to lead to a relative risk of about 1.2 for exposure at age of 20 years, and lower for exposure at older ages [W12]. Because of the small numbers involved, it is not expected that any potential increase in leukaemia incidence would be discernible.

E64. *Thyroid disease and disorder*. Approximately 2,000 workers (as of June 2013) received thyroid doses exceeding 100 mGy [M16], with an average dose of the order of 400 mGy. The question of whether the risk of thyroid cancer is elevated following exposure during adulthood in the interval 100 mGy to 1,000 mGy is under debate [M1, R5]. WHO estimated the risk at different ages at exposure: for a thyroid dose of 400 mGy at an age of 40 years, they estimated the relative increase of lifetime thyroid cancer risk to be 16% [W12]. Ultrasound surveys of these workers will increase the detection rate of baseline and potential radiation-induced thyroid cancer cases; the number expected to be detected will exceed considerably the number expected on the basis of reported incidence of thyroid cancer among population groups that do not undergo such surveys. Although there are very large uncertainties in estimating the risk of radiation-induced thyroid cancer, any increase in the incidence due to radiation exposure is not expected to be discernible.

E65. Thirteen TEPCO workers were estimated to have received committed absorbed doses to the thyroid in the range of 2 to 12 Gy, with an average of about 5 Gy. The two TEPCO operators in the control rooms for Units 3 and 4 who received the highest total effective doses (679 and 646 mSv, respectively), the highest cumulative effective doses from internal exposure (590 and 540 mSv, respectively), and who had not taken potassium iodine for thyroid blocking prior to their exposures, had no early deterministic health effects as a result of their exposures [I29]. The probability of occurrence of excess thyroid cancer cases during the lifetimes of the thirteen workers is small, because thyroid cancer is a rare disease even after high exposures (see the WHO estimate as outlined in table E4).

E66. Hypothyroidism (i.e. transient elevation of TSH) is a late deterministic effect observed after external radiotherapy of the neck and following nuclear medicine procedures using radioactive isotopes of iodine that deliver several grays [H2, H15, L2, M9, M10, O6, P5]. It has also been observed following heavy fallout from nuclear weapons testing in 1954 [C10]. Excess incidence of thyroid nodules have also been reported following external irradiation resulting from medical procedures or high levels of radioactive fallout [C10, N4, R7] and following protracted exposure to radioactive iodine [H1, L1, L2, Z1]. Given the magnitude of inherent uncertainties in the dose estimates, the Committee could not preclude the possibility of hypothyroidism among the more exposed workers. A particular issue is the suggestion that ionizing radiation induces Hashimoto thyroiditis (autoimmune thyroiditis). In its 2008 Report, the Committee stated that there had been few studies of significant size that had addressed the relationship between this disease and exposure to radiation, and that the largest study could not demonstrate any conclusive evidence of a relationship [U12].

E67. *Other diseases and health effects.* There is little likelihood of an excess incidence of circulatory diseases at the dose levels incurred by the group of workers with the highest effective doses [I26, S5, U9]. Beta particles may have contributed substantially to the dose to the eye lens of the workers. No direct information on beta-radiation fields at FDNPS was available to the Committee. For workers involved in response and recovery after the Chernobyl accident, the contribution of beta particles to the dose of the eye lens ranged between 0% and 350% of the dose from gamma irradiation (see annex D [U12]). Recently, ICRP published a statement on tissue reactions and considered a threshold level of absorbed dose to the lens of the eye of 500 mGy for tissue reaction effects [I26]. If the relative contribution of beta particles to the dose to the eye lens of workers at FDNPS were not higher than after the Chernobyl accident where posterior subcapsular cataracts have been detected, then no discernible excess incidence of cataracts due to the FDNPS accident would be expected. However, uncertainties remain about the doses to the eye lens and the dose–response relationship for cataracts.

E68. After technological disasters, the prevalence of post-traumatic stress disorder (PTSD), characterized by symptoms such as flashbacks, nightmares, hyper-vigilance and avoidance of reminders of the event, ranges from 15% to 75% [N9], depending on the gravity, severity and level of threat from the disaster, the population affected and the timing of the study.

E69. Initial observations have identified severe psychological effects following the earthquake, tsunami and FDNPS accident among emergency workers [M8, S7, S8, W1]. An initial voluntary self-reported questionnaire on the psychological status of workers at TEPCO's Fukushima Daiichi and Daini nuclear power stations was conducted 2 to 3 months after the disaster [S7]. Psychological distress and PTSD were observed among radiation workers. They reported intrusive flashbacks, avoidance of the plant, hyper-vigilance toward aftershocks, fear of irradiation and dissociative episodes. These health implications should not be attributed to radiation exposure itself, because they have been evoked by many other causes. Some workers suffered public harassment and were severely discriminated against as a result of TEPCO's negative image. In addition, many of them lived within the 20-km radius of the FDNPS while their families had been evacuated; they had experienced first-hand deaths from the tsunami, were placed in temporary housing with poor living conditions, and had been working long hours. Occupational health physicians and nurses provided mental health checks and consultations for the workers; however, there is a lack of trained psychiatrists for primary prevention of stress [S7, W1].

2. Experience from the Chernobyl accident relevant to the health implications of the FDNPS accident for workers

E70. In terms of health implications for workers, the Chernobyl accident differed from the FDNPS accident in many ways. The average effective dose received by the 530,000 Chernobyl recovery workers between 1986 and 1990, mainly from external exposure, was estimated to have been about 120 mSv. Some recovery workers received very high doses; for example, for 51 Russian Federation and 168 Ukraine recovery operation workers each receiving an effective dose in excess of 1 Sv, their average dose was as high as 9.4 Sv and 6.9 Sv, respectively [U12].

E71. In comparison, there were only 3,973 workers on-site at FDNPS during the first month after the accident and they received an effective dose during this period of about 21 mSv on average (see table D3). The highest effective doses (250−679 mSv) occurred among 6 TEPCO workers in the first month. During the first 19 months, 99.3% of 24,832 TEPCO and contractor workers were recorded as having an effective dose lower than 100 mSv and on average about 10 mSv; the remaining 173 workers received doses in excess of 100 mSv with an average of about 140 mSv. For all these workers, recorded doses over this period ranged from less than 10 mSv to 679 mSv. Although the periods of exposure differ significantly, these levels are far below those experienced by the Chernobyl recovery workers. Only doses to the thyroid of the six TEPCO workers with the highest effective doses reached levels received by the most exposed Chernobyl recovery workers.

E72. After the Chernobyl accident, acute radiation sickness (ARS) was diagnosed for 134 of the first responders and firefighters, 28 of whom died of ARS within a few months [U12]. In contrast, the FDNPS accident did not result in any cases of ARS.

E73. A radiation-related increase in the incidence of all solid cancers has been reported for the Russian Chernobyl recovery workers [I37], although not in another, albeit much smaller, study of recovery workers from Estonia [R2]. Owing to the much smaller number of workers exposed and their lower exposures, it is not expected that there will be an observable radiation-related general increase in the incidence of solid cancer among the FDNPS workers [P15, U11, U12].

E74. Elevated rates of thyroid cancer among the Chernobyl recovery workers compared with the general population have been reported; but no clear association with radiation dose has been found [I36, K8, M1, U12]. Similar results might be expected for the FDNPS workers, as a result of intensive thyroid screening, although substantially fewer workers were involved and they received lower doses.

E75. Studies of the Chernobyl recovery workers suggest an increase in the incidence of leukaemia. The limitations of these studies include uncertainties in dose reconstruction, potential biases and confounding factors [I38, K7, R6, U12]. A recent article reported statistically significant effects [Z2], however exposure estimates were based on proxy interviews, which implies a high uncertainty and potential for bias. The workers at FDNPS who incurred the highest external exposure received doses to the bone marrow of at most 200 mSv. Owing to the small number of workers involved, no discernible effect of the radiation exposure on leukaemia incidence is expected.

E76. Few studies assessed circulatory disease among the Chernobyl workers. More evidence is needed to conclude whether or not radiation exposure at doses below 500 mGy increases the risk of circulatory disease. Radiation doses of FDNPS workers were too low to expect an observable excess incidence of radiation-induced circulatory disease in the future. However, there may be secondary effects due to psychological stress that confound any relationship with radiation exposure.

E77. There have been two lines of research on the psychological impact of the Chernobyl accident on recovery workers: *(a)* potential radiation-related cognitive impairment; and *(b)* the psychiatric effects of exposure-related stress [B18].

(a) Four studies conducted in Kiev provide suggestive evidence of measurable cognitive or neuro-psychiatric effects of radiation exposure among highly exposed recovery workers [G1, L11, L12, P11]. Although consistent and suggestive, methodological limitations of the studies prevent general conclusions being drawn [B17, B19, W7].

(b) Significant long-term psychiatric effects are well documented among recovery workers following the Chernobyl accident [L10, R1, R3, V1]. Initial observations have identified psychological effects among FDNPS radiation workers following the earthquake, tsunami and nuclear accident [M8, S7, S8, W1].

D. Long-term medical monitoring

E78. On 3 August 2011, the Japanese Ministry of Health, Labour and Welfare (MHLW) announced the “grand design of a long-term health management of all the emergency operations workers at TEPCO’s No. 1 Fukushima Nuclear Power Plant” [M14]. The database would be constructed to contain radiation dose records that are systematically collected, and information about long-term health conditions of emergency operations workers. Health management would be provided by employers while workers were employed, and contact points located throughout Japan would be determined to provide appropriate long-term health management, consultation and regular health examinations of workers after leaving their workplace. Periodic health examinations would be given to workers to monitor for potential late radiation-related health effects. Special health examinations would be given to workers with the highest exposures, including annual eye check-ups (for lens opacity), and monitoring of the thyroid, stomach, large intestine and lung for cancer.

E79. Ultrasonography was planned to be performed for all emergency workers with absorbed doses to the thyroid exceeding 100 mGy. The eligible group consisted of about 2,000 workers. Modern ultrasonography is able to detect very small tumours; however the probability of occurrence of thyroid cancer due to radiation exposure in adulthood is small and would be unlikely to manifest as a discernible increase in statistics on cancer incidence [D2, F6].

E80. Three studies of cancer mortality among Japanese workers exposed occupationally in the nuclear industry have been previously conducted [A7, H11, I39]. The average cumulative effective dose ranged from about 12 to 15 mSv in these studies; this is similar to the dose received by most FDNPS workers as a result of the accident (average about 12 mSv from the accident until October 2012, see table D4). In one of the three analyses [I39], 4,161 workers had received doses over 100 mSv, with a mean dose of 154 mSv. This compares to only 173 FDNPS workers with doses greater than 100 mSv and an average dose of about 140 mSv. Because no change in the mortality rates due to cancer was detected among Japanese nuclear industry workers with follow-up from 1986 to 2002, it is unlikely that a study of the FDNPS workers would discern a difference in the mortality rate from that of the general population, or that a significant relationship between radiation dose and cancer mortality be any different from that found among other Japanese nuclear industry workers. Studies would lack sufficient statistical power to assess the risk of cancer due to irradiation; the doses would be too low and the population size too small [B13, W4]. Likewise, excess screening and diagnostic suspicion may bias studies of FDNPS workers, in particular detecting a greater incidence of small tumours, unrelated to radiation exposure, than would otherwise have been detected.

E81. Despite these scientific limitations, it is important that FDNPS workers be included in the existing Japanese nuclear worker cohort, and that long-term cohort studies of these workers be conducted. Finally, studies of the mental and physical health of workers exposed after the Chernobyl accident were conducted separately instead of integrating cohort studies of cancer and other disease outcomes with mental health research. If mental health measures were embedded in the Japanese nuclear worker cohort, the combined approach would track mental health effects and provide a unique opportunity to advance understanding of risk factors, such as perceptions about the health impact of radiation exposure and synergistic psychological effects of stress with radiation exposure [B19, B20]. Indeed, future studies of the FDNPS workers could improve understanding of the association of PTSD and depression with circulatory risk and recovery [K26] and other medical conditions [V5].

APPENDIX F. ASSESSMENT OF DOSES AND EFFECTS FOR NON-HUMAN BIOTA

I. INTRODUCTION

F1. This appendix underpins the Committee's findings regarding the exposure of non-human biota to ionizing radiation resulting from the accident, and any associated effects. Similar to humans, any organism in the natural environment can be exposed both *(a)* internally to incorporated radionuclides taken up from the environment, and *(b)* externally to radiation from sources in its habitat. The Committee had assessed exposures of non-human biota and associated effects in general in its scientific annexes to the 1996 [U6] and 2008 [U12] Reports. The consequences of radiation exposure for non-human biota can include increases in morbidity and mortality, decreases in fertility and fecundity, and increases in mutation rate. These types of effects, if observed at the level of the individual organism, may have consequences for a population of species. The Committee concluded that chronic dose rates of less than 100 µGy/h to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial communities, and that maximum dose rates of 400 µGy/h to any individual in aquatic populations of organisms would be unlikely to have any detrimental effects at the population level [U12]. Benchmarks developed for other contrasting purposes have also been published. For example, the ERICA[43] and PROTECT[44] projects [A10, G2] suggested a generic dose rate of 10 µGy/h for use in screening out situations of environmental exposure that were of negligible concern. The International Commission on Radiological Protection (ICRP) has also published "derived consideration reference levels" (DCRLs), which can be used to identify where there is likely to be some chance of

[43] ERICA = "Environmental Risks from Ionising Contaminants: Assessment and Management" an EC EURATOM Framework 6 funded project.
[44] PROTECT = "Protection of the Environment from Ionising Radiation in a Regulatory Context" EC EURATOM Framework 6 funded project.

deleterious effects of exposure to ionizing radiation on individual reference animals and plants [I22]. The values of DCRLs published are broadly consistent with the benchmarks presented above (see [U12]).

F2. As a consequence of the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS), terrestrial, freshwater and marine ecosystems were exposed to ionizing radiation. The exposure of non-human biota varied greatly in space and time reflecting large heterogeneities in radionuclide concentrations in the environment and in the time-dependent processes influencing radionuclide transfer through the environment and into organisms. Moreover, in any case, radiosensitivity of non-human biota varies widely between species and according to a complex dynamic of interactions between absorbed doses (or dose rates) and responses to radiation expressed at different levels of biological and ecological organization.

F3. *Published assessments.* Garnier-Laplace et al. [G3] calculated dose rates to selected organisms for the first three-week period after the accident. Their estimates of the absorbed dose rate to forest biota (including contributions from internal and external exposure) ranged from 2 mGy/d (in birds) to 6 mGy/d (in small mammals), accounting for a series of measured radionuclides. They considered that cytogenetic damage would certainly be measurable but that potential alterations to reproduction for conifers and vertebrates might be difficult to discern against the high natural variability. They estimated that, as a consequence of the peak release to the marine coastal zone, maximum dose rates to selected marine organisms ranged from 210 to 4,600 mGy/d. The authors considered that “At such high dose rates, marked reproductive effects, and even mortality for the most radiosensitive taxa are predicted for all marine wildlife groups whose life history characteristics confine them to the near-field, contaminant release area”. These exposure estimates were orders of magnitude higher than those calculated by Kryshev and Sazykina [K25], who considered a more limited set of radionuclides, restricted their analyses to internal exposure, and used substantially lower values for concentrations of radionuclides in seawater as input data. Kryshev and Sazykina considered that no detrimental effects to populations of marine organisms would arise from their calculated dose rates.

F4. *Reported observations.* As of December 2012, a few papers had been published reporting field observations on wildlife in terrestrial ecosystems within 100 km of FDNPS. Møller et al. [M22] reported an apparent negative correlation between the levels of ambient dose equivalent rate and the abundance of common birds in the Fukushima area. The abundance of several invertebrates and birds were determined by Møller et al. [M23] at over one thousand sites in the vicinity of the Chernobyl nuclear power plant and FDNPS. While all taxa showed significant declines in abundance with increasing level of ambient dose equivalent in the Chernobyl case, only three out of seven taxa showed such an effect for the Fukushima case.

F5. Hiyama et al. [H6] studied morphological and genetic characteristics of the pale grass blue butterfly *Zizeeria maha*. They collected first-voltine adults in the Fukushima area in May 2011. Some of these individuals showed relatively mild abnormalities. The F1 offspring from the first-voltine females showed more severe abnormalities, which were inherited by the F2 generation. Furthermore, adult butterflies collected in September 2011 showed more severe abnormalities than those collected in May. The authors concluded that artificial radionuclides from FDNPS caused physiological and genetic damage to this species and that the cumulative effects of exposures could have resulted in deterioration of the population.

F6. With regard to the above field studies, the Committee noted that uncertainties with regard to dosimetry and possible confounding factors (including the impact of the tsunami itself) made it difficult to substantiate firm conclusions. Furthermore, the main body of scientific data did not support the appearance of such effects at the dose rates recorded [A10, G2, I22, U12]. Most notably, in the study of Hiyama et al. [H6], manifestation of similar effects under laboratory conditions required radiation exposures that were considerably higher than those observed in the field.

F7. The Committee assessed the impact of radiation exposure resulting from the FDNPS nuclear accident on non-human biota inhabiting terrestrial, freshwater and marine ecosystems. The assessment was based largely upon measured data provided to the Committee, other relevant reports and published scientific papers. The radiation exposures were considered in terms of *(a)* the intermediate phase after the accident (approximately the first two months) and *(b)* the late phase (months to years). The Committee considered some areas of Fukushima Prefecture and neighbouring prefectures in detail within approximately 100 km of FDNPS with the highest deposition density of radionuclides.

II. METHODOLOGY TO ESTIMATE DOSES TO NON-HUMAN BIOTA

F8. Apart from direct observation, the presence or absence of radiation effects on non-human biota can be inferred through comparing exposure levels with relevant benchmarks. Prerequisites are robust estimates of absorbed dose and dose rates to biota in both time and space; the estimates are made by applying suitable assessment models. The primary source of data for the Committee's assessment was the information provided by the Government of Japan, which is discussed in appendix A along with considerations of its quality for the purpose of the assessment. Other datasets were also used [G11]. The datasets covered terrestrial, freshwater and marine environments, and characterized the levels of terrestrial deposition density of radionuclides and radionuclide concentrations in soils, aquatic sediments, and terrestrial and aquatic biota. The methodology used is described in detail in attachment F-1; a summary is provided below.

F9. The dose assessment methodology used by the Committee was based on the ERICA Integrated Approach [L3], making use of the ERICA assessment tool [B22], a software tool with supporting databases developed to calculate absorbed doses to non-human biota and to assist with analysing effects. The methodology consisted of the following steps: *(a)* select key species and radionuclides for analysis; *(b)* conduct the assessment preferably using actual radionuclide concentrations in biota, measured over time and space from the first day of the accident; additionally or alternatively *(c)* use equilibrium models (applying concentration ratios) to derive radionuclide concentrations in biota from those in media (such as soil and water) or *(d)* use dynamic models to calculate dynamic concentrations in biota based on measured concentrations in media; and *(e)* perform dose calculations using dose conversion coefficients (DCCs) from the ERICA Tool and make projections of dose rate as a function of time, from which integrated doses can be calculated. From this, the possibility of radiation effects on non-human biota could be assessed. This approach was considered to be the most appropriate, robust and practicable way of estimating the absorbed doses and dose rates to non-human biota, drawing on empirical data as far as possible, while relying on generic transfer parameters when such data were unavailable.

F10. In view of the great variety of plants and animals that can be exposed at any given site, it has been argued [P2] that an assessment can be reduced to manageable proportions by adopting reference exposure and dose models. The Committee has adopted this approach [U12], which is also in line with recommendations of the ICRP [I22]. The reference organisms selected in the UNSCEAR 2008 Report formed the basis for the exposure estimates made in the Committee's assessment (table F1). The radionuclides considered were selected primarily on the basis of data availability, their relative importance radiologically, and experience from other situations where radioactive material was released into the environment (e.g. past accidents).

Table F1. Reference organisms selected by the Committee [U12] for assessing exposures

Earthworm/soil invertebrate	Rat/burrowing mammal	Bee/above ground invertebrate
Wild grass/grasses, herbs & crops	Pine tree/tree	Deer/herbivorous mammal
Duck/bird	Frog/amphibian	Brown seaweed/macroalgae
Trout/pelagic fish	Flatfish/benthic fish	Crab/crustacean

F11. For terrestrial biota the equilibrium-based whole-body concentration ratio (CR) is defined as the concentration of a radionuclide in the whole organism at equilibrium divided by the concentration of the same radionuclide in soil. For aquatic organisms, the denominator is the concentration of the radionuclide in water. The Committee used the database on transfer factors in the ERICA Tool (based upon [B4, H12]), supplemented by more updated information provided by ICRP [I23], to derive radionuclide concentrations in non-human biota. While the intended application of this approach was for assessing the impact of routine releases of radionuclides to the environment, the approach was used by the Committee for a dynamic situation. Consequently, there may be substantial inaccuracies in the estimates of exposure.

F12. In contrast to equilibrium models, dynamic models typically characterize the environment in terms of compartments that represent distinct features, for example, soil layers and body organs. Rate constants are often used to express the exchange between compartments. When simulations are performed using a mathematical representation of the system, the net result is a description of the evolution of radionuclide concentration with time. Because of their somewhat different attributes, the dynamic models used for terrestrial and aquatic ecosystems are described separately below.

F13. Once radionuclide concentrations in environmental media and biota had been calculated, absorbed dose rates were derived by applying DCCs from the ERICA Tool. Occupancy factors for organisms were selected to represent exposure to simplified, yet realistic, source geometries. Absorbed dose rates were weighted by modifying factors to reflect the relative biological effectiveness of different radiation types in line with those applied in the UNSCEAR 2008 Report, and then the weighted absorbed dose rates from external and internal exposure were summed. The dosimetric calculations underpinning the derivation of DCCs are explained in detail elsewhere [U1, U2]. Radionuclide decay chains were truncated at the first radionuclide with a half-life of more than 10 days. The DCCs of shorter-lived radioactive progeny in the decay chain were then amalgamated with the DCC of their longer-lived parent. DCCs for internal exposure were derived assuming a homogeneous distribution of the radionuclide in the organism; the error introduced by this assumption is, in view of the assessment goals, considered to be of minor significance [G10].

A. Terrestrial environment

1. Using direct measurements and equilibrium models

F14. Data on radionuclide deposition densities were available for the period June–July 2011 and measurements of radionuclide concentrations in animals and birds were available primarily from September 2011 to March 2012. In order to estimate the corresponding deposition densities at the locations where direct measurements of radionuclide concentrations in animals were available and over their home range, it was necessary to interpolate between points where deposition densities had been measured. Empirical Bayesian Kriging (EBK) was used to construct maps of interpolated radionuclide deposition density and absorbed dose rate for the Fukushima area [G12, K22, P8]. Kriging methods also provide an estimate of uncertainty in the calculated values; in contrast, deterministic interpolation methods, like inverse distance weighting (which produce an interpolated raster based on surrounding data only) do not. The advantage of using EBK was that it required only minimal tuning of the semi-variogram model. The resulting raster for deposition density of ^{137}Cs is presented in figure F-I, together with the sampling locations of the animals measured.

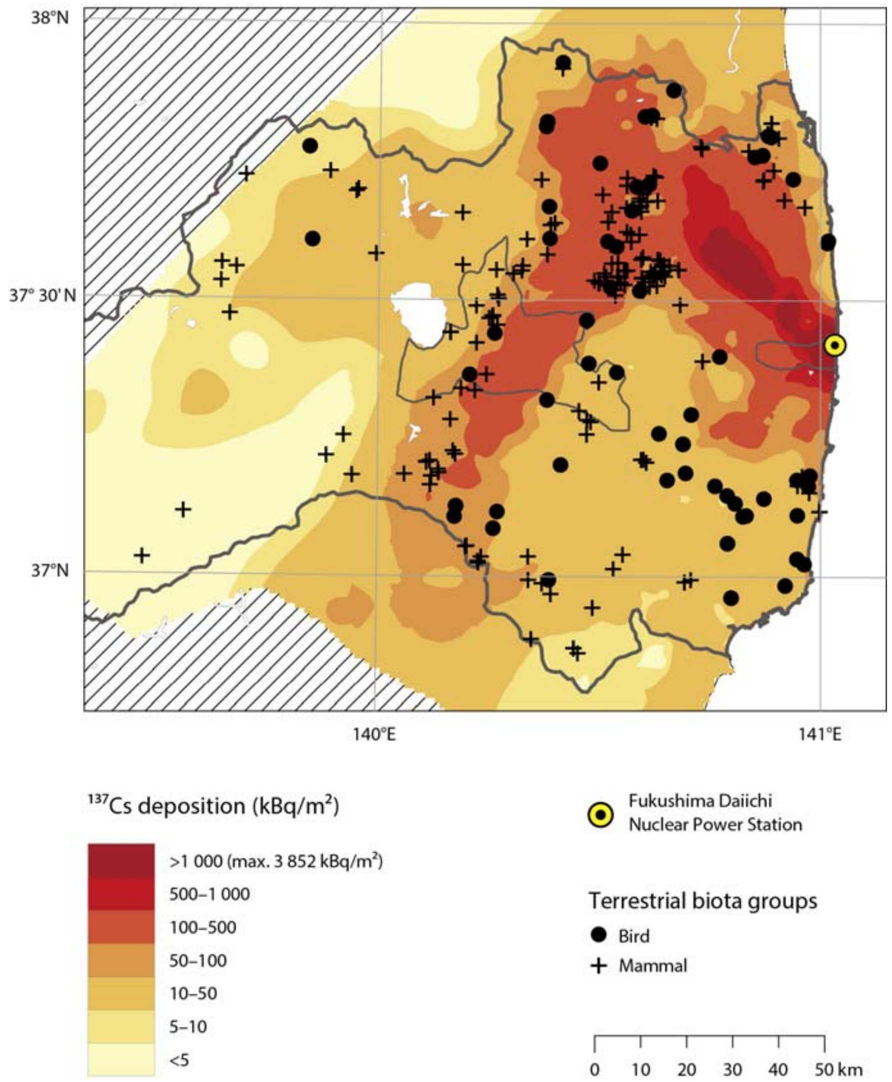
F15. The Committee used available measurements of concentrations of ^{131}I, ^{134}Cs and ^{137}Cs in mammals and birds to derive absorbed dose rates due to internal exposure directly. Additional information such as mass and length of the animal was used in selecting an appropriate model geometry to derive DCCs for internal exposure. Life history data sheets, containing basic ecological information such as the home range for selected organisms, were collated (attachment F-2) to assist calculation of absorbed dose from external exposure. There were distinct geographical clusters of samples for wild boar, whereas the data were more spread and without apparent clustering for other mammals and birds. For the spatial clustering of the wild boar data, an algorithm [K2] was applied to focus analysis on wild-boar groups with an average home range of 3 km. Owing to the limitation of available empirical data, this cluster approach was not applicable to other biota. To determine the range of exposure for other mammals and birds, data from Koriyama City were used as input to the dose-rate calculations (attachment F-2) because they covered all species of interest and reflected a wide range of deposition density. In order to extend data on deposition density for ^{137}Cs to all other radionuclides, scaling was applied using radionuclide ratios.

F16. Maps of interpolated absorbed dose rates to selected organisms were created, starting from deposition density data and using CRs to calculate values of radionuclide-specific absorbed dose rates. For comparison, both planar and volumetric source geometries were assumed to estimate absorbed doses from external exposure to large mammals; this comparison showed that using a volumetric source geometry provided slightly higher estimates of absorbed dose rate for radioisotopes of caesium. Locations of maximum deposition density, such as Okuma Town, were considered in detail to derive upper estimates of the absorbed dose rates and to gain insight on the various contributors to the absorbed dose rate. The input data used are provided in attachment F-2.

F17. Preliminary work on the data for Koriyama City showed that using default values of CRs had a tendency to overestimate the radionuclide concentrations in the organisms considered. Because caesium isotopes were the main contributors to absorbed dose rates once short-lived radionuclides had decayed, the available information was used to derive values of CRs that were more region-specific for caesium and for the animal groups under consideration. These values were then used in the subsequent dose-rate mapping. A further equilibrium-based analysis accounted for radioactive decay between the time of sampling and the initial deposition event.

Figure F-I. Deposition density of ^{137}Cs with sampling locations of mammals and birds overlaid

The municipal areas of Okuma Town (furthest East) and Koriyama (mid-figure) are delineated. There were 12 measurement points that exceeded 5 MBq/m^2 but these extreme data values are not illustrated with the Kriging interpolation method



2. Using dynamic models

F18. The FASTer model is a multi-compartmental model that can be used to simulate radionuclide transfer through a simple terrestrial food chain. The model was used to derive radionuclide concentrations in flora (vegetation including herbaceous plants, shrubs and trees) from deposition densities, using an expression that accounts for interception by foliage, growth dilution, weathering losses of radionuclides from vegetation, and the direct deposition onto soil and subsequent uptake from soil to plant. The model is described in more detail elsewhere [A13, B6, F1]. However it was parameterized using values specific to the environmental conditions at the time of the accident and subsequent months (see attachment F-1).

F19. As detailed in appendix B, a major wet deposition of radionuclides occurred on 15 March in the northern part of Fukushima Prefecture. This date was thus selected as a suitable time for which to assign the initial values for parameters, such as the biomass and the interception fraction, needed for the model simulations.

B. Aquatic environments

1. Using measurements of biological samples

F20. *Freshwater environment.* Results of measurements of ^{131}I, ^{134}Cs and ^{137}Cs in freshwater biota (predominantly radiocaesium concentrations in fish) from the prefectures of Fukushima, Iwate, Miyagi, and Ibaraki were provided to the Committee. None of the sampling stations were from the area of maximum deposition density (above 1,000 kBq/m^2); therefore, levels in fish for this area were reconstructed using correlations between deposition densities and radionuclide concentrations in fish for Japanese lakes. These data and interpolated values constituted the input datasets for estimating exposure (attachment F-3).

F21. The highest concentrations of radiocaesium in freshwater fish had been measured in a local area situated to the north and north-west of the FDNPS site (37.6–37.7°N; 140.5–140.9°E), characterized by deposition density of ^{137}Cs in the range 100–200 kBq/m^2. The typical concentration of radiocaesium in fish in this area was about 2–3 kBq/kg fresh weight; the maximum concentration measured had been in a single fish sampled in March 2012 and was 18.7 kBq/kg fresh weight. The very limited data on radionuclide concentrations in sediment from water bodies in this area indicated levels of 4.4 kBq/kg (dry weight) of ^{134}Cs, and 5.5 kBq/kg (dry weight) of ^{137}Cs.

F22. *Marine environment.* Results of measurements of marine organisms were provided to the Committee. The data for ^{137}Cs in marine fish, collated for the period from May 2011 until June 2012, were too scattered to confirm any definite trends, and there appeared to be no obvious substantial decrease in concentrations over one year of monitoring [B24]. On closer inspection there was a suggestion of an increase up to a maximum value around mid-May 2011, possibly followed by a slight decrease in levels. In contrast, changes in ^{137}Cs concentrations in seawater with time for the offshore coastal zone (out to 15–20 km from the FDNPS site) were quite dramatic, falling from levels exceeding 100 kBq/m^3 to around 1 kBq/m^3 by the end of 2011. Some of the highest levels of radiocaesium concentration, of the order of several hundred thousand becquerels per kilogram (fresh weight), were reported in benthic fish collected from within the port area adjacent to FDNPS in early 2013 [T18]. These later reports were outside of the period considered by the Committee's assessment, but the values reported imply substantially higher estimates of absorbed dose rates to fish for the late phase at locations close to FDNPS. This is an issue for follow-up by future scientific studies.

F23. Concentrations of ^{137}Cs in the marine organisms varied, ranging from a few becquerels per kilogram to more than one kilobecquerel per kilogram. Concentrations of ^{131}I tended to fall more rapidly than those of ^{134}Cs or of ^{137}Cs because of physical decay, environmental dispersion and turnover in biota. Values of radionuclide concentrations in seawater expressed in becquerels per litre were on average two orders of magnitude below values of concentrations in sediment expressed in becquerels per kilogram.

F24. The Committee established a spreadsheet-based method to organize the marine data and perform the dose calculations using a bespoke scripting language code. This involved several steps: *(a)* categorization of marine organisms—the 202 different species of marine biota were accommodated within nine categories of reference organisms used in the ERICA approach plus six newly-defined categories of organism; *(b)* calculation of absorbed dose rates from internal exposure for ^{131}I, ^{134}Cs and ^{137}Cs using values of DCCs derived from the ERICA assessment tool; *(c)* assignment, for each given radionuclide measurement sample in biota, of concomitant radionuclide concentrations in the habitat (water and sediment); and *(d)* calculation of absorbed dose rates and doses due to external exposure from the assigned radionuclide concentrations in sediment and water.

2. Using dynamic models

F25. The rate of radionuclide turnover by marine organisms can be determined experimentally and used to derive values for biological loss rates to be applied in dynamic models (see, for example, [O5, S14, V3, W13, W14]). The Committee used an improved version of a recent model, D-DAT [V4], to simulate biological transfer. This was a compartment model based upon the working simplification that marine organisms absorb radionuclides mainly from the surrounding seawater with a single phase function describing the biological loss rate for the radionuclides considered (^{131}I, ^{134}Cs and ^{137}Cs).

F26. In addition, computations were made using the "ECOMOD" modelling approach, which describes the dynamic processes of radionuclide migration in aquatic biota as radioactive tracers of analogous stable elements involved in the growth and metabolism of the organisms [K23, K24, S4]. The "ECOMOD" modelling approach had been developed to simulate non-equilibrium, non-linear processes in aquatic ecosystems. In view of the novel application of dynamic models to assessing the effects of the FDNPS releases on biota, the use of two independent modelling approaches was considered beneficial because this imbued more confidence in the results.

III. ESTIMATED DOSE RATES AND INFERRED EFFECTS

A. Terrestrial environment

1. Assessment for the late phase using measurements and equilibrium-based methods

F27. The Committee estimated weighted absorbed dose rates for the reference date of June 2011 based upon empirical data to various representative birds and mammals sampled at several terrestrial locations within a 100-km radius around FDNPS. Weighted absorbed dose rates were in the range of 0.8 to 1.1 µGy/h for all wild boar clusters and resulted primarily from ^{137}Cs and ^{134}Cs. However, these estimates were specifically for this one species of mammal and they poorly characterized variability in dose rates because the wild boar clusters pertained to areas of similar environmental concentrations. Thus, the Committee also determined weighted absorbed dose rates from internal and external exposure to four biota groups in Koriyama City (see table F2). The arithmetic mean of the estimated dose rates showed low variability among the biota groups; a value for the 95th percentile slightly exceeding 2 µGy/h was derived for wild boar. The contribution from ^{134}Cs dominated the dose rate to all biota groups with a substantial, but smaller, contribution from ^{137}Cs.

F28. The estimated dose rates are approximately an order of magnitude greater than those due to the presence of naturally occurring radionuclides in the environment as assessed by Beresford et al. [B5], although the Committee's earlier quantifications of these dose rates (in the order of a few micrograys per hour) [U6], would render this putative difference insubstantial. The estimated dose rates were compared with a benchmark for chronic effects (the lower bound of the ICRP's DCRL, whose purpose was to guide protection efforts rather than as an indicator of environmental damage) (see table F2). The calculated 95th percentile of the dose-rate distribution was divided by the aforementioned benchmark and this ratio (also known as a "risk index") suggested that effects were unlikely for these particular animals.

Table F2. Estimates of weighted absorbed dose rate in June 2011 to various species of wild terrestrial vertebrate within a 100-km radius of FDNPS

Species	*95th percentile of the dose-rate distribution (µGy/h) (location)*	*Ratio to the dose-rate benchmark[a]*
Wild boar	1.1[b] (cluster 3) 2.2 (Koriyama City)	0.28 0.55
Sika deer	1.3 (Koriyama City)	0.33
Asian black bear	1.2 (Koriyama City)	0.30
Bird[c]	1.5 (Koriyama City)	0.38

[a] *The dose-rate benchmark used was the lower bound of the ICRP DCRL band, namely 4 µGy/h for cervidae and anatidae, taken to be representative for mammals and birds, respectively.*

[b] *Maximum value.*

[c] *Included grey duck, mallard and Japanese pheasant. The benchmark for reference duck was used.*

F29. Dose rates to all biota groups were calculated based upon an equilibrium assessment using the mean deposition densities reported for Okuma Town (table F3). The maximum weighted absorbed dose rate to biota estimated for this area, for mid-June 2011, was for deer/herbivorous mammals and amounted to 71 µGy/h (or 1.7 mGy/d). This estimate was derived using default values for transfer and dosimetric parameters. Somewhat lower values were estimated for vegetation: 26 µGy/h and 17 µGy/h for grass and trees, respectively. Refining the estimates for Okuma Town, by applying region-specific CRs for animals, gave weighted absorbed dose rates to large mammals in the range 13–26 µGy/h. Radioisotopes of caesium contributed more than 90% of the dose rate and, except for the case of wild boar, the dose from external exposure predominated.

F30. These estimated weighted absorbed dose rates exceeded the ERICA screening benchmark of 10 µGy/h (for protecting ecosystem functioning and structure) by some margin and exceeded the relevant lower bound of the ICRP's DCRL band in some cases (table F3). However, comparing the calculated dose rates with a benchmark for manifest effects of 100 µGy/h (pertaining to viability of biota populations) [U12] suggested that any significant effects on terrestrial animal populations were unlikely. Because the estimated dose rates lay between the upper (UNSCEAR) and lower (ICRP and ERICA) benchmarks, more subtle effects at the individual level, such as cytogenetic damage or effects on reproductive endpoints, could not be ruled out for the areas of highest deposition density.

Table F3. Estimates of weighted absorbed dose rate in June 2011 to reference organisms in an area with relatively high deposition density (Okuma Town)

Reference organism	*Dose-rate estimate (µGy/h)*	*Dose-rate benchmark[a] (µGy/h)*	*Ratio of estimate to benchmark[a]*
Bee	18	400	0.04
Deer	71	4	17.8
Duck	21	4	5.3
Earthworm	46	400	0.11
Frog	18	40	0.45
Pine tree	17	4	4.3
Rat	46	4	11.5
Wild grass	26	40	0.65

[a] *The dose-rate benchmark used was the lower bound of the relevant ICRP DCRL band.*

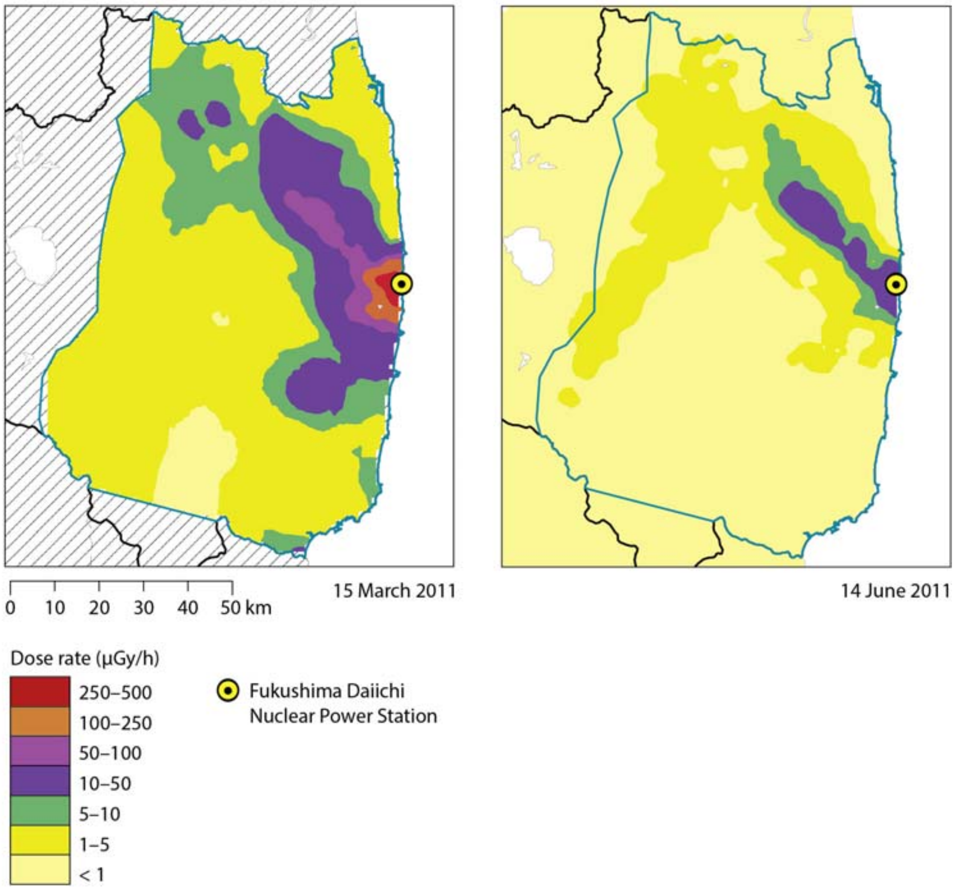
2. Assessment for the intermediate phase

F31. Because of the faster radioactive decay of short-lived radionuclides, the reconstructed estimates of weighted absorbed dose rates for Okuma Town for the time of the assumed main deposition event (15 March) were substantially higher than those reported for June. The highest reconstructed dose rates were estimated for soil-dwelling organisms with values of 290 µGy/h and 330 µGy/h for earthworm/soil invertebrates and rat/burrowing mammals, respectively. Values for deer/herbivorous mammals were estimated to be about 240 µGy/h, with ^{131}I and internal irradiation dominating contributions. In contrast, the external irradiation predominated for all other organisms considered. Reconstructed dose rates to vegetation were estimated as 110 and 130 µGy/h for pine tree and wild grass, respectively.

F32. Maps of interpolated estimates of weighted absorbed dose rates to a large mammal are provided in figure F-II; one map is based upon reported deposition densities of radionuclides (reference date of 14 June) and one is decay-corrected (to 15 March). The value of CR used was region-specific based on all available data for mammals.

F33. These estimates did not account for some of the very short-lived radionuclides that were present in fallout early on. Initial analyses suggested that the primary radionuclides contributing to dose rate at this time were ^{132}Te and ^{132}I. Estimations of the concentrations of these short-lived radionuclides in soil for an area receiving maximum deposition were reconstructed from ^{137}Cs concentration measurements, using ratios derived from [I33]. These direct empirical data for the specific location, as opposed to those derived from modelling the source term and dispersion of radioactive material presented in appendix B, were considered more appropriate as input for the purposes here. The analysis showed that these short-lived radionuclides contributed significantly to the early dose rates to organisms. The estimates of these early dose rates to soil-dwelling organisms (reference organisms from table F1: rat/burrowing mammal and earthworm/soil invertebrate) were higher by approximately a factor of three than estimates for mid-March without ^{132}Te and ^{132}I, mainly because of external exposure, and may have approached 1 mGy/h (1,000 µGy/h). However, such dose rates would have been of short duration, falling to levels of a few hundred micrograys per hour within a few days.

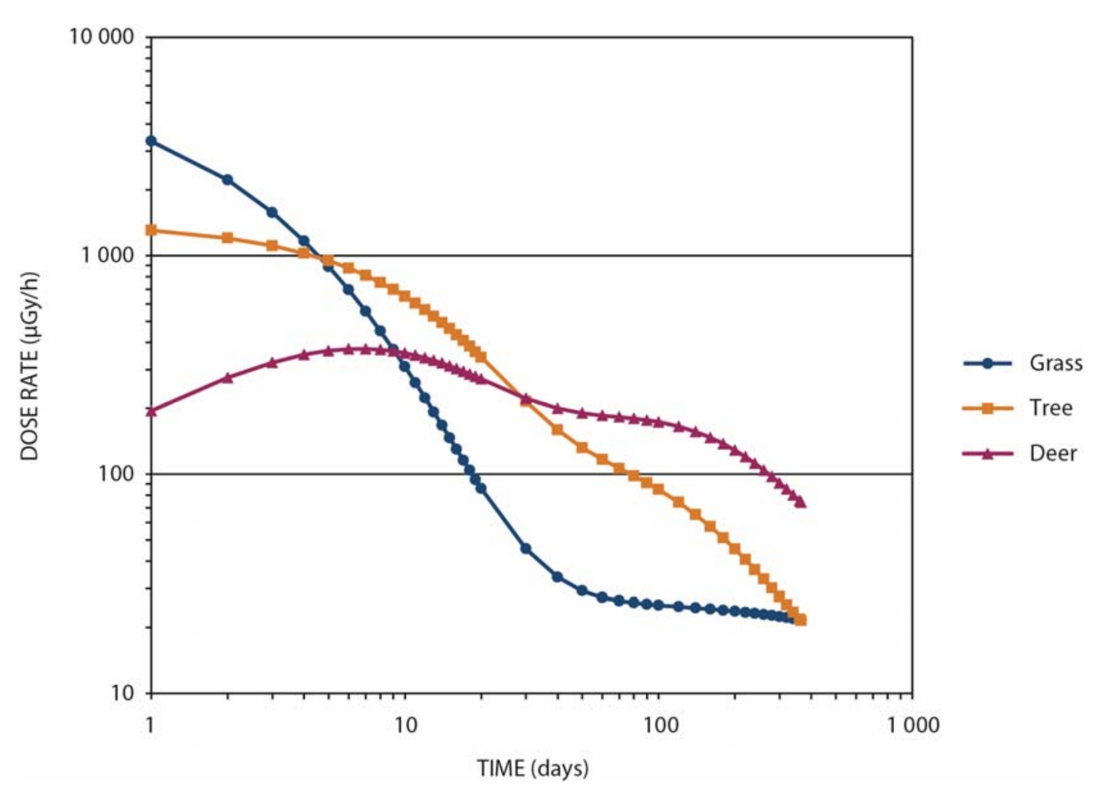
Figure F-II. Interpolated estimates of weighted absorbed dose rates to a large mammal



F34. The estimated variation of dose rate with time is illustrated in figure F-III. Dose rates due to ^{131}I, ^{134}Cs and ^{137}Cs were calculated for Okuma Town using arithmetic means of the deposition density data and the dynamic model. The deposition densities for ^{131}I were corrected for radioactive decay back to 15 March 2011. The highest weighted absorbed dose rates were estimated at approximately 5.6 mGy/h to grass at the time of deposition. More than 85% of this initial dose rate was due to ^{131}I. Weighted absorbed dose rates to trees were initially substantially lower, although dose rates declined less rapidly. The main contribution to dose was associated with the presence of ^{131}I on vegetation. Maximum weighted absorbed dose rates to deer/herbivorous mammals were estimated at 370 µGy/h and to have occurred within the first week following the main deposition event. A large fraction of this initial dose rate (some 64%) was associated with internal exposure due to ^{131}I. Although dose rates would have fallen quite rapidly, they were estimated not to fall below 100 µGy/h until about 275 days after the tsunami.

Figure F-III. Estimated weighted absorbed dose rates as a function of time to (a) grass or shrubby vegetation, (b) trees and (c) deer

The main initial deposition event for this purpose was assumed to have occurred on 15 March 2011



F35. For the calculated dose rates in the intermediate phase, changes in biomarkers of various types, potentially indicating transient loss of functions important for maintaining population stability, could not be ruled out, especially in mammals [G5]. Nonetheless, under the cautious assumption of a maximum continuing weighted absorbed dose rate of about 1 mGy/h, (based on estimates using an equilibrium approach and including contributions from short-lived ^{132}Te and ^{132}I as described above), about 375 and 40 days of exposure would have been needed to reach a level where acute effects might have been expected on populations of soil invertebrates and small mammals, respectively. This assessment was based upon observations of biota exposed to radionuclides after the Chernobyl accident [U12]. Furthermore, the length of exposure needed to reach the ERICA threshold value for acute effects on ecosystems (1.8 Gy) [U12] would have been approximately 75 days. These comparisons indicated that acute effects within the first two weeks after the accident would have been unlikely because, even if weighted absorbed dose rates to biota of 1 mGy/h had occurred, these would have been of very short duration (theoretically lasting from a few hours to a few days). This assessment appeared to be supported by no field observations of severe/immediate effects being reported for the intermediate phase of the accident. However, this lack of evidence per se cannot be used to confirm the contention that no acute effects on non-human biota occurred, because no corroborated information was available for this period.

F36. For vegetation, the weighted absorbed dose accumulated during the 30-day period after the accident was estimated to be approximately 0.5 Gy, representing about one tenth of the maximum doses at which no effects were observed in populations of herbaceous plants exposed after the Chernobyl accident [U12]. For a herbivorous mammal, the weighted absorbed dose accumulated during the 30-day period after the FDNPS accident was estimated to be about 0.2 Gy, representing about half of the maximum doses at which no effects were observed in populations of small mammals around the Chernobyl nuclear power plant after the 1986 accident [U12].

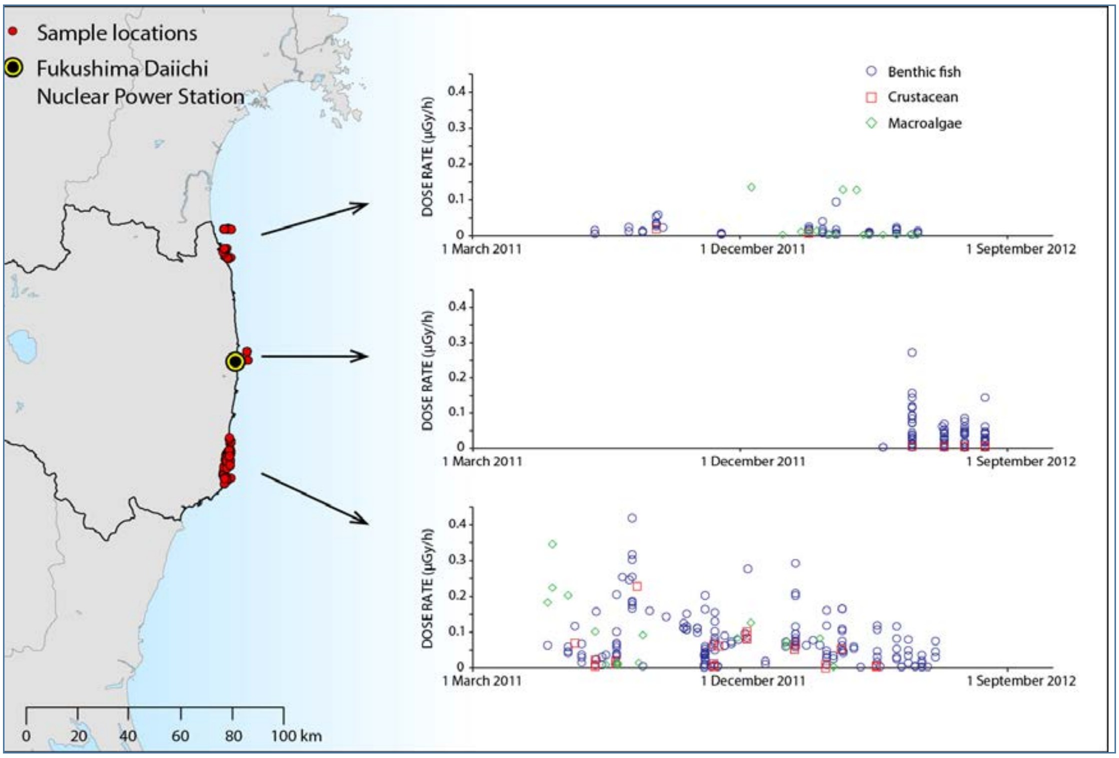
B. Aquatic environment

1. Assessment for the late phase using measurements of biological samples

F37. Weighted absorbed dose rates to freshwater fish from lakes and rivers with ^{137}Cs deposition densities in the range 100,000 to 200,000 Bq/m^2 were estimated to be within the range 0.4–3 µGy/h. Dose rates to fish with the highest measured radionuclide concentrations in the body were within the range 3.7–6.2 µGy/h (depending on the proportion of time the fish were assumed to stay near the lake-bottom sediments). Although these dose rates were more than an order of magnitude above background levels due to natural sources of exposure (see [H13]), they did not reach the threshold levels for chronic exposures above which acute effects in freshwater biota are expected.

F38. Estimates of weighted absorbed dose rates to biota for selected clusters of measurements for the Fukushima coastal area are presented in figure F-IV. The dose rates are highly variable in time and space, directly reflecting the variations in actual radionuclide concentrations in biota.

Figure F-IV. Estimated weighted absorbed dose rates to macroalgae, benthic fish and crustaceans



F39. Dose rates were estimated (summing internal and external exposure due to ^{131}I, ^{134}Cs and ^{137}Cs) from the compiled arithmetic means of radionuclide concentrations for each category (for all coastal stations where biological samples were available: 10 May 2011 to 12 August 2012). The highest estimated values were approximately 0.17–0.25 µGy/h to ascidians, macroalgae, sea urchins and holothurians and 0.10–0.17 µGy/h to benthic fish, crustaceans and molluscs. The dominant contribution to the dose rates to biota was from external exposure due to ^{134}Cs and ^{137}Cs because by the intermediate phase, much of any ^{131}I would have substantially decayed. The maximum estimated dose rate to biota was 4.4 µGy/h for benthic fish pertaining to a measurement in fat greenling (*Hexagrammos otakii*) sampled in August 2012.

F40. These dose rate estimates could be compared with benchmarks for chronic effects (table F4). Comparison with the lower bound of the ICRP DCRL or the UNSCEAR benchmark of 400 µGy/h (as appropriate) implied that radiation-induced effects would be negligible in the late phase. The dose rates to biota calculated were commensurate with background dose rates to biota in the marine environment [H13] and also substantially below the ERICA screening benchmark of 10 µGy/h (the highest ratio of estimated dose rate to the ERICA benchmark was 0.4 for benthic fish).

F41. As of August 2012, fish were still being found with radionuclide concentrations above the Japanese regulation value of 100 Bq/kg (fresh weight) for sale and human consumption [B24]. Although such a level may be of relevance to radiological protection of the public, the corresponding dose rates to non-human biota are insignificant, falling far below any relevant benchmarks for radiation effects. The Committee did not assess the long-term impact of continued release of various radionuclides to the marine environment from contaminated groundwater, which was still ongoing at the end of 2013. This issue requires consideration in future studies.

Table F4. Comparison between weighted absorbed dose-rate estimates obtained from radionuclides measured in selected marine species at various times and locations and relevant benchmarks for effects

Reference organism assigned to species	*Maximum dose rate (µGy/h) (date, location)*	*Dose-rate benchmark (µGy/h)[a]*	*Ratio to the benchmark*
Macroalgae	0.41 (16 Aug 2011; 36.9359°N, 140.9149°E)	40 (ICRP Reference [I22] brown seaweed)[b]	0.01
Benthic mollusc	0.42 (13 Jan 2012; 37.2030°N; 141.0862°E)	400 [U12]	0.001
Crustacean	0.63 (07 Oct 2011; 37.8863°N, 141.0266°E)	400 (ICRP Reference [I22] crab)	0.0016
Benthic fish	4.4 (02 Aug 2012; 37.5847°N, 141.0422°E)	40 (ICRP Reference [I22] flatfish)	0.11
Sea urchin	0.42 (13 Jan 2012; 37.2030°N, 141.0862°E)	400 [U12]	0.0011
Holothurian	0.65 (07 Oct 2011; 37.8863°N, 141.0266°E)	400 [U12]	0.0016
Ascidian	0.64 (07 Oct 2011; 37.8863°N, 141.0266°E)	400 [U12]	0.0016

[a] *The benchmarks used were those of the ICRP DCRLs; however the ICRP [I22] provide DCRL values for brown seaweed, crab and flatfish only. Where DCRL values were not available for a given category of biota, the generic UNSCEAR benchmark [U12] was used.*

[b] *The Committee understood that the ICRP intended a DCRL value a factor of 10 lower than published in [I22].*

2. Assessment for the intermediate phase using dynamic models

F42. The highest weighted absorbed dose rates to biota in the marine environment were derived from estimated concentrations in seawater (for before 10 May 2011, when biological samples were not available) using the D-DAT dynamic model [V4], for a location 30 m north of the discharge channel for Units 5 and 6 at FDNPS. For fish, the maximum dose rate was estimated to have occurred within the first month (approximately 140 µGy/h), and the accumulated dose over one year was estimated to be around 0.32 Gy. These doses fall substantially below levels where effects on mortality and survival, growth or reproduction would be expected. For macroalgae at the same location, the dose rate was dominated by the contribution from ^{131}I. The maximum values were estimated to have occurred after 23 days, in early April 2011, and exceeded 20 mGy/h, but were estimated to have fallen rapidly below

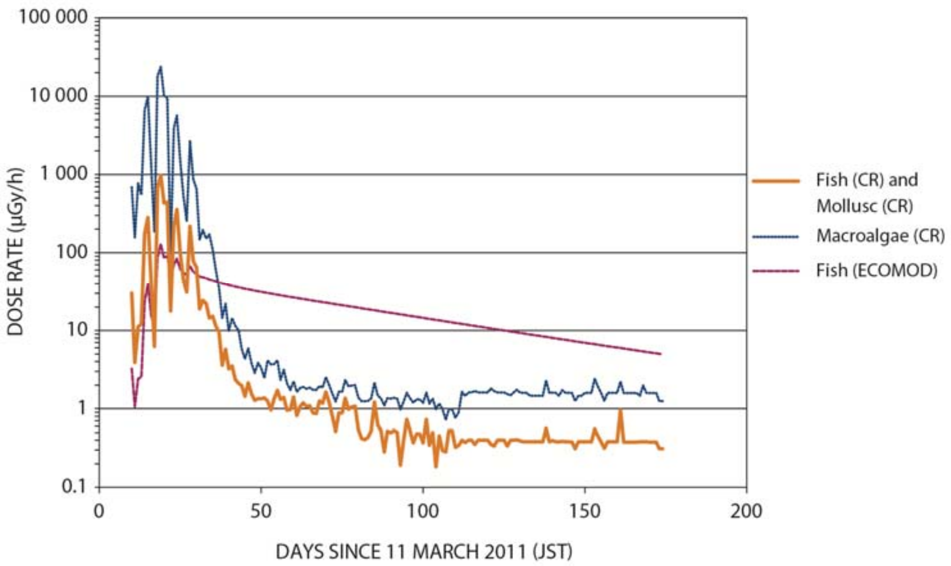
10 mGy/h by 32 days, largely reflecting a highly elevated uptake of short-lived radioiodine followed by rapid decay. The weighted absorbed dose to macroalgae accumulated over a one-year period was estimated to be approximately 7 Gy. There were few or no data on effects with which to compare, but dose rates in the range of 10–100 mGy/d were considered to cause potential effects on reproduction and growth rate [I22]. The estimated absorbed dose rates were therefore at a level where substantial impacts on seaweed could have occurred, although this conclusion is tempered by the scarcity of any available observations of actual effects.

F43. The estimated absorbed dose rates from internal exposure were generally two to three orders of magnitude higher than those from external exposure once biota had undergone significant uptake.

F44. To gain insight into the evolution of dose rates to selected biota with time, results from the ECOMOD and CR models (the latter assuming instantaneous equilibration between model compartments) are presented, by way of example, in figure F-V. The more realistic dynamic modelling approach, ECOMOD, estimated peak dose rates to fish that were an order of magnitude below those derived using the simple CR model. In the longer term, after 50 days, the relationship was reversed with dose rates estimated by the dynamic model substantially above those estimated by the equilibrium model. In general, dose rates to pelagic fish, molluscs and macroalgae were estimated to fall rapidly from their peaks within the first few weeks of the accident. The highest estimate of absorbed dose rate to biota was for macroalgae.

F45. The estimated dose rates to fish using dynamic modelling differed substantially from those presented by Garnier-Laplace et al. [G3]. This partly reflected the fact that Garnier-Laplace et al. assumed equilibrium between concentrations in organisms and in seawater [G3] whereas the Committee's assessment did not. Furthermore, the lack of equilibrium between radionuclide activities in the water–sediment system in this early phase rendered the modelling of sediment concentrations in the Committee's assessment, using distribution coefficients, unfeasible. This contrasted with the calculations for the late phase where such an approach was adopted. Because the sedimentation of suspended particles, transporting adsorbed radionuclides to the seabed, would have been a slow process associated with further dispersion of radionuclides across large areas, the Committee assumed that radionuclide levels in seabed sediments were such that they would not contribute substantially to absorbed dose rates. This was consistent with the results reported in appendix B of this report (for all areas except the port of FDNPS).

Figure F-V. Weighted absorbed dose rates to biota in the South Channel estimated using the ECOMOD and CR models



IV. UNCERTAINTIES

F46. Overall uncertainties associated with the types of models applied in this assessment, particularly those involving a biological transfer component, are normally large. This is typified by the observation that estimations using different models often differ from one another by more than an order of magnitude [L7]. By way of example, in order to estimate a distribution of weighted absorbed dose rate values to a large mammal arising from exposure to isotopes of caesium, a simulation model was run probabilistically using information on the variability in deposition density for Okuma Town and default probability distribution functions for CR values. The resulting 95th percentile of this distribution was approximately two orders of magnitude greater than the 5th percentile. In view of other unsubstantiated assumptions, such as those associated with the diet of the mammals, the uncertainties associated with dynamic modelling might have been even greater than this. In contrast, where dose rates were estimated using directly measured concentrations of radionuclides in biota, uncertainties were much lower.

F47. Absorbed doses to the thyroid of mammals from their inhalation of ^{131}I would have been a component of exposure in the intermediate phase of the accident. The methodology applied by the Committee did not account for this adequately: this particular pathway and the doses to specific organs (only activity concentrations in the whole organism were derived) were not modelled explicitly. This omission represents an additional uncertainty to the risks inferred for the first weeks and months following the accident.

F48. Empirical Bayesian Kriging (EBK) was selected as the method to estimate the deposition density and dose-rate rasters for the Fukushima area. EBK provides both a prediction and standard error. In addition, a cross validation was performed by randomly selecting 5% of the deposition density data and running the EBK on the remaining 95%. The differences between the predicted values and the measured values indicated the quality of the model fit. This process was repeated one hundred times to produce a robust quantitative estimate of the uncertainty associated with the modelling approach.

F49. The results from two dynamic models for marine biota, D-DAT and ECOMOD, using the same datasets corresponded closely. Furthermore, there was a degree of correspondence between modelled radionuclide concentrations in biota using D-DAT and measurements made by Greenpeace for the period 3–10 May 2011 [G11], although the degree of agreement was not so strong because of incomplete overlap between sampling and modelling stations. When compared with modelled data (except for the FDNPS drainage channels and most adjacent locations), the dose rates estimated from radionuclide concentration measurements were generally within an order of magnitude. For the FASTer model, parameters were reviewed and checked by external experts, and the model outputs were checked by independent groups of analysts. Values of dose rates derived using the ERICA Tool were checked by independent analysts who also ran simulations. This provided added confidence in the approaches used.

V. CONCLUSIONS

F50. Weighted absorbed dose rates to non-human biota inhabiting terrestrial ecosystems may have significantly exceeded the benchmark of 100 µGy/h (the dose rate below which significant effects are considered unlikely for most terrestrial communities) for limited periods in the intermediate phase (approximately the first two months) after the accident. However, population effects of major significance were unlikely, and would be expected to have been only transient, owing to the short duration of exposures at such dose rates. Changes in biomarkers for certain biota, in particular mammals, could not be excluded; however, their significance for population integrity is not well established. Accumulated doses over the intermediate phase were estimated to have fallen short of levels found to cause observable effects in non-human biota, as reported in reviews such as those concerning exposures in the aftermath of the Chernobyl accident. Estimated doses to marine biota during the intermediate phase did not indicate the potential for effects on populations of these organisms. This was the case even for the near field (tens of metres from the discharge channels), where a dynamic modelling approach was applied to simulate the absorption and excretion of radionuclides by biota. Accumulated absorbed doses over the intermediate phase were considered too low for observable acute effects. A potential exception was for macroalgae that were close to the discharge point.

F51. For the late phase (months to years) after the accident, a risk of effects to individuals of certain species, especially mammals, may exist in areas of highest deposition density. Difficulties exist in extrapolating potential effects on individuals to the significance at the population level, but effects on terrestrial biota at the population level were considered unlikely to be observable. The issue can be clarified only through continued monitoring and further study. This should also address the indications of harmful radiation effects in terrestrial biota reported by Møller et al. [M22, M23] and Hiyama et al. [H6]. The fact that no direct measurement data (for terrestrial and freshwater ecosystems) were available to the Committee for the areas of highest deposition density (which were evacuated) restricted the assessment for these areas to the use of transfer models; this meant that large uncertainties were unavoidable. Although predicted exposures for both freshwater and marine biota during the late phase were well below thresholds above which effects could be deemed likely, there is a need for further work to characterize radionuclide levels and potential exposures for these environments.

F52. The Committee concluded that the possibility of direct effects of radiation exposure on non-human biota was geographically constrained and that, in areas outside of that considered by this assessment, the potential for such effects on biota may be deemed insignificant.

F53. The Committee's assessment of the effects of radiation exposure due to the FDNPS accident on non-human biota is subject to uncertainty. In particular, it was difficult to account accurately for the contributions of short-lived radionuclides in the initial period after the accident. Although estimates were made for the biota in the terrestrial ecosystem, these were considered highly uncertain. Furthermore, there are limitations associated with the modelling of doses from external exposure for the marine environment, because it was not possible to include exposures from sediment in some of the model simulations. This and other factors were of potential concern in view of the releases still ongoing at the end of 2013.

GLOSSARY

Absorbed dose	Fundamental dosimetric quantity defined as the energy imparted by ionizing radiation in unit mass of matter; measured in grays (Gy); 1 gray is equal to 1 joule per kilogram (J/kg).
Activity	The rate at which spontaneous transformations occur in a given amount of radioactive material. (Strictly, the expectation value of the number of nuclear transformations occurring in a given quantity of material per unit time). It is measured in becquerels (Bq); 1 becquerel equals one transformation per second.
Acute exposure	Exposure received within a short time period (see also protracted exposure).
Becquerel (Bq)	The SI unit of activity, equal to one transformation per second. As the unit is so small, multiples are frequently used such as megabecquerels (MBq) which is 10^6 or a million becquerels. (1 GBq is 10^9 Bq; 1 TBq is 10^{12} Bq; and 1 PBq is 10^{15} Bq).
Biokinetic model	A mathematical model for the behaviour of radionuclides in the body which takes account of the movement, retention and excretion of a radionuclide as a function of time.
Cold shutdown	Defined in the context of this report by TEPCO and the Nuclear Emergency Response Headquarters as the state where the coolant water temperatures of Units 1–3 were less than 100ºC, the pressure inside the reactor vessels was the same as the outside air pressure, and where any further releases would not result in dose rates greater than 1 mSv per year at the site boundary.
Collective dose	The total radiation dose incurred by a population (that is the sum of all the individual doses); measured in man–sievert (man Sv) or man–gray (man Gy).
Committed dose	The integral, over a defined period of time, of the dose rate in a particular tissue or organ that will be received following the intake of radioactive material into the body.
Core cooling	The process by which heat is transferred from the reactor core (the central part of a nuclear reactor containing the fuel elements and any moderator) to the steam generators or directly to the turbines.
Decay heat	The heat generated by the transformation of radionuclides, particularly in the context of radionuclides in the core of a reactor.
Decontamination	The complete or partial removal of contamination by a deliberate physical, chemical or biological process.
Deterministic effect	A health effect of radiation exposure for which a threshold level of dose generally exists, above which the severity of the effect is greater for a higher dose.
Dose	A measure of the energy deposited by radiation in a target. Dose can be used as a shorthand for absorbed dose and effective dose when the context is clear.
Dose coefficient/dose per unit intake	The committed effective dose or committed absorbed or equivalent dose in a tissue or organ resulting from an intake, by a specified means (usually ingestion or inhalation), of unit activity of a specified radionuclide in a specified chemical form.
Dose rate	Dose delivered or received per unit time. Measurements are usually made in terms of the dosimetric quantity, ambient dose equivalent rate, H*(10), in units of μSv/h.

Dose and dose rate effectiveness factor	The factor by which the risk of occurrence of a health effect in a specified time period (usually over a lifetime) per unit dose for exposures at high doses and high dose rates exceeds that for exposures at low doses and low dose rates.
Dosimeter	A device for measuring an individual's exposure to ionizing radiation.
Effective dose	Fundamental dosimetric quantity for the purposes of radiological protection defined as the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body; measured in sieverts (Sv).
Equivalent dose	Fundamental dosimetric quantity for the purposes of radiological protection defined as the product of the absorbed dose in the tissue or organ and the appropriate radiation weighting factor for the type of radiation giving rise to the dose; measured in sieverts (Sv).
Evacuation	The rapid, temporary removal of people from an area to avoid or reduce short-term radiation exposure in an emergency.
Exposure	The act or condition of being subject to irradiation. External exposure is exposure to radiation from a source outside of the body. Internal exposure is exposure to radiation from a source within the body.
Geiger counter	A Geiger counter (or Geiger–Müller counter) detects ionizing radiation by the ionization produced in a low-pressure gas in a Geiger–Müller tube.
Gray (Gy)	Unit of absorbed dose, equal to 1 joule per kilogram (J/kg).
In vitro measurement	A procedure used to determine the nature, activity, location or retention of radionuclides in the body by analysis of material excreted or otherwise removed from the body.
In vivo measurement	A procedure used to determine the nature, activity, location or retention of radionuclides in the body by direct measurement.
Lifetime risk	Probability that a disease occurs from a given point of time (e.g. at exposure) until the end of life. The lifetime baseline risk refers to the probably of a disease occurring over a lifetime without exposure additional to the background from natural and other sources of radiation. Lifetime risk due to exposure is the additional probability of a disease occurring over a lifetime due to additional radiation exposure.
Linear Energy Transfer (LET)	As radiation interacts with matter, it loses its energy through interactions with atoms. LET measures the average amount of energy lost over a defined distance. The same absorbed dose of low-LET radiation (such as beta particles and gamma rays) creates less biological damage than of high-LET radiation (such as alpha particles).
Occupationally exposed worker	Any person who is employed, whether full time, part time or temporarily, by an employer, and who has recognized rights and duties in relation to occupational radiological protection. The Japanese regulations use another similar term, radiation worker.
Protracted exposure	Exposure persisting in time (see also acute exposure).
Radionuclide	A radioactive isotope of an element. Different isotopes of an element have the same number of protons but different numbers of neutrons and hence different atomic masses. If there are too many or too few neutrons, the nuclei of the isotope tend to be unstable and transform into the nuclei of another element and in the process emit radiation.
Relative risk	Ratio of the risk for two groups, estimated from the relative rates of disease between, for example, an exposed group and an unexposed group.
Relocation	The non-urgent removal or extended exclusion of people from a contaminated area to avoid protracted exposure. This corresponds to the Deliberate Evacuation Area policy enacted in Japan.

Remediation	Any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.
Scram	A safety feature that triggers immediate shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a “reactor trip”.
Shielding	The absorbing property of material between a radiation source and a receptor which results in reduced exposure.
Sievert (Sv)	Unit of equivalent dose and of effective dose, equal to 1 joule per kilogram (J/kg).
Source term	Mathematical expression used to denote information about the actual or potential release of radiation or radioactive material from a given source. Here this term includes the release rate, radionuclide composition, physico-chemical form and their changes over time of the radionuclides released.
Stochastic effect	A radiation-related health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose.
Thyroid blocking	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 in the event of an accident in which these isotopes are released.
Whole-body monitoring	The measurement from outside the human body (generally extending at least from the neck below the chin to the mid to upper parts of the thigh) of the quantity of specific radionuclides within the body by measuring radiation emitted by such radionuclides.

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