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United Nations Scientific Committee on the Effects of Atomic Radiation

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

UNSCEAR 2013 Report

Volume I

REPORT TO THE GENERAL ASSEMBLY

SCIENTIFIC ANNEX A:

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

UNITED NATIONS

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR 2013
Report to the General Assembly with Scientific Annexes

VOLUME I
Scientific Annex A

UNITED NATIONS
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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

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The attachments cited in this annex are electronically available on CD-ROM and for download from http://www.unscear.org/unscear/en/publications/2013_1.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]

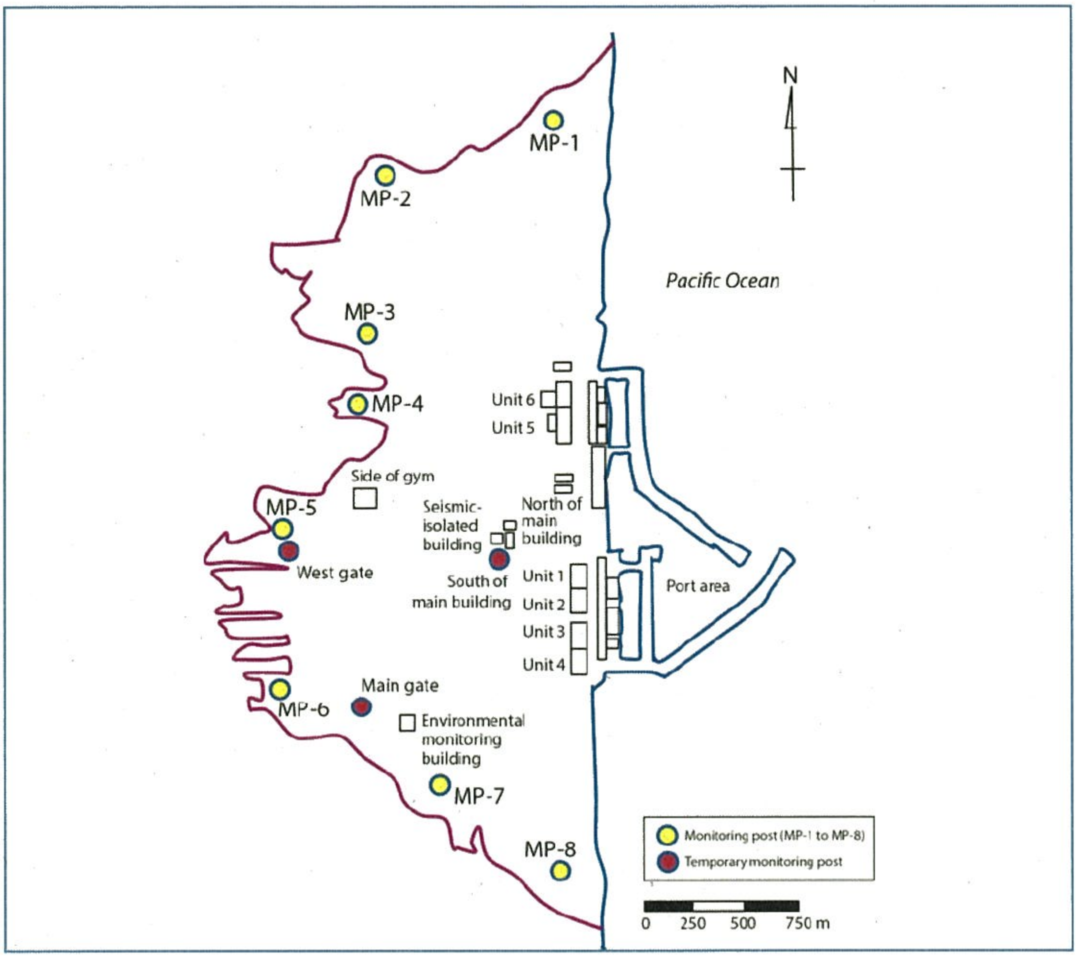

Table 1. Timeline of events following the earthquake and tsunami

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			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)
			18:25, evacuation within 20 km ordered Screening began of residents at refuges using Geiger–Müller survey meters	

[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 containment 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.

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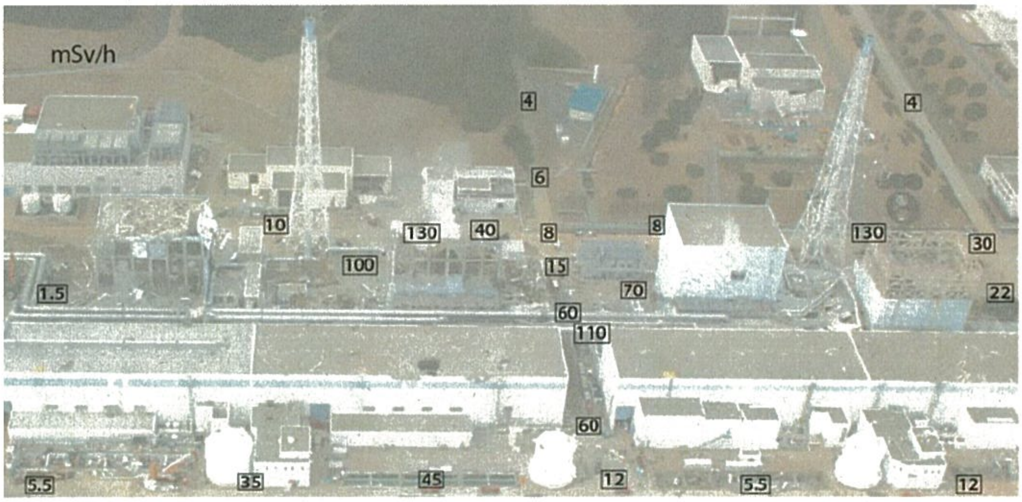
[7] Defined by TEPCO and the Nuclear Emergency Response Headquarters (NERHQ) as the state where the coolant water temperatures of Units 1–3 were less than 100°C, the pressure inside the reactor vessels was the same as the outside air pressure, and where any further releases would not result in an annual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

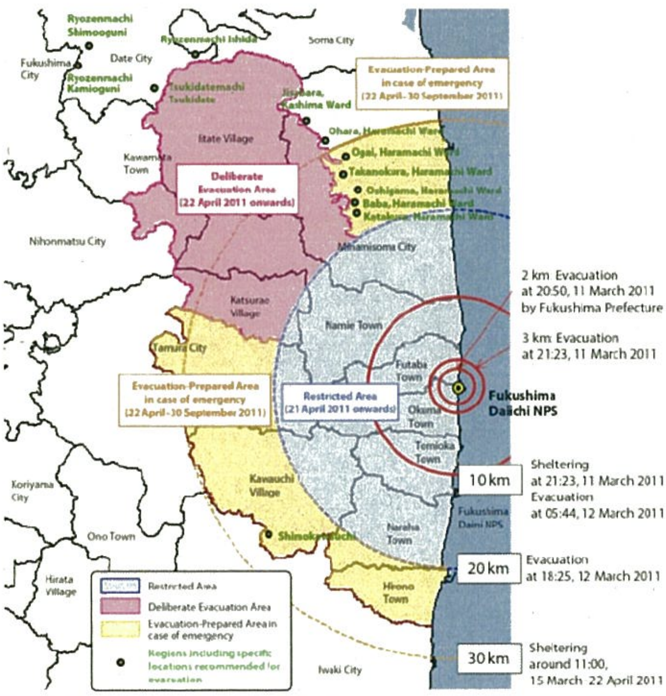
did not immediately follow the instructions to evacuate is uncertain). At the time of the earthquake, about 78,000 people were living within what became the 20-km evacuation zone and about 62,000 were living between 20 km and 30 km from FDNPS [N8].

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

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[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.

1. 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

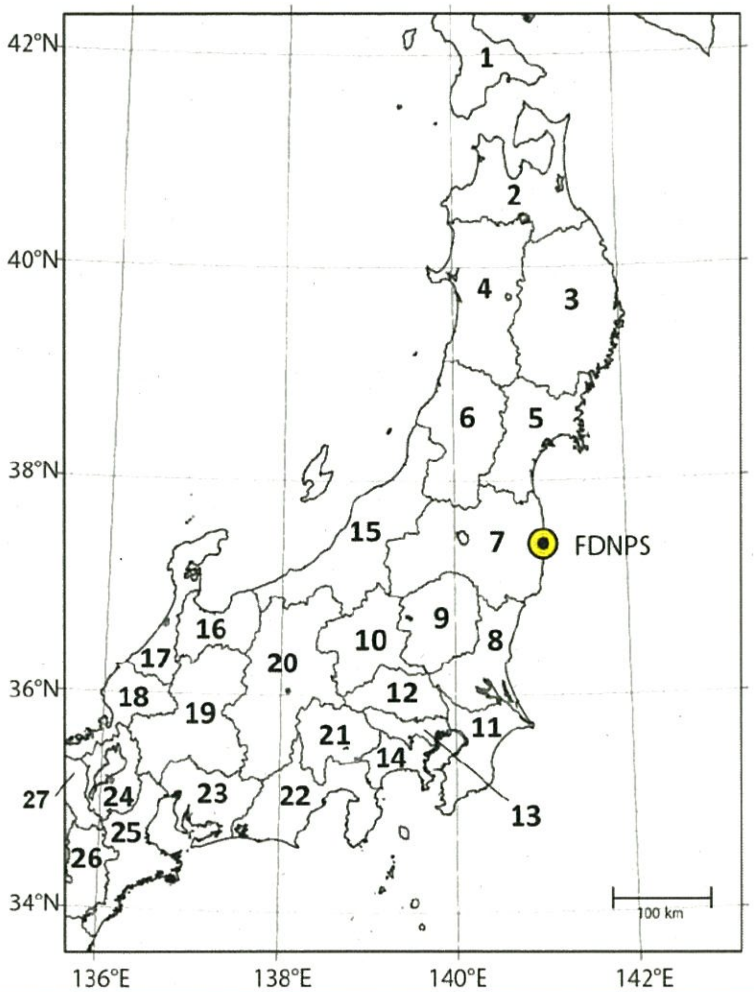
54. The fate of radioactive material released to the atmosphere during the accident at FDNPS was determined by the meteorological conditions pertaining at the time and the physical characteristics of each release, such as its height and whether it was in gaseous or particulate form. These conditions, 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

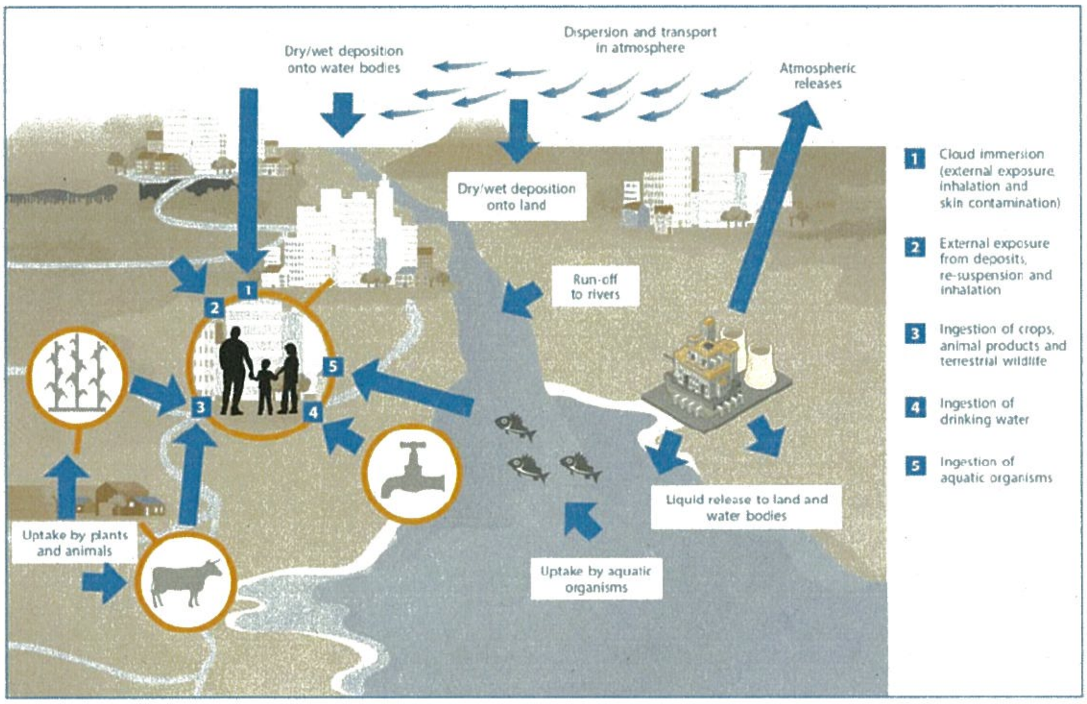
64. This chapter sets out how the knowledge about the distribution of radioactive material in the environment discussed in chapter III was used to estimate doses to the public in Japan and presents a summary of the doses estimated. The Committee's aim was to make realistic estimates of doses and, to 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.*

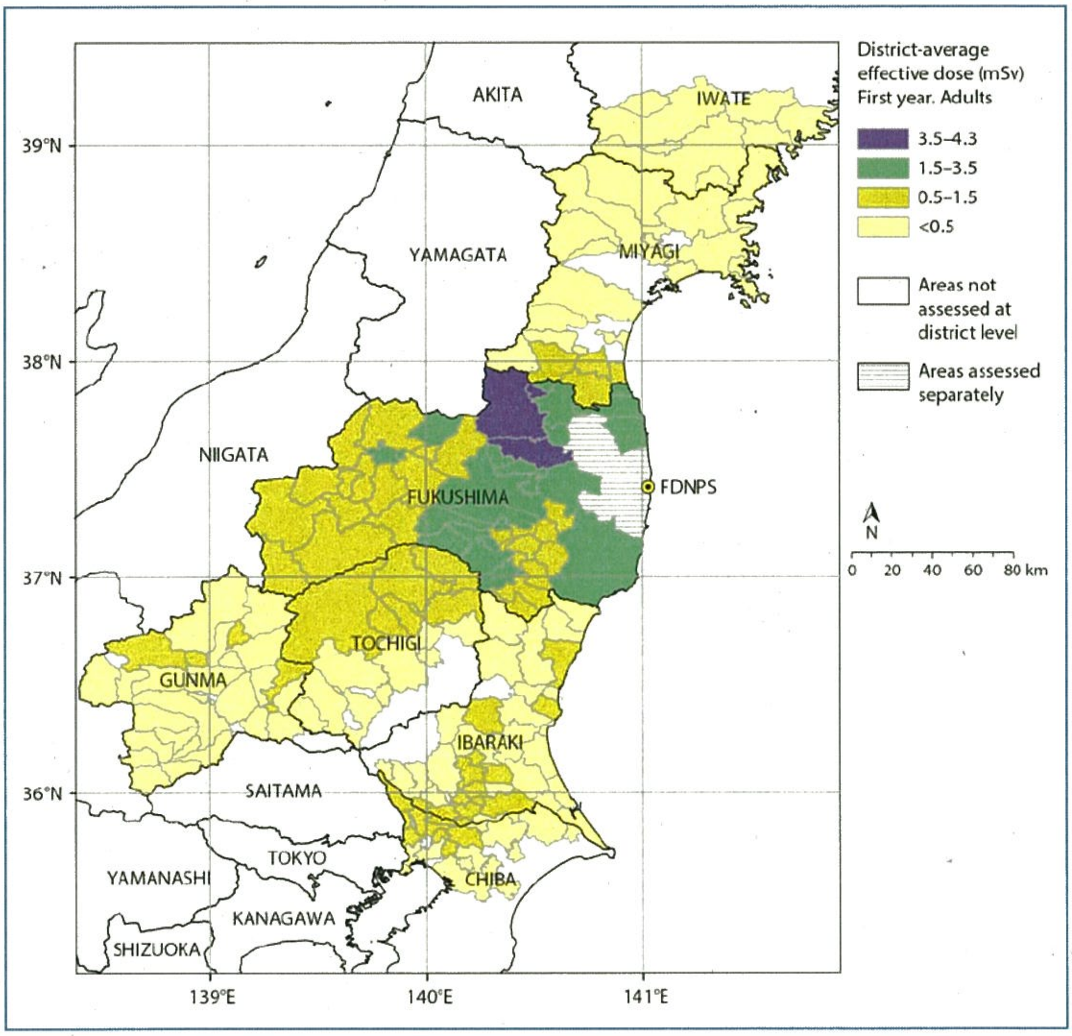
[c] *Group 4 - Members of the public living in the remaining prefectures of Japan.*

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.

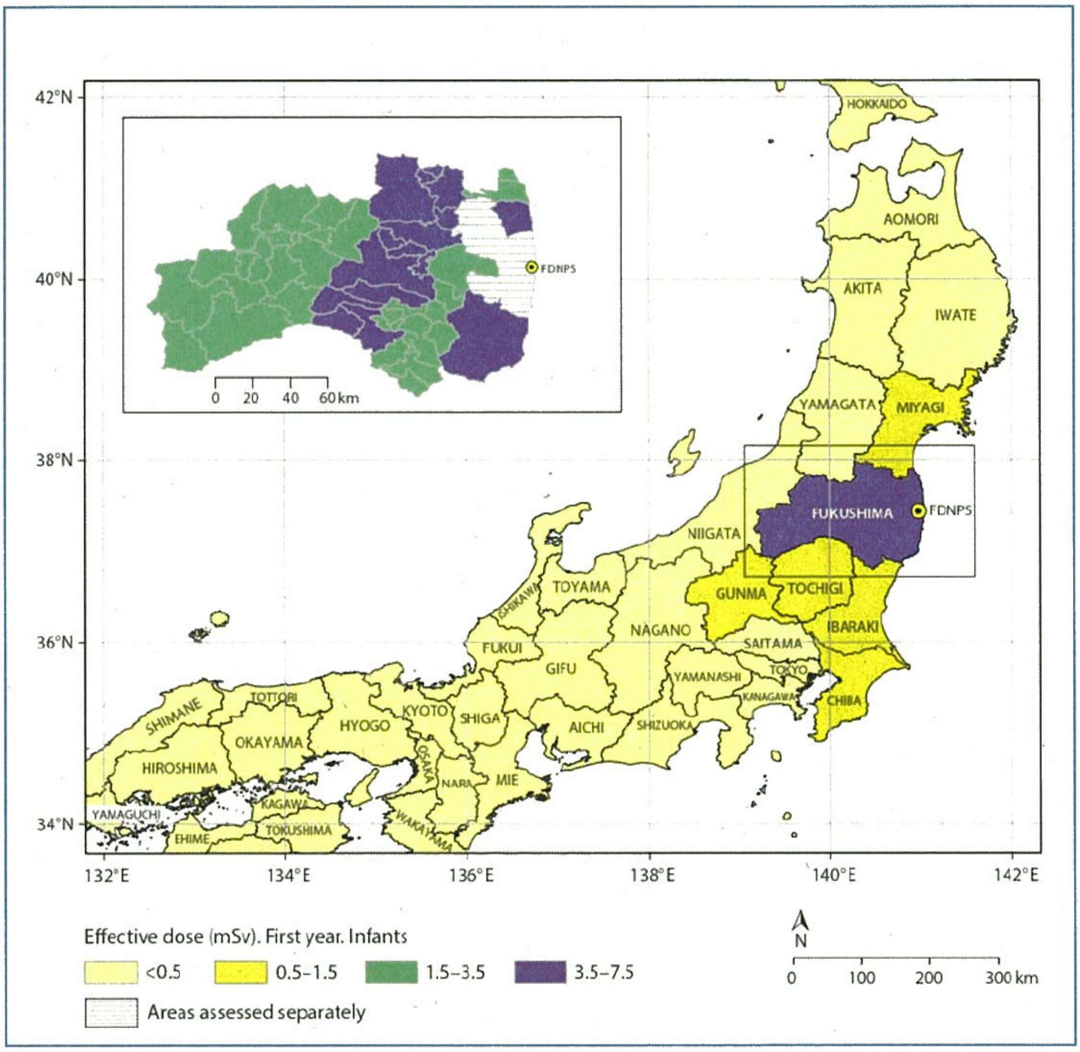
93. For the districts of the Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average effective doses to adults were in the range 0.2 to 1.4 mSv for the first year, including 0.2 mSv from ingestion of food in the prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi. 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, and the damage to the reactors following the hydrogen explosions (i.e. very high dose rates and levels of contamination at various locations on site) [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 and 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).

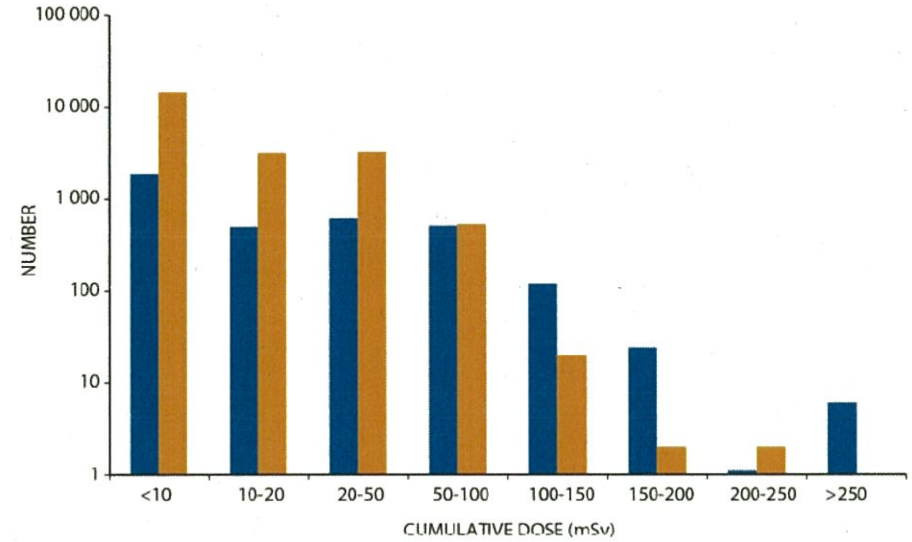
137. After November 2011, TEPCO presented the data in terms of cumulative totals for the number of workers in each dose band; the data published in November 2012 are reproduced in table D4 in appendix D [T16] and are illustrated in figure VIIIa. The data indicate that 34% of the workforce received cumulative 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



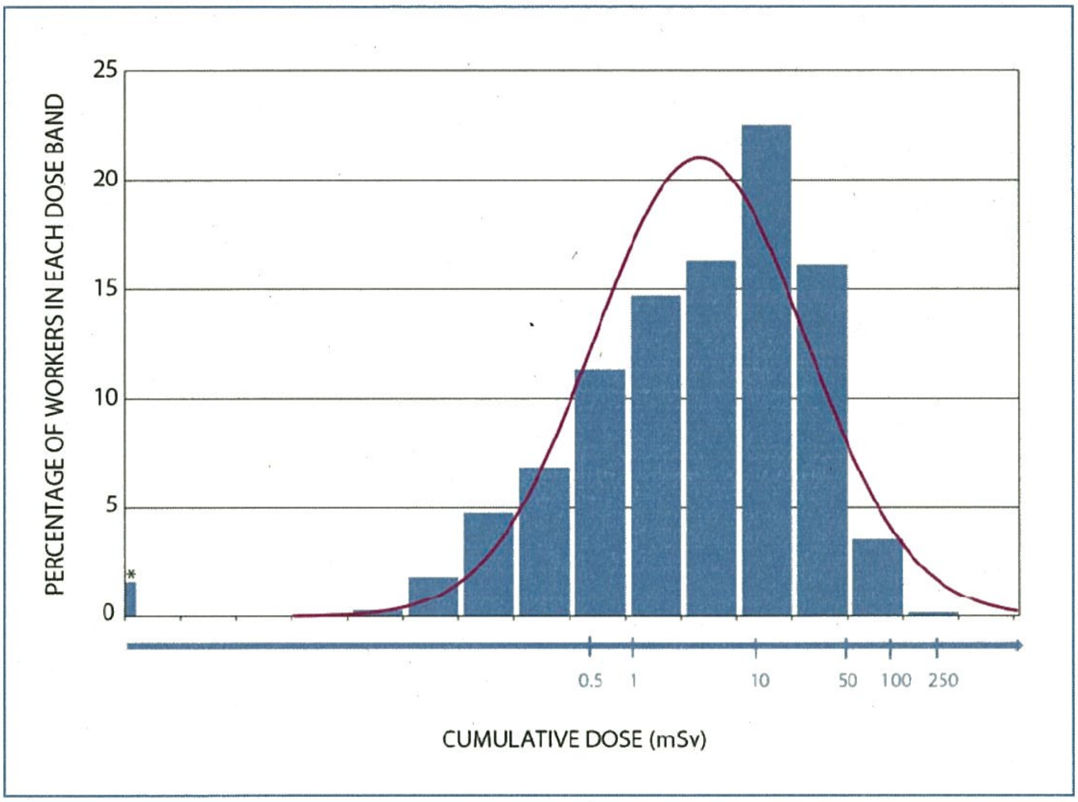
	TEPCO workers	Contractors	All
Average dose (mSv)	25	10	12
Maximum dose (mSv)	679	238	679

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, 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.

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

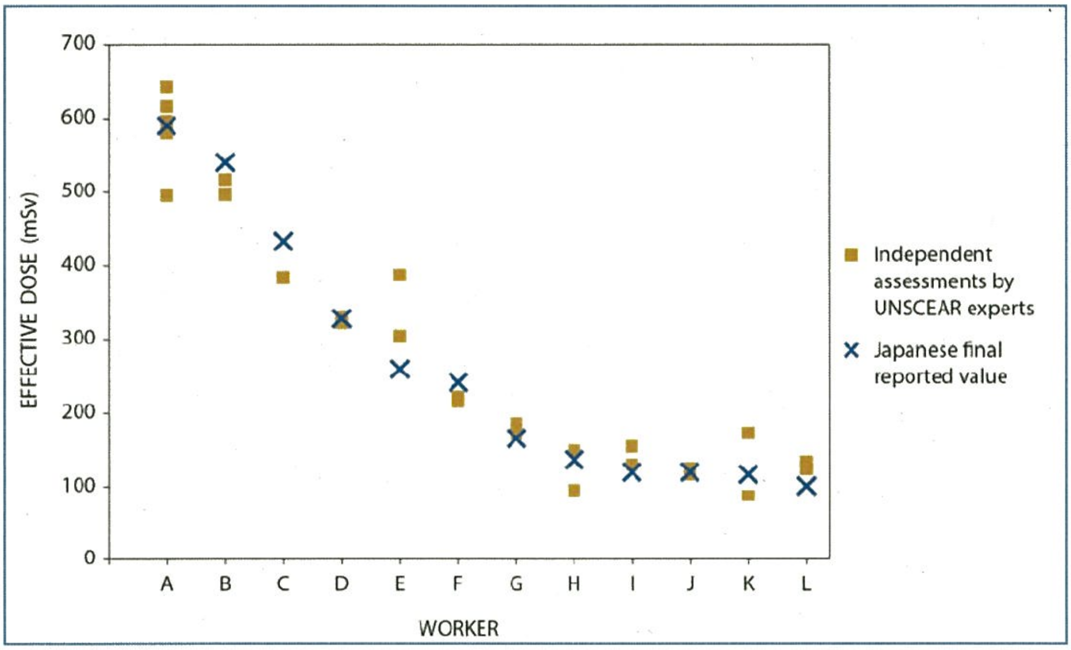
[21] Following the Committee's independent assessment of internal exposure for the 12 most exposed workers, the relevant Japanese organizations reviewed their estimates of doses due to internal exposure in July 2013; this resulted in the identification of one further TEPCO worker with a committed effective 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.

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 to 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.

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[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 incidence 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[22] 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

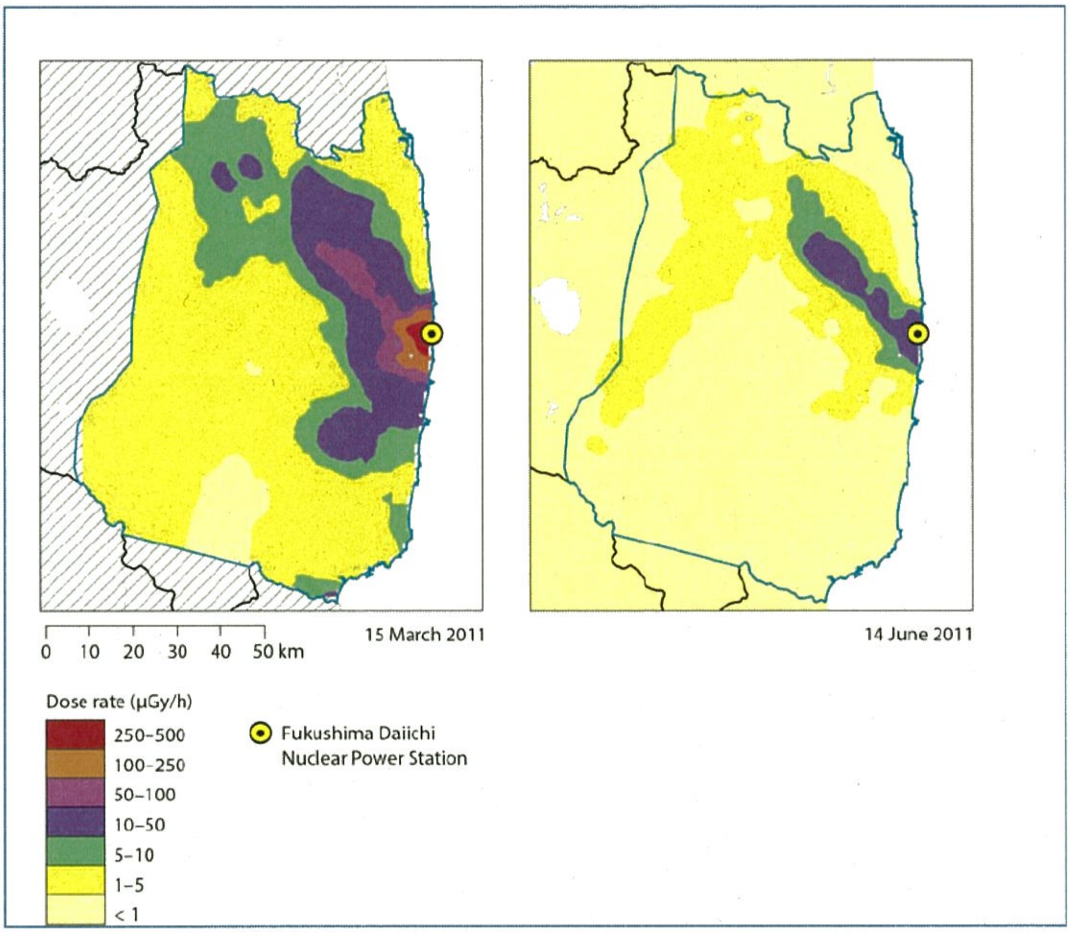
194. An interpolated map of estimated weighted[26] absorbed dose rates from internal and external exposure for a large mammal is provided in figure X.

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 lens opacity and 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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