United Nations Scientific Committee on the Effects of Atomic Radiation

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

UNSCEAR 2020/2021 Report

Volume II

SCIENTIFIC ANNEX B:

Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report

UNITED NATIONS

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR 2020/2021
Report to the General Assembly
with Scientific Annexes

VOLUME II
Scientific Annex B

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NOTE

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Corrigenda

Annex B, page 11

Fukushima and Ibaraki Prefectures

Paragraph 18 *should read*

Specifically, concentrations of different radionuclides in the air in the early stage of the FDNPS accident have been estimated at several monitoring posts in Fukushima and Ibaraki Prefectures from results of gamma spectrometry with sodium iodide (NaI(Tl)) scintillation detectors [H17, M44, T29].

Appendix A, page 120

Fukushima and Ibaraki Prefectures

Paragraph A29 *should read*

Specifically, concentrations of different radionuclides in the air in the early stage of the FDNPS accident have been estimated at several monitoring posts in Fukushima and Ibaraki Prefectures from gamma spectrometry using sodium iodide scintillation detectors [H17, M44, T29].

ANNEX B

LEVELS AND EFFECTS OF RADIATION EXPOSURE DUE TO THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER STATION: IMPLICATIONS OF INFORMATION PUBLISHED SINCE THE UNSCEAR 2013 REPORT

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LIST OF ABBREVIATIONS

AMAD	Activity median aerodynamic diameter
ARS	Acute radiation syndrome
ATDM	Atmospheric transport, dispersion and deposition modelling
CNPS	Chernobyl Nuclear Power Station
CR	Concentration ratio
DoD	Department of Defense
DOE	Department of Energy
DRF	Dose reduction factor
EMDB	Environment Monitoring Database
FDNPS	Fukushima Daiichi Nuclear Power Station
FM	Fresh mass
FHMS	Fukushima Health Management Survey
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICSA	Intensive contamination survey area
JAEA	Japan Atomic Energy Agency
JST	Japan standard time
M2013	Model used in the UNSCEAR 2013 Report
M2020	Model for estimating external doses from deposited radionuclides. An update of the model used in the UNSCEAR 2013 Report for estimating external doses from deposited radionuclides
MEXT	Ministry of Education, Culture, Sports, Science and Technology
MHLW	Ministry of Health, Labour and Welfare
MOE	Ministry of Environment
MRI	Magnetic resonance imaging
NIRS	National Institute of Radiological Sciences
OOP	Out of prefecture
RET	Rearranged during transfection
RIP	Radiocaesium interception potential
SDA	Special decontamination area
TEPCO	Tokyo Electric Power Company

UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WBC	Whole-body counting
WSPEEDI	Worldwide version of system for prediction of environmental emergency dose information

I. INTRODUCTION

1. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) assessed radiation exposures of the public, workers and non-human biota that resulted from the 11 March 2011 accident at the Fukushima Daiichi Nuclear Power Station (FDNPS) of the Tokyo Electric Power Company (TEPCO) in Japan and reported its findings, including a discussion of the associated health risks and health effects, to the United Nations General Assembly in October 2013 [U10]. A full report with scientific annexes was published by the United Nations on 2 April 2014 [U10].

2. Most of the scientific information used in the report of the Committee (referred to as the “UNSCEAR 2013 Report” [U10] hereafter) was limited to that published or provided officially (by the Japanese Government, TEPCO and international organizations) by the end of October 2012. Subsequently, a significant amount of relevant information has been published and, with time, questions were anticipated from delegations, government authorities, scientists, civil society and the media about the continuing validity of the UNSCEAR 2013 Report. Accordingly, the Committee implemented a plan to maintain awareness of new scientific developments in the follow-up to the accident and published three white papers [U11, U13, U14] setting out evaluations of the implications of such developments for the period up to the end of 2016.

3. The results of these reviews of new information generally confirmed the broad findings and conclusions of the UNSCEAR 2013 Report [U10] within the inherent uncertainties [U11, U13, U14]. However, the Committee became aware of increasing evidence that some of the doses to the public were overestimates, with those from ingestion significantly so [U10, U11, U13, U14]. In addition, there was a considerable amount of new information becoming available on the levels of radionuclides in the environment, and in particular on concentrations of released radionuclides in the air as a function of time and on their physico-chemical forms. This information could enable better and less uncertain estimates of doses to the public, particularly from inhalation. The Committee recognized that carrying out some more detailed analyses of this information would contribute to an improved understanding and communication of differences in the estimates of doses to the public and of the underlying science and its implications. It would also help address inevitable questions within various constituencies and enable more authoritative statements (with reduced uncertainty) to be made on a number of issues.

4. Against this background, the Committee decided at its sixty-fifth session (11–14 June 2018) to prepare a report summing up all of the information available (up to the end of 2019)[1] on the levels and effects of radiation exposure due to the FDNPS accident and on the implications of this information. It was agreed that the report should be based on reviews of the peer reviewed literature supplemented by limited, but more detailed, analyses. These analyses were to focus on doses to members of the public where more recent information, specifically from measurements on people and from measurements of the levels of radionuclides in the environment, would support estimates appreciably different from those presented in the UNSCEAR 2013 Report [U10], and on understanding the reasons for, and implications of, the differences. The aim was to provide an authoritative and updated assessment of the levels and effects of radiation exposure due to the FDNPS accident.

[1] The Committee has, exceptionally, taken account of information that became available after this date, where it would affect the findings of the report.

5. The reviews of the literature reported in the three published white papers and carried out subsequently have been conducted by a group of scientific experts (the Expert Group), supported by a group of scientific experts from Japan (the Japanese Working Group), and under the direction of two senior technical advisers, and a project manager. The detailed analyses were conducted by expert task groups set up for the purpose under the leadership of relevant members of the Expert Group and with involvement of relevant members of the Japanese Working Group. Some of the experts were assisted in their work by supplementary staff in their national institutes. An expert supported by Japan assisted the secretariat in Vienna. All involved were required to declare any potential conflicts of interest, which were reviewed by the secretariat to confirm that there were no conflicts of interest for the work in which the experts were involved. The work was carried out in accordance with a quality plan for the project.

6. The secretariat provided support to the technical work, inter alia, by arranging a visit by the Expert Group to Japan to discuss research work being carried out in Japan on the levels and effects of radiation exposure due to the FDNPS accident with Japanese researchers, by convening meetings in Vienna of the task groups carrying out the detailed analyses to facilitate the planning and implementation of this work, by providing a platform for online meetings and an online workspace for sharing and managing data and information, and by liaising with governments and other international organizations. The Governments of Australia, France, Germany, Japan, Norway and the United Kingdom made in kind contributions through expertise in this project.

7. The aim of this scientific annex is to provide a summary of all of the scientific information available (up to the end of 2019) relating to the levels and effects of radiation exposure due to the FDNPS accident and an appraisal of the implications of this information for the UNSCEAR 2013 Report [U10]. Specific objectives are to:

(a) Summarize all of the information available and assess its implications for the findings and conclusions presented in the UNSCEAR 2013 Report;

(b) Validate and, where necessary, revise estimates of doses to the public, based on more detailed analyses of the available information, and update the commentary on the health implications;

(c) Set out an improved appraisal of the uncertainties and variabilities in the estimates of doses to the public;

(d) Where possible, better address issues and objectives not fully addressed in the UNSCEAR 2013 Report.

While self-standing, the annex is intended to be read in conjunction with the UNSCEAR 2013 Report and the subsequent white papers and does not repeat all of the information available in these publications. In particular, it does not repeat detailed background or contextual information set out in the UNSCEAR 2013 Report or in the subsequent International Atomic Energy Agency (IAEA) report on the accident [I5], for example, about the chronology of the accident or the actions taken in response, where understanding has not significantly changed. Where relevant, the reader is, instead, referred to these reports, where further information can be found.

8. The annex does not address policy issues with respect to human rights, public health protection, environmental protection, radiation protection, emergency preparedness and response, accident management, nuclear safety, radioactive waste management, prospective releases and related issues; it does not intend to provide advice to local governments, the Government of Japan or to national and international bodies. The annex also does not address other effects (not associated with exposure to radiation) that can arise as a result of accidents such as that at FDNPS, including distress and anxiety from, among other things, disruption of life, loss of homes and livelihoods, and social stigma, which can

have major impacts on mental and social well-being. Evaluating such effects is not part of the Committee's mandate; however, they are important for understanding the broader health implications of the accident.

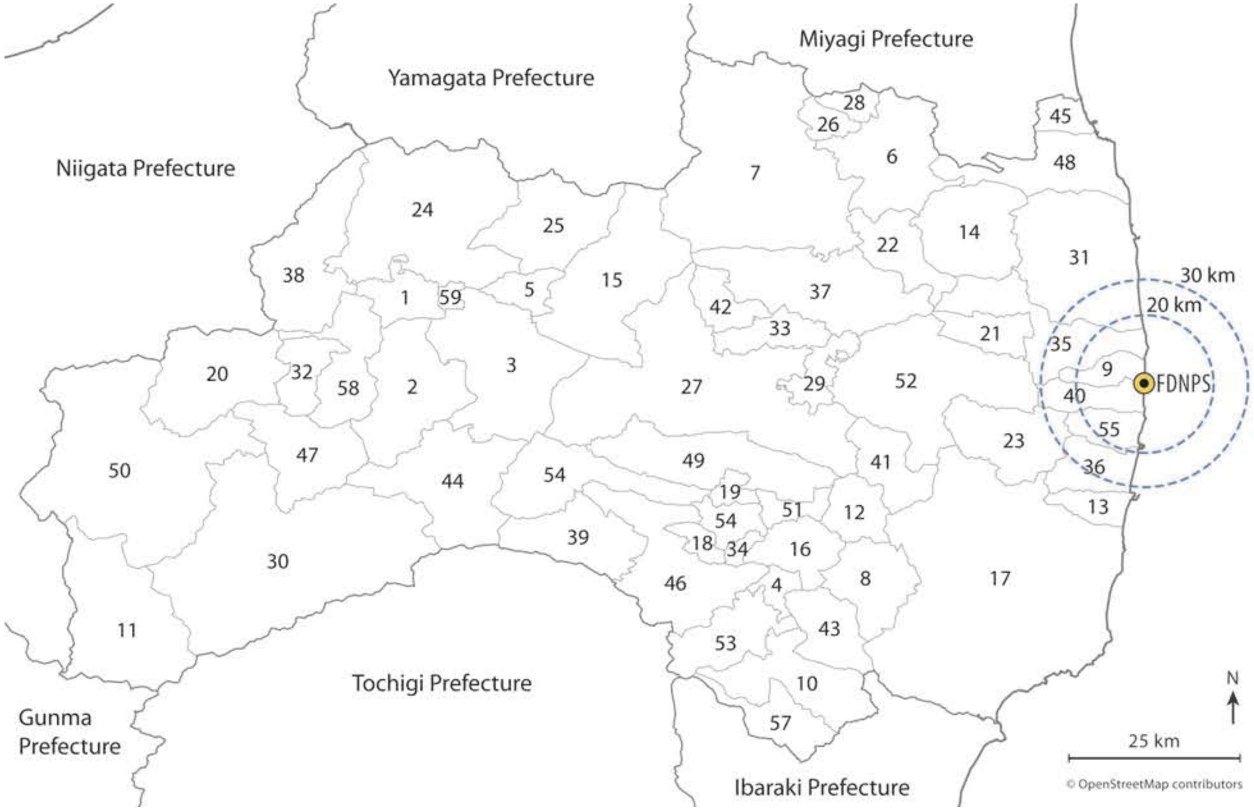
9. The annex comprises a main text with nine chapters and two appendices, supported by 23 attachments. Chapter I introduces the aim, background, scope and method of working. Chapters II to VIII set out summaries of all of the information available (up to the end of 2019) in each of the following areas relevant to the understanding of the levels and effects of the FDNPS accident:

- Chapter II: Radionuclide releases to atmosphere, dispersion and deposition;
- Chapter III: Radionuclide releases to, and dispersion and deposition in, the marine environment;
- Chapter IV: Transfer of radionuclides in terrestrial and freshwater environments;
- Chapter V: Assessment of doses to the public;
- Chapter VI: Assessment of doses to workers;
- Chapter VII: Health implications;
- Chapter VIII: Assessment of doses and effects for non-human biota;
- Finally, chapter IX sets out conclusions.

10. Appendix A describes the Committee's updated dose assessment and presents revised estimates of the doses to members of the public. Appendix B contains a comparison between the accident at FDNPS with the accident at Chernobyl to provide an overview of the main differences and similarities between them. Supplementary information lists the supporting attachments. Where numerical values have been estimated by the Committee, they are generally quoted to two significant figures (although, for estimated doses of the order of a few microsieverts (μSv) or less, only one significant figure has generally been quoted); where numerical values are quoted directly from other publications, the number of significant figures used in the original publication have been given. 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.

11. FDNPS lies in Fukushima Prefecture (see figures I(a) and (b)) of the Tōhoku region in Japan. It is located about 230 km north-east of Tokyo on the east coast of Japan. On 11 March 2011, an earthquake of magnitude 9.0 occurred along the Japan Trench. The earthquake and the following tsunami triggered a severe nuclear accident at FDNPS. In the UNSCEAR 2013 Report [U10], the Committee provided an overview of the main events that took place at the FDNPS site that led to releases of radioactive material into the environment and the measures taken by the Japanese authorities to protect the public and workers. In its subsequent report, IAEA [I5] has provided a more detailed description of the accident, including its chronology and context, and the actions taken in response.

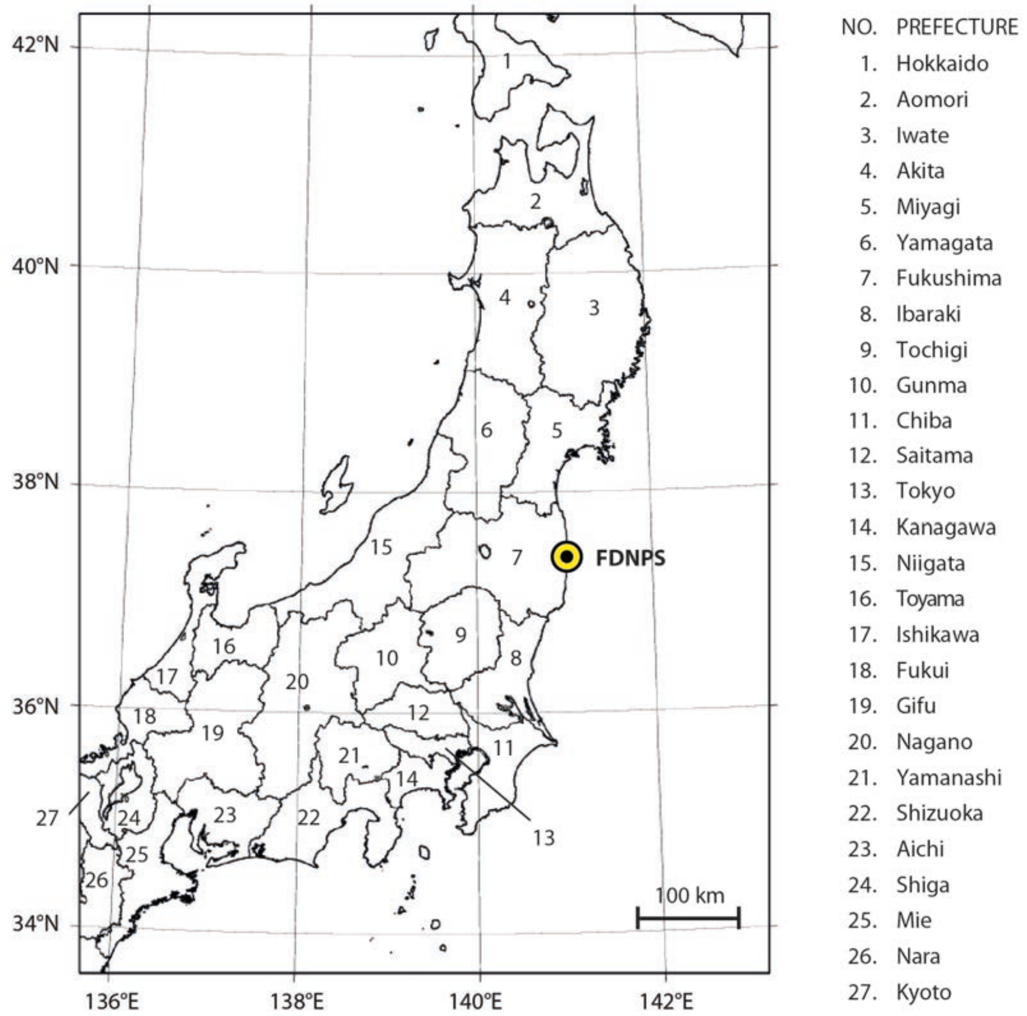
Figure I(a). Map of Fukushima Prefecture showing its municipalities, the location of the Fukushima Daiichi Nuclear Power Station, the 20 km restricted area and the 30 km evacuation prepared area



NO.	MUNICIPALITY	NO.	MUNICIPALITY
1.	Aizubange Town	31.	Minamisoma City
2.	Aizumisato Town	32.	Mishima Town
3.	Aizuwakamatsu City	33.	Motomiya City
4.	Asakawa Town	34.	Nakajima Village
5.	Bandai Town	35.	Namie Town
6.	Date City	36.	Naraha Town
7.	Fukushima City	37.	Nihonmatsu City
8.	Furudono Town	38.	Nishiaizu Town
9.	Futaba Town	39.	Nishigo Village
10.	Hanawa Town	40.	Okuma Town
11.	Hinoemata Village	41.	Ono Town
12.	Hirata Village	42.	Otama Village
13.	Hirono Town	43.	Samegawa Village
14.	Iitate Village	44.	Shimogo Town
15.	Inawashiro Town	45.	Shinchi Town
16.	Ishikawa Town	46.	Shirakawa City
17.	Iwaki City	47.	Showa Village
18.	Izumizaki Village	48.	Soma City
19.	Kagamiishi Town	49.	Sukagawa City
20.	Kaneyama Town	50.	Tadami Town
21.	Katsurao Village	51.	Tamakawa Village
22.	Kawamata Town	52.	Tamura City
23.	Kawauchi Village	53.	Tanagura Town
24.	Kitakata City	54.	Ten-ei Village
25.	Kitashiobara Village	55.	Tomioka Town
26.	Koori Town	56.	Yabuki Town
27.	Koriyama City	57.	Yamatsuri Town
28.	Kunimi Town	58.	Yanaizu Town
29.	Miharu Town	59.	Yugawa Village
30.	Minamiaizu Town		

The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure I(b). Map showing nearby prefectures [U10]



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

12. The measures taken by the Japanese authorities included immediate and late ("deliberate") evacuation, sheltering in homes, iodine prophylaxis, and restricting distribution and consumption of contaminated foodstuffs (milk, vegetables, grains, meat, fish, etc.) and water. These actions were supported by radiation surveys of people and places. People within 3 km of FDNPS were ordered to be evacuated late on 11 March 2011, and those within 20 km were ordered to be evacuated on 12 March 2011. On 15 March 2011, people living between 20 km and 30 km from FDNPS were ordered to shelter indoors, and on 25 March 2011 were advised to begin voluntary evacuation and be prepared to evacuate depending on future developments at FDNPS. In addition, environmental monitoring revealed that there were areas where radioactive material had been deposited at high levels[2] outside of the 20-km evacuation zone. "Deliberate evacuation areas" were established for specific areas where the effective dose might exceed 20 mSv within a year, and most residents of these areas were then evacuated between April and June 2011. More localized areas ("specific spots recommended for evacuation") were designated from

[2] 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 [U10].

June 2011 onwards, and the local authorities provided advice to potentially affected residents on their options for relocating or remaining and information on how to mitigate future radiation exposures. The localized areas included areas within Date City, Minamisoma City, and Kawauchi Village. Decisions were made and instructions issued on taking stable iodine, but were not fully implemented. On 16 March 2011, an instruction was issued that anyone still remaining within 20 km of FDNPS should take stable iodine, but this instruction was not implemented, because the area was considered to have already been evacuated. On 14 March 2011, the Fukushima Prefectural government decided to distribute two stable iodine tablets to each resident younger than 40 years of age between 20 km and approximately 50 km of FDNPS, distributing approximately 1 million stable iodine tablets by 20 March 2011, but administration was not implemented uniformly. The UNSCEAR 2013 Report [U10] and the IAEA report [I5] provide further details.

II. RADIONUCLIDE RELEASES TO ATMOSPHERE, DISPERSION AND DEPOSITION

A. Introduction

13. In the UNSCEAR 2013 Report [U10], the Committee presented a summary of the main events in the progression of the accident at FDNPS that followed the earthquake and tsunami [U10]. Several of these events led to releases of radioactive material to the environment. Estimates of the amounts and temporal pattern of the releases to the atmosphere, and understanding of the transport and dispersion of the released material in the air and its deposition on to the ground are summarized in this chapter; estimates of the releases to the marine environment are summarized in chapter III.

14. Radioactive material was released to the atmosphere from FDNPS over an extended period. The pattern of release was complex, both temporally and spatially. Releases began on 12 March 2011 and the rate of release varied considerably in magnitude over the following week, with marked increases associated with particular events at each reactor 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 2011, the release rates were thousands of times less than the release rates that occurred during the first week of the accident, although these much lower release rates persisted for many weeks [U10].

15. During the preparation of the UNSCEAR 2013 Report [U10], the Committee was provided with access to the results of extensive measurements that had been made in Japan, particularly of the levels of various radionuclides deposited on the ground, and based its assessment of doses to the public largely on these measurement data. There were gaps in the measurement data, however, and there was little information available on concentrations of released radionuclides in the air and how they varied with time, so the Committee had to make use of modelling to supplement the measurement information. A considerable amount of measurement data has become available since the publication of the UNSCEAR 2013 Report and all of the measurement information available is summarized in this chapter. This information has provided an important input into the detailed analyses described in appendix A, aimed at validating and, where necessary, revising the approaches used to estimate doses to the public in the UNSCEAR 2013 Report.

B. Overview of current understanding

1. Measurement data

16. Dose-rate measurements from automatic stations within Japan were the most abundant data available over the course of the accident, although in Fukushima Prefecture most automatic monitoring posts were inoperative due to loss of communication and power, and measurements there came mostly from portable dose-rate monitors, such as hand-held type survey-meters and the so-called car-borne survey system. 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. Measurements of concentrations of radionuclides in air over Japan while the release was happening were much more limited, especially in the early stages of the accident and in the areas devastated by the tsunami. 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, including both measurements of concentrations in the air and measurements of deposition density on the ground. The measurement information available at the time of the UNSCEAR 2013 Report [U10] was described in detail in that report.

17. At the time of the FDNPS accident, there were about 70,000 United States Department of Defense (DoD) affiliated individuals based in Japan. In response to the accident, DoD provided humanitarian assistance and disaster relief and developed radiation dose assessments for the DoD-affiliated individuals. To support the dose assessments, measurements were made on samples collected by DoD and the United States Department of Energy (DOE) at or near locations where DoD-affiliated individuals worked or lived. This measurement information has been made available and includes new data on concentrations of several radionuclides in air for five locations on the Japanese mainland for each hour in the period from 12 March to 11 May 2011 [D7].

18. Aside from this new source of measurement information, additional information about the levels of radionuclides in the air and deposited on the ground has come from reanalysis of monitoring data collected at the time and from the application of some novel analysis methods. Specifically, concentrations of different radionuclides in the air in the early stage of the FDNPS accident have been estimated at several monitoring posts in Fukushima and Ibaraki Prefectures from results of gamma spectrometry with sodium iodide (NaI(Tl)) scintillation detectors [H17, M44, T29]. In addition, concentrations of ^{137}Cs and ^{129}I (from which levels of ^{131}I can be inferred) in air at ground-level in the Fukushima and Kanto[3] areas are being derived from an analysis of filter-tapes of air pollution stations (for monitoring suspended particulate matter) [E1, O25, T50, T51], although it should be noted that only iodine in particulate form will have been collected on the filter-tapes. The latest version of the data set produced by this work, which includes information on ^{137}Cs (and ^{134}Cs) concentrations in air for 101 locations and on ^{131}I concentrations in air for 4 locations, has provided an important input into some of the models and assumptions underpinning the update to the estimation of doses to the public described in appendix A (and particularly attachments A-9 and A-12). The locations within and close to Fukushima Prefecture where concentration measurements of ^{137}Cs (and ^{134}Cs) in air are available from this work are shown in figure II.

[3] Kanto area contains six prefectures (Chiba, Ibaraki, Gunma, Kanagawa, Saitama and Tochigi) and Tokyo Metropolis.

Figure II. Locations of continuous measurements of radiocaesium concentrations in air from filter-tapes in or close to Fukushima Prefecture) [O25, T51]

The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

19. Another major advance has been the retrospective reconstruction of deposition densities of ^{131}I from the measured deposition densities of ^{129}I [F13, M50], which has been completed for nearly 1,000 surface soil samples from across Fukushima Prefecture and in the neighbouring prefectures of Miyagi and Ibaraki [M18]. The reconstructed data for ^{131}I deposition have the potential to further improve estimations of the ^{131}I source term and also to improve assessments of doses to members of the public, including evacuees, from inhalation. This data set has also provided an important input into the Committee's updated public dose assessment reported in appendix A.

20. Ohba et al. [O4] measured the short-lived radionuclides, ^{132}I, ^{132}Te, ^{133}I and ^{135}I, on the clothing of two individuals using gamma spectrometry, and found average ratios (relative to ^{131}I, and decay corrected to 12:00 on 12 March 2011) for ^{132}Te (and its daughter ^{132}I), ^{133}I and ^{135}I of 2.3, 1.1 and 0.3, respectively. Recent results of measured $^{137}Cs/^{129m,132}Te$ ratios in the environment are consistent with ^{132}Te being transported, dispersed and deposited in the environment as a particulate species [D2].

21. Measurements of ^{90}Sr [R4, Z2, Z3], ^{238}Pu and $^{239+240}$Pu [K13] have been reported for a small number of sampling points, generally in locations within Fukushima Prefecture. The deposition densities of ^{90}Sr [R4, Z2] and ^{110m}Ag [M29] were significantly (many orders of magnitude) lower than those of ^{137}Cs. The deposition densities of ^{238}Pu and $^{239+240}$Pu were very low and often below detection limits, but indicated that trace amounts of uranium from the fuel cores were released together with plutonium isotopes [D10, I23, K13, S4]. Bu et al. [B14] have developed and applied mass spectrometric methods to samples to assess deposition densities of actinides and fission products.

22. Several studies have found radiocaesium associated with water-insoluble “glassy spherules”, several micrometres in diameter [A1, A3, Y1]. Ikehara et al. [I28], using a novel method based on autoradiography, detected radiocaesium associated with microparticles, with a typical size of a few micrometres, and with an extremely high level of specific radioactivity (about 10^{11} Bq/g) in the environmental samples. These glassy microparticles do not adsorb to the mineral phase of soil and are quite persistent in the environment [S37]. Such particles have been collected from various materials, including aerosol filters (e.g., [A1]), soil [F24, I28, S14], plant leaves and other tissues [Y1, Y4], breathing protection [H13], and particulate matter in river water [M33]. Satou et al. [S15] isolated considerably larger particles associated with radiocaesium from environmental samples within a small region close to FDNPS. These particles were up to 400 micrometres in diameter, and some were associated with more than 20 kBq of radiocaesium per particle, but they had much lower radiocaesium concentrations than the particles with diameters of a few micrometres. It is not clear to date what proportion of the radioisotopes of caesium released to the atmosphere from the FDNPS accident may have been associated with such particles. Ikehara et al. [I29] studied radiocaesium (^{134}Cs and ^{137}Cs) in soil and reported that the percentage of radiocaesium associated with such particles in the studied samples ranged from 2% to 80%. Further information on the distribution of these particles and their possible influence on the levels of exposure of the public is given in appendix A and attachment A-3.

2. Releases to the atmosphere

(a) *Estimates of the total releases of radionuclides*

23. In the UNSCEAR 2013 Report [U10], the Committee summarized the numerous estimates that had been published of the magnitude of the release of radionuclides from FDNPS. The Committee noted that the majority of the estimates were made using either reverse or inverse modelling from measurements in the environment. The estimates were not always directly comparable: some were estimates of the total quantities released; others were releases over a limited period of time, or only included that fraction of the release partly or wholly dispersed over the Japanese land mass (i.e., did not include the fraction of the release dispersed directly over the ocean). The Committee concluded that the total release of ^{131}I fell within the range of about 100 to about 500 PBq, and that of ^{137}Cs fell generally in the range of 6 to 20 PBq. In the report by IAEA on the accident [I5], the releases to atmosphere were estimated to lie in the ranges of 100 to 400 PBq for ^{131}I and 7 to 20 PBq for ^{137}Cs, when the very first estimates based on limited information were excluded. Estimates of the total release published since the UNSCEAR 2013 Report are summarized in table 1 for comparison with the estimates in that report and other relevant publications.

Table 1. Comparison of range of estimates given in the UNSCEAR 2013 Report [U10] with estimates made since of the total amounts of ^{131}I and ^{137}Cs released to the atmosphere as a result of the Fukushima Daiichi Nuclear Power Station accident

Reference	*Date of publication*	*Total release (PBq)*	
		^{131}I	*^{137}Cs*
UNSCEAR 2013 Report [U10]	2014	100–500	6–20
[A2][a]	2014	400	11
[W17][a]	2014		12–19
[K6][a]	2015	151	15
[I5][b]	2015	100–400	7–20
[Y28][a]	2016		8
[S16][a]	2016		8
[K19][c]	2017	754	29
[T28][d]	2020	120	10

[a] Estimate based on inverse or reverse modelling.

[b] Based on a summary of 20 published estimates made in 2011–2013 by different organizations.

[c] Estimate based on forward projection using severe accident progression code.

[d] Estimate using optimization based on Bayesian inference.

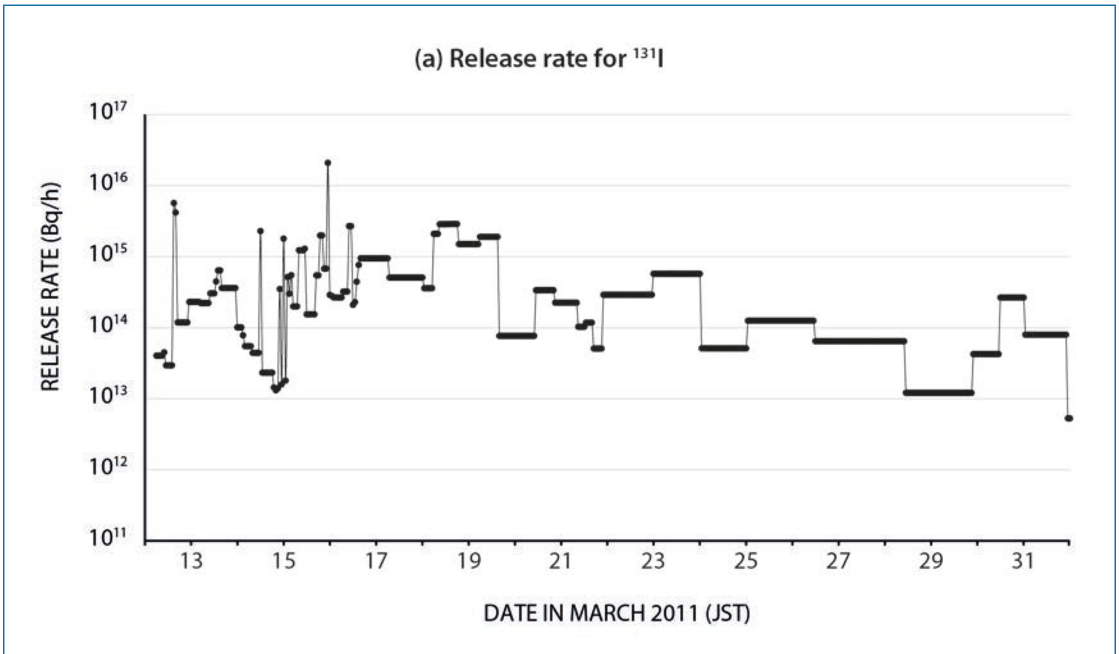
24. The estimates made since the UNSCEAR 2013 Report [U10] generally confirm the ranges estimated by the Committee and IAEA, with most of the estimates at the lower end of the ranges [I5, K6, K19, S16, S19, T28, W17, Y28]. The exceptions are the estimates of Kim et al. [K19], which were somewhat higher. These estimates were based on a severe accident progression code and were therefore reliant on assumptions about the exact conditions and the timing of various accident-related events inside the reactors. As noted in the UNSCEAR 2013 Report, while all of the estimates are associated with uncertainty, those based on inverse or reverse modelling using measurements of radioactive material in the environment are preferable in the context of assessing levels and effects of exposure as a result of the releases. Excluding the estimates of Kim et al. [K19], the ranges correspond to about 2% to 8% of the total inventory of ^{131}I and about 1% to 3% of the total inventory of ^{137}Cs in the three operating reactors (Units 1–3) from which the releases occurred at the time of the accident. For perspective, the estimated releases (based on the averages of published estimates) of these radionuclides from the FDNPS accident were about 10% and 20% for ^{131}I and ^{137}Cs, respectively, of the releases of these radionuclides estimated for the Chernobyl accident (see appendix B).

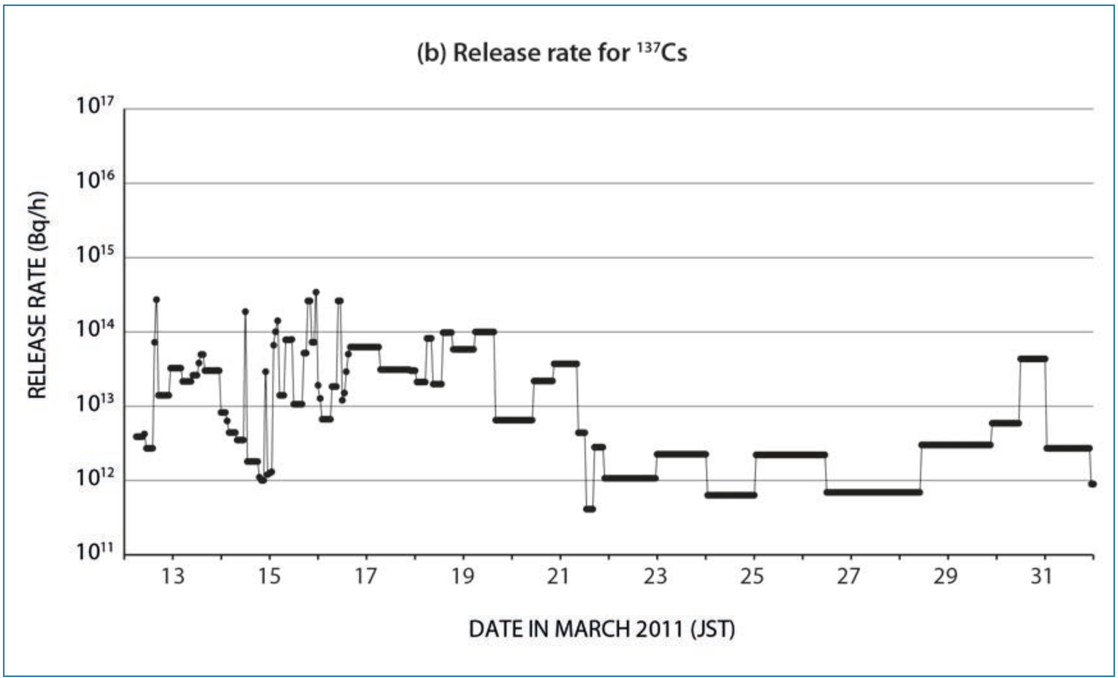
25. The two radionuclides ^{131}I and ^{137}Cs, together with ^{134}Cs, made by far the largest contribution to the exposure of the public. A large number of other radioisotopes of iodine, caesium and other elements was also released, with the relative amounts released determined by their volatility. For example, essentially the entire inventory of ^{133}Xe, ^{85}Kr and other noble gases would have been released [B7], and the estimates in table 1 suggest that a few per cent of the inventory of volatile elements, including iodine, caesium and tellurium was released; on the other hand, the volatilities of strontium, barium and plutonium are much lower and their releases were correspondingly also much lower. This has been confirmed by measurements of their levels in the environment [D10, H21, H29, I25, S18, T30, Z4]. 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 (see appendix B).

(b) *Estimates of the source term*

26. Numerous estimates have also been made of the temporal pattern of the rate of material released (commonly referred to as the “source term”), in particular for ^{131}I and ^{137}Cs. In the UNSCEAR 2013 Report [U10], the Committee noted that, although there was broad agreement on 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 correlated with events on site. For the purposes of providing a sound basis for estimating levels of radioactive material in the terrestrial environment where no measurements existed and the subsequent estimation of doses to the public, the Committee chose, in the UNSCEAR 2013 Report, to use the source term estimated by Terada et al. [T27]. The Committee has subsequently [U11, U13, U14] recommended for future assessments the use of the latest in a series of estimates of the source term for releases to atmosphere by the same group of researchers at the Japan Atomic Energy Agency (JAEA). These estimates have been made through progressive refinements to the previous estimate, taking account of all of the measurement information as it has become available. In the latest source term produced by this group, Terada et al. [T28] improved the atmospheric transport, dispersion and deposition modelling (ATDM) simulation with an optimization method based on Bayesian inference, and used various measurements such as air concentration, surface deposition, fallout, and newly released estimates of hourly air concentrations of ^{137}Cs derived by analysing the filter-tapes of air pollution stations. This optimization improved not only the source term but also the wind field in the meteorological calculation, which led to a reduction in the discrepancies (between the calculations and the measurements) in the plume passage time at monitoring points to less than three hours. The Committee has used this source term in the revised estimates of doses to members of the public (see chapter V and appendix A). The pattern of the release for this source term [T28] is illustrated in figure III for the releases of ^{131}I and ^{137}Cs.

Figure III. Release rate as a function of time[a] for *(a)* ^{131}I and *(b)* ^{137}Cs





[a] Decay corrected at the shutdown time of 14:46 Japanese Standard Time (JST) on 11 March 2011, according to [T28].

27. Since the UNSCEAR 2013 Report [U10], several researchers have investigated which events during the course of the accident were the dominant sources of atmospheric releases at different times during the major release period of 12 to 21 March 2011. They have been able to identify which reactor unit was the source of releases that resulted in deposition on to specific areas of the Japanese mainland, mainly based on measured small differences in the ratios of different radioisotopes of caesium [C4, J1, S34, T51, T52, Z4]. Other researchers [N5, T50] have used environmental monitoring data to identify at least nine major, separately identifiable releases from FDNPS.

28. There remains particular uncertainty about the chemical form in which iodine was released from FDNPS: Lebel et al. [L1] estimated that, overall, about one half of the iodine had been released as a particulate, with the other half released in a volatile or gaseous form (which comprised both elemental and organic forms, although the relative amounts released of each remains uncertain). Amano et al. [A10] reported $^{131}I_{gas}/^{131}I_{total}$ ratios as: 0.7 from 15 to 16 March 2011; 0.52 from 20 to 21 March 2011; and 0.68 from 22 to 23 March 2011. Tsuruta et al. [T52] summarized $^{131}I_{gas}/^{131}I_{total}$ ratios ranging from 0.44 to 0.72 for the releases that occurred at different times. The Committee has recommended [U13] that explicit account should be taken of releases of iodine in organic forms in any future update of the UNSCEAR 2013 Report [U10]. The source term that has been used in the revised dose assessment described in appendix A includes estimates of the amount of iodine released in all three chemical forms (elemental, organic and particulate). It assumes constant ratios (over time) of 0.2 for $^{131}I_{elemental}/^{131}I_{total}$, 0.3 for $^{131}I_{organic}/^{131}I_{total}$ and 0.5 for $^{131}I_{particulate}/^{131}I_{total}$ [K6, T28], but the Committee has also given explicit consideration to the uncertainty in these ratios (see appendix A and attachment A-12).

29. Hirose [H21] has suggested that the particle size of the ^{131}I-bearing particles may have differed from those bearing radiocaesium, and therefore that the dispersion and deposition behaviour of ^{131}I-bearing particles may have differed from those bearing ^{134}Cs and ^{137}Cs. The Committee considers that the effects of any differences in particle size suggested by Hirose are likely to be small (in terms of exposure of the public) compared with those due to assumptions about the chemical form of radioiodine and therefore

that it is reasonable to assume that particulate iodine and caesium behave in a similar way during atmospheric transport and deposition.

30. Steinhauser et al. [S36] have pointed out that continuing releases of radioactive materials from the FDNPS site to the atmosphere are possible as a result of decommissioning and dismantling activities on the site. Steinhauser et al. further noted, as have Igarashi et al. [I24], Ochiai et al. [O2] and Akimoto [A7], that resuspension of deposited ^{137}Cs can lead to continuing concentrations of ^{137}Cs in the air and its redeposition. The process by which any resuspension predominately occurs is still not fully understood [K21]. Nevertheless, all of these studies have confirmed that resuspension did not significantly contribute to the long-term exposure of the public.

3. Dispersion in the atmosphere

31. 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 the 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 deposited on the Japanese land mass occurred on 12, 14–16, and 20–23 March 2011. Oura et al. [O25], Mathieu et al. [M9], Sato et al. [S13], Tsuruta et al. [T52], and Moriizumi et al. [M44] have carried out comprehensive analyses of the main events and have generally agreed that the meteorological features that determined the fate of these releases were probably as follows:

(a) Material initially released on 12 March 2011 went towards the Pacific Ocean, but the release in the afternoon of 12 March 2011, in particular that resulting from the venting operation and also 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. This has been verified by relatively low $^{134}Cs/^{137}Cs$ ratios in this area, indicating Unit 1 as the source of this deposition [K29];

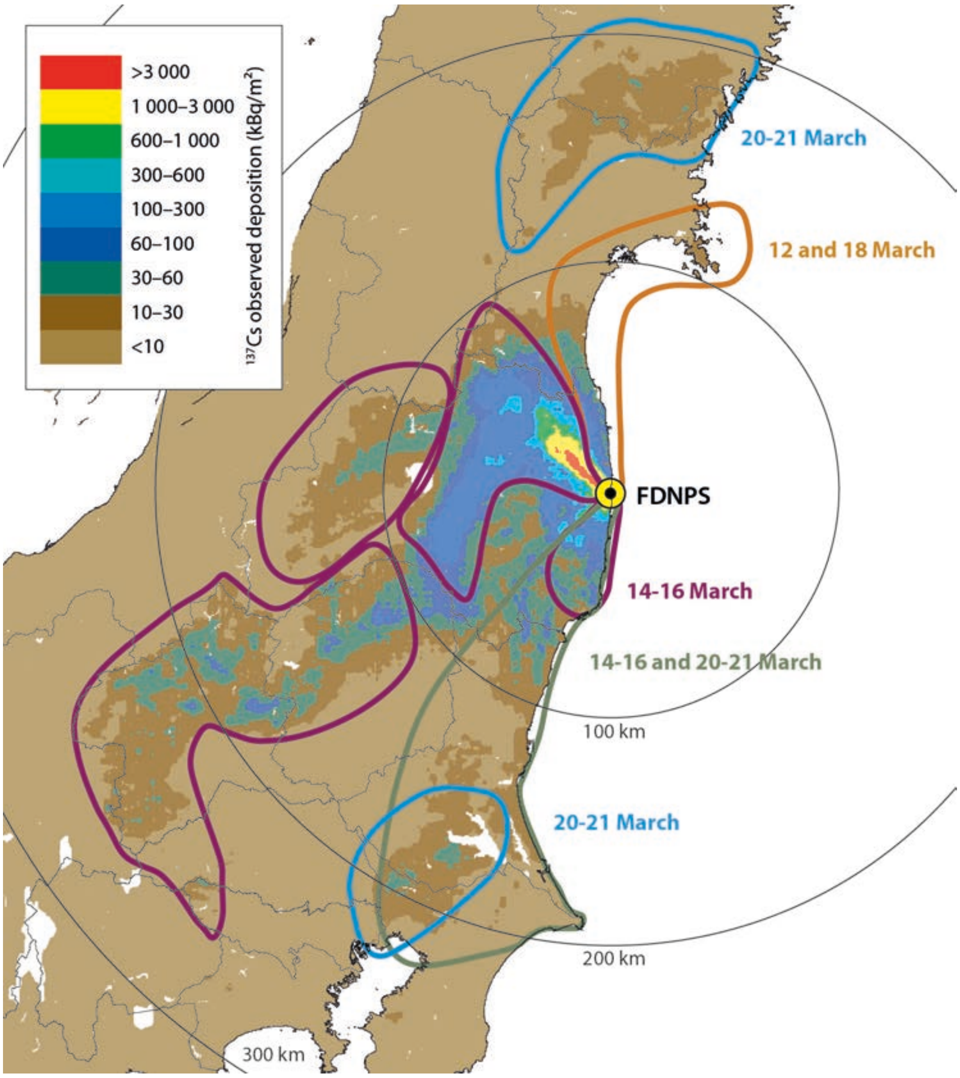
(b) Material released from late at night on 14 March until 16 March 2011 (first from Unit 2, later from both Units 2 and 3 [C4]) moved towards the south, depositing along the southern coastal area of Fukushima Prefecture and the north-eastern area of Ibaraki Prefecture on the morning of 15 March 2011. Then, the direction of plume gradually changed clockwise from towards the south to towards the north-west and encountered rainfall on the evening and night of 15 March 2011. The plume moved towards the south again before daybreak on 16 March 2011 and released material was deposited by wet deposition. In this region the $^{131}I/^{137}Cs$ ratio (of the deposited material) was significantly elevated [H29], and it has been noted that the $^{135}Cs/^{137}Cs$ ratio was also different in this area [Z4]. The released material was further dispersed and resulted also in dry deposition of radionuclides in the prefectures of Tokyo, Saitama and Kanagawa, albeit at reduced levels;

(c) A major discharge of radioactive material from Unit 2 on 15 March 2011 resulted in a release that was firstly transported south-west and later gradually transported north-north-west by the prevailing wind. Precipitation scavenging (rainfall and possibly snowfall washing radioactive material out of the air and depositing it on to the ground) occurred during 15 March 2011 and continued until the morning of 16 March 2011. These events are acknowledged to be the cause of the relatively high ^{137}Cs deposition densities monitored to the north-west of FDNPS [D10];

(d) Material released during the period 20 to 23 March 2011 (from Units 2 and 3 [C4]) was dispersed over parts of the Japanese territory encountering rainfall on occasions and resulting in wet and dry deposition, for example in areas of the prefectures of Iwate, Miyagi, Ibaraki and Chiba. The episode of 20 to 21 March 2011, in particular, involved the release of several plumes, and light winds favoured stagnation of the released material. Releases during this period are the main source of deposition in the Kanto plain region to the south, and in the zone to the north between the north of the Miyagi Prefecture and the south of the Iwate Prefecture [M9]. During this time (mainly during 20 March 2011), the plume of released material was monitored along the coast, then to the north and then the north-west (e.g., [T29]).

The fate of these releases relative to the measured deposition density levels of ^{137}Cs is illustrated in figure IV.

Figure IV. The regions impacted by the deposition from the main release episodes (indicated in outline with the corresponding periods of releases) superimposed on a map of measured ^{137}Cs deposition [M9].



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

32. The dispersion and deposition of released material has been modelled by many groups (e.g., [K6, N1, S13, T27, T28, W18]). There is general agreement that most of the radioactive material released to the atmosphere was blown eastward by the prevailing winds, depositing on to and dispersing within the North Pacific Ocean. The Science Council of Japan [S20] evaluated and compared several models used to analyse the transportation and deposition of radioactive materials released during the FDNPS accident. One of the findings was that deposition of ^{137}Cs on to the mainland of Japan, as assessed with different regional-scale models, was about 27 ± 10% of the total emission. A review by Hirose [H21] based on many papers published between 2011 and 2016 concluded that around 80% of the total atmospheric release of ^{137}Cs was deposited on to the North Pacific Ocean, and this has been confirmed by Terada et al. [T28]. Estimates of the amounts released into the marine environment via this route are considered further in chapter III. All the above-mentioned dispersion model predictions were able to replicate the broad pattern of measured deposition density of ^{137}Cs over the Japanese land mass. At specific locations, the model estimates were generally within a factor of 10 (higher or lower) of the measured deposition levels, but sometimes better.

33. The Committee has used the results of the source term and ATDM carried out by Terada et al. [T28] in its revised dose assessment described in chapter V and appendix A. Time-dependent concentrations in air and deposition densities of the radionuclides[4] ^{132}Te (and its daughter radionuclide, ^{132}I, with which it is assumed to be in equilibrium), ^{131}I, ^{134}Cs, and ^{137}Cs have been provided to the Committee for two nested grids:

(a) The finer grid covering most of Fukushima Prefecture with a horizontal resolution of 1 km;

(b) The coarse grid covering Fukushima Prefecture and all neighbouring prefectures with a horizontal resolution of 3 km [T28].

Terada et al. did not include the short-lived radionuclide ^{133}I and the Committee has therefore estimated the concentration of ^{133}I in air from the calculated concentrations of ^{131}I in air. The three different chemical forms of radioiodine have been considered separately. Further details of the ATDM results provided to the Committee and how they have been used in the dose assessment are provided in appendix A and attachments A-9 and A-10.

C. Summary

34. There was a considerable amount of measurement data available at the time of the UNSCEAR 2013 Report [U10] on the concentrations in the terrestrial environment of the radionuclides released as a result of the accident that contributed most to the exposure of the public. This extensive information provided the basis for the majority of estimates of the quantities of radionuclides released and of the temporal pattern of the release, and for the assessment of exposures of the public. However, there were some gaps in the measurement data with little information available on concentrations of radionuclides in the air and their variation with time. Some additional measurement information has become available since the UNSCEAR 2013 Report. In addition, reanalysis of, and the application of techniques not previously applied to, the results of monitoring and sampling carried out earlier has provided additional data,

[4] The ATDM results of Terada et al. did not include ^{133}Xe, a radionuclide also released in significant quantities. This radionuclide is not deposited on the ground from the atmosphere but would have contributed to the dose from external exposure to airborne radioactive material. Because it is soluble in body tissue, it would also have made a minor contribution to internal exposure from inhalation of airborne material. However, its overall contribution to doses to the public would have been small (less than 1%, see attachment A-10) and it was accordingly not included in the revised dose assessment.

particularly on concentrations of radionuclides in the air and how these varied with time. These developments have led to refinements in estimates of the source term and to an improved basis for assessing exposures of the public.

35. In the revised assessments of doses to the public described in chapter V and in more detail in appendix A, the Committee has made use of the latest in a series of estimates of the temporal pattern of release (source term) for releases to atmosphere by the same group of researchers at JAEA that made the estimate of the source term used in the UNSCEAR 2013 Report [U10]. In this source term, the total release of ^{131}I was estimated to be 120 PBq and of ^{137}Cs was estimated to be 10 PBq. The Committee has also made use of the modelling carried out by this group of the transport, dispersion and deposition of the source term in the atmosphere. As in the UNSCEAR 2013 Report, this modelling has been used to infer the concentrations of radionuclides in the air or on the ground where measurement information was not available or where measurements could no longer be made.

36. The Committee continues to consider that the total release to the atmosphere of ^{131}I was within the range of about 100 to about 500 PBq, and that of ^{137}Cs was generally in the range of 6 to 20 PBq. The ranges correspond to about 2% to 8% of the total inventory of ^{131}I and about 1% to 3% of the total inventory of ^{137}Cs in the three operating reactors (Units 1 to 3) from which the releases occurred at the time of the accident. For perspective, the estimated releases (based on the averages of published estimates) of these radionuclides from the FDNPS accident were about 10% and 20% for ^{131}I and ^{137}Cs, respectively, of the releases of these radionuclides estimated for the Chernobyl accident.

37. The releases that largely determined the levels and patterns of radionuclides deposited on the Japanese land mass occurred on 12, 14–16, and 20–23 March 2011. About 20% of the total atmospheric release of ^{137}Cs was dispersed over, and a substantial fraction of this was deposited on to, the Japanese land mass.

III. RADIONUCLIDE RELEASES TO, AND DISPERSION AND DEPOSITION IN, THE MARINE ENVIRONMENT

A. Introduction

38. The accident at FDNPS was, because of its coastal location, the first major nuclear power station accident in which significant amounts of radioactive material were released directly and indirectly into the marine environment. Firstly, as noted in chapter II, a large proportion of the releases of radioactive material to the atmosphere were dispersed over, and deposited on to, the surface of the Pacific Ocean, as a result of the westerly/south-westerly winds that blew part of the time during the release periods and during the initial dispersion phase. Secondly, radioactive material was released directly into the ocean, initially as a result of leakage of highly contaminated water from a trench outside Unit 2. Compared to the Chernobyl accident, in which dispersion of radioactive material released to atmosphere and its deposition over sea surfaces (particularly in the Baltic and Black Seas) resulted in a maximum concentration of ^{137}Cs in the sea of 2,400 Bq/m^3, direct releases into the ocean as a result of the FDNPS accident led to peak concentrations three to four orders of magnitude higher. For

comparison, prior to the FDNPS accident, background concentrations of ^{137}Cs, released from atmospheric weapons tests conducted in the late 1950s and early 1960s, ranged from 1 to 2 Bq/m^3 in North Pacific surface waters [B17].

39. During the course of the accident, following the initial leakage from the trench, direct releases to the marine environment occurred as a result of the deliberate discharge of weakly-contaminated water from storage tanks, emptied to create capacity for the storage of highly-contaminated water from the trench. These releases and the earlier leakage were localized, occurring at the power station's outlet channels and through the harbour. The releases occurred mainly between the end of March and the first week of April 2011. On 6 April 2011, the direct release of highly contaminated water to the ocean from the trench outside Unit 2 was brought to an end by the transfer of the water to the storage tanks.

40. After this first phase, releases decreased considerably, but a number of sources of continuing releases to sea have been identified. Inside the FDNPS site, groundwater was contaminated by the highly radioactive reactor cooling water contained in the basements of the reactor buildings, and there had been leakage from the storage facilities. These releases had been progressively reduced by remedial actions, such as the establishment of sealing barriers and pump wells and the replacement of damaged storage tanks. Outside the FDNPS site, rivers draining catchment areas on to which radioactive material released to the atmosphere had been deposited transported some of this material to the ocean. These inputs from rivers increased during periods of heavy rain and floods that transported high suspended sediment loads with adsorbed radiocaesium to the ocean.

41. Monitoring of some radionuclides (^{131}I, ^{134}Cs and ^{137}Cs) started on 21 March 2011, after detection of radioactive material in seawater, at a few points in the coastal area around FDNPS, firstly in seawater and then in the sediment and marine organisms. The number of measurement points gradually increased. These measurements were carried out at the time using high detection limits, but numerous samples have subsequently been reanalysed using more precise techniques. In the months following the accident, scientific cruises and various sampling operations were carried out allowing measurements to be acquired throughout the North Pacific Ocean.

B. Overview of current understanding

1. Releases to the marine environment

(a) *Releases in the initial phase*

42. Estimates that have been made of the total releases to the marine environment in the initial phase (March–April 2011) for a number of the more radiologically-significant radionuclides are summarized in table 2. These estimates include some reviewed in the UNSCEAR 2013 Report [U10] and some more recent estimates.

Table 2. Summary of estimates of total releases to the marine environment in the initial phase (March–April 2011)

Radionuclide	*Estimated release in the initial phase*	*References*
DIRECT RELEASES FROM THE FDNPS SITE		
^{137}Cs (and ^{134}Cs)	3.5–5.6 PBq	[E6, K11, K30, M35, T48, T49]
^{131}I	9–13 PBq	[K11, K30, T48]
^{129}I	7–8 GBq	[G7, H31]
^{90}Sr	0.04–1 PBq	[C1, P3]
^{3}H	0.3–0.7 PBq	[K1]
^{239}Pu and ^{240}Pu	Negligible (concentrations close to the background level)	[B13, M19]
DEPOSITION FROM THE ATMOSPHERE		
^{137}Cs (and ^{134}Cs)	5–11 PBq	[E6, K11, K30, T44]
^{131}I	57–100 PBq	[K11, K30]

43. Different methods have been used to estimate direct releases of ^{137}Cs to the ocean. An inverse model approach based on concentration measurements made by TEPCO at the outlet of the FDNPS discharge channels has led to estimates of the release of ^{137}Cs ranging from 3.5 to 5.6 PBq [E6, K11, K30, M35, T48, T49]. Other methods have been based on estimates of inventories in seawater. For example, Charette et al. [C2] estimated a release of ^{134}Cs of 11 PBq using a ^{134}Cs inventory based on:

(a) Samples collected in June 2011 at 50 stations spanning the area extending from 50 up to 600 km off Japan;

(b) A water mass age (the time since the water parcel left the coast) derived from radium isotopes.

As noted by the Committee in the UNSCEAR 2013 Report [U10], estimates of releases from backward extrapolation of inventories are likely to be more uncertain and to overestimate the source term. Less weight has been given to these estimates, and they are not included in table 2.

44. The direct releases of other radionuclides have, in many cases, been made using measured ratios of the concentration of these radionuclides to the concentration of ^{137}Cs.

45. Numerical modelling of dispersion in the atmosphere and deposition onto the ocean surface has been used to estimate indirect releases to the marine environment. This method has led to estimates of the indirect release of ^{137}Cs (and of ^{134}Cs, the two radioisotopes being found in the reactors of the affected units, and released to the environment, in approximately equal amounts) to the whole Pacific Ocean in the range of 5 to 11 PBq [E6, K11, K30, T44]. Of this total, 1.14 PBq has been estimated to have been deposited over a 300,000 km^2 area of high deposition to the north-east and south-east of FDNPS [T49].

46. There is little information on the deposition of other radionuclides on to the ocean surface, apart from estimates of 57 and 99 PBq for ^{131}I [K11, K30].

47. The percentage of the total release of ^{137}Cs to atmosphere that was deposited on to the surface of the Pacific Ocean has been estimated at around 80% [H21]. For comparison, for the Chernobyl accident, of the order of 7% of the release of ^{137}Cs to atmosphere (which was larger than the release from FDNPS) was estimated to have been deposited on to the surface of the Baltic and Black Seas combined (see appendix B).

(b) *Estimation of the long-term releases*

48. On 6 April 2011, the major leakage of contaminated water to the ocean was brought to an end by the transfer of the water in the trench to the storage tanks. This resulted in a reduction in the ^{137}Cs concentration measured at the outlets of FDNPS by about a factor of 100 in one month. However, over the longer term (2012–2013), the ^{137}Cs concentration has not decreased as rapidly, falling by a factor of about three between October 2011 and 2013 at the northern discharge outlet [H20]. Discharge of groundwater contaminated by the leakage of radioactive reactor cooling water was found to be responsible for most of these residual concentrations. Monitoring also showed sporadic increases in the concentration of ^{137}Cs at the outlets [H20], some of which corresponded to heavy rainfall events. TEPCO, the FDNPS operator, has suggested that these increases may be due to contaminated water pooled on the roof of the buildings of the damaged reactors being washed by rainfall into coastal waters via the site drainage.

49. Based on measured concentrations of ^{137}Cs in the FDNPS harbour and the exchange rate between the harbour and the ocean, Kanda [K3] estimated the release of ^{137}Cs between June 2011 and September 2012 to be 17 TBq, less than 1% of the total release before June 2011. On the basis of modelling and using the concentration of ^{137}Cs at the outlet of the FDNPS discharge channels, Tsumune et al. [T49] estimated the release at 40 TBq for the period June 2011 to February 2012, and a simple calculation based on this estimate would indicate a release of about 19 TBq for the period from February 2012 to mid-2015. The construction of an impermeable wall to reduce the outflow of groundwater to the sea was completed in October 2015 and has resulted in a significant decrease in the concentrations of ^{137}Cs in the harbour. Based on Tsumune et al. [T49], annual releases to the ocean from groundwater on the FDNPS site subsequently (i.e., after October 2015) can be estimated to be about 0.5 TBq.

50. Rivers draining catchment areas onto which radionuclides that were released to the atmosphere have been deposited are a further source of releases into the Pacific Ocean. Yamashiki et al. [Y9] estimated that about 5 TBq of ^{137}Cs was washed from the Abukuma river basin into the ocean between August 2011 and May 2012, but much of this release (61%) occurred during an 8-day period corresponding to the passage of typhoon Roke. Other authors have estimated the annual discharge of ^{137}Cs from rivers to be between 5 and 10 TBq [A4, K22], equating to about 1% to 2% of the initial deposition on to the catchment area of the rivers most affected by the FDNPS accident. These catchments would be expected to be a continuing source of radiocaesium releases to the Pacific Ocean in the future.

51. Finally, groundwater beneath sand beaches has been found to be a reservoir of ^{137}Cs, probably accumulated in the days and weeks after the accident [S6]. Annual releases from this reservoir have been estimated at 0.6 TBq.

(c) *Summary of releases to the marine environment*

52. Table 3 summarizes the estimated amounts of ^{137}Cs released into the marine environment via the different routes identified and over the short and longer time periods. By far the majority of the material that has been released into the ocean entered the marine environment in the first one to two months after the accident, with the amounts entering during the first month from deposition of radioactive material released to atmosphere (deposited over a very large area of ocean) and the amounts entering coastal water from leakages and deliberate releases from the FDNPS site in the first two months being broadly comparable. Direct releases from the FDNPS site thereafter, following the various countermeasures put in place, were two to three orders of magnitude lower. Releases to the marine environment from rivers draining catchments on to which radioactive material released to the atmosphere was deposited may now be larger than the direct

releases from the FDNPS site. In addition, these inputs occur mostly over short timescales, during rare events such as typhoons, and from localized sources, particularly river mouths, and are likely to continue for many years. There may also be some continuing releases from groundwater.

Table 3. Summary of estimates of releases of ^{137}Cs to the marine environment

Source	*Period*	*Amount of ^{137}Cs released*
Deposition from the atmosphere	March 2011	5–11 PBq
Direct releases from the FDNPS site	March–May 2011 June 2011–February 2012 February 2012–October 2015 After October 2015	3–6 PBq 40 TBq 19 TBq[a] 0.5 TBq/y[b]
Input from rivers	Years	5–10 TBq/y
Groundwater under beaches	Years	0.6 TBq/y

[a] Estimated from [T49] using a mean concentration of 1,000 Bq/m^3 at the outlets of the discharge channels for the period.

[b] Estimated from [T49] using a concentration of 100 Bq/m^3 at the outlets of the discharge channels.

2. Dispersion of released material in the marine environment

53. A large number of the radiocaesium measurements made in the coastal area near FDNPS were initially recorded as below the detection limit, which was elevated in the immediate post-accident period (at around 10 kBq/m^3) because the priority was to carry out a large number of simple, rapid measurements. Many of the samples collected have subsequently been reanalysed [K49, O17] with lower detection limits (0.1 to 1 Bq/m^3). The measurements have been used to interpret the transport of radiocaesium at different temporal and spatial scales and show:

(a) Rapid dispersion of released radiocaesium out of the coastal zone (on a time scale of about one month);

(b) Rapid transport of radiocaesium in surface water, mainly directed to the east and towards the North American coast (on a 1 to 4 year time scale);

(c) Downward transport of radiocaesium in the water column to depths of a few hundred metres of the ocean during March and early April 2011.

(a) *Concentrations in the coastal zone of the Fukushima Daiichi Nuclear Power Station*

54. In the first few months after the accident, a rapid decline in radiocaesium concentrations was observed around FDNPS. At the outlet channel of FDNPS, a peak value of 68 MBq/m^3 of ^{137}Cs was recorded on 6 April 2011. By the end of April 2011, after the major leakage was stopped, the radiocaesium concentration had reduced to about 200 kBq/m^3; it then reached about 1 kBq/m^3 in May 2012 and remained around this stabilized average value until mid-2015 [B16], after which it decreased to 0.1 kBq/m^3. The rapid decrease in the first few months after the accident at this point, very close to FDNPS, mainly reflects the decrease in the source term. In the first 10 km off the coast of FDNPS, Fukuda et al. [F16] showed that the dissolved ^{137}Cs concentrations in seawater measured during May and October each year between 2013 to 2015, remained one to two orders of magnitude higher than those before the accident. Concentrations were highest

within the first 5 km from the coast (20 to 220 Bq/m^3), and showed higher temporal variability, probably related to heavy rainfall increasing the input from rivers and/or increased discharges from the FDNPS harbour. Concentrations reached 2 to 4 Bq/m^3 at 30 km from the coast.

55. As described in more detail in the UNSCEAR 2013 Report [U10] and the IAEA Report on the accident [I5], models of the dispersion of radionuclides released directly into the ocean have indicated that, during the first month after the accident, radioactive material was initially transported in a southerly direction along the coast by the wind blowing mainly towards the south at the time. The released material was then subsequently transported eastwards by the Kuroshio current and (following the separation of the current from the coast) the Kuroshio Extension, which transport warm, saline waters northwards along the south coast of Japan and then eastward. After mid-April 2011, the wind blew mainly northwards inducing a northward and eastward surface current and dispersion of radionuclides in the entire coastal area together with interaction with the Oyashio current, which transports cold, less saline water southwards along the north-eastern coast of Japan.

56. Modelling has similarly indicated that radionuclides released to atmosphere were deposited on to the ocean over a wide region. The contribution to concentrations of radiocaesium in surface water due to these deposits from the atmosphere was much lower than that due to the direct releases into the ocean, except perhaps during the first days, when direct releases were not detected, and at large distances during the first month.

(b) *Dispersion at the scale of the Pacific Ocean*

57. The various measurements taken in the months and years following the accident have shown the dispersion of radiocaesium in surface waters across the Pacific Ocean and its migration down the water column. Radiocaesium was first transported eastward in surface water by the Kuroshio Extension at speeds of 3 to 7 km/d [A13]. Concentrations of ^{137}Cs reached a peak of a few thousand Bq/m^3 in 2011 in the surface water of the western Pacific (and a few hundred Bq/m^3 further east and north), then rapidly decreased to a few tens of Bq/m^3 in 2012 and generally less than 3 Bq/m^3 in 2015 [A14]. By June 2013, ^{137}Cs attributable to the FDNPS accident had spread on to the Canadian continental shelf, and, by February 2014, had increased the concentration of ^{137}Cs throughout the upper 150 m of the water column to 2 Bq/m^3 [S31], about double the levels of ^{137}Cs found prior to the accident. The first observation on the shoreline of British Columbia was on February 2015 with a concentration of 6 Bq/m^3 [S32]. At the same time, there was also dispersion in a north-south direction (radiocaesium was detected between 25°N and 63°N during summer 2012) [K49]. In addition, as a result of the cooling and sinking of surface water during March and early April 2011, radiocaesium moved downward in the first few hundred metres of the water column north and south of the Kuroshio current and Kuroshio Extension, in the intermediate water masses known as central mode water and subtropical mode water. Peaks of ^{134}Cs concentration of 10 to 20 Bq/m^3 (corrected to the accident date) were observed at depths of around 300 to 400 m [K50]. Based on a synthesis of observations from August to December 2012, Inomata et al. [I33] found that about 56% of the ^{134}Cs released into the North Pacific Ocean had been transported eastward in the surface layer, with 28% and 16% transported in intermediate waters, respectively, south and north of the Kuroshio current and Kuroshio Extension.

58. Radiocaesium released from FDNPS has also been detected at low concentrations in other areas: the concentration of ^{134}Cs and ^{137}Cs in the surface waters of the Sea of Japan gradually increased during the 2013–2016 period from 1.5 to 2.5 Bq/m^3 [I34, T19]; and the ^{134}Cs concentration in the Bering Sea increased to about 1 Bq/m^3 (decay corrected) in 2017 [K51]. On the other hand, the transport of radiocaesium westward from Japan appears to have been limited, as no increase in concentration has been detected at different locations in Indonesia [S44, S45] or in the northern South China Sea [Z5].

(c) *Radionuclides in sediment and suspended matter*

59. Many interacting processes influence the distribution of ^{137}Cs in sediments and suspended matter. Radiocaesium is extremely soluble in seawater with less than 1% of ^{137}Cs in the open ocean found on marine particles that may accumulate on the ocean floor. On the other hand, radiocaesium inputs from rivers and groundwater are generally bound to the clay minerals of sediments, although some degree of desorption would be expected once the sediments enter seawater. Sediments accumulated on the coastal shelf can be resuspended by strong currents and waves and then transported laterally. Bioturbation of sediments can mix radionuclides sorbed on to sediment particles deeper into the sediment layer, but can also return deeper material to the sediment surface. Finally, bioirrigation can increase the rate of exchange between sediment pore water and bottom seawater.

60. Numerous samples of seabed surface sediment (with initial monitoring coordinated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan [K59]) were analysed from the end of April 2011 off Fukushima Prefecture and surrounding prefectures. In the coastal zone of Fukushima Prefecture, ^{137}Cs concentrations generally lay between 10 Bq/kg and 1,000 Bq/kg of dry sediment, compared with values of 1 Bq/kg before the accident [A11]. In general, the concentrations of radiocaesium in the uppermost sediment layer were highest off the FDNPS site, and higher south of FDNPS than north of it. However, high resolution measurements have revealed strong horizontal heterogeneities in ^{137}Cs concentrations in the sediment at the small scale (1 m to 100 m), with isolated peak values larger than 5,000 Bq/kg [T32].

61. The inventory of ^{137}Cs in ocean sediments has been estimated at between 38 and 230 TBq for the coastal region (up to 30 km from the coast) around FDNPS [B5, K59, K60, O22], corresponding to about 1% to 5% of the total direct release to the ocean. However, ^{137}Cs concentrations in the water column have decreased since the accident, and, by the end of 2012, the sediment inventory was estimated to be 5 to 10 times larger than the inventory in the overlying water [B15, B16].

62. The concentration of ^{137}Cs in the surface sediment and its vertically integrated amount have also been observed to decrease with time [K60, O23] (although the authors disagree over the importance of downward migration of ^{137}Cs in the sediment), and the same has been observed for ^{129}I [O24]. Kusakabe et al. [K60] estimated that 76% of the ^{137}Cs deposited in the surface sediment had been transported out of the FDNPS coastal area within about 5 years. Matsumoto et al. [M14] postulated that the small particles with which ^{137}Cs is more associated moved due to wave action from shallow areas to deeper areas, where they accumulated. The significant inverse correlation observed between the concentration of ^{137}Cs in bulk suspended matter and distance from FDNPS [K42] also suggests an input of radiocaesium from the land to the sediment and its gradual transportation to offshore regions.

63. Studies of sediments in Tokyo Bay have illustrated the transfer by rivers of radiocaesium released to atmosphere, deposited on to the area located in the north-eastern part of the Tokyo Metropolitan Area, and then washed out into the bay. In 2016, the sediments with the highest concentrations of radiocaesium were found in the areas of the river estuaries where the currents were weakest, with very much lower levels in the deeper central bay [Y11], suggesting accumulation of sediments containing radiocaesium in the river estuaries. However, in 2017, Kubo et al. [K43] noted an increase in the radiocaesium inventory in the central bay by a factor of three compared to the previous inventory assessed over the 2011–2016 period, and suggested that the radiocaesium present in the sediment at the river estuaries will gradually enter the bay, particularly after heavy rains. In addition, Kubo et al. estimated that only about 9% of the ^{137}Cs which had been deposited over the basin draining into Tokyo Bay had already flowed into the bay.

64. Ikenoue et al. [I30] used autoradiography to detect ^{137}Cs-enriched particles in sediment samples, and found that a small number of these particles contributed a relatively large proportion (between 9%

and 64%) of the ^{137}Cs concentration in sediment samples. The heterogeneous distribution of these particles is therefore likely to be one of the main factors responsible for the temporal and spatial variations of ^{137}Cs concentrations in sediment samples. Kubo et al. [K42] found the contribution of highly radioactive particles of a few microns in size to the radiocaesium concentration of samples of suspended matter ranged from 13% to 54%.

65. A more detailed, comprehensive and up-to-date review of the transfer of radionuclides released as a result of the FDNPS accident in the marine environment around Japan, including the distribution of radionuclides in sediments and in marine organisms has recently been published by IAEA [I9] and should be consulted for further information.[5]

(d) *Summary of dispersion of released material in the marine environment*

66. Figure V summarizes the ranges of concentrations of ^{137}Cs observed in different compartments and areas of the Pacific Ocean[6] and how these have changed over time. This figure shows two major effects:

- Firstly, in 2011, there is a strong decrease in concentrations of ^{137}Cs in seawater with distance from FDNPS: in the coastal strip (between 15 and 30 km offshore), concentrations are systematically several orders of magnitude lower than at the outlet of the power station. This is probably due to the energetic and variable currents in the region, and these energetic dynamics are also likely to be the cause of a very rapid decrease in the concentrations of radiocaesium close to FDNPS in 2012 and thereafter, following the cessation of the main leakage in April 2011;

- Secondly, it is clear that concentrations in sediment have not declined over time as rapidly as concentrations in seawater, indicating that the sediments could provide an important long-term source of ^{137}Cs in seawater.

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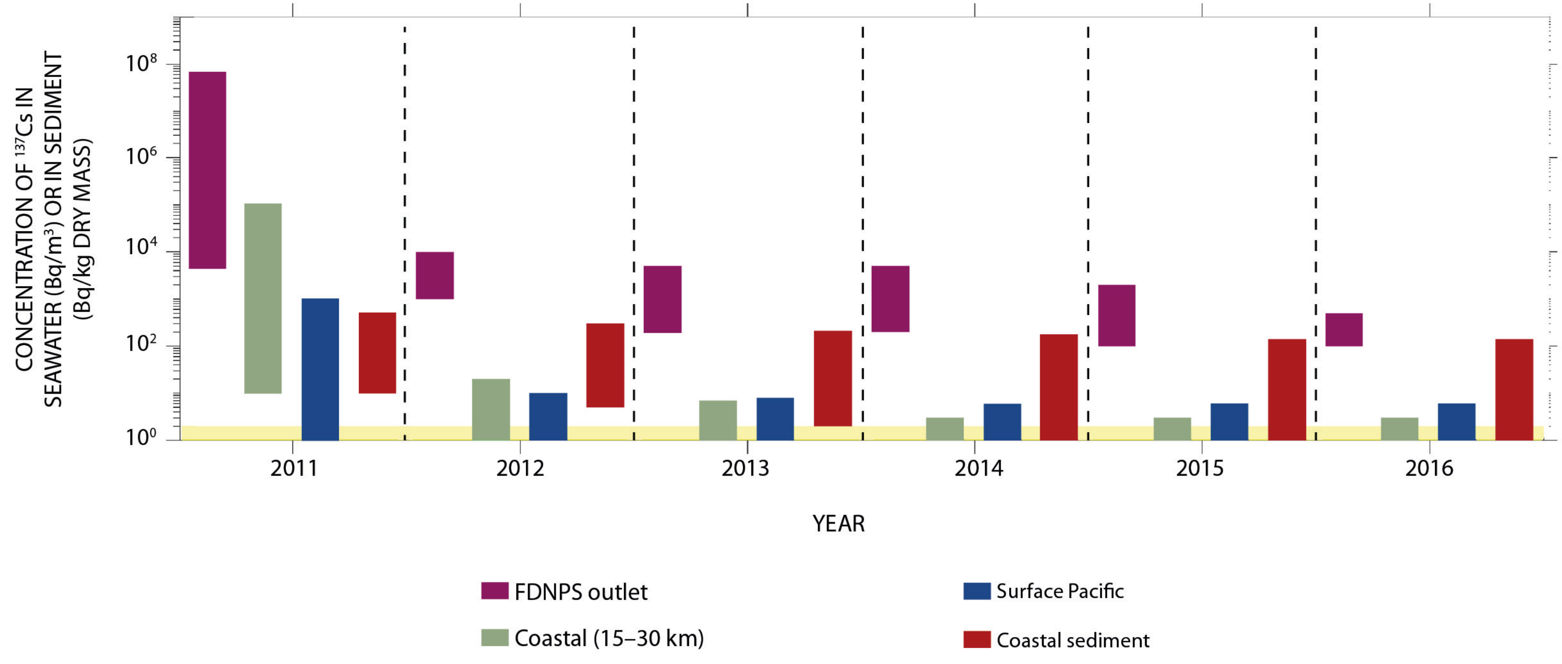
[5] The IAEA report became available after the end of 2019 and was accordingly not included among the information reviewed by the Committee and summarized in this report. Further, the information included in the IAEA report, while a valuable compendium in its own right, does not affect the findings of this Committee's report and therefore did not warrant being reviewed as an exception by the Committee.

[6] The maximum values observed in the surface of the Pacific Ocean have been progressively moving from west to east as the released material has been transported eastward.

Figure V. Range of concentrations of ^{137}Cs in different regions and compartments of the marine environment[a] and at various time scales (the yellow zone represents the range of background values found in seawater before the accident)



[a] "FDNPS outlet" refers to the outlets to the ocean from the FDNPS site; "Coastal (15–30 km)" refers to water between 15 and 30 km from the FDNPS site; "Surface Pacific" refers to water at distances greater than 200 km from the FDNPS site; and "Coastal sediment" refers to sediments within 30 km from the FDNPS site.

3. Radionuclide transfers to and concentrations in marine foods

67. As part of the response to the FDNPS accident on 17 March 2011, the Japanese Government established "provisional regulation values" for radioactive material in foodstuffs above which foodstuffs were prohibited from distribution and consumption. For fish products, the provisional regulation values were 2,000 Bq/kg for radioiodine and 500 Bq/kg for radiocaesium. From 1 April 2012, a lower "standard limit"[7] of 100 Bq/kg was introduced by the Japanese Government for radiocaesium. The Japanese and prefectural governments began regular monitoring of foodstuffs in March 2011 and have made the results available on websites (see, for example, [M4, M5, M6]). TEPCO also sampled marine products from within a 20 km radius of FDNPS and has made the results publicly available (see supplementary material to [W2, W3]).

68. Wada et al. [W3] analysed all of the data relevant to the coastal waters off Fukushima Prefecture to present a detailed description of ^{131}I, ^{134}Cs and ^{137}Cs levels in marine foods after the FDNPS accident. Measurements were focused on the concentrations of radionuclides in the muscles of different species of pelagic and demersal fish, as well as different invertebrates (cephalopods, bivalves, gastropods, and crustaceans), and seaweeds of various kinds. In total, nearly 40,000 samples were analysed.

69. Regarding ^{131}I, all samples collected after August 2011 showed levels that were below the detection limit (16.2 Bq/kg-wet mass[8] on average), reflecting the short, 8-day, half-life of this radionuclide. Only three samples (two from larvae of sand lance and one from a seaweed), from April and May 2011, were found which exceeded the provisional regulation value of 2,000 Bq/kg [W2].

70. The trend for radiocaesium is shown in figure VI. This presents the total number of samples analysed every three-month period off the coast of Fukushima Prefecture, and the number of samples which exceeded the limit for radiocaesium of 100 Bq/kg established by the Japanese Government to apply from 1 April 2012. In 2011, 41% of samples exceeded 100 Bq/kg. The highest concentrations frequently corresponded to products from the shallow coastal waters south of FDNPS [W2, W3]. In 2012, the percentage exceeding 100 Bq/kg decreased to 17% and in 2015 to 0.05%.

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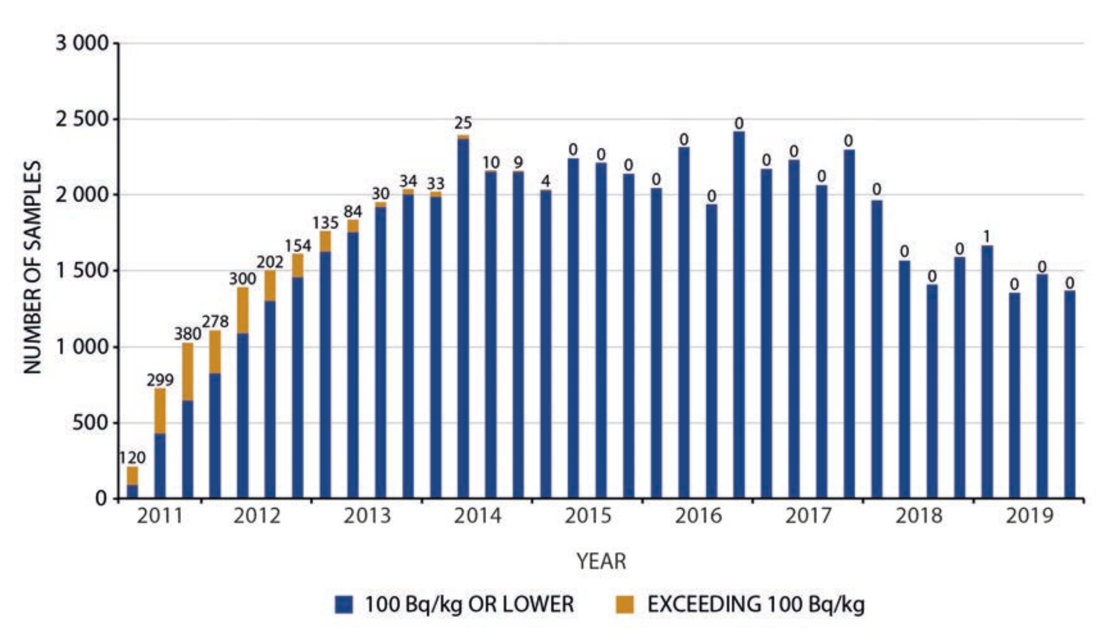
[7] The terms "provisional regulation value" and "standard limit" are those used in the English version of handbooks providing information on effects of the FDNPS accident published by the Radiation Health Management Division, Ministry of the Environment, Government of Japan and the Japanese National Institute for Quantum and Radiological Science and Technology. The terms used in Japan may not correspond exactly with the Japanese translation of these terms. The equivalent guideline levels for the purposes of international trade, as recommended by the Codex Alimentarius Commission, are 100 Bq/kg for radioiodine and 1,000 Bq/kg for radiocaesium [F1].

[8] Much of the radioecology literature and most of the source publications quoted give concentration values in Bq/kg-wet weight or Bq/kg-dry weight. The correct quantity for the amount of matter, measured in kilograms, is mass, and not weight. The Committee has used "mass" in this report, while recognizing that the source publications have often used "weight".

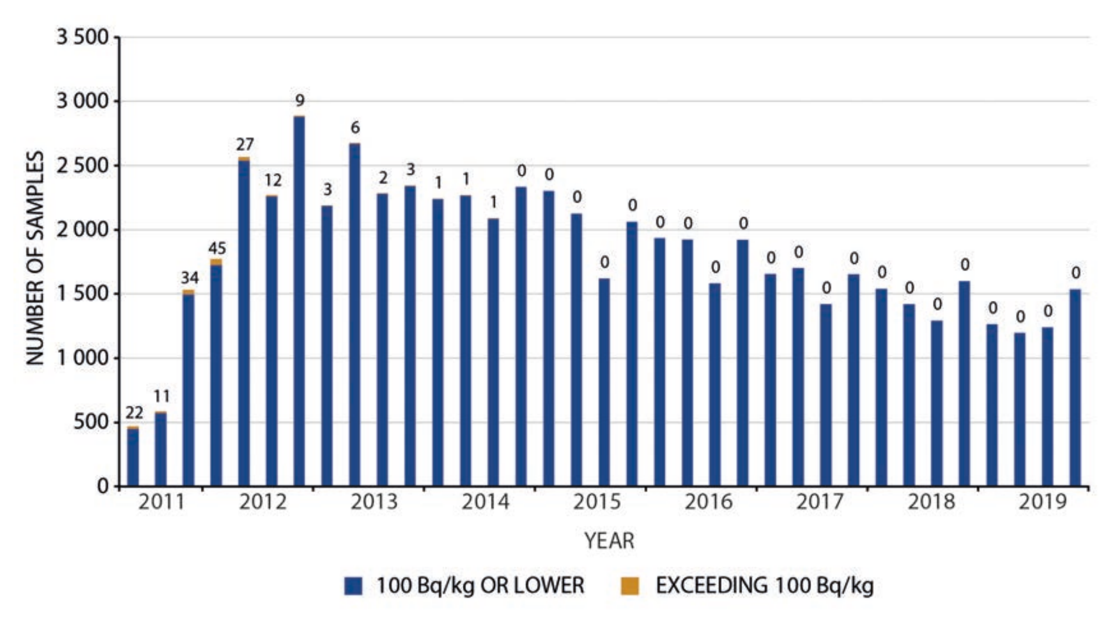
Figure VI. Number of fishery product samples caught each quarter off the coast of Fukushima Prefecture, showing the number of samples with a concentration of radiocaesium above 100 Bq/kg [M6]



71. The corresponding trend for prefectures other than Fukushima Prefecture is shown in figure VII. The percentages of samples with radiocaesium concentrations exceeding 100 Bq/kg were significantly lower than in Fukushima Prefecture at 2.6% in 2011 and 1% in 2012, and have decreased further with time. Takata et al. [T20] reports that in the Sea of Japan and the southern coast influenced by the Kuroshio current, the maximum concentration of ^{137}Cs in fish after the accident was 1.1 Bq/kg-wet mass, while the following year it was less than 0.32 Bq/kg-wet mass, about two orders of magnitude lower than in the coastal waters off Fukushima Prefecture.

72. In terms of the guideline level recommended by the Codex Alimentarius Commission for the purposes of international trade [F1], 76 samples of marine fish caught off Fukushima Prefecture (about 2.5% of the total measured) were found with radiocaesium concentrations exceeding the guideline level (of 1,000 Bq/kg) in the first year after the accident. In the second year, this had reduced to 17 samples (about 0.3% of the total) and in the third year to one sample (about 0.01%) (see supplementary material to [W3]).

Figure VII. Number of fishery product samples caught each quarter off the coast of prefectures other than Fukushima Prefecture, showing the number of samples with a concentration of radiocaesium above 100 Bq/kg [M6]



73. Wada et al. [W2] showed that some demersal fish (i.e., those living and feeding near the sea floor) frequently had radiocaesium concentrations above the limit established by the Japanese Government, and that the decreasing trend of radiocaesium concentrations in these fish was more gradual than those found for pelagic fish species (i.e., those living far from the sea floor), invertebrates and seaweeds. Tateda et al. [T23] used a dynamic biological compartment model to show that the rapid increase of radiocaesium concentrations observed in bivalves, gastropods, seaweeds and plankton feeding fish was due to the direct uptake of water with elevated radiocaesium concentrations immediately after the FDNPS accident. The subsequent rapid decrease in radiocaesium concentrations in seawater after the accident was then reflected in a decline in radiocaesium concentrations in these marine species at a rate governed by biological processes. In contrast, the more gradual decreasing trend in the concentrations found in demersal fish are indicative of possible sources of radiocaesium other than seawater. Tateda et al. [T23] and Wang et al. [W10] have explained this more gradual rate of decrease as due to the ingestion of sediment-based prey (benthic invertebrates with radiocaesium concentrations reflecting levels in the sediment rather than levels in seawater [S35]) as well as of detritus and sediments [T23, T24]. They postulate that the continuing elevated levels of radiocaesium in sediment, particularly of the coastal zone, may be the reason for the few specimens still found to be exceeding the limit established by the Japanese Government in 2015. On the other hand, Fievet et al. [F8] used a model of the transfer of radiocaesium to fish from seawater and feeding to explain the higher and more persistent concentrations of radiocaesium in demersal fish compared with pelagic fish as due to their more confined habitat along a narrow coastal strip close to the source of the continuing inputs of radioactive material into the marine environment.

74. No concentration of ^{137}Cs higher than 50 Bq/kg-wet mass has been detected in fish that migrate over a wide area in the ocean. Such migratory fish moving between the western and eastern North Pacific Ocean could be biological vectors of radionuclides between these two distant regions. This has been confirmed by measurements in the muscle of 15 Pacific bluefin tuna sampled in August 2011 in the California region, which showed a ^{137}Cs concentration of 6.3 ± 1.5 Bq/kg-dry mass [M1] and the presence of ^{134}Cs indicating that the source was releases from the FDNPS accident.

C. Summary

75. In the UNSCEAR 2013 Report [U10], the Committee concluded that the FDNPS accident resulted in direct releases to the ocean of about 10 to 20 PBq of ^{131}I and 3 to 6 PBq of ^{137}Cs and ^{134}Cs. In addition, it concluded that 60 to 100 PBq of ^{131}I and 5 to 11 PBq of ^{137}Cs and ^{134}Cs entered the ocean indirectly following release to atmosphere and dispersion over and deposition on to the ocean surface. Information and analyses that have since become available have generally confirmed these ranges of releases in the first one to three months after the accident. Over a longer timescale, about a further 60 TBq of ^{137}Cs was released from the FDNPS site, largely from releases of site groundwater. Once measures to reduce these releases were completed in October 2015, releases of ^{137}Cs from the site declined to about 0.5 TBq per year. A larger source of continuing direct releases of ^{137}Cs to the marine environment is rivers draining land on to which radioactive material released to atmosphere was deposited. Inputs of ^{137}Cs to the marine environment from rivers have been estimated at 5 to 10 TBq per year. In addition, these inputs occur mostly over short timescales, during rare events such as typhoons, and from localized sources such as river mouths.

76. Measurements and analysis of ^{137}Cs in seawater around the FDNPS site, across the Pacific Ocean and in neighbouring seas have confirmed the rapid dispersion and dilution of the released material in seawater and its general movement eastwards. By 2013, the concentrations of ^{137}Cs even in the coastal waters (15 to 30 km) off the FDNPS site were of the order of the levels prevailing before the accident (1 to 2 Bq/m^3). Concentrations of ^{137}Cs in coastal sediments have not declined as rapidly. These are more likely to be influenced by inputs of ^{137}Cs bound to clay minerals in sediments. The inventory of ^{137}Cs in coastal sediments is now thought to exceed the inventory in the overlying water column, and the sediments could provide a long-term source of ^{137}Cs in seawater.

77. Concentrations of ^{137}Cs in marine foods have also generally declined rapidly following the accident: while 41% of samples caught off the coast of Fukushima Prefecture in 2011 had radiocaesium concentrations exceeding 100 Bq/kg, the limit established by the Japanese Government to apply from 1 April 2012, this had declined to 17% in 2012 and, 0.05% in 2015.

78. The regular monitoring that began just after the accident in the vicinity of FDNPS was gradually extended to more water sampling stations and also to the monitoring of sediment and edible marine products. The monitoring was primarily performed for decision-making and in response to the concerns of civil society. However, the results have also improved the scientific understanding of the radionuclide transfer pathways in the different compartments of the marine environment. The monitoring carried out was complemented by numerical modelling. Within a period of about a month, it provided initial estimates of the dispersion of the released radioactive material. In addition, the combination of observations and modelling made it possible to quantify the amount of radiocaesium (^{134}Cs and ^{137}Cs) released directly into the ocean.

IV. TRANSFER OF RADIONUCLIDES IN TERRESTRIAL AND FRESHWATER ENVIRONMENTS

A. Introduction

79. Radionuclides released to the atmosphere from the FDNPS accident were transported and dispersed in the air as described in chapter II. Most of this radioactive material was dispersed over the ocean and deposited on to the ocean surface, entering the marine environment, as described in chapter III. Radioactive material dispersed over the Japanese land area was deposited on to surfaces in the urban, agricultural and natural environments, including tree canopies, other plant surfaces, soil, lakes, rivers and streams. This chapter summarizes current understanding of the subsequent movement of this material through different components of the terrestrial and freshwater environments. A good understanding of the transfer of radionuclides in terrestrial and freshwater environments is important in supporting the estimates of exposures from ingested radionuclides described in chapter V and appendix A. It is also important in developing appropriate environmental remediation programmes.

80. In the UNSCEAR 2013 Report [U10], the Committee based its estimates of doses from ingestion in the first year after the accident on measurements of concentrations of radionuclides in foodstuffs. Thereafter, modelling was used to predict the transfer of radionuclides through terrestrial food chains. The model [B12] had been developed for use in Europe and was modified for use in Japan by taking account of Japanese agricultural practices, crop yields and data on the transfer of radionuclides to specific foods (e.g., rice). New information that has since become available on the transfer of radionuclides through both terrestrial and freshwater environments in Japan is summarized in this chapter and the implications of this new information for the findings of the UNSCEAR 2013 Report are discussed. A more detailed, comprehensive and up-to-date review of the transfer of radionuclides released as a result of the FDNPS accident in the terrestrial and freshwater environments in Japan has recently been published by IAEA [I9] and should be consulted for further information.

81. The focus of this chapter is generally on transfers of ^{134}Cs and ^{137}Cs in the terrestrial and freshwater environments. Other radionuclides released in significant quantities (e.g., ^{132}Te, ^{132}I, ^{133}I and ^{133}Xe) either have short radioactive half-lives (less than a few days) or do not deposit on the ground, and would not have contributed significantly to exposure of the public as a result of transfer through terrestrial and freshwater environments. Iodine-131 (with a longer half-life of 8 days) was measured in foodstuffs in the monitoring that began several days after the accident, in some cases above the regulation value that was applied. However, information on its transfer in terrestrial and freshwater environments is sparse. In addition, measurements made of radionuclide concentrations (including of ^{131}I) in food and drinking water have been used directly to estimate the exposure of the public in the first year after the accident from ingestion of foodstuffs (see, in particular, [M47]). A detailed understanding of the transfer of ^{131}I through terrestrial and freshwater environments is therefore much less relevant to the Committee's updated estimates of doses to the public than that of the two longer-lived caesium radionuclides (with half-lives of more than 2 years).

B. Overview of current understanding

1. Radiocaesium migration and fixation in soil

82. Rapid penetration of radiocaesium was reported to depths of 20 cm in some soils within one to two months after the FDNPS accident [T1] and in paddy fields before cultivation [S28]. However, a number of sources subsequently reported that most radiocaesium[9] remains in the top 5 cm soil layer of undisturbed soils indicating that strong fixation occurred in the upper soil layers [F2, L4, M10, M15, N16]. Radiocaesium has been found to have migrated down sampled soil in Japan at variable rates that were influenced by factors such as the rate of precipitation, the amount of organic matter present, bioturbation and soil temperatures in Japan [K37, K38]. In the catchment of Okuma Town, with high levels of deposited radionuclides, vertical migration in undisturbed soils was reported to be relatively fast with small amounts of ^{134}Cs and ^{137}Cs detected in some soils at soil depths of more than 20 cm [K37, K38].

83. Radiocaesium deposited onto agricultural land soil surfaces in March 2011 was subsequently mixed by ploughing, commonly to a depth of around 15 cm for rice paddies and 25 cm for other agricultural products and upland fields in Japan. Radiocaesium concentrations in soil around plant roots will, therefore, have been diluted considerably by this routine practice.

84. The extent of binding of radiocaesium in soils is measured using the distribution (partition) coefficient (K_d), which relates the concentration associated with soil to that in the soil solution. A high K_d indicates strong sorption and low amounts of radiocaesium in the soil solution, leading to low bioavailability of radiocaesium for transfer to plants and animals, although this also depends on the potassium concentration in the soil solution. The radiocaesium interception potential (RIP) is an intrinsic soil property, normally experimentally determined under laboratory conditions, and quantifies the specific radiocaesium fixation capacity of a soil.[10] Bioavailability of radiocaesium is higher when there is a low potassium concentration in the soil solution. Three separate extensive studies of many different soil samples in Fukushima Prefecture and surrounding regions [T21, U3, Y3] have found RIP values to be lower for Andosols[11] compared with other soil types in Japan. Surveys of paddy fields [N6] and of farmland soil samples [Y3] have found widely varying values of RIP even among samples with identical soil types and geological features. For the farmland soils, the measured RIP values were positively correlated with the clay, silt, and exchangeable potassium and calcium content. Many soils and sediments in areas affected by releases from the FDNPS accident contain relatively high amounts of micaceous clay minerals and Yamaguchi et al. [Y3] has postulated that this has contributed to strong binding of radiocaesium in soil in Japan. Soil RIP values in most areas of Fukushima Prefecture are generally higher than those of the radioecologically sensitive regions, with Histosols and podzols,[12] around the Chernobyl Nuclear Power Station (see appendix B).

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[9] Some studies reported in this section give data specifically for ^{137}Cs only as it has a longer radioactive half-life than ^{134}Cs. When the term radiocaesium is used in this section it refers to both ^{134}Cs and ^{137}Cs.
[10] K_d can be derived from RIP by taking account of the concentrations of potassium and ammonium in soil solution. Decreasing potassium and ammonium concentrations in soil solution increase K_d.
[11] Andosols are soils found in volcanic areas and are usually defined as soils containing high proportions of glass and amorphous colloidal materials.
[12] A Histosol is a soil consisting primarily of organic materials; podzols are the typical soils of coniferous or boreal forests.

2. Radionuclide transfers to, and concentrations in, crops and animal products

85. The deposition of radionuclides released to atmosphere from the FDNPS accident occurred at a time of year when there were only a few crops present that might enter the food chain, such as leafy vegetables, winter wheat, green tea and evergreen fruit [Y2]. The extent of interception of deposited radionuclides by plants depends on many factors such as the area and characteristics of the plant surfaces. Radionuclide concentrations on these surfaces then decline due to processes such as wash-off during precipitation and dilution due to plant growth. Fesenko et al. [F4] found that the time for ^{131}I and radiocaesium concentrations to decline to half that initially present in weed leaves in areas affected by the FDNPS accident was 4 and 8 days respectively when samples were taken from one week to two months after the major deposition period. A portion of the radionuclides retained on plant surfaces has been found to be partially absorbed and translocated into edible parts such as green tea leaves and fruits [S9, T9, T15, T18].

86. In general, however, root uptake was the major pathway of ^{137}Cs transfer to most crops after the FDNPS accident occurred. Since the FDNPS accident, a number of site-specific studies have reported concentration ratio[13] (CR) values from soil to brown rice derived from both pot and field experiments (e.g., [E3, E4, F10, F11, I27, K7, K36, O14, O15, S3, T47, W6, Y13]). The site-specific CR values varied with soil type, exchangeable potassium status, management approaches and time after the accident and, for the period 2011–2013, were mostly within an order of magnitude of that assumed in the UNSCEAR 2013 Report [U10] (5.0×10^{-3}). Irrigation water may influence rice concentrations [U4], but radiocaesium entering paddy fields via irrigation water was reported to be a minor contributor to the concentrations in rice [T47].

87. Uematsu et al. [U5] showed that the radiocaesium concentration in rice plants and ryegrass was significantly correlated with the ratio of radiocaesium to potassium concentrations in soil water. A detailed analysis of the factors influencing the transfer of ^{137}Cs to rice was also carried out using extensive data from a large-scale study on paddy fields [Y8]. Higher CR values were observed in paddy fields in which the exchangeable potassium contents were low. The results enabled the CR from soil to brown rice to be predicted from the exchangeable potassium content. Furthermore, they also allowed a recommended value of exchangeable potassium to be established that would ensure that the radiocaesium content of brown rice remained below the level at which the food would be restricted.

88. The results of recent large-scale studies that provide information on how CR for the transfer of ^{137}Cs to brown rice changes with time are summarized in table 4. The studies show a general decline in CR with time, thought to be due to binding of radiocaesium with soil components. Yamamura et al. [Y8] derived a modelled rate of decline in CR from soil to rice of 0.17 ± 0.02/y and an effective half-life[14] of 4.0 years from 2012 to 2015. This is consistent with the conclusions of Tagami et al. [T7], and the studies suggest that the mean soil-to-rice CR for ^{137}Cs in Japan was approaching that prevailing before the accident (3.4×10^{-3}) after less than three years, although analysis over a longer time period would provide further confidence in these observations. Figure VIII shows how the concentration of ^{137}Cs in rice has declined rapidly while its deposition density in soil has remained elevated.

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[13] The transfer of radionuclides to crops is normally quantified as the concentration ratio (defined, in this chapter, as the ratio of the concentration of a radionuclide in the food product to its concentration in soil to 20 cm depth on a dry mass basis). The term transfer factor is also used for this ratio.

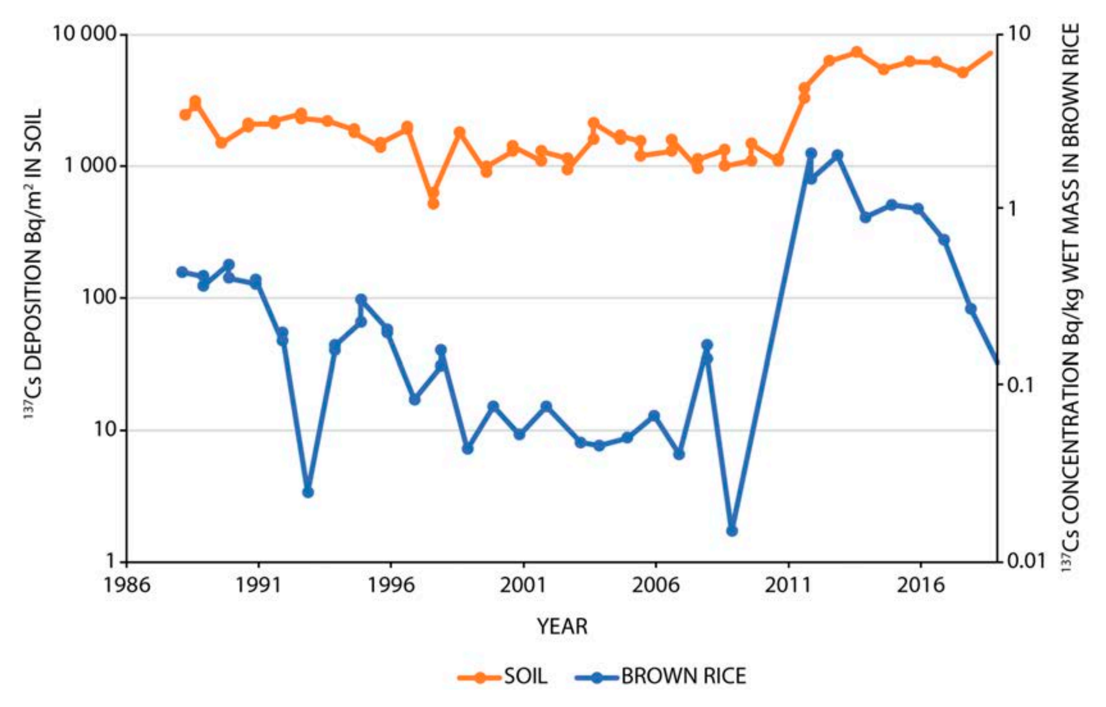
[14] The effective half-life is specific to each radionuclide, medium and compartment of interest and is defined as the time required for the radionuclide concentration in a specific compartment to be reduced to half of the initial value as a result of all environmental factors, including radioactive decay.

Table 4. Time dependence of ^{137}Cs concentration ratio for transfer to brown rice

CR measure	*Year*					*Reference*
	2011	*2012*	*2013*	*2014*	*2015*	
Median		4.7×10^{-3}	2.3×10^{-3}	1.9×10^{-3}	2.0×10^{-3}	[Y8]
Maximum		1.8×10^{-1}	1.4×10^{-1}	1.9×10^{-1}	2.6×10^{-2}	
Minimum		5.3×10^{-4}	2.5×10^{-4}	2.7×10^{-4}	2.2×10^{-4}	
Mean	1.2×10^{-2}	5.6×10^{-3}	3.5×10^{-3}	2.3×10^{-3}		[T7][a]

[a] Data from Tagami et al. [T7] are geometric means.

Figure VIII. Comparison of ^{137}Cs concentration in brown rice and the ^{137}Cs deposition density in soil at the same site over time,[a] showing the effect of releases from the Fukushima Daiichi Nuclear Power Station accident



[a] Nuclear Regulation Authority "Environmental Radiation Database" [N16].

89. The transfer of radiocaesium to soybean [H27, L6, T21] and buckwheat [K44] seems to have been higher than that to other agricultural crops [Y2], although detailed scientific analysis of all relevant data has not yet been undertaken to confirm these findings. A large sample study by Takeda et al. [T21] reported CR values for soybean in 2011 of 5.2×10^{-3} to 5.3×10^{-1} from 46 sample sites. The vast majority of monitored samples of soybean and buckwheat had radiocaesium concentrations below the level at which food restrictions were applied (see table 5); the small number of exceedances were associated with lack of potassium fertilization in fields with low contents of micaceous minerals [Y2].

90. Concentration ratio values have been reported for crops such as adzuki seeds, rye, Amaranthus, Kenaf, brassica crops, leafy green vegetables, green tea and root crops [A17, A18, D3, H19, H27, H28, K44, W16]. The average CR values reported for such crops were generally similar to those assumed in the model used in the UNSCEAR 2013 Report [U10] of 1.0×10^{-2} for cereals and leafy green vegetables, and 7.0×10^{-3} for root crops.

91. Studies of these and other crops have noted reductions with time in the CR for ^{137}Cs since the FDNPS accident similar to those noted above for rice. In many cases the rate of reduction of ^{137}Cs uptake into crops has been rapid, with an effective half-life of 2 to 3 years (e.g., butterbur, soybean, green tea and buckwheat [T2, T4, T9]). However, for three to four years after the accident, CR values for some grasses have remained relatively high compared with other crops in Japan [S42]. The radiocaesium concentration of Italian rye grass was linearly correlated with the amount of adhered soil, and plants with a higher yield had less adhered soil [S43]. Adhered soil accounted for about half of the total radiocaesium measured in the plant samples.

92. Relatively high radiocaesium CR values (up to a factor of 20 higher than for other areas) were also reported for a range of plants, including eggplant, pumpkin, soybean and cabbage, grown in soil with high radiocaesium deposition densities and low potassium concentrations in Okuma Town, near FDNPS, in 2012 [O15].

93. Fruit is an important crop in Fukushima Prefecture. Initial radiocaesium concentrations among fruits were highest for evergreen fruits and for Japanese cherry, which had partially emerged at the time of the accident. Persimmon is often dried in Fukushima Prefecture to form an astringent persimmon (Hoshi-gaki) and semi-dried astringent persimmon (Ampo-gaki). The drying process leads to higher radiocaesium concentrations. Some studies on green tea plants [T9], orchard trees [T13, T14, T16, T17] and other trees have shown, for the first time, that bark, branches, leaf buds and old leaves can constitute a significant store of radiocaesium for several years after deposition. The upper soil layer contains few roots of fruit trees, which are mostly located lower down the soil profile, so root uptake of radiocaesium by fruit trees was probably not important after the FDNPS accident [S11]. Therefore, radiocaesium adhered to bark surfaces was a more important source of radiocaesium in fruit than radiocaesium retained in the upper 3 cm soil layers, above the rooting zone of fruit trees [K57, K58, S7, S9, T15, T18]. Long-term changes in ^{137}Cs concentrations in mature fruit after the FDNPS accident have most often been described by two decreasing components: an initial rapid component with a half-life of 100–200 days, followed by a slower component with a half-life of several years [S10, T4].

94. The transfer of radioiodine and radiocaesium to milk, and radiocaesium to other animal tissues, has been measured in controlled conditions with a range of different animals [H6, K28, O13, O18, O19, T11]. Reported transfer coefficient[15] values were similar to those in the international literature [H33, I3] and to those assumed in the model used in the UNSCEAR 2013 Report [U10] to assess doses to members of the public from ingestion of food after the first year. However, in that model, based on experience in Europe and experience following the Chernobyl accident, it was assumed that cows grazed on pasture from mid-April to November and that sheep were fed outdoors all year, whereas, sheep production is rare in Japan, and few cattle graze pasture. Of the 17,100 dairy cattle in Fukushima Prefecture, only 720 were reported to have been grazing outdoors during February 2011 [M3]. Most farm animals are kept in closed barns in Japan [M7] and were fed on uncontaminated stored feed after the FDNPS accident [H33]. Consequently, in early spring 2011, milk from housed dairy cows had lower concentrations of ^{131}I, ^{134}Cs and ^{137}Cs compared with those few animals that were outdoors on pasture [K28]. In contrast, after the

[15] Feed transfer coefficient is the radionuclide activity concentration in the animal product (milk, meat, eggs) (Bq/kg wet mass or Bq/L) divided by the daily radionuclide intake of the animal (Bq/d).

Chernobyl accident, most livestock were grazing pasture when deposition occurred and intake of radionuclides from ingestion of meat and milk was significant (see appendix B). The model assumptions used in the UNSCEAR 2013 Report therefore overestimated the radiocaesium concentrations in milk and meat from cattle, as has been confirmed by the low ^{137}Cs and ^{134}Cs concentrations reported in monitoring data for agricultural animal products.

95. There were some exceptions to this general finding. In summer 2011, elevated radiocaesium concentrations were measured in beef from cattle fed on rice straw which had intercepted deposited radiocaesium. A few ruminants grazing on upland slopes, with low fertility stony soils, were found to have radiocaesium concentrations exceeding the limits established by the Japanese Government, despite remediation using inverse tillage [M7].

3. Radiocaesium transfer to, and concentrations in, wild food products

96. The estimates of ingestion doses to the public made in the UNSCEAR 2013 Report [U10] did not include edible plants from forests, wild game animals or fish and other species from freshwater systems. After the Chernobyl accident, the transfer of radiocaesium to berries, mushrooms and hunted wild animals in forests, and to grazed plants in extensively managed uplands, was much higher than that for agricultural crops. The collection and consumption of produce from forests, hunting and the use of uncultivated, poor nutrient status land for animal grazing provided important exposure pathways. The transfer of radiocaesium to freshwater fish was also relatively high. A similarly enhanced transfer of radiocaesium to these food groups has been observed in Japan.

97. A wide range of edible wild plants are consumed by Japanese people, especially those communities living in mountainous areas. The new sprouts growing from rhizomes of bamboo shoots, butterbur and udo are widely consumed, and also the new buds on the top of branches of Koshiabura, which has had the highest reported radiocaesium concentrations of wild plants, and fatsia [N10]. The relatively high and sustained transfer of radiocaesium to these plants [H14, K25], is reported to be associated with:

(a) The low potassium status of associated soils and relatively low clay mineral content [N10];

(b) The plants' need for potassium in the early stages of growth [K26];

(c) Mycorrhizal fungi (in Koshiabura) [S41]. Annual mean radiocaesium concentrations in bamboo shoots have gradually decreased with time, but the rate of reduction was slower than that of agricultural produce [F21].

98. The transfer of radiocaesium to forest mushrooms in Japan was higher in many different species than that for agricultural crops. Species with both high and low accumulation of both radiocaesium released from the FDNPS accident (e.g., [K35, N4, N7, T6] and radiocaesium from historic atmospheric nuclear weapons tests have been identified in Japan [T5]. There is also widespread cultivation of the widely consumed shiitake mushrooms grown on logs.

99. Particularly high radiocaesium concentrations have been reported for wild boar in many forested areas (e.g., [F20]). Tagami et al. [T3] reported high aggregated transfer factors[16] of radiocaesium to muscle of a range of wild animal species (particularly in bear, wild boar, sika deer and copper pheasant) in five prefectures between 2011 and 2015. The decrease in radiocaesium concentrations with time was

[16] Aggregated transfer factor (m^2/kg), is the ratio of the radiocaesium concentration in the sample of the animal (e.g., muscle) (Bq/kg wet mass) divided by the deposition density (Bq/m^2).

initially fast, but the longer-term decline has been comparatively slower, with an effective half-life of 0.6 to 1.4 years, although confidence in these values is low due to the limited time period of measurements. Aggregated transfer factor values of ^{137}Cs for muscle of bear and wild boar from Fukushima Prefecture were lower than those observed after the Chernobyl accident [N9].

100. An extensive monitoring programme by Fukushima Prefecture showed that concentration ratios were higher for freshwater fish than coastal marine fish [W5]. A higher proportion of freshwater fish than marine fish had exceeded the limit established by the Japanese Government, especially in the first two years after the accident [W4]. Cultured fish, which are more commonly eaten in Japan than "wild" fish, are fed with commercial pellets and had much lower radiocaesium concentrations than wild fish [W4, Y7].

101. Radiocaesium concentrations in freshwater fish have been found to be highly variable, as they are affected by the characteristics of the surrounding catchment, the water, and their food source. The radiocaesium concentrations found in both river and lake fish were reported to be correlated with that of the surface soil of the catchment [A15, M10, T37]. A trophic level effect was also reported, whereby radiocaesium concentrations were generally in the order: carnivorous (e.g., salmonids) > omnivorous > herbivorous > planktivorous species [A15, I26, W4]. Radiocaesium concentrations in freshwater fish and amphibians were affected more strongly by their feeding preferences than by water chemistry [I36, I37]. For many, but not all fish species, larger fish in both rivers and lakes had higher radiocaesium concentrations than smaller fish [I36, I37, W5].

102. There was an initial rapid reduction with time since 2011 in both the radiocaesium concentrations and CR [17] values in freshwater fish species [A15, I26, W4], which are influenced by radiocaesium concentrations in both water and the food web constituents [W4]. The ^{137}Cs concentration reduced by one half within 1 to 2.5 years in lake fish [S49, S50, W4], and, with a few exceptions, there was little further decline in the CR values for freshwater fish with time in both lakes and rivers after 2015. Similarly, CR values for ^{137}Cs in edible species other than fish, such as crabs, shrimps and frogs, continued (up to 2018) to be 1 to 2 orders of magnitude higher than those observed before the FDNPS accident [T8].

4. Food monitoring

103. As part of the response to the FDNPS accident, the Japanese Government and prefectural authorities began monitoring food and drinking water on 16 March 2011. Provisional regulation values were established by the Japanese Government for radioactive material above which foodstuffs were prohibited from distribution and consumption. From 1 April 2012, lower limits were introduced by the Japanese Government for radiocaesium (^{134}Cs and ^{137}Cs). The provisional regulation values and limits for radiocaesium are summarized in table 5.

[17] The concentration ratio for aquatic food is the ratio of the concentration of a radionuclide in the aquatic food product (Bq/kg wet mass) to its concentration in water (Bq/kg).

Table 5. Concentrations of radiocaesium (^{134}Cs and ^{137}Cs) in foodstuffs and drinking water above which restrictions on supplies were introduced in Japan from March 2011[a]

Provisional regulation values established by the Japanese Government for radiocaesium from March 2011		*New limits established by the Japanese Government for radiocaesium from 1 April 2012*	
Food and water category	*Regulation value (Bq/kg)*	*Food and water category*	*Limit (Bq/kg)*
Drinking water	200	Drinking water	10
Milk, dairy products	200	Milk	50
Vegetables Grains Meat, eggs, fish	500	General foods	100
		Food for infants	50

[a] The equivalent guideline level for the purposes of international trade, as recommended by the Codex Alimentarius Commission, is 1,000 Bq/kg for radiocaesium in all of the food products listed [F1].

104. Radiocaesium (^{134}Cs and ^{137}Cs) concentrations exceeding the provisional regulation value of 500 Bq/kg were initially detected in crops from the areas to the north and west of FDNPS. A comprehensive monitoring scheme was then put in place for agricultural products (rice, cereals, vegetables, and orchard fruit), forest products (e.g., mushrooms and edible wild plants), agricultural animal products (e.g., beef, pork, milk) and freshwater products, which were measured for radioactive material content before sale. Many thousands of measurements have been carried out each year since the accident. The percentage of measured samples in Fukushima Prefecture in which the radiocaesium concentration exceeded 100 Bq/kg between March and June 2011 was 18% in crops, 3% in livestock products, 49% in forest products, and 52% in fishery products [S27] (although the provisional regulation values that applied at that time were higher than 100 Bq/kg). After June 2011, measured radiocaesium concentrations in all monitored agricultural foods reduced quickly and were mostly below the new limit of 100 Bq/kg established by the Japanese Government for general food in most agricultural crop and livestock products (see figure IX). Radiocaesium concentrations in wild food and freshwater fishery products have declined more slowly, with only a small number of samples exceeding the new limit of 100 Bq/kg for general food after 2014 (see figures X and XI).

Figure IX. Changes with time in the percentage of monitored terrestrial agricultural foodstuffs [M4, M5] that exceeded 100 Bq/kg of radiocaesium (^{134}Cs and ^{137}Cs)

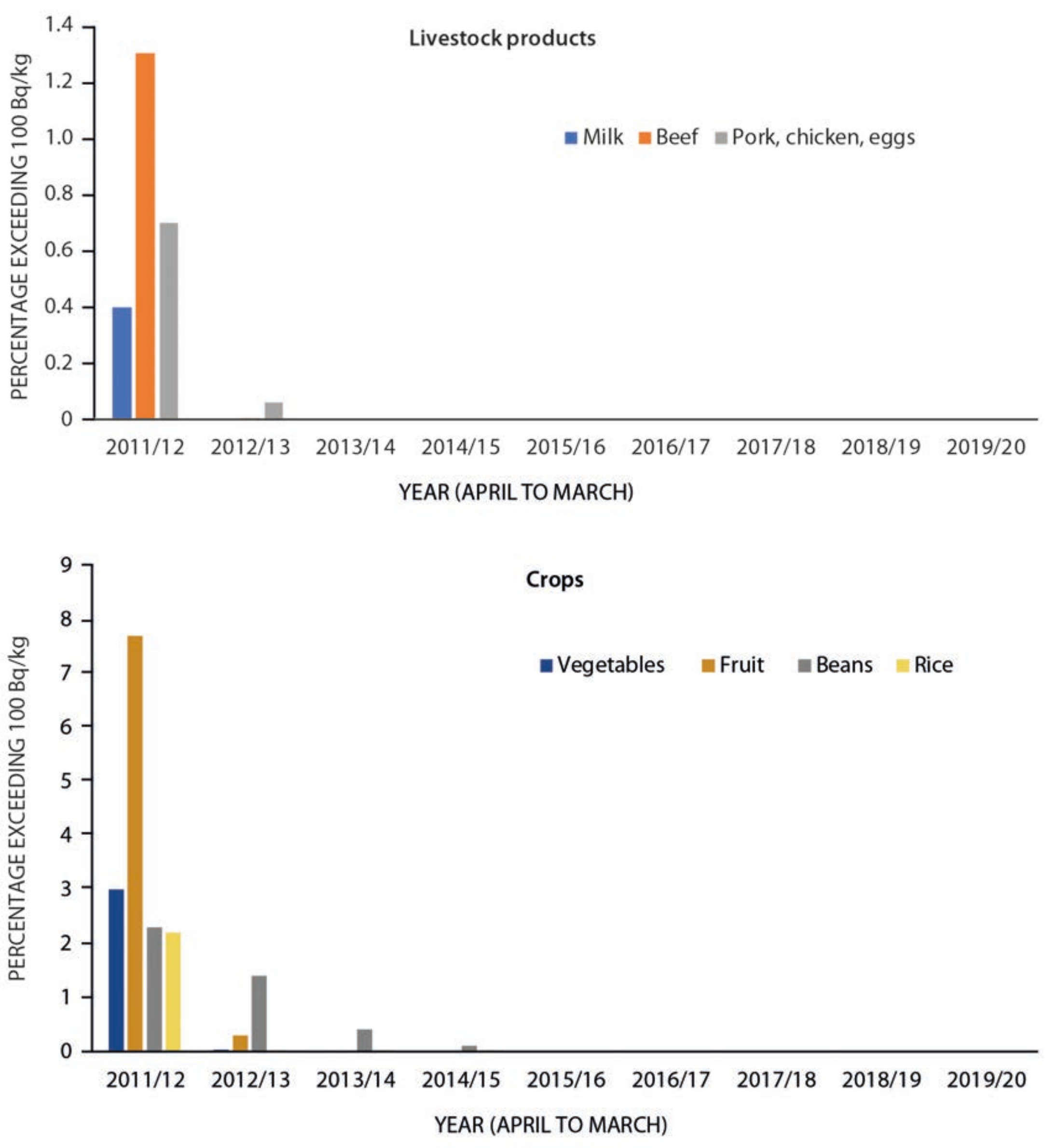


Figure X. Changes with time in the percentage of monitored wild foodstuffs [M4, M5] that exceeded 100 Bq/kg of radiocaesium (^{134}Cs and ^{137}Cs)

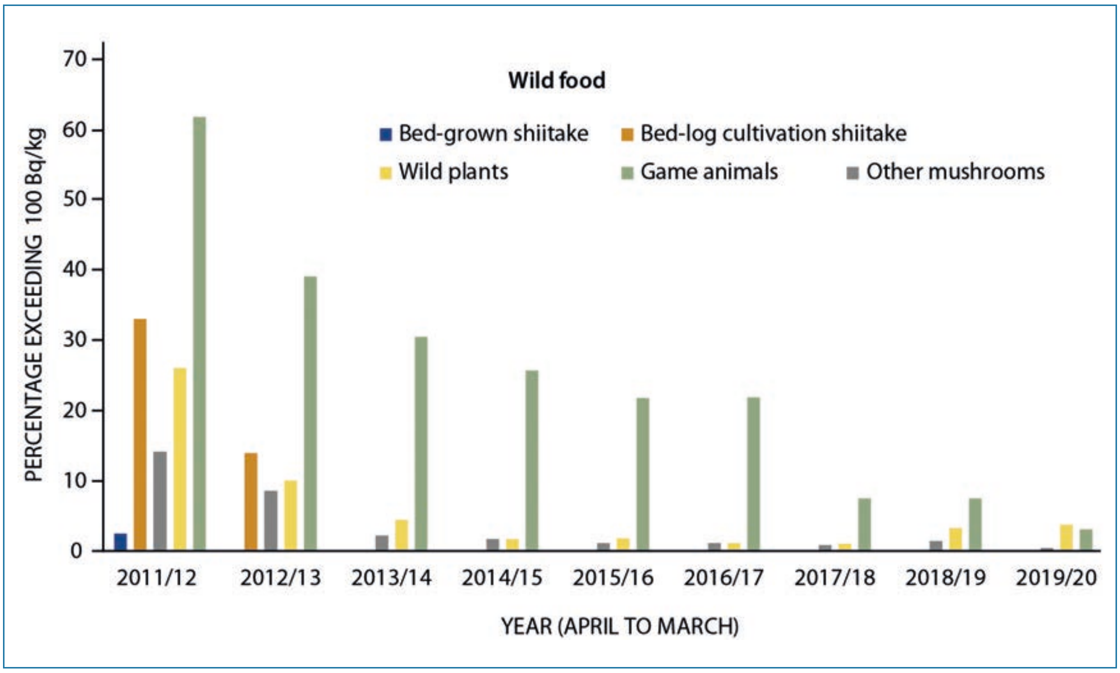
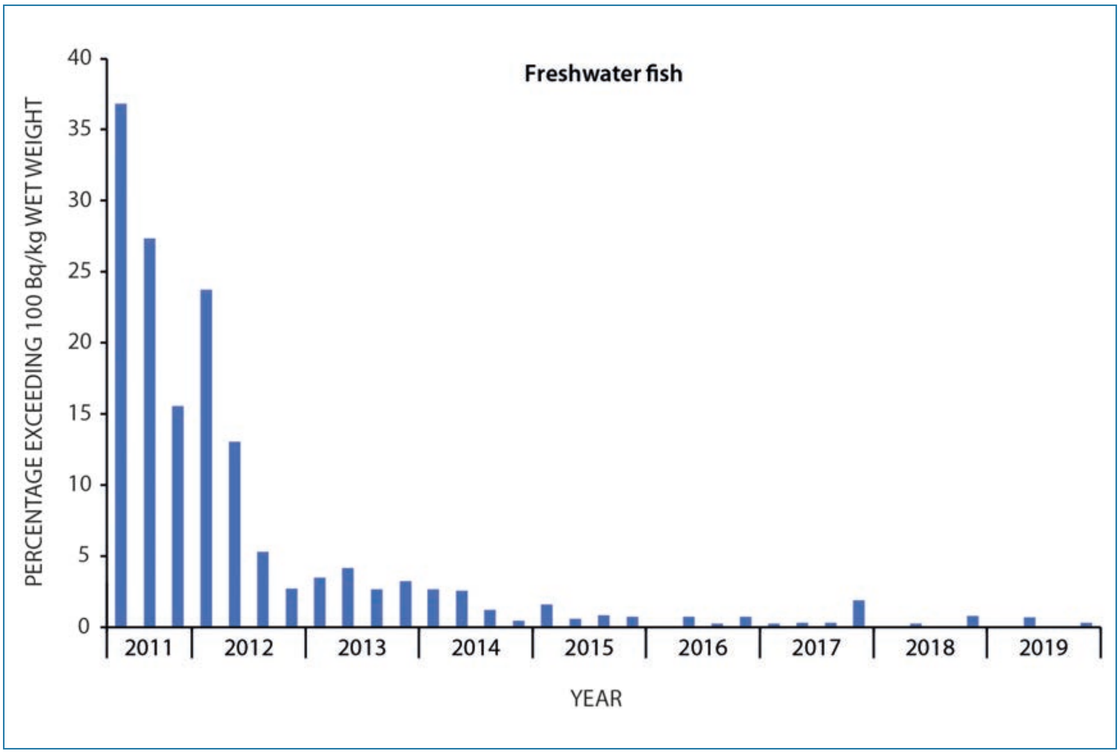


Figure XI. Changes with time in the percentage of monitored freshwater fish samples caught each quarter [M6] that exceeded 100 Bq/kg of radiocaesium (^{134}Cs and ^{137}Cs)



105. Some agricultural foodstuffs monitored in 2011 exceeded the Codex Alimentarius guideline levels recommended for the purposes of international trade [F1]. Four hundred and forty-two samples of vegetables (3.6% of the total measured) and 43 samples of milk (2.2% of the total measured) were found to have ^{131}I concentrations exceeding the guideline level of 100 Bq/kg. In the same year, radiocaesium concentrations exceeded the guideline level of 1,000 Bq/kg in 89 meat samples (0.70% of the total measured), three fruit samples (0.11% of the total measured), and 39 vegetable samples (0.04% of the total measured). No agricultural samples exceeded the guideline levels from 2012 onwards [H1, M4, M5]. For freshwater fish, 19 samples of fish (2.2% of the total measured) exceeded the guideline level for radiocaesium in the first year after the accident, and one sample (0.03% of the total measured) was above the guideline level in the second year after the accident [M6].

106. The vast majority of food consumed in Japan after the accident had radionuclide concentrations that were lower than the limits established by the Japanese Government. This was due to *(a)* prohibition of the collection and consumption of wild foods in affected areas, *(b)* rapid reduction in radiocaesium transfer over the first three years after the FDNPS accident for crops grown on agricultural land due to strong binding of radiocaesium in the prevailing soil types in affected areas, and *(c)* application of remediation options for crops, notably the application of potassium to agricultural land where necessary. There was also little production of food in areas with high levels of radiocaesium deposition due to restrictions and the evacuation of residents from these areas.

C. Remediation

107. The natural processes by which radiocaesium was transferred through terrestrial and freshwater environments have been discussed in section IV.B. These processes, as well as radioactive decay, have generally reduced the concentrations of caesium radionuclides in the compartments of the environment to which the public were most exposed. The Japanese Government decided to implement large-scale remediation projects to further reduce these concentrations and, therefore, the exposures of members of the public, and to enable people to return to the areas evacuated following the accident, by establishing an acceptable basis for this to occur. Details of the projects and their outcome have been published by the Ministry of the Environment (MOE) [M39]. These projects were carried out based on the “Act on Special Measures concerning the Handling of Environment Pollution by Radioactive Materials”, enacted in August 2011 [M40]. The MOE established the structures and institutional arrangements necessary for this work, including the related laws and decontamination guidelines. The total cost of the work has been estimated at 29 trillion yen (as of September 2017), with about 15 trillion yen contributed by the Government and about 14 trillion yen by municipalities [M39]. About 77,000 workers were involved in these activities in the period 1 January 2012 to 31 December 2016.

108. The areas to be remediated were designated into two categories based on the estimated additional annual effective dose that would be received by people living in these areas as assessed in autumn 2011:

(a) Special decontamination area (SDA). This included the eleven municipalities in the areas that were within a 20-km radius of FDNPS and the “Deliberate evacuation areas”, situated beyond the 20-km radius, where the additional annual effective dose for individuals might exceed 20 mSv. The Japan Self-Defense Force remediated key locations, such as municipal offices in this area, starting in December 2011, and, from January 2012, remediation was carried out in affected municipalities by construction companies under contract to MOE. Most of the remediation work was completed in March 2017, although agricultural remediation continues. A total of 23,000 residential lots, 8,700 hectares of farmland, 7,800 hectares of forest, and 1,500 hectares of roadways have been

remediated. As a result of the work, evacuation orders were lifted for an area of 780 km^2, about 70% of the total area affected by evacuation orders, and it was confirmed that the additional annual effective dose for residents who returned to this area was about 1 mSv [M39];

(b) Intensive contamination survey area (ICSA). This included 92 municipalities in eight prefectures where the additional annual effective dose for individuals was estimated to be between 1 and 20 mSv in some parts of the municipality. The work was carried out by the municipalities supported by central Government, starting in around April 2011, when requests from residents triggered the remediation of schools, kindergartens, nursery schools and parks, etc. Subsequently, under the “Act on Special Measures” [M40], construction companies were contracted by each municipality to carry out work based on its specific remediation implementation plan. This work started in January 2012 and was completed in March 2018. As a result of the work in the ICSA, it was confirmed that the additional annual effective dose for residents living there was 1 mSv or less in 2016, and that the long-term goal set in the basic policy of the “Act on Special Measures” [M40] was almost fully achieved [M39].

109. Remediation efforts addressed the two pathways of internal exposure from ingestion of food and drinking water containing radionuclides released as a result of the accident and external exposure to radionuclides deposited on to surfaces. The focus was on the caesium isotopes, ^{134}Cs and ^{137}Cs.

1. Remediation measures addressing internal exposure

110. Internal exposure from ingestion was greatly reduced by the imposition of widespread restrictions on the sale and distribution of foodstuffs containing radionuclides above the limits established by the Japanese Government, supported by extensive monitoring of food products from affected areas. Demonstration pilot studies into remedial measures focused on soil removal and the application of additional potassium and of a caesium binder, zeolite. A large number of other studies provided crop-specific and soil type-specific information [S26] that assisted the farming community to produce food in which concentrations of radionuclides were below the limits established by the Japanese Government. In contrast to the Chernobyl accident, where uptake of radiocaesium by crops from some of the prevailing soil types was high and persisted for many years in some areas [F5], in the SDA and ICSA the uptake of radiocaesium by crops was relatively low, in part due to the presence of micaceous minerals binding the radiocaesium, the high fertility and exchangeable potassium status of most farmland soils in Japan, and intensive farming methods employed in Japanese agriculture [H32].

111. Because the FDNPS accident happened before the growing season, there was limited interception of deposited radionuclides by early crops such as leafy vegetables, evergreen fruit and wheat seedlings. To address subsequent radiocaesium uptake into crops, crop production was only permitted on farmland where concentrations of radiocaesium in soil were below specified levels dependent on the CR value for each crop. For example, for growing rice, the permitted radiocaesium concentration in soil was initially less than 5,000 Bq/kg-dry mass, based on an assumed maximum CR value of 0.1 (for the initial limit established by the Japanese Government of 500 Bq/kg). For the remediation of areas with higher radiocaesium concentrations in soil, removal of top soil was the most effective action, although top soil removal not only produced large amounts of waste but also enhanced soil erosion, encouraged weeds and reduced the fertility of the soil. Other measures included reverse tillage to bury radiocaesium, soil suspension in water and removal in paddies, ploughing soil to dilute the radiocaesium concentrations in the rooting zone, and the application of additional fertilization.

112. From 1 April 2012, when the limit established by the Japanese Government for general foods was reduced to 100 Bq/kg, addition of potassium fertilizer to the soil became a more widely used action, based on the strong correlation between the uptake of radiocaesium and the exchangeable potassium status of the soil. The application of additional potassium to farmland soils was carried out to maintain an exchangeable potassium concentration above a specified threshold during the growing season. An initial threshold of 25 mg K_2O/100 g soil was subsequently reduced to 20 mg K_2O/100 g soil to take into account reductions in radiocaesium concentrations due to radioactive decay and fixation of radiocaesium by soil, and concerns regarding the environmental impact of enhanced potassium inputs. In Tomioka Town, in 2016, the exchangeable potassium content in more than 80% of soils which had top soil removed was below the threshold level of 20 mg K_2O/100 g soil [K56]. The application of potassium fertilizer was, therefore, particularly important for agricultural fields where excessive top soil removal may have caused a considerable decrease in exchangeable potassium content.

113. It is difficult to estimate the reduction in internal exposure due to these remediation measures compared with the effects of natural decay, migration and food monitoring. After 2011, only a very small number of farm products exceeded the limits established by the Japanese Government, and there was a rapid reduction with time in the uptake of radiocaesium in crops and agricultural animal products in both the SDA and the ICSA. Research studies on farmland to evaluate potential remediation options continue in the so-called “Areas where Returning is Difficult”.[18]

114. Remediation activities to address continued elevated radiocaesium concentrations in wild plants, game and fish are more difficult to develop than for farmland, emphasizing the importance of local monitoring of all such products. Some remediation efforts in contaminated catchments may affect radiocaesium concentrations in aquatic foodstuffs. Ongoing research efforts provide information on processes such as the removal of radiocaesium from the water column by adhesion to sediments.

2. Remediation measures addressing external exposure

115. To address external exposure to radionuclides deposited on to surfaces, including natural surfaces such as soil, sediment or trees, and man-made surfaces such as asphalt, concrete, walls, roofs, and floors, a range of different remediation techniques was developed. The application of the different techniques depended on the ambient dose rate. For residential areas in the SDA and for relatively higher dose areas in the ICSA, remediation included comprehensive removal of all contaminated surfaces (including top soil removal and power washing). For farmland, vegetation and the top 5 cm of topsoil were removed. In some higher dose SDA areas, the soil was covered with crushed granite, and the entire soil profile was mixed to dilute the residual radiocaesium present. For other farmland in the SDA and ICSA, the soil was ploughed and potassium and zeolite were added. In more contaminated areas, the topsoil and subsoil were also exchanged. For roads, remediation involved shot blasting the surface in the SDA, and cleaning of road surfaces and ditches in both the SDA and ICSA. For forests, remediation activities were focused on forest boundaries close to housing or areas where farmers worked and involved removal of fallen leaves and other plant material.

116. An indication of the effectiveness of remediation can be provided by comparing the ambient dose rate before and after remediation. Such a simple comparison will also include the effects of radioactive decay and vertical and horizontal migration as well as the effects of remediation. Table 6 presents the fractional ambient dose rate reduction (the ratio of the reduction in the ambient dose rate at 1 m above

[18] Areas designated in the context of the review of evacuation areas where the annual cumulative dose exceeds 50 mSv and where the annual cumulative dose may not fall below 20 mSv in the subsequent five years.

the target surface after remediation had been implemented at each measurement location[19] to the ambient dose rate before remediation) for a range of remediation activities carried out in the SDA and ICSA. The fractional reductions measured varied widely for the different target areas and depended on the method applied and the ambient dose rate prior to remediation (see table 6).

Table 6. Fractional ambient dose rate reductions in the special decontamination area and the intensive contamination survey area [E8], adapted from [Y23] (based on Fukushima Prefecture data [F19, K31, M37])

Target area	*Remediation*	*Fractional ambient dose rate reduction[a]*			
Ambient dose rate prior to remediation (µSv/h)		*≤1*	*1–3*	*3–10*	*>10*
AGRICULTURAL LAND					
SDA	Cut weeds, remove 5 cm topsoil and cover with clean soil	0.34	0.49	0.47	0.80
SDA/ICSA	Interchange topsoil and subsoil, add zeolite and potassium	0.34	0.49	0.47	0.80
SDA/ICSA	Ploughing with zeolite and potassium	0.21	0.31	0.29	0.50
FOREST					
SDA	Remove fallen leaves and organic matter	0.19	0.27	0.39	0.59
ICSA	Remove fallen leaves	0.10	0.14	0.20	0.30
ROADS					
SDA	Shot blasting and cleaning ditches	0.15	0.30	0.20	0.33
ICSA	Cleaning roads and ditches	0.08	0.15	0.20	0.33
RESIDENTIAL AREAS					
SDA/ICSA	Full remediation	0.29	0.35	0.49	0.70
ICSA	Localized remediation (in higher dose areas)	0.15	0.18	0.25	0.35

[a] The ratio of the reduction in the ambient dose rate at 1 m above the target surface after remediation at each measurement location to the ambient dose rate before remediation.

117. The fractional reductions given in table 6 include all factors contributing to a reduction in ambient dose rates, namely the effect of remediation, radioactive decay (which would be similar for all target areas), and vertical and lateral migration. The contribution of remediation to these reductions tended to be greater for areas with higher ambient dose rates before remediation.

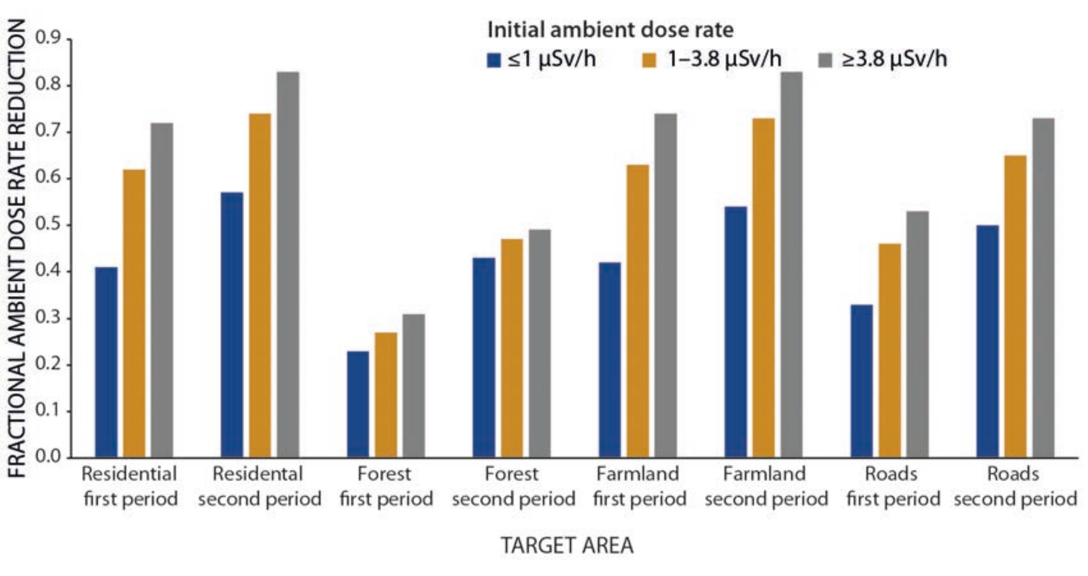
118. For the SDA, the reductions in the ambient dose rates following remediation were measured immediately after completion of the work, and then again about 6 months to a year afterwards to verify the reduction (see figure XII). The first set of measurements showed average fractional reductions in

[19] The background dose rate was deducted in each case.

mean ambient dose rate of 0.60 for residential areas (including schools, parks, cemeteries and large facilities), 0.58 for farmland (including fruit orchards), 0.42 for roads and 0.27 for forests [M39]. The second set of measurements showed the ambient dose rate to have reduced on average by 0.73, 0.68 and 0.61 in residential areas, farmland and roads respectively, and by 0.46 in forested areas, which cover about 70% of Fukushima Prefecture [M39]. The greater reductions in the second set of measurements reflect the influence of other contributing factors (e.g., radioactive decay, migration). In forests, surface material is continually accumulated due to the loss of tree components and attached radiocaesium from tree surfaces that is affected by rainfall intensity [A19]. According to Thiry et al. [T31], remediation in forests was likely to be more effective when conducted after the peak of transfer to the organic layer, which typically occurs around three to five years after the initial deposition, although the time period varies with tree and soil organic layer characteristics.

119. The fractional reductions in the ambient dose rates in the SDA reported by MOE [M39], and the variation with the ambient dose rate before remediation are illustrated in figure XII. No information was provided by MOE [M39] about the uncertainties in these ambient dose rate reductions or their statistical significance.

Figure XII. Fractional ambient dose rate reductions[a] for different target areas and initial ambient dose rates in the special decontamination area (based on data from [M39])



[a] The ratio of the reduction in the ambient dose rate at 1 m above the target surface after remediation at each measurement location to the ambient dose rate before remediation.

120. In municipalities within Fukushima Prefecture that were within the ICSA, the average fractional ambient dose rate reduction after remediation was 0.42 in residential areas, 0.55 in schools and parks and 0.21 in forests [M39]. Measurements were made between June 2011 and February 2016.

121. These reductions for the SDA and ICSA include not only the reduction in the ambient dose rate achieved by remediation, but also those due to natural decay and weathering. Using monitoring data collected before remediation, MOE [M39] estimated the decline over time in the ambient dose rate without remediation for comparison with the reduction in the estimated average ambient dose rate achieved after remediation, to assess the effect of remediation alone. In the SDA, the average ambient

dose rate was estimated to be 59% lower in March 2018 than it would have been without remediation. In the ICSA, the average ambient dose rate was estimated to be 38% lower in March 2016 than it would have been otherwise. The detailed methodology used to derive these estimates has not, however, been provided in the MOE report.

122. Detailed analysis of the ambient dose rate reduction with time was reported by Saito et al. [S2] who compared the contribution of different factors to the rate of reduction in the ambient dose rate over the first five years within an 80-km zone around FDNPS. The average ambient dose rate measured in undisturbed fields in the 80-km zone was estimated to be reduced as a result of remediation alone by approximately 20%.

3. Production of radioactive waste

123. An important consequence of the remediation efforts was the production of large amounts of radioactive waste (about 2.68 million tonnes by the end of May 2020 [M41]) stored at temporary storage sites. The total volume of removed soil generated is approximately 22 million m^3. From 2016 onwards, the temporary storage sites have been gradually dismantled and restored. Some of the wastes generated have been reduced in volume using incinerators, and less contaminated waste has been recycled and used for civil engineering projects. Work is ongoing on the treatment and the transport of radioactive waste to the interim storage facilities that are being built near FDNPS.

D. Summary

124. The extensive investigations carried out following the FDNPS accident have enhanced understanding of the transfer of radionuclides through the terrestrial and freshwater environments in Japan. In terms of the model used in the UNSCEAR 2013 Report [U10] to estimate transfers of radionuclides to foodstuffs from the first year after the accident onwards, a number of observations can be made:

(a) The concentration ratios assumed in the 2013 model for radiocaesium in crops (e.g., cereals, leafy green vegetables, root crops) were similar to the ranges of values subsequently reported for Japanese crops, resulting in broadly consistent estimated concentrations of radiocaesium in these foodstuffs;

(b) The concentrations of radiocaesium in milk and meat were likely overestimated, owing to the assumption that cattle grazed pasture outdoors between mid-April and November whereas, in practice, the majority of cattle (≈95%) in Fukushima Prefecture were housed in closed barns and fed (uncontaminated) stored feed following the accident;

(c) The concentrations of radiocaesium in fruit were likely to have been underestimated as it was assumed that soil was the only source of radiocaesium and no allowance was made for its transfer from bark, branches, leaf buds and old leaves of trees;

(d) Individuals consuming significant amounts of wild produce and freshwater products may have received doses from ingestion appreciably higher than those set out in the UNSCEAR 2013 Report.

This model has not, however, been used in the revised dose assessment described in chapter V.

125. Radiocaesium appears to be strongly bound to many soils in Japan, and there were no soils that had particularly high rates of radiocaesium uptake into plants, as occurred after the Chernobyl accident. The concentration ratios for the transfer of radiocaesium from soil into agricultural food have generally declined rapidly from elevated levels found immediately after the FDNPS accident to values that were not much higher than those reported prior to the accident within a few years, although this needs confirmation by further analysis over longer periods of time.

126. Monitoring programmes that began immediately after the accident enabled timely restrictions to be applied to prevent foodstuffs being marketed, where the radionuclide concentration exceeded regulation values and limits established by the Japanese Government. The radionuclide concentrations in most monitored foodstuffs have declined rapidly following the accident. Since 2015, no samples of livestock and crop products and only a few samples of monitored wild food and freshwater fish have been found to exceed the limits. In addition, a small number of monitored agricultural food samples (less than a few per cent) exceeded the Codex Alimentarius guideline levels for international trade in 2011, and no samples have done so from 2012 onwards.

127. The large-scale remediation projects implemented by the Japanese Government and the municipalities have been successful in further reducing the concentrations of radiocaesium in terrestrial and freshwater environments, in addition to the effects of natural processes and radioactive decay and allowing the lifting of evacuation orders. In the SDA, reductions in the ambient dose rates (including radioactive decay and migration of radiocaesium, as well as remediation) of between about 20% and 80% have been found, depending on the surface remediated and the initial dose rate. In the ICSA, reductions in the ambient dose rates of between about 20% and 55% were observed. The implications of these reductions in ambient dose rates for the assessment of doses to the public are considered further in chapter V and attachment A-1.

128. The assessment of levels of exposure following accidental releases of radioactive material is greatly facilitated by the availability of a validated model or models for reliably predicting the time-dependent transfer of radionuclides through terrestrial and freshwater environments. Such models need to take into account country-specific consumption and agricultural habits and the potentially important influence of soil types on radionuclide bioavailability.

V. ASSESSMENT OF DOSES TO THE PUBLIC

A. Introduction

129. This chapter sets out the basis for the Committee’s revised estimates of doses to the public in Japan and presents a summary of the doses estimated.[20] More details on the information available to the Committee, the methodology it has used, and its revised dose estimates can be found in appendix A. As in the UNSCEAR 2013 Report [U10], the Committee’s aim has been to make realistic, rather than

[20] Throughout this report, the estimates of doses to the public presented are those from exposure to radioactive material released as a result of the FDNPS accident, i.e., the doses are those in addition to doses from exposure to natural sources of radiation and any other sources of exposure. The average annual effective dose to the Japanese population from natural sources has been estimated at 2.2 mSv [O21].

conservative, estimates of doses. For ease of comparison with the UNSCEAR 2013 Report, estimates were made of municipality- and prefecture-average doses for the same population groups (those people who were evacuated, residents of municipalities in Fukushima Prefecture that were not evacuated, municipalities in some neighbouring prefectures, and prefectures in the rest of Japan). While the same population groups have been used as in the UNSCEAR 2013 Report, the allocation of some prefectures to these groups is slightly different (see table 7). This is due to differences in the spatial coverage of the most recent radionuclide deposition density information used in the dose assessment.

Table 7. Population groups considered

Population group	*Geographical areas*	*Spatial resolution*
1	Locations where people were evacuated in the days to months after the accident	Representative areas were used for each location identified in 40 evacuation scenarios
2	Municipalities[a] and parts of municipalities of Fukushima Prefecture[b] not evacuated	Municipality level for external and inhalation pathways, based on the estimates for each of the 1-km grid points, averaged over the municipality Prefecture level for ingestion pathway
3	Selected prefectures (Miyagi, Tochigi, Ibaraki and Yamagata) in eastern Japan that are neighbouring to Fukushima Prefecture	Municipality level for external and inhalation pathways, based on the estimates for each of the 1-km grid points, averaged over the municipality Average for the four prefectures (Miyagi, Tochigi, Ibaraki and Yamagata) for ingestion pathway
4	All remaining prefectures of Japan	Prefecture level for external and inhalation pathways Average of the rest of Japan (i.e., the 42 prefectures, excluding Fukushima, Miyagi, Tochigi, Ibaraki and Yamagata) for ingestion pathway

[a] Each prefecture of Japan is divided into municipalities. A municipality is a local administrative unit; the municipalities are used primarily in the Japanese addressing system to identify the relevant geographical areas and collections of nearby towns and villages. The term “municipality” has been used in this report in place of the term “district” used in the UNSCEAR 2013 Report [U10].

[b] Japan comprises 47 prefectures. In Japanese the word “prefecture” is used for translating references to “ken” in Japanese.

130. Average doses in the first year after the accident have been estimated for the same age groups (represented by the 20-year-old adult, the 10-year-old child and the 1-year-old infant) and the same dosimetric endpoints (the absorbed dose to selected organs – the thyroid, red bone marrow, colon and female breast – and the effective dose) as in the UNSCEAR 2013 Report [U10]. In addition, estimates have been made of the average absorbed doses to the fetal thyroid over the 30-week development period of the fetus and of the average absorbed dose in utero to the red bone marrow over the 40-week term of pregnancy. Projections were also made for the three age groups of effective dose and absorbed dose to the thyroid over the first 10 years after the accident and until an attained age of exposed individuals of 80 years. In this report the Committee has also estimated the distributions of individual doses in each municipality or prefecture taking account of uncertainties (e.g., arising from modelling assumptions) and all major sources of variability among the population, including the age distribution, varying levels of exposure within a municipality or prefecture, behaviours (such as the amount of time spent indoors or outdoors), types of diet, and the filtering of the air and shielding provided by different types of buildings. The 5th and 95th percentiles of the distributions have been presented as well as some example distributions (see section V.E.2).

Exposure pathways

131. For the radioactive material released to the atmosphere, the principal pathways by which members of the public can be exposed are:

(a) External exposure to radionuclides in the air;

(b) External exposure to radionuclides deposited from the air on to the ground surface by either wet or dry deposition;

(c) Internal exposure from inhalation of radionuclides in the air;

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

These pathways were considered in the UNSCEAR 2013 Report [U10] and have again been considered in the dose assessment reported here. Members of the public could also have been exposed to radioactive material released to the marine environment, through ingestion of fish and other seafood and exposure to radionuclides in the sea or on sediments at the seashore. The former pathway has been included in the estimation of internal exposure from ingestion of radionuclides in food; the latter pathway has not been included because it was not expected to be a significant contributor in view of the 20-km evacuation zone established around the FDNPS site.

B. Overview of dose assessment in the UNSCEAR 2013 Report

132. In general, measurements made on people, either of external exposures or of radionuclides in the body, provide a direct source of information for estimating doses. At the time of the UNSCEAR 2013 Report [U10], information on such measurements covered only a limited number of people and locations and was insufficient to make comprehensive estimates of doses to the public; the measurements were only used as one means of checking the validity of the Committee’s dose assessment.

133. The dose assessment in the UNSCEAR 2013 Report [U10] was accordingly largely based on measurements of radioactive material in the environment, combined with models describing how people were exposed to this material. Further details of the methodology used can be found in the UNSCEAR 2013 Report. 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; and 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 and the Committee also considered data made available by several non-governmental organizations. All data were evaluated to determine their suitability for the assessment. Most of the scientific information used in the UNSCEAR 2013 Report was limited to that published or disclosed by the end of October 2012.[21]

[21] In finalizing the report, the Committee took into account where appropriate and practicable any significant new scientific information that became available after this date up until the end of 2013.

134. Models were used, inter alia, for estimating:

(a) The levels of radionuclides deposited on the ground where insufficient measurement information was available (generally only in the evacuated areas in the weeks following the accident), where the Committee's chosen source term was used with ATDM;

(b) Concentrations of radionuclides in the air, where the source term and ATDM were used, either directly for the period of evacuation and for radionuclides which were not deposited on the ground (e.g., noble gases), or to derive air concentrations from measured deposition densities;

(c) The variation, as a function of time, of the external dose rate from deposited radionuclides;

(d) Levels of radionuclides in food beyond the first year after the accident, for which measurements were not available, where the Committee used a modified version of the FARMLAND model [B12] for estimating the transfer of radionuclides through terrestrial food chains.

135. The Committee took account of the measures implemented by the Japanese authorities to protect the public, including the precautionary evacuation of approximately 78,000 residents within the 20-km area around the FDNPS site and some nearby areas, which took place between 11 and 15 March 2011, and the deliberate evacuation, based on environmental measurements, of about 10,000 residents of several municipalities to the north-west of the FDNPS site, which took place between April and June 2011. About a further 30,000 people were also included among those evacuated: these included residents of other parts of municipalities that were partly within the 20-km area, some of the people living within the "evacuation prepared area" between 20 and 30 km of the FDNPS site, who were advised to begin voluntary evacuation on 25 March 2011, as well as some living outside the 30-km radius. In addition, foodstuffs and drinking water containing more than prescribed concentrations of radioactive material were prohibited from sale or consumption. The Committee did not take account of other protective measures including directives to shelter in place during the main releases and to take stable iodine, as sufficiently precise information was not available. Nor was the Committee able to take account of the large land remediation programmes that were initiated in some of the more affected parts of Fukushima Prefecture and neighbouring prefectures due to the lack of detailed information at the time of the UNSCEAR 2013 Report [U10] about the scale and efficacy of the implemented remediation actions.

C. Information for dose assessment

136. The Committee's revised estimates of doses to the public from internal and external exposures in this chapter use information collected for the UNSCEAR 2013 Report [U10], together with new information that has since become available (up to the end of December 2019) [22]. This includes measurement data on people (in particular, personal dosimeters, whole-body counting (WBC) and thyroid measurements), and new information on concentrations of radionuclides in the air during the release and on the ground, on food and drinking water consumption, on occupancy factors, on location factors and on protective measures, including evacuation scenarios.

137. Chapters II, III and IV have provided summaries of the information now available on releases to the atmosphere and to the ocean, on the distribution of the released radioactive material in the air, on the ground and in the ocean and on transfers through the terrestrial, freshwater and marine environments to

[22] New information that has become available after December 2019 has been taken into account exceptionally where it may have a significant impact on the estimates of doses.

foodstuffs. More measurement-based information is available on the levels of released radionuclides deposited on to the ground surface and on concentrations of radionuclides in air. More information is also available on the transfer of radionuclides through the terrestrial environment in Japanese conditions, and more measurements are available, over a longer period of time, on the levels of radionuclides in foods.

138. In addition, there is further information available relevant to the dynamics of ambient dose rates, including about natural migration and weathering processes in Japanese conditions, and on dose rates above different types of surface from car-borne surveys and those carried out on foot. Numerous measurement campaigns have been conducted to assess individual doses from external exposure through surveys of daily activity patterns of residents, and individual measurements using personal dosimeters. The most significant of such measurement campaigns (some thousands of measurements per year) were carried out by municipalities, including, for example, Minamisoma City, Date City, Fukushima City, Naraha Town and some others [F18, M31]. The results of these large-scale measurement campaigns have been made widely available to the public and additional external exposure measurement data has been provided to the Committee by the municipalities of Minamisoma City and Naraha Town. The Committee has made use of the survey data and the scientific results published in peer-reviewed journals to develop a revised model to apply to the wider population, and used the results of the measurement campaigns to provide validation of the estimates of dose from external exposure made using this model.

139. Thyroid monitoring was conducted from as early as 15 March 2011 on evacuees and permanent residents of Fukushima Prefecture, covering around 1,200 persons of various ages and both sexes. Whole-body monitoring campaigns have been carried out by national institutes, such as JAEA and the Japanese National Institute of Radiological Sciences (NIRS), and by universities, hospitals and municipalities. These large-scale measurements began in July 2011 for evacuees and in October 2011 for residents. The Committee has used publicly available information from these monitoring campaigns to validate its estimates of doses from internal exposure, as well as data provided by Japan and the Russian Federation.

140. New sources of information that are available and relevant to estimation of the dose from ingestion include measurements of the radiocaesium content in the whole daily diet sampled by the duplicate-diet or market-basket methods.[23] These methods are based on measurements made on the food and drinking water as consumed by people, and some studies (e.g., [T53]) have taken account of factors such as removal of radionuclides during food preparation and cooking. In addition, studies have been published setting out well-founded estimates of doses from ingestion of food and drinking water which take account, for example, of specific food distribution systems in Japan, or specific circumstances for those who were evacuated, based on surveys (e.g., [M47]).

141. Further details about the information available and the data that the Committee has used to make its updated estimates of doses to members of the public can be found in appendix A.

D. Overview of methodology for assessing public exposures

142. There is considerably more, good quality, measurement information available than was available to the Committee at the time of preparation of the UNSCEAR 2013 Report [U10]. In addition, Japanese researchers have carried out many detailed assessments of doses and published the results in the peer-reviewed literature. The Committee’s use of this information and its

[23] In the duplicate-diet method, subjects weigh and put aside a duplicate portion of all the foods they have eaten for analysis; in the market-basket method, the analysis is carried out on a basket of food, based on per capita food consumption data, as purchased at a food market.

assessment results are described in detail in appendix A and summarized in the paragraphs below. In its revised assessment of doses to members of the public, the Committee has placed greater reliance on the results of studies published in the peer-reviewed literature rather than carrying out its own modelling. However, it still needed to make use of some models for a full dose assessment comparable with that in the UNSCEAR 2013 Report. The approaches used by the Committee, including the models used, are described in appendix A. The Committee has used the additional information that has become available to refine its models, reducing, and providing a better estimation of, uncertainties and assessing the distribution of doses in the population taking account of variabilities. The measurements made on people, in particular, have proved valuable in validating the models that had to be used for estimating doses in the wider population. Some of the main differences between the approaches used in the UNSCEAR 2013 Report and those the Committee applied to update its dose assessment are summarized in the following paragraphs.

143. While there is more information available on the concentrations of radionuclides in the air and deposited on to the ground and other surfaces, all of the information now available is still not sufficient to allow estimates of doses based solely on measurements and some modelling has been necessary. In particular, in order to estimate doses from radioactive material in the air, both from external exposure to this material and from internal exposure from inhalation of this material, modelling was needed to obtain estimates of concentrations of radionuclides in air at all locations of interest and for particular time periods, as measurements remain sparse. The approach used in the UNSCEAR 2013 Report has again been used. Nonetheless, the greater amount of measurement information now available has been used to test this approach and provide greater assurance about its validity.

144. Accordingly, exposures from radioactive material in the air at specific times and locations have been estimated from the assumed time sequence of the release of the more significant radionuclides and their transport through the atmosphere using ATDM. In this report, the Committee has used the latest source term developed by the group of researchers at JAEA [T28], derived from measurement information on levels of radionuclides in the air and deposited on the ground using reverse modelling and ATDM (Worldwide version of System for Prediction of Environmental Emergency Dose Information – WSPEEDI), and better correlated with events on the FDNPS site. Terada et al. [T28] have then used the same ATDM with this source term to estimate the time-dependent concentrations in air and deposition densities of the radionuclides ^{132}Te (and its daughter radionuclide, ^{132}I, with which it is assumed to be in equilibrium), ^{131}I, ^{134}Cs and ^{137}Cs. For ^{131}I, three chemical forms have been considered: elemental vapour, inorganic particulate, and organic, using the constant ratios, based on experimental and other evidence, of 0.2 for $^{131}I_{elemental}/^{131}I_{total}$, 0.5 for $^{131}I_{particulate}/^{131}I_{total}$, and 0.3 for $^{131}I_{organic}/^{131}I_{total}$. These ATDM results have been provided to the Committee for two nested grids:

(a) The finer grid covering most of Fukushima Prefecture with a horizontal resolution of 1 km;

(b) The coarse grid covering Fukushima Prefecture and all neighbouring prefectures with a horizontal resolution of 3 km [T28].

145. Terada et al. [T28] did not include the short-lived radionuclide ^{133}I and the Committee has therefore estimated the concentration of ^{133}I in air from the calculated concentrations of ^{131}I in air by applying a time-dependent ratio of the two radioisotopes based on the ratio at 14:46 on 11 March 2011 from Nishihara et al. [N12], adjusted for their radioactive half-lives. Terada et al. [T28] also did not include ^{133}Xe which would have contributed significantly to the dose from external exposure to airborne radioactive material, adding about 30% to the estimated effective doses from this pathway. However, the estimated effective dose from this pathway is typically only about 1–3% of the estimated effective dose from internal exposure from inhalation of airborne radioactive material, so the contribution of ^{133}Xe to the estimated total effective doses from airborne material would have been less than 1%, which is small

compared with uncertainties in these estimates. Further details of the ATDM results provided to the Committee and how they have been used in the dose assessment are provided in appendix A and attachments A-9 and A-10.

146. As in the UNSCEAR 2013 Report [U10], the ATDM estimates of concentrations of radionuclides in the air as a function of time have been used directly to estimate doses to evacuees from external exposure to the airborne radionuclides and doses from internal exposure from inhaled radionuclides. At locations where members of the public were not evacuated, the ATDM estimates of deposition density and of time integrated concentration of each radionuclide in air have been used to calculate ratios by which measured deposition densities have been scaled to infer a time-integrated air concentration. From the latter, external exposure to airborne radionuclides and internal exposure from inhalation have been derived. New measurement information on time-integrated concentrations of ^{137}Cs in air at a number of locations has been compared with estimates based on ATDM and estimates derived using the ratio method (see appendix A). The comparisons provide support to the method being used by the Committee to estimate time-integrated air concentrations of radionuclides and the resulting public doses from exposure to radionuclides in the air.

147. Since the UNSCEAR 2013 Report [U10], further information has become available relating to the deposition densities of ^{131}I and to the dynamics of ambient dose rates, in particular on dose rates above different types of surface in the environment specific to Japanese conditions. Extensive measurements of external exposure made directly on people have also become available. In addition, the International Commission on Radiological Protection (ICRP) has developed new dosimetric data and models relevant for external dose assessment in a post-accident situation [I22]. The Committee has taken account of these developments to derive an improved model (M2020) for assessing doses from external exposure to deposited radionuclides and made comparisons with the measurements made on people to provide more robust testing and validation of this model. Using this model, external dose rates are higher in residential areas and decline more gradually over time than predicted by the model used in the UNSCEAR 2013 Report (see appendix A).

148. The Japanese population traditionally has an iodine-rich diet, containing up to tens of thousands of micrograms of stable iodine a day, that is greater than the worldwide average by about two orders of magnitude [K5, L3, N2, Z6, Z7]. As a result, the fractional uptake of radioiodine into the thyroid following intake via ingestion or inhalation among the Japanese population can be expected to be lower than the reference ICRP value used in the UNSCEAR 2013 Report [U10]. The new ICRP model of iodine biokinetics in adults [I21] has been used to calculate dose coefficients for inhalation and for ingestion of ^{131}I, ^{132}I, ^{133}I and ^{132}Te, for three types of diet that may be more appropriate for the Japanese population: a typical Japanese diet; a kelp-rich diet; and a Western pattern diet, that is popular among some groups of the Japanese population. The dose coefficients were developed for dose to the thyroid, red bone marrow, female breast, and colon, as well as for effective dose. The indicative dose coefficients for intake by inhalation and ingestion have been calculated for an adult female, an adult male, and for a 10-year-old child, a 1-year-old infant, and the 35-week fetus. The resulting dose coefficients for those with a typical Japanese diet are about a factor of two lower than those used in the UNSCEAR 2013 Report (and recommended by ICRP for general application worldwide). Further details can be found in appendix A and attachments A-2 and A-4.

149. In the UNSCEAR 2013 Report [U10], the Committee made no allowance for any reduction in the dose from inhalation for people being indoors during the passage of the plumes of released material, in the absence of more specific information. Based on new information about the factor by which doses from inhalation may be reduced while indoors, which was experimentally derived for Japanese houses, the Committee has used a reduction factor varying between 0.1 and 0.95, with an average of 0.5, for

assessing doses from inhalation of radionuclides when people were indoors. Account has been taken of the amount of time different groups of people spent indoors. Further details can be found in appendix A and attachment A-10.

150. In the UNSCEAR 2013 Report [U10], the Committee estimated doses in the first year from ingestion from measurements of ^{131}I, ^{134}Cs and ^{137}Cs made in a wide variety of foods and in drinking water in Japan. From emerging information from whole-body monitoring, the Committee was aware, at the time of preparation of the UNSCEAR 2013 Report, that these estimates were likely to be substantial overestimates. Possible reasons for this included that the food monitoring measurements used, particularly in the first year, were not based on random sampling, but on samples aimed at identifying foods containing high concentrations of radionuclides that should be subject to restrictions. In addition, where measurement results were below the minimum detection level, a constant concentration of 10 Bq/kg was assumed.

151. Further information has since become available that has enabled the Committee to make more realistic and robust estimates of doses from ingestion. For radiocaesium, this includes WBC measurements made on people; measurements made on food actually consumed by people, either from market-basket or from duplicate-diet surveys; and detailed assessments based on measured levels in food in Japan. For radioiodine, this includes: measurements of the radioiodine content of thyroids; and detailed assessments based on measured levels in food and drinking water in Japan. Appendix A provides further details about these sources of information. Making use of these different sources of information to estimate doses is complicated by factors such as the timing of the measurements, and the different routes of intake and the different radionuclides included in each case.

152. In light of the strengths and weaknesses of these sources of information and the dose estimates that can be derived from them, the Committee has based its estimates of doses from ingestion in the first year to both adult and child residents on the estimates of Murakami and Oki [M47] derived by modelling intakes of ^{131}I, ^{134}Cs and ^{137}Cs using food monitoring data. While this is a similar approach to that used in the UNSCEAR 2013 Report [U10], Murakami and Oki used data from a wider range of sources than was available to the Committee when preparing that report, and, unlike that report, took account of the regional trade in foods (specifically, of the proportion of foods from different parts of Japan on sale at food markets, where most Japanese citizens purchase food). Murakami and Oki compared their estimates of the effective dose from ingestion of ^{134}Cs and ^{137}Cs in food and drinking water with the estimates derived from market-basket and food-duplicate surveys and found good agreement. The Committee has adjusted the estimates of Murakami and Oki to take account of the specific dose coefficients it has derived for radioiodine intakes for Japanese people. The Committee has compared the dose estimates for the first year with the results of the whole-body monitoring studies and the thyroid monitoring studies (see appendix A and attachments A-2 and A-3).

153. For time periods after the first year, the Committee has used estimates of doses to adults and children from ingestion of radiocaesium derived from the market-basket and duplicate-diet studies as its starting point, and then used the model developed by Smith et al. [S33] to estimate how intakes of radiocaesium from food and drinking water change over the longer term. This model was developed from an analysis of long-term measurement data collected annually from 1963 to 2008 on the ^{137}Cs content of food products and in the whole diet in Japan resulting from fallout of radiocaesium from atmospheric nuclear weapons testing. Further details of the approach used by the Committee in updating its assessment of doses from ingestion can be found in appendix A.

154. As part of the response of the Japanese authorities to the FDNPS accident, there was widespread evacuation of residents living nearby at different times to reduce radiation exposures. In a recent study, Ohba et al. [O5] have refined the 18 evacuation scenarios used to assess doses to evacuees in the UNSCEAR 2013 Report [U10], resulting in 37 new representative evacuation scenarios. As these 37 new

evacuation scenarios did not include those evacuated from Hirono Town and Katsurao Village, the Committee has also included three scenarios, considered in the UNSCEAR 2013 Report, which represent those evacuated from these locations, giving 40 evacuation scenarios in total. Within these 40 scenarios, the Committee has considered four types of human activities: *(a)* normal living conditions; *(b)* preparing for evacuation; *(c)* evacuation; and *(d)* sheltering, and used a method to estimate doses consistent with that used for residents, although no allowance was made for any reduction in dose from inhalation that may have occurred while in buildings or vehicles during evacuation. Doses from ingestion of food before and during evacuation have been assumed to be negligible, based on survey results [H15, K10], and the doses from drinking water estimated by Miyatake et al. [M34] have been used, again with adjustment for the specific dose coefficients for iodine intakes for Japanese people. The assessment of doses to those evacuated also included doses received at their evacuation destinations, mostly in less affected areas of Fukushima Prefecture but also in other prefectures; it was also assumed, as in the UNSCEAR 2013 Report, that evacuees remained at these destinations subsequently. Projected doses from deposited radionuclides have also been assessed for the evacuated locations, in order to determine the dose averted by evacuation.

155. Experimental studies and tests of environmental remediation technologies started in the affected areas of Japan in summer 2011 and continued in Fukushima Prefecture until 2013. Large scale remediation of the evacuated municipalities started in 2013 in the SDA, with the support of the Government of Japan, and local authorities initiated remediation activities in the ICSA. The information available about the technologies used, the scale of the implemented environmental remediation actions, and the resulting reductions in ambient dose rates have been summarized in chapter IV. However, information about the reductions achieved by remediation in the dose actually received by the public remains quite limited. As a result, an assessment of the effects of environmental remediation on the estimates of doses has been limited to the doses received by evacuees following return to their homes.

E. Results of dose estimation

156. As in the UNSCEAR 2013 Report [U10], the Committee has produced an extensive set of estimates of effective doses and absorbed doses to particular organs for the public in Japan. This is presented in more detail in appendix A. The Committee has firstly made estimates of municipality- and prefecture-average doses to defined groups of the population for ease of comparison with the equivalent estimates made in the UNSCEAR 2013 Report.

157. In this report, the Committee has, in addition, made more quantitative and comprehensive estimates of the uncertainties and variabilities about these municipality- or prefecture-average doses. The results include the 5th and 95th percentiles of the distribution of individual doses in the different population groups, taking account of major sources of uncertainty and variability among the population, including data and modelling uncertainties, the age distribution of the population, varying levels of exposure within a municipality or prefecture, lifestyle (such as the amount of time spent indoors or outdoors), types of diet, and the filtering of the air and shielding afforded by different types of buildings. The estimated 5th and 95th percentiles are presented with the estimated average doses in section V.E.1; and some examples of the distributions of individual doses in different population groups are presented in section V.E.2. Further details on how uncertainties and variabilities have been addressed can be found in attachment A-12.

1. Average doses to different population groups in Japan

(a) *Average doses to residents (i.e., those not evacuated) in the first year*

158. Table 8 summarizes the estimated municipality- or prefecture-average effective doses and absorbed doses to the thyroid for the first year following the accident for adults,[24] children and infants living in areas of Japan that were not evacuated. Compared with the equivalent table in the UNSCEAR 2013 Report [U10] (see table 5 in that report), the Committee's updated estimates of the average effective doses at the upper end of the ranges are generally a few tens of per cent lower than in the UNSCEAR 2013 Report and more than ten times lower at the lower end of the ranges; average absorbed doses to the thyroid are around half those in the UNSCEAR 2013 Report at the upper end of the ranges and more than ten times lower at the lower end of the ranges. These differences are largely due to the more realistic estimates made in this report of doses from ingestion and the use of dose coefficients for intakes of radioiodine that are specific to the Japanese population. These differences and their effects on the dose estimates are explored in more detail in appendix A.

Table 8. Ranges of estimated municipality- 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.[25] The values are the ranges of the average doses in the municipalities of the Group 2 and Group 3 prefectures and the ranges of the average doses in the prefectures of the Group 4 prefectures. These estimates were intended to be characteristic of the average dose received by people living in a given municipality or prefecture and do not reflect the range of doses received by individuals within the respective populations

Geographical area	*Ranges of effective dose (mSv)*			*Ranges of absorbed dose to the thyroid (mGy)*		
Age group[a]	*Adult*	*10-year-old*	*1-year-old*	*Adult*	*10-year-old*	*1-year-old*
Group 2[b] – Fukushima Prefecture	0.079–3.8	0.10–4.5	0.12–5.3	0.48–11	1.0–17	1.2–21
Group 3 – neighbouring prefectures[c]	0.10–0.92	0.13–1.1	0.15–1.3	0.31–3.3	0.52–5.2	0.62–6.3
Group 4[d] – rest of Japan	0.004–0.36	0.005–0.43	0.005–0.51	0.034–0.48	0.073–0.63	0.087–0.74

[a] Detailed estimates are not tabulated here for doses to the fetus but can be found in attachment A-14. Ranges of average fetal absorbed doses to the thyroid over the 30-week development period of the fetus are about 70% to 80% of the tabulated adult thyroid doses.

[b] Group 2 – Members of the public resident in the municipalities or parts of municipalities in Fukushima Prefecture that were not evacuated.

[c] Group 3 – Members of the public resident in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata. The radionuclide deposition density information in parts of these prefectures was sufficient for estimates of doses to be made from inhalation and external exposure pathways at the municipality-average level on a 1-km square basis. As a result, prefectures making up Group 3 are different from those considered in the UNSCEAR 2013 Report [U10].

[d] Group 4 – Members of the public resident in the remaining 42 prefectures of Japan, including the previous Group 3 prefectures of Gunma, Chiba and Iwate.

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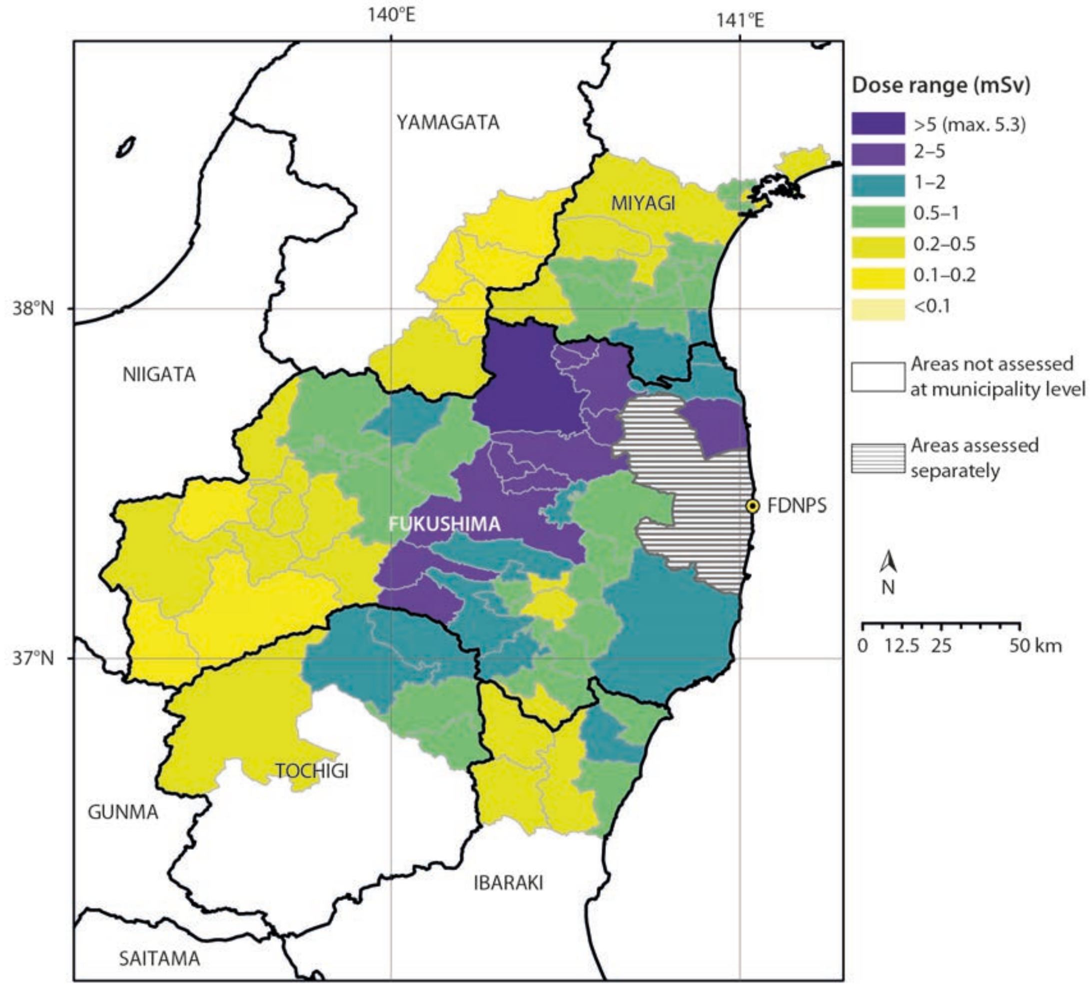
[24] Average doses to adults who were indoor workers have been chosen to be representative of adults as a whole. The variability of the effective doses and absorbed doses to the thyroid among the population, including whether adults were indoor or outdoor workers, or retired has been considered in section V.E.2 below.

[25] The average annual effective dose to the Japanese population from natural sources has been estimated at 2.2 mSv [O21].

159. Figure XIII shows a map illustrating municipality-average effective doses in the first year to infants living in municipalities of Fukushima Prefecture that were not evacuated and in parts of the neighbouring prefectures where there was sufficient spatial coverage of the deposition density information. Absorbed doses to the thyroid for all ages and effective doses to children and adults show a similar geographical pattern that broadly reflects the deposition density of radionuclides in the different areas (see appendix A). In addition, figure XIV shows the municipality-average effective dose in the first year to infants residing in each of the municipalities of Fukushima Prefecture that were not evacuated (Group 2).

Figure XIII. Estimated municipality-average effective doses in the first year following the accident to infants living in Group 2 municipalities of Fukushima Prefecture and some municipalities of Group 3 prefectures



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

160. External exposure to deposited radionuclides generally makes the largest contribution to the effective dose. Internal exposure from intakes of radionuclides (in particular, radioiodine)[26] by inhalation generally makes the largest contribution to the absorbed dose to the thyroid, although external exposure to deposited radionuclides also makes an important contribution. This is in contrast to the doses estimated in the UNSCEAR 2013 Report [U10] where ingestion of radionuclides in food and water was a comparatively more important exposure pathway[27] for both effective dose and absorbed dose to the thyroid. The Committee had acknowledged in the UNSCEAR 2013 Report that its estimates of doses from ingestion had been likely overestimates. The Committee has made more realistic estimates of doses from the ingestion of food and drinking water in this report, in the light of the information that has become available from a wide range of sources about intakes of radionuclides by members of the public (see appendix A for further information).

161. Within Fukushima Prefecture, the municipalities with high ground deposition density (of Fukushima City, Nihonmatsu City, Date City, Koriyama City, Koori Town and Otama Village, see figure XIV) had the highest estimated average effective doses to individuals who were not evacuated, with the municipality-average effective doses to infants in the range of 3.6 to 5.3 mSv in the first year. Average effective doses in the first year for adults were estimated to be about 70% of those for infants. The 5th and 95th percentiles of the distribution of individual doses in each municipality are up to about two times lower and higher, respectively, than the estimated average doses.

162. For the municipalities of the Group 3 prefectures (Ibaraki, Miyagi, Tochigi and Yamagata), the municipality-average effective doses to adults were in the range of 0.1 to 0.9 mSv for the first year, with the dominant contribution again being from external exposure to deposited radionuclides. The prefecture-average effective doses to adults for the prefectures in the remainder of Japan were in the range of 0.004 to 0.4 mSv, with external exposure to deposited radionuclides being the dominant pathway.

163. Figure XV shows a map of the estimated prefecture-average effective dose in the first year for infants in Japan, with municipality-average effective dose also shown for Fukushima Prefecture as an inset. 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 doses due to natural sources of radiation.

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[26] The radioiodines included in the dose estimates comprise ^{131}I, $^{132}Te/^{132}I$ and ^{133}I. Of the total absorbed doses to the thyroid from inhalation of radioiodines, ^{131}I has been estimated to contribute about two-thirds or more (see attachment A-10 for further details).

[27] It is also in contrast to the Chernobyl accident where doses from ingestion made a more significant contribution. This is due to many differences between the Chernobyl accident and that at FDNPS, including the time of year the accidental releases occurred (early spring for Fukushima; late spring for Chernobyl), differences in soil composition, the food restrictions imposed and the level of dependence of the local population on local food.

Figure XIV. Estimated municipality-average effective doses in the first year following the accident to infants living in each municipality of Fukushima Prefecture apart from those evacuated

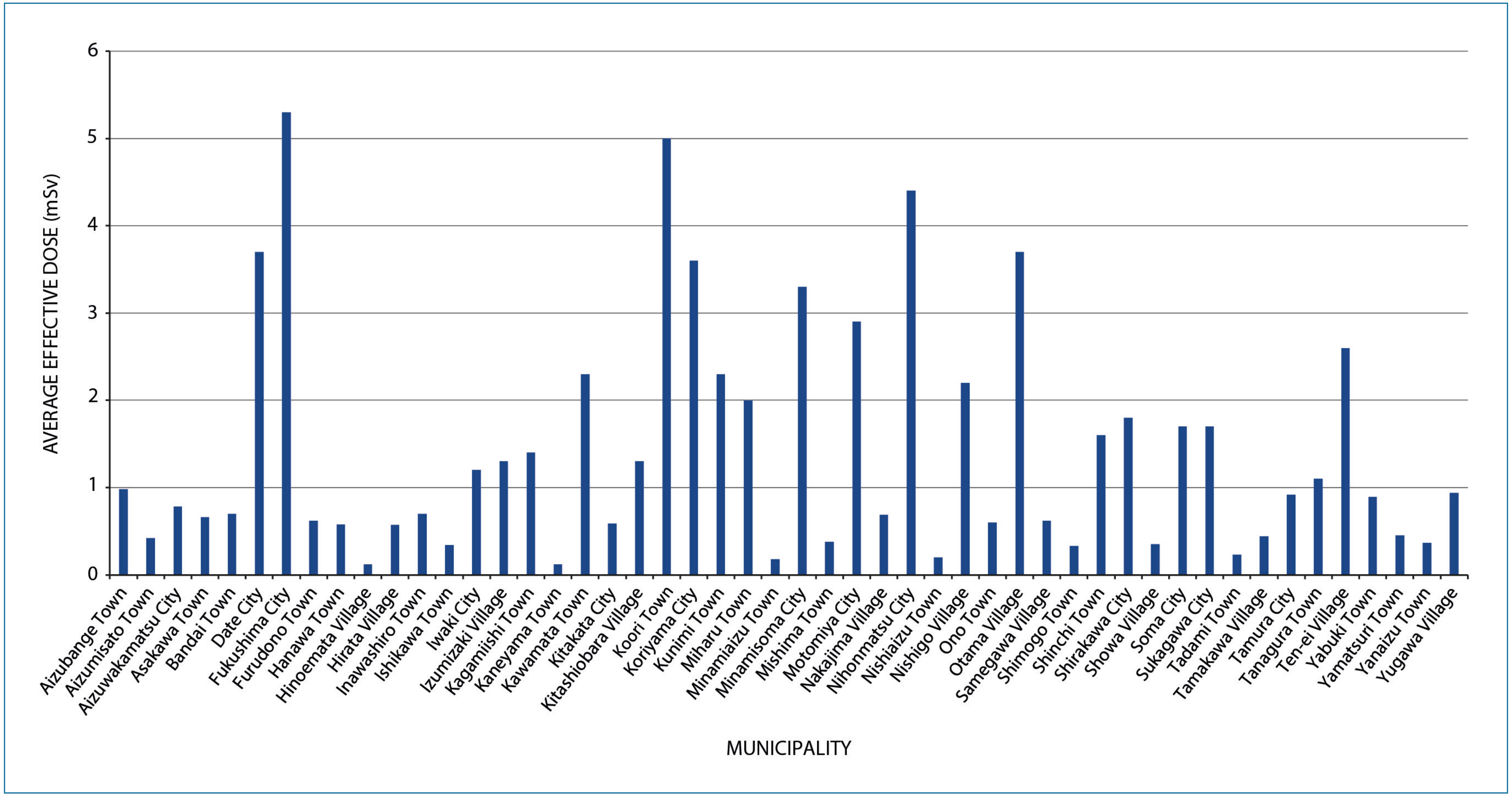
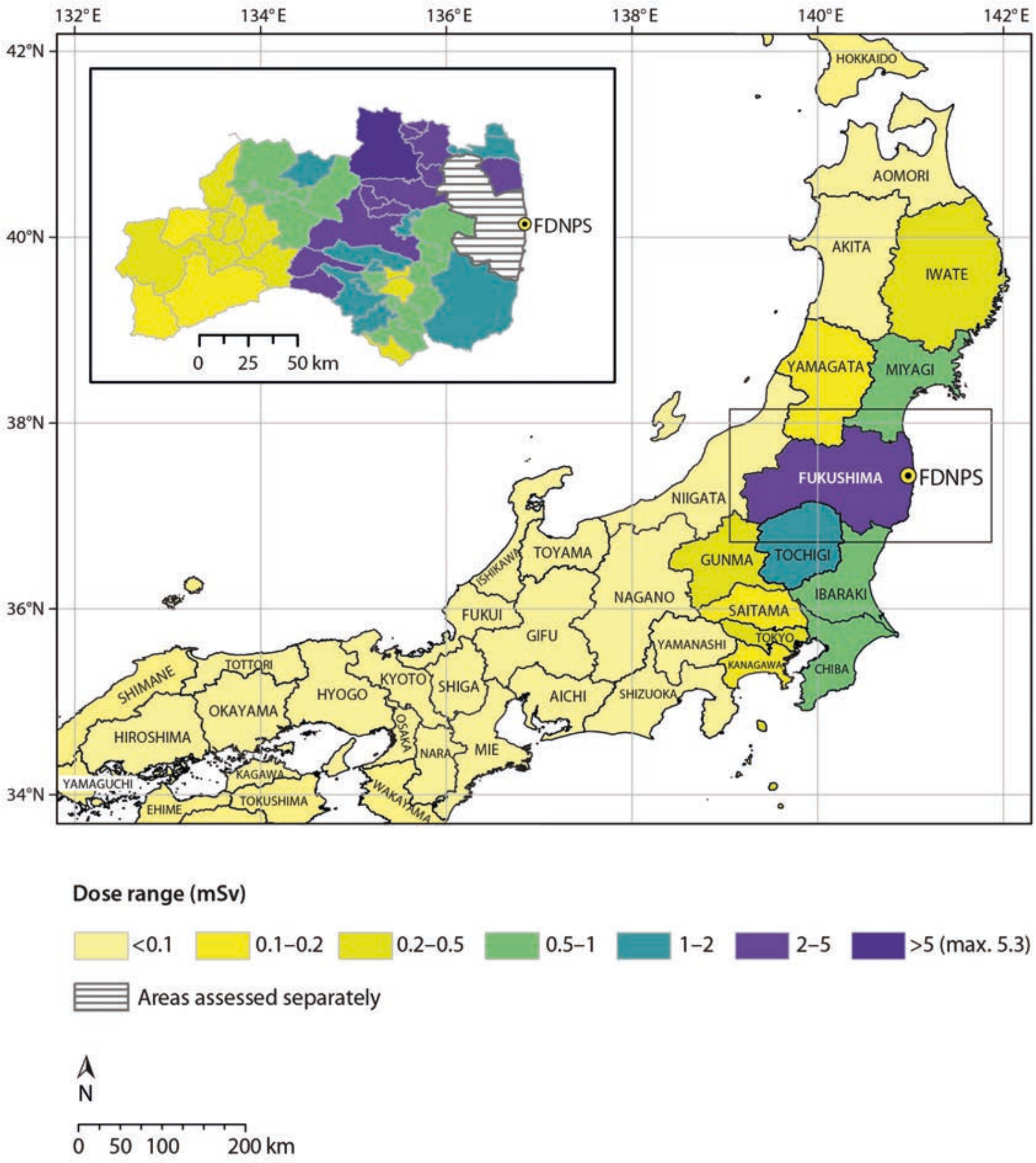


Figure XV. Estimated prefecture-average effective doses in the first year following the accident to infants

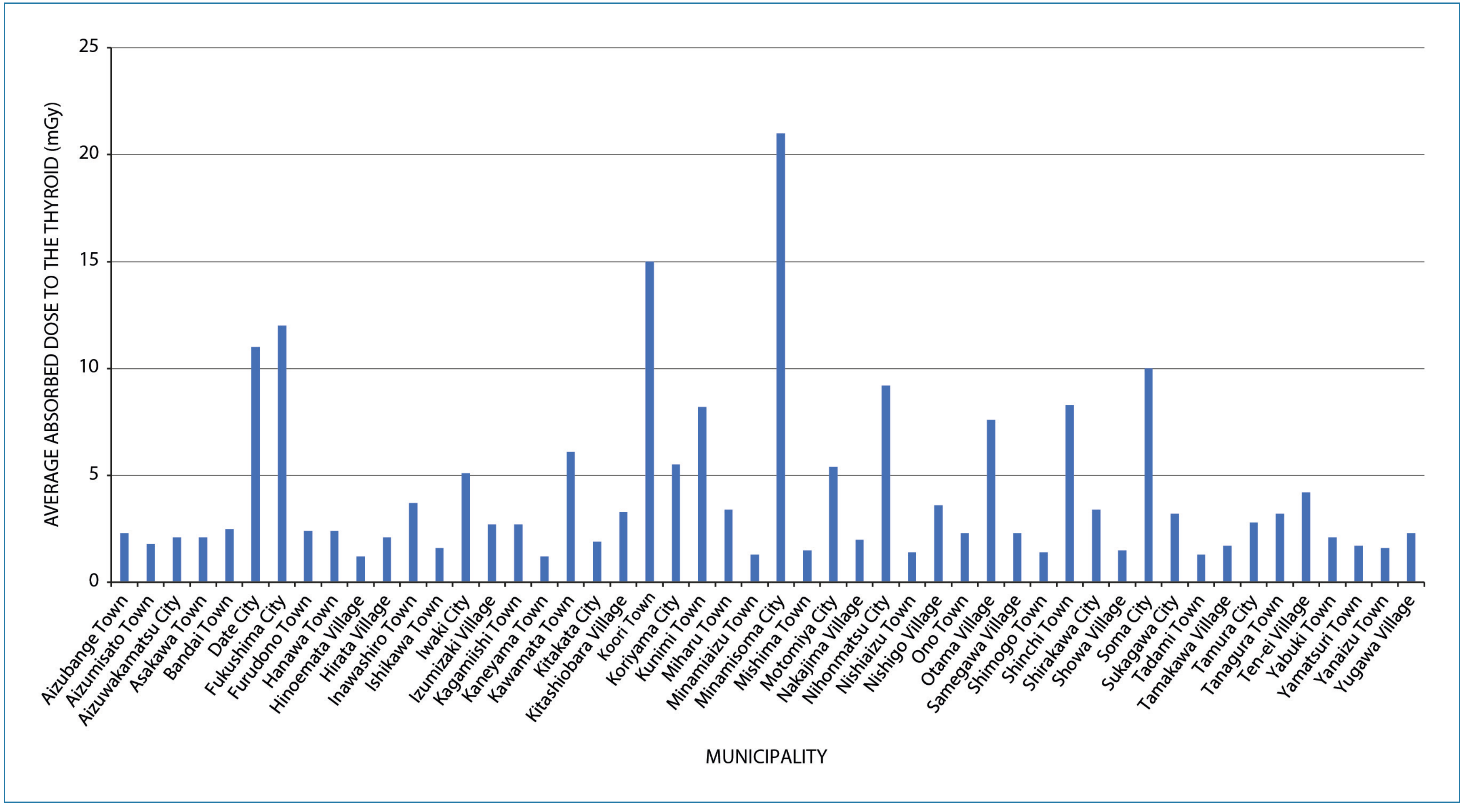
The main map shows the prefecture-average effective doses. The average dose for Fukushima Prefecture includes only locations that were not evacuated. The inset map shows the municipality-average doses for the Group 2[a] municipalities of Fukushima Prefecture



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

[a] Group 2 includes all municipalities or parts of municipalities of Fukushima Prefecture that were not evacuated.

Figure XVI. Estimated municipality-average absorbed doses to the thyroid in the first year following the accident to infants living in each municipality of Fukushima Prefecture apart from those evacuated



164. Figure XVI shows the estimated municipality-average absorbed dose to the thyroid in the first year for infants residing in the municipalities of Fukushima Prefecture that were not evacuated (Group 2). The highest absorbed doses to the thyroid in the first year were to individuals living in the municipalities of Minamisoma City, Date City, Fukushima City, Soma City and Koori Town. The highest municipality-average absorbed dose to the thyroid in the first year was estimated to have been about 21 mGy for infants living in the municipality of Minamisoma City. More than 80% of this dose was due to inhalation, more than 10% was due to external exposure to deposited radionuclides, and about 5% was due to ingestion. The estimated absorbed doses to the thyroid in the first year for adults and children living in the municipality of Minamisoma City were about 60% and 85%, respectively, of those for infants. Estimates of the average absorbed doses to other organs can be found in appendix A. The 5th and 95th percentiles of the distribution of individual absorbed doses to the thyroid are generally about 2 to 3 times lower and 2 to 3 times higher than the estimated average doses, respectively, although they can be more than four times lower and higher respectively, in municipalities where internal exposure from inhalation of radionuclides has been estimated to make the largest contribution to the total dose.

165. For Group 3 prefectures (Ibaraki, Miyagi, Tochigi and Yamagata), the municipality-average absorbed doses to the thyroid of infants in the first year were estimated to be in the range of 1 to 6 mGy, with the dominant exposure pathway again being inhalation. For the remainder of the 42 prefectures of Japan, the prefecture-average absorbed doses in the thyroid of infants were estimated up to about 1 mGy, with the dose from ingestion and from external exposure to deposited radionuclides making comparatively larger contributions (about 40% each) to the total than that from inhalation.

(b) *Average doses to evacuees in the first year*

166. Doses in the first year to people evacuated from Group 1 municipalities (Futaba Town, Hirono Town, Namie Town, Naraha Town, Okuma Town, Tomioka Town, Iitate Village, Kawamata Town, Minamisoma City, Tamura City, Kawauchi Town and Katsurao Village) 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 ranges of average effective doses and absorbed doses to the thyroid for different groups of evacuees are summarized in table 9.

167. The estimated average effective doses to adults in the first year for the different evacuation groups ranged from less than 0.05 mSv to about 6 mSv. The 5th and 95th percentiles of the distributions of individual effective doses are generally two to three times lower and higher, respectively, than the average effective doses. The corresponding average absorbed doses to the thyroid in the first year ranged from less than 1 mGy to about 15 mGy for adults and between about 2 mGy to about 30 mGy for infants. The 5th and 95th percentiles of the distributions of absorbed doses to the thyroid are between about two and four times lower and about two to three times higher, respectively, than the average doses. The Committee estimated that the evacuation of municipalities averted effective doses to adults of up to about 40 mSv and absorbed doses to the thyroid of infants of up to about 500 mGy (see tables A12 and A13 of appendix A).

Table 9. Estimated ranges of average effective doses and absorbed doses to the thyroid for groups of 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 average doses for groups of evacuees represented by the different evacuation scenarios. These estimates were intended to be characteristic of the average dose received by people evacuated from each municipality and do not reflect the range of doses received by individuals among the population of the evacuated municipality

Age group[a]	*Before and during evacuation*	*At the evacuation destination*	*First year total*
	RANGE OF EFFECTIVE DOSE (mSv)		
Adult	0.027–3.6	0.005–2.7	0.046–5.5
10-year-old	0.058–4.3	0.006–3.2	0.10–6.5
1-year-old	0.079–5.2	0.005–3.8	0.15–7.8
	RANGE OF ABSORBED DOSE TO THE THYROID (mGy)		
Adult	0.39–15	0.034–3.2	0.79–15
10-year-old	0.65–21	0.072–4.1	1.6–22
1-year-old	0.78–30	0.087–4.7	2.2–30

[a] Detailed estimates are not tabulated for doses to the fetus, but can be found in attachment A-18. Ranges of the average fetal absorbed dose to the thyroid over the 30-week development period of the fetus are about 70% to 80% of the tabulated total adult thyroid doses.

(c) *Doses over longer time periods*

168. The Committee also estimated municipality-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 10 for residents. Compared with the equivalent table 7 in the UNSCEAR 2013 Report [U10], the average effective doses accumulated over the first 10 years and up to the age of 80 years at the upper end of the ranges are generally within a few tens of per cent of those estimated in the UNSCEAR 2013 Report (although the differences for the Group 4 prefectures are larger due to the different prefecture groupings used in this report). At the lower end of the ranges, they are up to ten or twenty times lower. The 95th percentiles of the distributions of effective doses over a lifetime are generally less than a factor of two greater than the average doses. The more realistic estimates of doses from ingestion made in this report and the different model used to estimate doses from external exposure to deposited radionuclides are largely responsible for these differences. The differences between the estimates made in this report and those made in the UNSCEAR 2013 Report are explored further in appendix A. External exposure from deposited radionuclides is generally by far the most important exposure pathway for effective dose over the longer-term.

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

Age group in March 2011	*Ranges of municipality- or prefecture-average effective dose[a] (mSv)*		
	Group 2[b] – Fukushima Prefecture	*Group 3[c] – neighbouring prefectures*	*Group 4[d] – rest of Japan*
1-YEAR EXPOSURE			
Adult	0.079–3.8	0.10–0.92	0.004–0.36
10-year-old	0.10–4.5	0.13–1.1	0.005–0.43
1-year-old	0.12–5.3	0.15–1.3	0.005–0.51
10-YEAR EXPOSURE			
Adult	0.16–11	0.25–2.5	0.009–1.0
10-year-old	0.19–12	0.30–2.9	0.008–1.2
1-year-old	0.22–14	0.34–3.4	0.007–1.3
LIFETIME EXPOSURE TO AGE 80 YEARS[e]			
Adult	0.22–15	0.32–3.6	0.010–1.4
10-year-old	0.24–17	0.38–4.0	0.009–1.6
1-year-old	0.27–19	0.43–4.5	0.008–1.8

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

[b] Group 2 includes all municipalities or parts of municipalities of Fukushima Prefecture that were not evacuated municipalities.

[c] Members of the public living in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata.

[d] Members of the public living in the remaining 42 prefectures of Japan. This group now includes the prefectures of Chiba, Gunma, and Iwate, which were included in Group 3 in the UNSCEAR 2013 Report [U10].

[e] For adults, this is the dose from age 20 years at the time of the accident up to age 80 years.

169. Generally, the municipality-average or prefecture-average effective doses that would be incurred over the first 10 years were estimated to be between about two and three times the doses in the first year, and the lifetime doses were up to about a factor of four times higher. These increases over time are larger than estimated in the UNSCEAR 2013 Report [U10] and are the result of the dose rate from deposited material observed in Japanese conditions declining more slowly over time than in the model used in the UNSCEAR 2013 Report (M2013). Most of the absorbed dose to the thyroids of residents of Japan was received during the first year from inhalation of radioiodine. The absorbed dose to the thyroid up to age 80 years is estimated to be about twice that received in the first year, largely due to continued exposure from the longer-lived radioisotopes of caesium (from external radiation from deposited radionuclides and intake by ingestion). These dose estimates do not take account of the effects of remediation work carried out in the ICSA; this remediation work may have reduced doses in the ICSA from external exposure to deposited radionuclides by about an additional 10–20% following completion of the work (see appendix A and attachment A-1), and the overall effect on the estimates of doses in table 10 (and in table 11) would have been small in comparison with the uncertainties in these dose estimates.

(d) *Estimates of current levels of exposure*

170. To provide an indication of the current levels of exposure resulting from the accident, the Committee has estimated annual effective doses in 2021 in the non-evacuated municipalities of Fukushima Prefecture (Group 2), the Group 3 prefectures and the remaining prefectures in Japan (Group 4) and these are summarized in table 11. The estimated average annual effective doses are all less than 0.5 mSv in Fukushima Prefecture (Group 2) and below 0.1 mSv elsewhere in Japan. The 5th and 95th percentiles of the distributions of individual doses are about two to three times lower and two times higher than the average doses, respectively. External exposure to deposited radionuclides generally accounts for more than 95% of the total dose. Figure XVII shows the estimated average annual effective dose to infants in 2021 by municipality for Fukushima Prefecture and parts of the Group 3 neighbouring prefectures. In contrast to table 11 (which considers only the municipalities in Fukushima Prefecture that were not evacuated), the figure also includes the municipalities in Fukushima Prefecture that were evacuated (apart from the "Areas where Returning is Difficult"), assuming that residents have returned, and takes account of remediation, but only in the SDA (see below).

Table 11. Ranges of estimated municipality- or prefecture-average effective doses to adults, children and infants in the year 2021

Geographical area	*Ranges of municipality- or prefecture-average annual effective dose[a] (mSv)*		
	Adult	*10-year-old*	*1-year-old*
Group 2[b] – Fukushima Prefecture	0.004–0.31	0.004–0.36	0.004–0.42
Group 3[c] – neighbouring prefectures	0.005–0.070	0.006–0.082	0.006–0.097
Group 4[d] – rest of Japan	<0.001–0.028	<0.001–0.033	<0.001–0.039

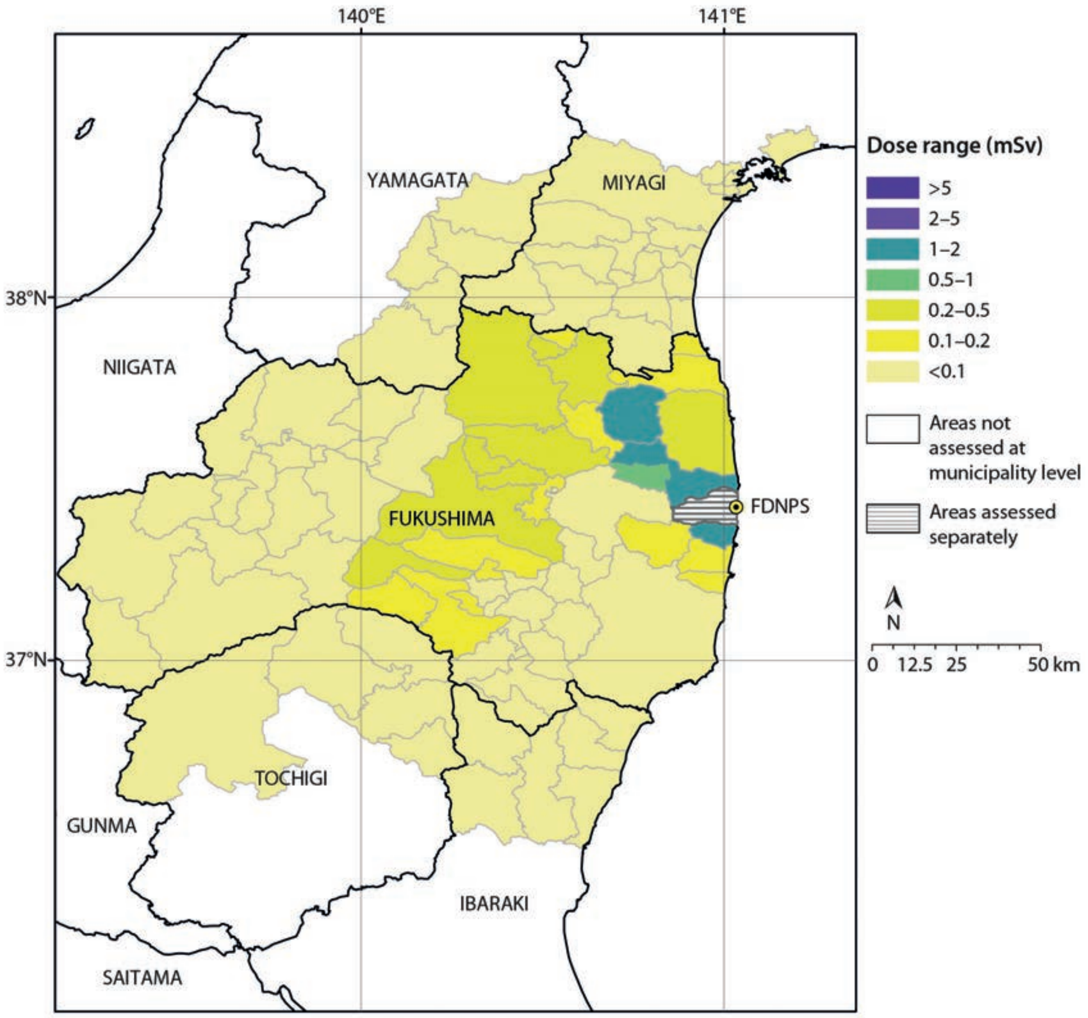
[a] The reported doses are ranges of the municipality-averaged doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates of dose are representative of the average doses received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations. The doses are in addition to doses from natural background radiation and other sources of exposure and are for the people in the specified age groups in 2021. The adult doses are for indoor workers as representative of adults as a whole.

[b] Municipalities of Fukushima Prefecture that were not evacuated.

[c] Members of the public living in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata.

[d] Members of the public living in the remaining prefectures of Japan.

Figure XVII. The average annual effective dose in 2021 for infants living in municipalities of Fukushima Prefecture[a] and some municipalities of Group 3 prefectures



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

[a] Includes municipalities that were evacuated (with the exception of the "Areas where Returning is Difficult"), assuming people have returned to their homes, and assuming a dose reduction factor of 1.3 for remediation in the SDA.

171. Estimates of the effective doses due to external exposure that would be received by evacuees if they were to return to their homes are summarized in table 12 and discussed in more detail in appendix A. The dose estimates include a dose reduction factor of 1.3 to take account of the remedial actions that have been completed in the SDA (see appendix A and attachment A-1 for further details).

Table 12. Estimated ranges of average effective doses from external exposure to adults and infants (as of 2011) annually up to 2021 and up to age 80 years if they were to return to the municipalities from which they were evacuated

Age group	*Ranges of annual effective dose and effective dose up to age 80 years from external exposure (mSv)[a]*			
	2019	*2020*	*2021*	*Lifetime*
Adult	0.050–1.2	0.040–1.1	0.040–0.99	0.69–18
1-year-old	0.050–1.5	0.050–1.4	0.050–1.2	0.69–19

[a] Excluding municipalities containing "Areas where Returning is Difficult".

(e) *Collective doses*

172. 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.[28] 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[29] are given in table 13. These time periods were chosen for comparison with the UNSCEAR 2013 Report [U10] and to indicate the annual collective dose and to illustrate the temporal accumulation of the collective dose commitment. The main contributor to the collective effective dose was external exposure from radionuclides deposited on the ground. The main contributor to the collective absorbed dose to the thyroid in the first year was internal exposure due to inhalation and ingestion of radioiodine. Compared to the Committee's estimate in 2013 (table 8 of the UNSCEAR 2013 Report) the collective effective dose is slightly lower, while the collective absorbed dose to the thyroid is reduced by a factor of two. The estimates of the collective doses to the population of Japan can be compared with estimates for populations of European countries exposed to radiation following the 1986 Chernobyl accident (see appendix B). 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, and the collective absorbed dose to the thyroid is approximately 3% of that due to the Chernobyl accident. For further perspective, the annual collective effective dose to the population of Japan from natural background radiation can be estimated to be about 280,000 man Sv[30] (about 20 times the collective effective dose in the first year after the FDNPS accident).

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[28] The Committee has used the quantity, collective (effective) dose, for many years to compare the radiation exposures of populations from different sources of ionizing radiation, or following different protection measures. The collective (effective) dose is always estimated for a defined population over a specified period of time. It is the product of the mean effective dose to a specified population from a particular source, and the number of people in that population, integrated over a defined period of time. Importantly, calculated doses are recommended only for comparative purposes and not for estimations related to health effects. Collective dose is not intended as a tool for epidemiological risk assessment. Moreover, the aggregation of very low individual doses over extended time periods is inappropriate for use in risk projections and, in particular, the calculation of numbers of cancer deaths from collective doses based on individual doses that are well within the variation in background exposure should be avoided.
[29] In this report, the Committee has used the terms "collective effective dose" and "collective absorbed dose to the thyroid" and described them as being for different time periods. This follows the approach used in the UNSCEAR 2013 Report. Strictly, the correct terms are "collective effective dose commitment" and "collective absorbed dose commitment to the thyroid" (for the time-integrated quantity), and the descriptions should make clear that the dose commitment (time-integrated) has been truncated at the different time periods. The Committee has retained the same terms as used in the UNSCEAR 2013 Report for ease of comparison with that report and for simplicity, while recognizing that it is not strictly correct.
[30] Based on a population of 128 million and an average annual effective dose from natural radiation of 2.2 mSv [O21].

Table 13. Collective effective doses and absorbed doses to the thyroid for the population of Japan (128 million in 2010)

Dose category	*Exposure duration*		
	First year	*10 years*	*Lifetime*[a] *(up to age 80 years)*
Collective effective dose (thousand man Sv)	12	32	44
Collective absorbed dose to the thyroid (thousand man Gy)	24	44	57

[a] The collective dose over a lifetime (up to age 80 years) represents more than 97% of the collective dose commitment in each case.

(f) *Estimation of doses in countries neighbouring, or in close proximity to, Japan*

173. The Committee's assessment of doses to the public in countries neighbouring, or in relatively close proximity, to Japan has been based on the assessment in the UNSCEAR 2013 Report [U10] and a review of more recent estimates published in the peer reviewed literature. The Committee confirmed its conclusion that the effective doses and the equivalent doses to the thyroid for people living outside of Japan were less than 0.01 mSv in the first year following the accident (see appendix A, chapter IV, section E).

2. Distributions of doses to individuals

174. The Committee's estimates of municipality- and prefecture-average doses set out above are intended to be characteristic of the average doses received by people living in each municipality or prefecture. The ranges of doses indicated reflect how the average doses for a particular age at exposure vary between municipalities or between prefectures rather than the range of doses received by individuals within a given municipality or prefecture.

175. The Committee has, in addition, made estimates of the distributions of individual doses in each municipality and prefecture taking account of numerous factors that may influence how doses may vary between individuals (e.g., concentrations of radionuclides in air and on the ground where they live and work, their diet, lifestyle (e.g., fraction of the time spent indoors/outdoors), shielding provided by buildings where they live and work, etc.). These distributions are presented in attachment A-21, and attachment A-12 provides further details of how these distributions were derived. The Committee has provided estimates of the 5th and 95th percentiles of these distributions of doses in the relevant population to accompany the estimates of the average doses.

176. Distributions of individual doses (both effective dose and absorbed dose to the thyroid) in the first year and up to age 80 for some example municipalities within Fukushima Prefecture and for the prefecture as a whole are provided in appendix A, section IV.F. The distribution for the effective dose in the population of Fukushima Prefecture (excluding evacuees) in the first year is shown in figure XVIII, as an example. This shows that most individuals received doses within a range from about 10 times lower to 3 times higher than the prefecture-average dose (of about 2 mSv). The distribution shows a double peak, which is likely to be a consequence of the dominance of the pathway of external exposure to deposited material and the different deposition densities of released radionuclides in areas where most people in Fukushima Prefecture live. As a further example, the distribution of the absorbed dose to the thyroid in the population of

Fukushima City in the first year is shown in figure XIX. This shows a similar pattern, but with a narrower range, with most individuals receiving absorbed doses to the thyroid within a range of about three times lower than the average and two times higher than the average dose of about 9 mGy.

Figure XVIII. Distribution of effective dose in the first year in the population of Fukushima Prefecture (of 2 million people)

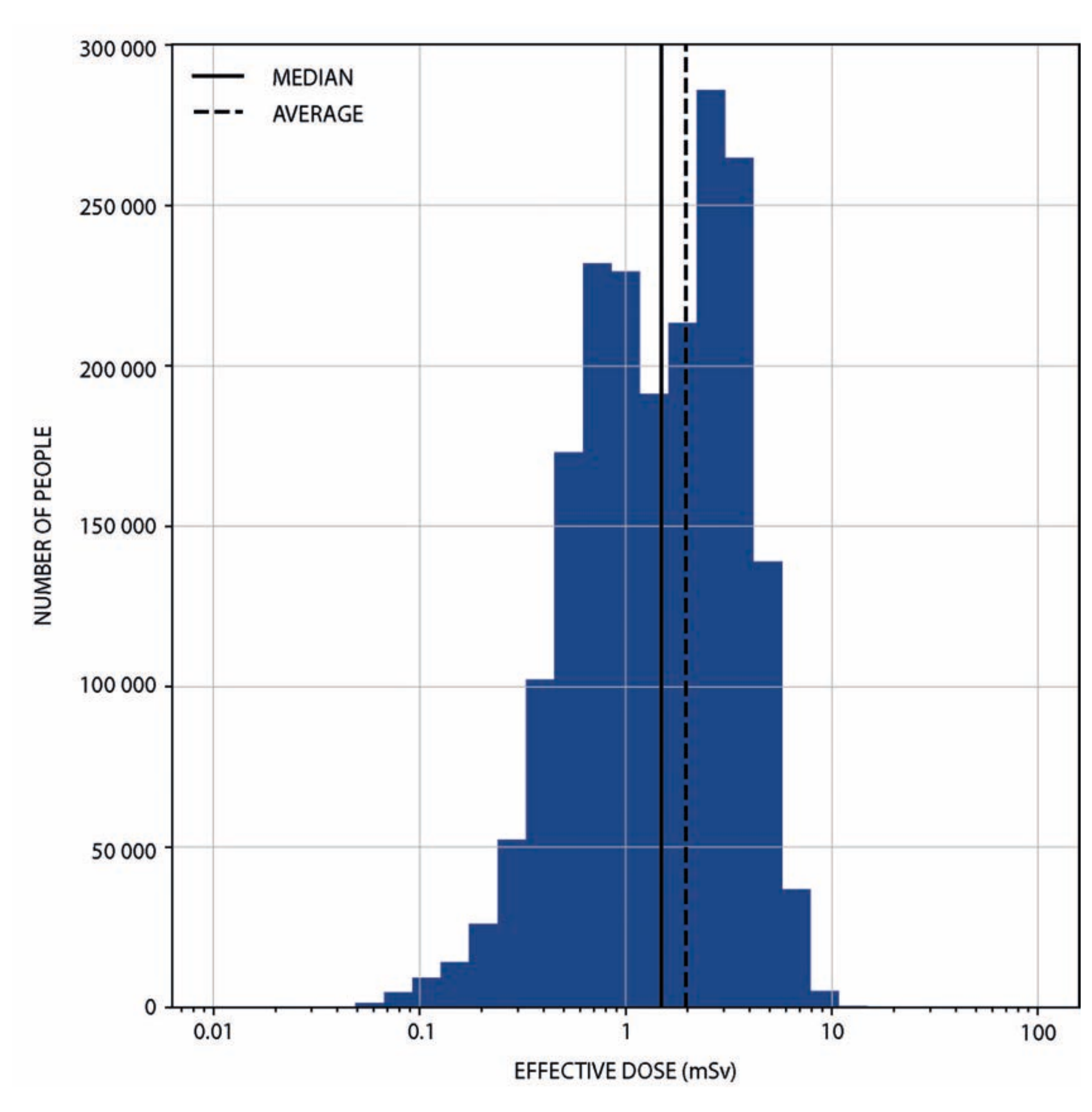
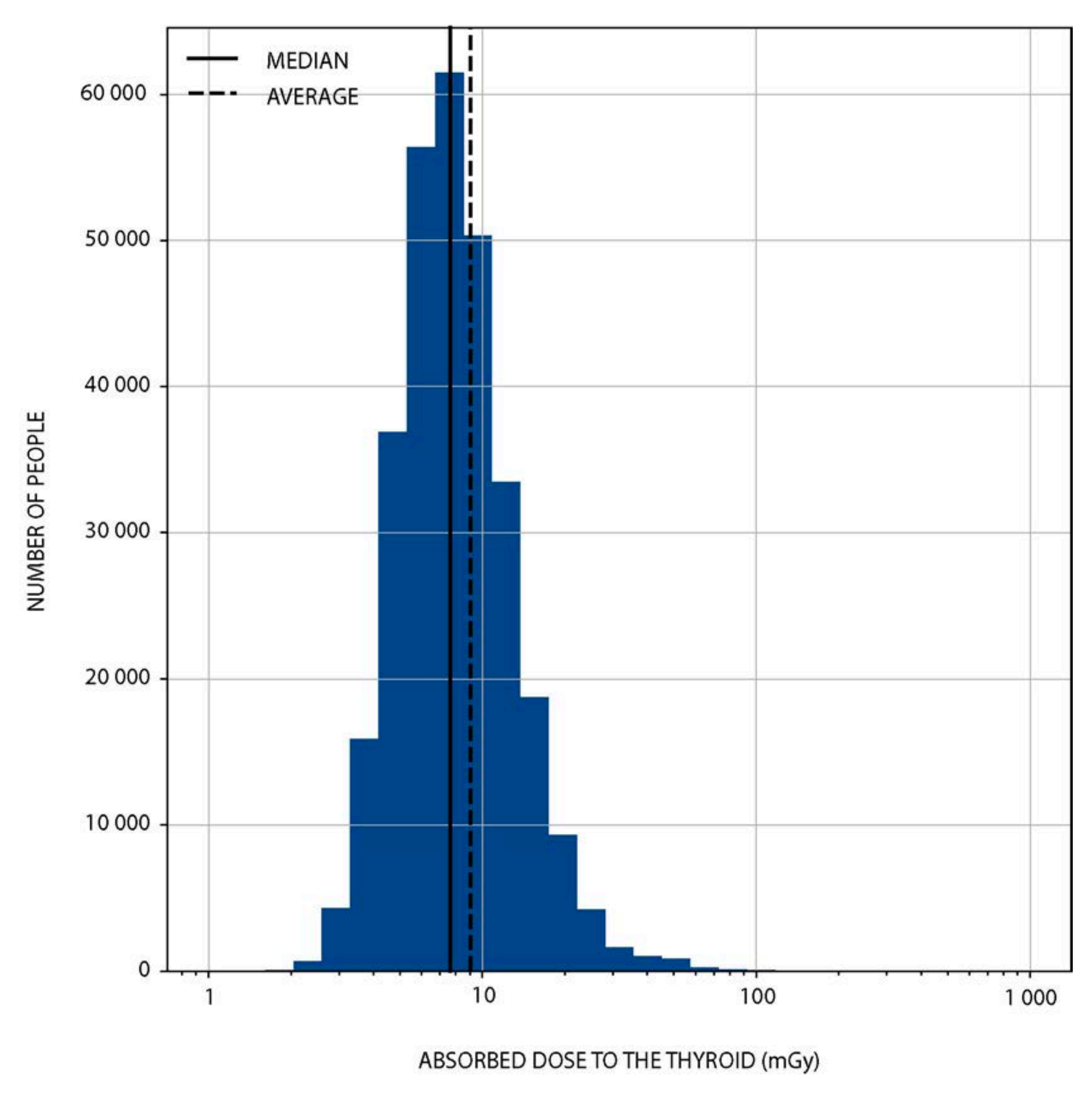


Figure XIX. Distribution of absorbed dose to the thyroid in the first year in the population of Fukushima City (of 296,000 people)



F. Summary

177. In the UNSCEAR 2013 Report [U10], the Committee's aim had been to make realistic estimates of doses. However, because of the lack of information in some areas, conservative assumptions were sometimes made, most, if not all, of which were recognized at the time and acknowledged in the report. The assumptions made in the estimation of doses from ingestion of foodstuffs in the first year were among the more significant of these.

178. In this report, the Committee has been able to make more realistic assumptions because of the availability of much more information since the UNSCEAR 2013 Report [U10]. This information included: *(a)* improved estimates of the temporal pattern of release of radionuclides from FDNPS and of their dispersion in the atmosphere and deposition on to the ground or over the ocean; *(b)* more extensive

measurements of the radionuclides in the environment, for example, in air, on the ground, in foodstuffs and drinking water; *(c)* measurements of radionuclides in people, in particular, their thyroids and whole-body; *(d)* extensive personal dosimetry campaigns in a number of municipalities to measure external doses for people with different habits; and *(e)* various assessments, published in the peer reviewed literature by Japanese and other researchers, of doses to people from one or other exposure pathway.

179. In updating its dose assessment, the Committee has chosen to rely, to the extent possible, on measurements of radiation or radioactive material in people and/or the environment. In some cases, such measurements have been used, almost directly, as the basis of the dose estimates in this report; in others, the measurements have been used to validate models developed for the purposes of estimating doses to the wider population. The use of models (e.g., M2020) validated by local radiation measurements, including human measurements, has improved the reliability and reduced the uncertainty of the dose estimates.

180. The main changes and/or improvements in the approach adopted by the Committee and their implications are:

(a) An improved source term (based on the totality of measurements in the environment, correlated with the main events on the FDNPS site and taking account of the three chemical forms in which radioiodine was released) was used, together with improved ATDM, to estimate the concentrations of radionuclides in air for which only limited measurements were available; this resulted in a different spatial and temporal pattern of concentrations of radionuclides in air, with increases in air concentrations (and doses) at some location and decreases at others;

(b) A new empirical and validated model was developed to estimate external doses from radionuclides deposited on the ground based on extensive measurements of the variation of dose rate with time in Japanese conditions (e.g., soil types, climate); this generally resulted in an increase in estimated external doses, typically by several tens of per cent, compared with the UNSCEAR 2013 Report [U10], and a slower decrease in the dose rates with time;

(c) A biokinetic model was developed, specific to the Japanese population, whose diet is generally iodine-rich, to make more realistic estimates of doses from intakes of radioiodine by inhalation or ingestion; this resulted in a decrease in the estimated thyroid doses by a factor of about two compared with the UNSCEAR 2013 Report;

(d) Greater realism was incorporated into the modelling of various factors used in estimating doses (e.g., air filtration when inside different types of buildings, habits and behaviours, etc.) to take account of Japanese specific information. By far the most significant change, compared with the UNSCEAR 2013 Report, was making an allowance for the filtration of air afforded by buildings; as a result, estimates of doses from the inhalation of radionuclides decreased by a factor of about two;

(e) Much more realistic estimates of doses from the ingestion of food and drinking water were made based on better information about what members of the public actually bought and consumed, including from duplicate-diet and market-basket studies. Over the longer-term, an empirical model was used, based on measurements over 45 years of radiocaesium in food products and the whole diet in Japan from fallout from atmospheric nuclear weapons testing. These changes have reduced the estimates of doses from ingestion of food and drinking water by at least a factor of ten compared with the UNSCEAR 2013 Report.

181. Taken together, the effect of these changes has been revised estimates of municipality- and prefecture-average doses at the upper end of the ranges that are up to a few tens of per cent lower compared with those presented in the UNSCEAR 2013 Report [U10] for effective doses in the first year,

and up to about a factor of two lower for thyroid doses in the first year. The effect of the changes on estimated effective doses over a lifetime is more complex because of several competing factors:

(a) For estimated average doses at the upper end of the ranges (where external exposure to deposited material is the dominant pathway), the differences are generally less than a few tens of per cent;

(b) Estimated average doses at the lower end of the ranges (where ingestion is a more important component) are up to an order of magnitude or more lower than in the UNSCEAR 2013 Report.

182. The much greater amount of information available has enabled the Committee to assess not only the municipality- and prefecture-average doses to members of the public, but also the distributions of doses among individuals within a municipality or prefecture (and 5th and 95th percentile bounds), taking account of uncertainties (such as measurement and modelling uncertainties) and major sources of variability. This includes the age distribution, varying levels of exposure within a municipality or prefecture, lifestyle (such as the amount of time spent indoors or outdoors), types of diet, and the filtering of the air and shielding afforded by different types of buildings. These distributions typically show that most individuals were estimated to have received doses within a range of about 10 times lower to a few times higher than the average dose, with many more people estimated to have received doses less than the average than doses greater than the average.

VI. ASSESSMENT OF DOSES TO WORKERS

A. Introduction

183. A few thousand occupationally-exposed workers were employed at the FDNPS site prior to the accident. Many more (in excess of 21,000 up to the end of 2012) were employed following the accident in recovery and related operations; the majority of these (almost 18,000) were employed by contractors of TEPCO [M22]. In addition, a few hundred workers from the emergency services, including firefighters, police, Japan Coast Guard and personnel of the Japan Self-Defense Force, were deployed on the site, and tens of thousands were engaged in emergency response activities off-site. Further tens of thousands of municipal workers and United States military personnel carried out environmental radiation measurements and other support activities in the areas evacuated.

184. 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. The “upper radiation exposure dose limit”[31] of 100 mSv was immediately applied for workers engaged in emergency works at FDNPS. This was increased to 250 mSv on 15 March 2011, and returned to its pre-existing value of 100 mSv, on 1 November 2011 for workers commencing work after that date, on 16 December 2011 for most other workers, and on 30 April 2012 for all remaining workers [M22, W1]. Initial capabilities for monitoring radiological conditions effectively were severely hampered [I35]. 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 were also lost when the tsunami flooded the electrical

[31] The English translation of the term used in the relevant Japanese legislation [M21].

distribution equipment [I35]. Emergency responders needed to share electronic personal dosimeters and to log their individual doses manually until the end of March 2011. For teams where personnel were thought to be working under similar conditions, only one worker in the team wore a dosimeter for many missions [I4].

185. TEPCO gradually improved on-site radiological monitoring [Y15]. From 1 April 2011, personal dosimeters were provided to every worker. Comprehensive radiation maps based on measured dose rates were used to optimize the protection of workers. A coordination centre was established 20 km to the south of FDNPS to manage and oversee radiation protection of all personnel entering the restricted area and the facility, including the provision of full-face respirators and protective clothing. Potassium iodide tablets were prescribed to selected workers from 13 March 2011 to 21 November 2011 in order to block radioiodine uptake to the thyroid. During this period, approximately 17,500 tablets were prescribed to 2,000 workers. Further information on the selection criteria for workers and the distribution of tablets is summarized by IAEA [I7].

186. To assess doses from internal exposure, on 22 March 2011, JAEA, at the request of TEPCO, started individual in vivo monitoring of workers who were responding to the emergency. These initial measurements were made with a simple mobile whole-body counter, which 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 JAEA facilities, and, where the assessed dose from internal exposure was in excess of 250 mSv, the worker was also monitored by NIRS. For most workers, the only radionuclides detected were ^{131}I, ^{134}Cs and ^{137}Cs and reported doses due to internal exposure only took account of intakes of these radionuclides. For some workers with higher effective doses, ^{136}Cs and ^{129m}Te were also detected, but the contribution to the assessed dose from internal exposure due to intakes of these radionuclides was small (less than 0.5%). Data on exposure to other short-lived radionuclides such as ^{132}Te, ^{132}I and ^{133}I were lacking. Wherever possible, effective doses and thyroid doses resulting from internal exposure were assessed from the results of in vivo measurements. Assessments of internal exposure for TEPCO workers were performed either by TEPCO or by NIRS, using quality-assured software tools.

B. Overview of current understanding

1. Doses to the Fukushima Daiichi Nuclear Power Station workers

187. The information available to the Committee on FDNPS worker exposures is drawn from the dose distribution data regularly published by the Japanese Ministry of Health, Labour and Welfare (MHLW) [M22]. These data provide information on the numbers of workers with assessed doses within specified ranges, in defined time periods. Distributions of effective dose from external and internal exposure were presented separately until April 2012. Subsequently, distributions were published for total effective dose. Distributions of thyroid equivalent doses among FDNPS workers for the period March–December 2011 were published separately by TEPCO [T25]. Additional information on doses due to internal and external exposure up to April 2012 for 21,776 workers was provided to the Committee. Only a limited amount of data for individual workers has been provided to the Committee, and this has always been anonymized.

188. The UNSCEAR 2013 Report [U10] summarized the doses received by occupationally-exposed workers in the period up to the end of October 2012. In this period, 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.

189. In the UNSCEAR 2013 Report [U10], the Committee carried out an assessment of the extent to which the individual doses to workers reported in Japan provided a reliable and accurate measure of the doses actually incurred, by reviewing the methodologies used in Japan and by making independent assessments of doses for small numbers of workers within defined groups.[32] TEPCO provided the Committee with detailed information on the types of personal dosimeter, technical standards and calibration methods used, and of the system used for allocating personal dosimeters to individuals, for monitoring external exposure. TEPCO, JAEA and NIRS provided the Committee with detailed information on the instruments, measurement systems, calibration phantoms and methodologies used for in vivo monitoring and assessing doses from internal exposure, together with monitoring data for selected workers. Further details on the approaches and methods used by the Committee can be found in the UNSCEAR 2013 Report. In that report, the Committee judged that the instrumentation, technical standards, calibration methods and other methodologies used to monitor and assess external exposures in Japan met generally-accepted requirements for individual monitoring during a radiation emergency. The major factor potentially affecting the reliability of external exposure assessments had been the sharing of electronic personal dosimeters during March 2011. The Committee judged the measurement systems, calibration phantoms, calibration and quality control data and software packages used to assess internal exposures to be appropriate for the types of dose assessments performed. Through its independent assessments of selected workers, the Committee confirmed the reliability of the assessments of internal exposure reported by TEPCO for those of its workers where ^{131}I in the body had been detected, but not for those of its workers for whom ^{131}I had not been detected in the body because of the delays in initiating monitoring. Due to discrepancies between the Committee's estimates of dose due to internal exposure in the UNSCEAR 2013 Report and those reported by contractors, the Committee could also not confirm the reliability of the internal exposure assessments reported by contractors for their workers [U10]. The reasons for these discrepancies have been discussed in detail in the UNSCEAR 2013 Report and subsequent publications [U10, Y16, Y19].

(a) *Effective doses*

190. As the Committee noted in its 2015 White Paper [U11], doses for a significant number of workers have been re-evaluated and revised since the UNSCEAR 2013 Report [U10, Y16, Y19]. The Committee considers the two re-evaluations to be well-designed and thorough and the revised dose estimates to be reliable given the shortcomings (outlined above) of some of the monitoring data that underlie them.

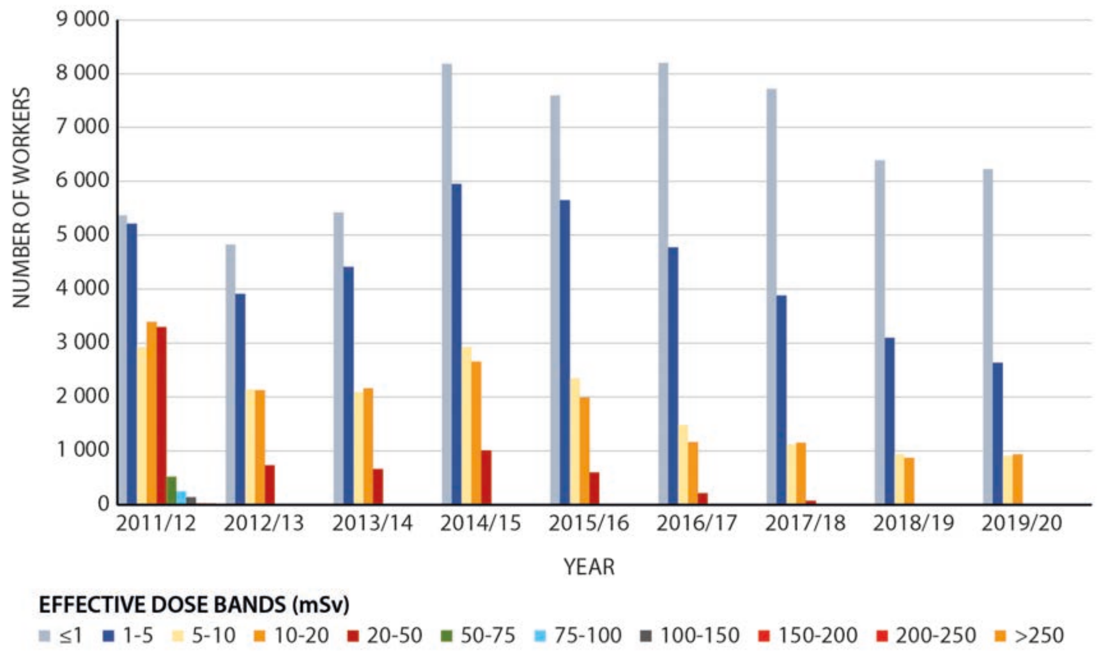
191. As well as reporting re-evaluated doses, TEPCO has continued to report regularly on distributions of annual effective doses among occupationally-exposed FDNPS workers, including those employed by TEPCO and by contractors.[33] Dose distributions up to 31 March 2020 are shown in figure XX with summary information in table 14 [M22]. These dose distributions reflect the dose re-evaluations carried out in 2013 and 2014. They are presented in years following the accident (to the end of March each year) [M22], although updates are available on a monthly basis.

[32] In the UNSCEAR 2013 Report [U10], the Committee carried out independent assessments of the doses due to internal exposure for 12 of the 13 workers with the highest reported internal exposures, for 42 randomly selected workers (21 TEPCO workers and 21 contractor workers) and for 13 workers from the emergency services.
[33] Including subcontractors.

192. The highest reported effective dose was 679 mSv[34] (see table 14) for the TEPCO worker who also received the highest reported committed effective dose due to internal exposure (590 mSv). Six workers (all employed by TEPCO) received effective doses from internal and external exposure greater than 250 mSv, and a further 168 workers (TEPCO and contractors) received effective doses from internal and external exposure in the range of 100 to 250 mSv [M22]. Of the six workers receiving total doses greater than 250 mSv, five were assessed to have received effective doses from internal exposure alone in excess of 250 mSv. Also, nine workers were assessed to have received effective doses from internal exposure alone between 100 and 250 mSv [Y16, Y19]. These doses are all cumulative doses for the period up to the end of March 2012.

193. Since April 2013, no individual annual effective dose has exceeded 50 mSv, and since April 2018, no individual annual effective dose has exceeded 20 mSv. The average effective dose (from both internal and external exposure) has fallen from about 13 mSv, in the period after the accident up to the end of March 2012, to an annual dose of 2.5 mSv in the year to the end of March 2020 [M22].

Figure XX. Dose distributions for Fukushima Daiichi Nuclear Power Station workers[a] since the accident



[a] Includes both TEPCO and contractors' workers.

[34] Doses, numbers of workers and other numerical values quoted from source publications are reported in this chapter to the number of significant figures given in the source of this information (e.g., [M22]) to avoid any confusion that may result from rounding to two significant figures. The number of significant figures used does not indicate the precision or uncertainty in the quoted figure.

Table 14. Maximum and average effective doses to Fukushima Daiichi Nuclear Power Station workers [M22][a]

Time period	*Maximum effective dose (mSv)*	*Average effective dose (mSv)*	*Number of workers*
March 2011–March 2012	679	13	21 135
April 2012–March 2013	54	5.7	13 742
April 2013–March 2014	42	5.3	14 746
April 2014–March 2015	40	5.0	20 730
April 2015–March 2016	43	4.3	18 196
April 2016–March 2017	39	2.9	15 835
April 2017–March 2018	33	2.7	13 943
April 2018–March 2019	20	2.4	11 306
April 2019–March 2020	20	2.5	10 708

[a] Includes both TEPCO and contractors' workers.

(b) *Thyroid doses*

194. Wherever possible, internal exposures of FDNPS workers were assessed from the results of in vivo measurements of radionuclide amounts in the body. Where ^{131}I was measurable in the thyroid, absorbed doses to the thyroid were assessed from the measurements; and where ^{131}I was not measurable in the thyroid, more indirect methods had to be used to estimate absorbed doses to the thyroid.[35] As reported by TEPCO for the period March–December 2011 [T25], 1,757 workers were assessed (by TEPCO, NIRS and/or contractors) to have received committed absorbed doses to the thyroid greater than 100 mGy. Thirteen TEPCO workers were estimated to have received committed absorbed doses to the thyroid of 2 Gy or more. In the UNSCEAR 2013 Report [U10], the Committee carried out independent dose assessments for 12 of these 13 workers and confirmed the dose assessments made by TEPCO.

195. A worker epidemiology study, the Nuclear Emergency Workers Study [J4, K24, M23, Y18], has been established in Japan to examine adverse health effects in a target group of approximately 20,000 FDNPS emergency workers. As part of this study, more sophisticated evaluations of individual doses of FDNPS workers are being carried out. The doses reported by TEPCO, and the standard methods defined by MHLW for assessing these doses, are based on a Reference Worker.[36] For the epidemiology study, doses to the participating individuals are being assessed, taking into account information and parameter values specific to each individual. In particular, for six of the workers with the highest thyroid doses, Kunishima et al. [K54] have created realistic mathematical models (known as voxel phantoms) of

[35] In estimating doses to the public, account has been taken of dose coefficients for intakes of radioiodine specific to the Japanese population to reflect the iodine-rich diet more typical in Japan (see chapter V). For many workers, absorbed doses to the thyroid have been estimated directly from measured levels of ^{131}I in the thyroid (and therefore already reflect actual uptake of radioiodine into the thyroid). For those workers where ^{131}I was not measurable (about 40% of the total, but those more likely to have received lower doses), one of two indirect methods had to be used to estimate absorbed doses to the thyroid. Where the "environmental ratio" method was used, the use of dose coefficients specific to the Japanese population could have led to some differences in the estimated doses. However, these differences would have been small compared with the large uncertainties associated with the use of the indirect methods.

[36] An idealized male or female worker with characteristics defined by ICRP for the purpose of radiological protection with defined anatomical and physiological characteristics [I15].

the neck and the thyroid gland from magnetic resonance imaging (MRI) and ultrasound scans carried out on the workers. Numerical simulations have then been carried out to determine:

(a) In vivo measurement calibration factors for ^{131}I in the thyroid;

(b) Committed[37] absorbed doses to the thyroid corresponding to a measurement of unit ^{131}I activity in the thyroid at a specified time after the intake.

The committed absorbed doses to the thyroid for the six workers resulting from this assessment (which is described as preliminary) are compared in table 15 with the assessments reported in the UNSCEAR 2013 Report [U10]. The absorbed doses to the thyroid assessed by Kunishima et al. [K54] for these six individuals show some significant differences from their reported doses: with one exception, the re-evaluated doses are higher, by between a few per cent and almost a factor of three. The differences are largely due to differences between the thyroid volumes of these individuals and the ICRP Publication 30 reference value of 19.9 cm^3 [C5], with all but one of the six workers having lower thyroid volumes, and proportionately lower thyroid masses compared with the reference value.

Table 15. Thyroid volumes, original thyroid dose estimates and re-evaluated thyroid dose estimates for six workers with the highest thyroid doses

Subject code		*Thyroid volume[a,c] (cm^3)*	*Thyroid absorbed dose[a] (Gy)*		*Ratio (B/A)*
Kunishima[a]	*UNSCEAR 2013 Report[b]*		*Original values (A)[d]*	*Re-evaluated values (B)*	
A	A	28.2	12	8.4	0.7
B	B	6.5	11	32	2.9
C	F	18.7	4.6	4.8	1.0
D	C	10.4	7.5	14	1.9
E	D	12.3	5.8	9.0	1.6
F	E	12.9	5.3	7.9	1.5
Arithmetic means		14.8	7.7	12.7	1.6

[a] From [K54], tables 1, 2 and 3.

[b] From the UNSCEAR 2013 Report [U10], inferred from information presented by Kunishima et al. [K54].

[c] To be compared with the ICRP Publication 30 reference value of 19.9 cm^3 [C5].

[d] Differences between these values and the NIRS values presented in table D12 of the UNSCEAR 2013 Report [U10] are minor.

196. The Committee considers that the reassessment of thyroid doses carried out by Kunishima et al. [K54] to be of high quality and that, where they are to be used for the purposes of epidemiology or health risk assessment, the assessed committed absorbed doses to the thyroid for these six workers should be revised accordingly. The largest assessed committed absorbed dose to the thyroid due to internal exposure from inhalation of ^{131}I is now 32 Gy.

197. The results of this reassessment raise the question of whether other workers are also likely to have generally lower thyroid volumes than assumed for a Reference Worker and have received correspondingly higher thyroid doses. There is, however, evidence that mean thyroid masses for defined groups of adults in Japan do not differ significantly from the standard reference values used in dosimetry.

[37] The committed dose is the dose received during a specified period after intake, usually 50 years for workers.

Kudo et al. [K47], for example, examined data from Japanese autopsy subjects in the age range of 19 to 52 years obtained between 2012 and 2016, and found a mean thyroid mass of 21.9 g, with standard deviation ± 11.3 g, for 2,204 males, and a mean of 17.8 g, with standard deviation ± 11.5 g, for 698 females. Although there is considerable variation, these mean values compare well with the most recent recommended reference values of 20 g for males and 17 g for females [I17]. Clearly, using parameter values, including thyroid mass or volume, that are specific to the individual, provides the best basis for assessing absorbed dose to the thyroid for any particular individual, but there is no evidence to suggest that using standard reference values for thyroid mass or volume is not appropriate for the Japanese population in general. The use of standard reference values in the assessment of absorbed doses to the thyroid for FDNPS workers as a whole therefore remains valid. Nevertheless, for workers whose individual thyroid absorbed dose is to be reassessed for the purposes of epidemiology or health risk assessment, measurement of thyroid volume, either by MRI or ultrasound scan, subject to appropriate ethical approval, would be beneficial, with the reassessment of absorbed dose to the thyroid then making use of the corresponding individual thyroid mass.

198. To assess the health implications of the estimated exposures of workers, the Committee has made estimates of the mean and the upper bound (or limit) of the 95% interval of the absorbed dose to the thyroid for the workers with assessed dose greater than 100 mGy. It has based the estimates on the published dose distributions of thyroid equivalent doses among FDNPS workers for the period March–December 2011 [T25]. The mean absorbed dose for these workers was approximately 370 mGy, with an upper bound of about 1 Gy. These values for mean and upper bound take into account the re-evaluated thyroid dose estimates presented in table 15.

(c) *Assessment of doses from short-lived radionuclides*

199. In vivo monitoring of FDNPS workers was started on 22 March 2011 and the results were used in the assessment of doses from internal exposure. However, the delay from the start of the accident meant that the shorter-lived radioisotopes that were likely to have been present, including ^{132}Te, ^{132}I, ^{133}I and ^{136}Cs, would not have been detectable. In its UNSCEAR 2013 Report [U10], the Committee had estimated the contribution from such short-lived radionuclides to be in the order of 20% relative to that from ^{131}I. In its review of the methods used in Japan, MHLW considered that the standard methods it subsequently prescribed were sufficient to account adequately for the contribution of the short-lived radionuclides ^{132}I and ^{132}Te [Y16]. It estimated the contribution from ^{132}Te to the committed effective dose to be approximately 10% of the contribution from ^{131}I, which is broadly consistent with the Committee’s estimate, given the uncertainties in both.

(d) *Biodosimetry assessments of Fukushima Daiichi Nuclear Power Station workers*

200. Dicentric chromosome assays were performed for 12 workers, for the purposes of medical triage and planning for the selected workers [S46, S47]. Estimated whole body absorbed doses of 10 of the individuals who had provided samples for dicentric chromosome assay were all less than 300 mGy (95% upper limit). Reasonable agreement was found with the results of personal dosimeter measurements for the eight individuals for whom these measurements were available, particularly at the higher assessed doses.

(e) *Assessment of doses to the eye lens of Fukushima Daiichi Nuclear Power Station workers*

201. In the UNSCEAR 2013 Report [U10], the Committee found insufficient information on the external exposure of workers to beta radiation to make an informed assessment of dose to the eye lens. In 2017, Yokoyama et al. [Y24] proposed that eye lens dose in the early stages of the accident could be equated to measured values of $H_p(10)$ (the personal dose equivalent at a depth of 10 mm in soft tissue) arising from exposure to gamma radiation. $H_p(10)$ is an operational quantity that generally provides a conservative estimate of effective dose from external exposure. Yokoyama et al. [Y25] subsequently reported annual distributions of eye lens doses of FDNPS workers determined by TEPCO using $H_p(0.07)$, the personal dose equivalent at a depth of 0.07 mm. For the time period March 2011 to the end of March 2012, a total of 77 workers were estimated to have received an equivalent dose to the eye lens of more than 100 mSv and 10 of these were estimated to have received more than 150 mSv, although none received more than 200 mSv [T26, Y25].

202. The highest doses would have been received in the early days after the accident in March 2011. Yokoyama et al. [Y24] state that, at that time, radiation exposure was mainly to gamma radiation and that the use of full-face masks was obligatory for almost all areas. In those circumstances, the dose to the eye lens from beta radiation would be a small fraction of total dose (from beta and gamma radiation) due to the shielding effect of the mask, and $H_p(10)$ would provide an adequate measure. However, it remains to be established whether full-face masks, which would have adequately limited beta irradiation of the eye lens, were actually used by workers who were exposed to high air concentrations of iodine radioisotopes emitting beta and gamma radiation during the early stages of the accident. If full-face masks were not worn, measurements of dose due to exposure to gamma radiation could underestimate the true dose to the lens of the eye. As pointed out by Kunishima et al. [K54], workers with the highest absorbed doses to the thyroid from inhalation of ^{131}I "… were in charge of operations at places with high radiation levels during the early phase of the accident, such as the main control rooms of the reactors, outside near the damaged reactor buildings. Some of the workers were not provided with masks having charcoal filters at the beginning and had to eat and drink at the main control rooms when air with high concentrations of radioiodine entered from outside." The magnitude of the assessed absorbed doses to the thyroid of those workers who received significant intakes of radioiodine during these early stages suggests that adequate respiratory protection (such as would have been provided by a full-face mask) was not always used, or not completely effective, during that period.

203. The worker epidemiology study [J4, K24, M23, Y18] includes plans for an evaluation of doses to the eye lens, but no results have yet been published. The Committee suggests that a possible approach to the assessment of the dose to the eye lens for the most exposed workers may be to estimate the dose to the eye lens (using $H_p(3)$ if feasible) that would result from immersion in airborne ^{131}I and associated shorter-lived radionuclides at concentrations that would give rise to the measured thyroid ^{131}I contents of these workers. Such an assessment would require information on material-specific factors including the physico-chemical form of the airborne material and individual-specific parameters including breathing rate, which ideally would be derived from information on exposure conditions in the workplace at the time.

2. Assessment of doses to other workers

204. The UNSCEAR 2013 Report [U10] also summarized reported doses to workers other than FDNPS workers. For the 260 firefighters who were deployed on-site, the maximum reported effective dose from external exposure was 29.8 mSv. The maximum committed effective dose from internal exposure for the

firefighters was less than 1 mSv. Of the Self-Defense Force personnel who were deployed on-site, 15 were reported to have received effective doses from external exposures in the range of 10 to 100 mSv, and the remainder (132 people) were reported to have received less than 10 mSv. For those deployed off-site, five were reported to have received effective doses from external exposures in the range of 10 to 20 mSv, with the remainder (8,453) reported to have received less than 10 mSv. A limited number of doses from internal exposure were reported; the maximum committed effective dose was 3.8 mSv for one on-site worker. For the 13 police officers who were deployed on-site, reported effective doses from external exposure and committed effective doses from internal exposure were less than 10 mSv and less than 0.1 mSv, respectively.

205. United States military personnel provided humanitarian assistance and disaster relief support to Japan. The United States Defense Threat Reduction Agency has reported doses for DoD personnel and affiliated people located at or near United States military facilities in Japan (comprising service members, civilian employees, family members of service members and civilian employees, and contractor employees). Doses were assessed for about half of 58,000 individuals who were shore-based [D9], the remainder being located away from the Japanese mainland in the Okinawa Prefecture. Exposures were assumed to have occurred during the 60-day period starting on 12 March 2011. Reported total effective doses to adults from external and internal exposure lay in the range of 0.01 to 1.2 mSv, while reported equivalent doses to the thyroid lay in the range of 0.07 to 12 mSv [D5]. These dose estimates were intended to be conservative, and a later probabilistic analysis showed that this was indeed the case, with the reported values lying above the 95th percentile of the probability distributions determined using realistic model parameter values [D6]. Most of the measurements of radionuclides in the body were below the minimum detectable level; for the remainder, the reported committed effective doses lay in the range of 0.02 to 0.25 mSv, while the reported committed equivalent doses to the thyroid lay in the range of 0.29 to 4.2 mSv [D8]. A separate assessment was made for the approximately 17,000 fleet-based (i.e., naval) personnel [D9]. Dose estimates were again intentionally conservative. Maximum values of effective dose and equivalent dose to the thyroid were estimated to be 0.35 and 3.4 mSv, respectively.

206. A number of studies have addressed the topic of exposures of the large number of workers (up to 40,000 at the peak in 2015) involved in off-site environmental remediation activities [K2, T12, T39]. Yasui [Y17] reported on the establishment in December 2013 of a central dose registration system, and presented results for the years 2012, 2013 and 2014, while Asano and Ito [A16] updated these results for the years 2015, 2016 and 2017. An MOE report [M39] utilized the same database to report dose statistics for the 76,951 workers who were involved in remediation activities during the period 1 January 2012 to 31 December 2016. Of these workers, 67% received cumulative doses in the 5-year period of 1 mSv or less, while 31%, 1.9%, 0.2% and 0.01% received doses in the ranges of 1 to 5 mSv, 5 to 10 mSv, 10 to 15 mSv and 15 to 20 mSv, respectively. No workers received a cumulative dose greater than 20 mSv. The average cumulative dose received was 1.0 mSv. These results confirm that doses to remediation workers were small.

207. Various studies have addressed the exposure of other types of workers employed in areas around the FDNPS site after the accident. Sakumi et al. [S5] found that, during 2013, 64 workers employed within the deliberate evacuation area received annual effective doses from occupational exposure in the range of 0.9 to 3.6 mSv. Matsuda et al. [M12] found that five members of a radiation emergency medical assistance team received effective doses in the range of 0.05 to 0.13 mSv during a 6-day period in March 2011, while Kodama et al. [K32] found that 101 employees at Minamisoma General Hospital had committed effective doses from radiocaesium intakes received up to August 2011 that were less than 1 mSv in all cases. Kim et al. [K18] assessed the exposure of workers involved in transportation of radioactive remediation waste and found that effective doses lay in the range of 0.27 to 1.1 mSv for a specified number of journeys made.

C. Summary

208. Although the reported doses to workers as a result of the FDNPS accident have been subject to some revision since the UNSCEAR 2013 Report [U10], the general findings of that report remain valid: the average effective dose of the 21,135 workers involved in mitigation and other activities at the FDNPS site from March 2011 to the end of March 2012 was about 13 mSv. About 36% of the workforce received total effective doses of more than 10 mSv over that period, while 0.8% received doses of more than 100 mSv. Annual effective doses have been considerably lower since April 2012, with average annual effective doses declining from about 6 mSv in the year to end of March 2013 to 2.5 mSv in the year to end of March 2020, and no individual receiving an annual effective dose of more than 50 mSv since the year to end of March 2013.

209. A recent re-evaluation of the absorbed doses to the thyroid of six workers who received the highest doses has revealed that their absorbed doses to the thyroid, estimated using individual-specific measurements of thyroid size, are with one exception higher than previously reported, in one case by almost a factor of three. The largest assessed committed absorbed dose to the thyroid due to internal exposure from inhalation of ^{131}I is now 32 Gy. However, there is no evidence to suggest that using standard reference values for thyroid mass or volume is not appropriate for the Japanese population in general, and the Committee believes that the absorbed doses to the thyroid reported in the UNSCEAR 2013 Report [U10] for the workers as a whole remain valid. For workers whose individual absorbed dose to the thyroid is to be reassessed for the purposes of epidemiology or health risk assessment, measurement of thyroid volume, either by MRI or ultrasound scan, subject to appropriate ethical approval, would be beneficial, with the reassessment then making use of the corresponding individual thyroid mass.

210. Some estimates of dose to the lens of the eye have become available, but they rely on assumptions about the wearing of full-face masks, when there is evidence that those workers who would have received the highest exposures of the eye lens may not have been wearing such equipment during the early stages of the accident. The Committee has suggested a possible approach to the assessment of the dose to the eye lens for these workers, based on measured ^{131}I content of the thyroid.

211. The delay in commencing monitoring of radioiodine in the thyroid of workers is potentially the source of the largest errors in the assessed doses to workers from internal exposure. Timely monitoring (e.g., WBC, thyroid measurements, personal dosimetry, etc.) of representative groups of workers at the earliest opportunity in the event of a similar incident in the future would greatly enhance the quality and informativeness of any assessment of doses made for the purpose of evaluating health risks to workers. If appropriate human measurements are not made in the immediate aftermath of an accident, doses to people can only be assessed using models together with other measurements that may be available. Experience has shown that the use of such models often leads to conservative estimates of doses.

VII. HEALTH IMPLICATIONS

A. Introduction

212. The UNSCEAR 2013 Report [U10] set out the Committee's assessment of the health implications of the FDNPS accident based on the estimates of the doses to the public and to workers made in that report, the health risk assessment carried out by the World Health Organization [W14] and the Committee's knowledge and understanding of the health effects of radiation exposure. The Committee summarized the state of understanding about the health effects associated with radiation exposure, including that health effects have traditionally been classified in two categories:

(a) Deterministic effects or tissue reactions, which occur after high doses of radiation normally delivered over a short period of time, and which occur above specific dose thresholds and, in most cases, shortly after exposure;

(b) Stochastic effects, which manifest as an increased incidence of disease in a population, with the incidence after irradiation tending to increase with increasing dose, but where it is not possible to distinguish by observation or testing whether or not the disease of a specific patient has been caused by the radiation exposure.

213. The Committee explained that, in estimating values of the risk of stochastic effects due to exposure for members of various exposed groups, it has used the term "discernible" for cases where the estimated risk of the disease was sufficiently large in a large enough population to be detectable, compared to the normal statistical variability in the baseline incidence of the disease in that population. Conversely, when risks may be inferred from existing knowledge (i.e., using models), but the level of the inferred risk is low and/or the number of people exposed is small, the Committee has used the phrase "no discernible increase" [38] 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 (that is, the attributable risk is too small compared to the baseline levels of risk to be detected). The Committee emphasized that its use of the term "no discernible increase" did not equate to an absence of risk or rule out the possibility of excess cases of disease due to irradiation, nor the possibility of detection of a biomarker for certain types of cancer in certain subgroups being identified in the future that could be associated with radiation exposure. Nor was it intended to disregard the suffering associated with any such cases should they occur.

214. In the UNSCEAR 2013 Report [U10], the Committee also noted that nuclear accidents of the magnitude of the FDNPS accident, and the associated protective measures, tend to lead to distress and anxiety from, among other things, disruption of life, loss of homes and livelihoods, and social stigma, which can have major impacts on psychological and social well-being [U10]. The Committee pointed out that evaluating such effects is not part of its mandate, although they are important for understanding the broader health implications of the accident. It also noted that the evacuation following the accident caused immediate aggravation of the condition of already vulnerable groups: for example, more than 50 hospitalized patients were reported to have died either during or soon after the evacuation [T22] and

[38] The Committee further elaborated that it had used the phrase "no discernible increase" where, although a disease risk in the longer term can be theoretically inferred on the basis of existing risk models, an increased incidence of effects is unlikely in practice to be observed in future disease statistics using currently available methods, because of a combination of the limited size of population exposed and low exposures, i.e., consequences that are small relative to the baseline risk and their uncertainties.

upwards of 100 elderly people may have died in subsequent months because of a variety of conditions linked to the evacuation [Y21].

B. Overview of current understanding

1. Health implications for the public

215. Based on its understanding of the exposures of the public as estimated in the UNSCEAR 2013 Report [U10], which fell well below the thresholds for deterministic effects, the Committee expected no deterministic tissue reactions, and noted that no acute health effects that could have been attributed to radiation exposure had been reported. No information has become available since the publication of the UNSCEAR 2013 Report, either on the understanding of the exposures of the public or on any reported acute health effects, that would alter the Committee's conclusions.

216. Based on its understanding of the exposure levels of the public as estimated in the UNSCEAR 2013 Report [U10], the Committee also estimated in that report that, compared to the baseline risk in the general Japanese population of total solid cancer, and cancers of nearly all specific anatomical sites, a general radiation-related increase in the incidence of such cancers would not be expected to be discernible [U18, W14]. However, the Committee noted, "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." (paragraph 172 of the UNSCEAR 2013 Report).

217. To address the discernibility of risks from its revised estimates of exposures of the public resulting from the FDNPS accident, the Committee has assessed the statistical power to detect excess risks of total solid cancer (excluding thyroid cancer and non-melanoma skin cancer) and of several cancer types that are notably radiation-induced (leukaemia, breast cancer and thyroid cancer). The approach used in the risk estimation was the same as used in the World Health Organization calculations of risk [W9, W14] and the calculations for the UNSCEAR 2013 Report [U10] (described in [U11]), but with updates of background cancer incidence rates in Japan and risk coefficients [B10, B11, F23, G6, I10, L5, U17, U18, W7, Z1], as well as the updated dose estimates (see chapter V). The statistical power was estimated for lifetime risk and for early risks up to ages 30 or 40 for males, females and both together. Risks were calculated for exposure at age 1 (based on the number of residents of Fukushima Prefecture exposed at ages from in utero through to 5 years), age 10 (based on the number of residents of ages 6 to 19 years), and age 20 (based on the number of residents of ages 20 to 35). In addition, the detectability of excess thyroid cancer risk in the cohort of children who have been screened for thyroid cancer incidence in the Fukushima Health Management Survey (FHMS) was estimated. The analyses incorporated several conservative assumptions so as not to underestimate statistical power. The analyses used the lifetime (or, as relevant, the 30 or 40 years) estimated mean absorbed dose in the relevant organ and the corresponding 95th percentile upper bound on the mean dose for each of the non-evacuated municipalities and the evacuated municipalities in Fukushima Prefecture. The 95th percentile upper bounds have been assessed using Monte Carlo analysis (see attachment A-12 for further details). To concentrate on the areas with higher exposures, the analyses were also repeated including only the municipalities that had lifetime average effective doses of over 5 mSv. In the case of thyroid cancer, first-year absorbed doses in the thyroid over 5 mGy were used to define the higher dose group. The statistical power to detect excess risk in those who were in utero at the time of the FDNPS accident was also evaluated. The discernibility of

risks for the various groups and tumour outcomes is briefly summarized in the substantive sections that follow. Further details can be found in attachment A-23.

218. The Committee's revised estimates are that municipality-average effective doses to adult evacuees were less than 6 mSv in the first year after the accident. In the most affected municipalities that were not evacuated, average effective doses to adults in the first year were estimated to be less than 4 mSv, and lifetime effective doses to adults were up to about 15 mSv. The uncertainties are such that the 95% upper bounds of the average doses were less than about twice these values. The Committee has again focused its attention on the organs, age groups and time periods where an increased risk is more likely to become discernible as an increase in the incidence of the disease. Considering both evacuated and non-evacuated municipalities, estimated mean lifetime absorbed doses pertinent to the risks of all solid cancers (colon dose), leukaemia (red bone marrow dose) and breast (breast dose) were all under 15 mGy for those exposed in early (ages 0 to 5 years) or later childhood (ages 6 to 19 years), or in early adulthood (ages 20 to 35). These low doses are in contrast to the dose distributions of most studies where excesses of these cancers have been observed, which have larger proportions of higher doses [B10, B11, F23, G6, H34, L12, P6, R2, R3, W7, Z1].

(a) *Thyroid cancer among children and adolescents*

Inferred increases in incidence of thyroid cancer

219. In the UNSCEAR 2013 Report [U10], the Committee concluded that the occurrence of a large number of radiation-induced thyroid cancers, as were observed after the Chernobyl accident, could be discounted because doses were substantially lower. However, it considered that doses towards the upper bounds of the ranges of doses estimated in the UNSCEAR 2013 Report 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.

220. From all of the information now available, the Committee estimates the municipality-average absorbed doses to the thyroid of infants in the first year to be up to about 30 mGy, for those who were evacuated, and up to about 20 mGy, for those who remained in the non-evacuated areas (see chapter V and appendix A). The uncertainties in these estimates of average doses have been assessed using Monte Carlo analysis (see attachment A-12 for further details). The uncertainties are such that the 95% upper bounds on the average absorbed doses to the thyroid were around twice these values. Across evacuated and non-evacuated municipalities, the estimated mean thyroid dose in the first year for infants was about 13 mGy. There were five non-evacuated municipalities and 16 groups of evacuees with estimated mean thyroid doses in the first year for infants of over 10 mGy, and one non-evacuated municipality and two groups of evacuees with mean thyroid doses of over 20 mGy. Estimated mean absorbed doses to the thyroid for children and for adults (ages 10 and 20 years at exposure, respectively) were about 15% and 40% lower, respectively, than those in infancy.

221. The likelihood of discernibility of excess thyroid cancer risk among children and young adults in Fukushima Prefecture exposed as a result of the FDNPS accident was evaluated in three ways. First, assessments were made of the lifetime risk of thyroid cancer among those exposed from in utero to 5 years of age, 6 to 19 years of age, and 20 to 35 years of age using recent sex- and age-specific thyroid cancer rates from four unexposed Japan prefectures. These groups were analysed as if they were ages 1, 10 and 20, respectively. Estimated thyroid doses and radiation risk coefficients for thyroid cancer from the Hiroshima-Nagasaki Life Span Study, from Chernobyl studies and from a recent pooled analysis of nine studies with low-dose data were applied to evaluate whether an excess would likely be detectable [B10, F23, L12, Z1]. Second, since the radiation risk of thyroid cancer is thought to be

highest at younger attained ages, similar analyses were conducted up to ages 30 and 40 years. Third, the rates of incident thyroid cancer detected in the FHMS (see below) ultrasound examination programme were modelled and extended proportionally to ages 30 or 40 years, with estimates of the distribution of participants by age at exposure, municipality of residence, and participation rates in FHMS in adulthood.

222. All these statistical power analyses suggest that excess thyroid cancer risk attributable to radiation exposure was most likely not discernible in any of the age groups (see attachment A-23). For example, females of ages in utero to five years at initial exposure comprise the most susceptible subgroup. For this subgroup, about 16 to 50 cases of thyroid cancer attributable to radiation could be inferred from the estimated exposure, depending on the risk model assumed. By comparison, an average of about 650 incident thyroid cancers (with a 95% confidence interval of approximately 600 to 700 cancers) would be observed in Fukushima Prefecture over the lifetime in the absence of systematic population screening for thyroid cancer. In addition, the extensive variation in thyroid cancer rates (over 60%) seen among unexposed prefectures would likely be even larger for smaller geographic units such as municipalities, and would create considerable statistical "noise" that would limit the ability to discern radiation risk. A statistical power analysis showed that an excess of 50 cases or less would be undetectable among the much larger, uncertain baseline number of thyroid cancers. For thyroid cancer incidence in FHMS up to either age 30 or 40 years, analyses of children for the age groups of in utero to 5-years old, or 6 to 18-years old, at the time of the FDNPS accident, did not indicate that excess thyroid cancer would likely be discernible up to either age 30 or 40 (see attachment A-23).

223. An additional possible concern is thyroid cancer risk after antenatal (in utero) exposure. Studies of thyroid cancer prevalence among those exposed antenatally by the atomic bombings in Japan [I31] and by the Chernobyl accident [H7, H8] found too few cancers to provide informative quantitative estimates, so the thyroid cancer risk after in utero exposure is unknown to date. Antenatal thyroid doses from releases from the Mayak facility averaged about 10 mGy [E5] but thyroid cancer risk has not yet been reported for the antenatal group. No studies have been reported on thyroid cancer occurrence among those exposed in utero to radiation from the FDNPS accident. The Committee has estimated absorbed doses to the thyroid of those exposed in utero and found that the statistical power was too low to discern an excess risk of thyroid cancer because of the combination of relatively low thyroid doses and a small sample size: about 16,000 in utero individuals at the time of the accident (see attachment A-23).

Observed incidence of thyroid cancer

224. The Fukushima Health Management Survey launched in 2011 to "evaluate radiation doses of citizens and [record] their health conditions", and included thyroid ultrasound examinations of children, as well as general health examinations, reproductive health assistance, and mental health counselling in view of radiation risk concerns. Between October 2011 and April 2015, FHMS conducted the first round of thyroid screening of 300,472 individuals who were aged 18 years or younger at the time of the FDNPS accident to detect thyroid cancer prevalence [F7, S24]. The screening used highly sensitive ultrasound equipment, and fine needle aspiration cytology of cysts larger than 20 mm and of nodules larger than 5 mm in diameter was performed as necessary. Those suspected to be malignant were surgically removed after informed consent; 116 were cytologically diagnosed as malignancy or suspected malignancy. Additional rounds of screening were conducted to detect thyroid cancer incidence. The second round of ultrasound screening of 270,540 individuals in 2014–2015 diagnosed 71 suspected or confirmed thyroid cancers [F7]. Those who were in utero at the time of the FDNPS accident were added to the second and subsequent rounds of thyroid ultrasound screening. The third round of screening included 217,921 individuals and 31 cases were cytologically diagnosed as malignancy or suspected malignancy [F7]. A fourth round of thyroid ultrasound screening is underway, with cytological confirmation and surgery as needed [F7].

225. In the first round of screening, the rates of diagnosed, suspected or confirmed thyroid cancer among the approximately 300,000 individuals who were children or adolescents (ages 0–18) at the time of the FDNPS accident were found to be much higher than those documented in the cancer registries of other prefectures of Japan. One author group has argued [T45, T46] that the higher rates provide evidence of an increased risk of thyroid cancer due to radiation exposure. However, most other authors attribute the difference in rates to the ultrasensitive thyroid screening used in FHMS (e.g., [W8]), noting that rates for Japan as a whole are based primarily on clinically-indicated thyroid examinations, not on universal child population screening. When the Republic of Korea introduced widespread population thyroid screening of adults, unrelated to any radiation exposure, thyroid cancer incidence rates increased greatly [A5, P1], although thyroid cancer mortality rates did not increase appreciably. Other countries have reported similar findings [V1]. These observations suggest that the increased incidence rates may be due to over-diagnosis (i.e., detection of thyroid cancer that would not have been detected without the screening and would not have caused symptoms or death during a person's lifespan) [A5, I11, M28, V1].

226. Several additional pieces of evidence add weight to the suggestion that the apparent detected excess of thyroid cancers is probably unrelated to radiation exposure:

(a) At the absorbed doses to the thyroid estimated by the Committee, a large excess of thyroid cancer, as seen in the FHMS screening programme, would not be expected [I38, K15];

(b) In studies following the Chernobyl accident, an increased incidence of thyroid cancers was not observed during the first four years after the Chernobyl accident (when a radiation-related excess would not be expected because the minimum latency period after exposure had not yet been reached) [T35, W12]. During the first four years after the FDNPS accident, 116 suspicious or malignant thyroid cancers were found in the first round of the FHMS screening programme [F6, F7, O16]. This is suggestive of a screening effect rather than the result of exposure to radiation [W15];

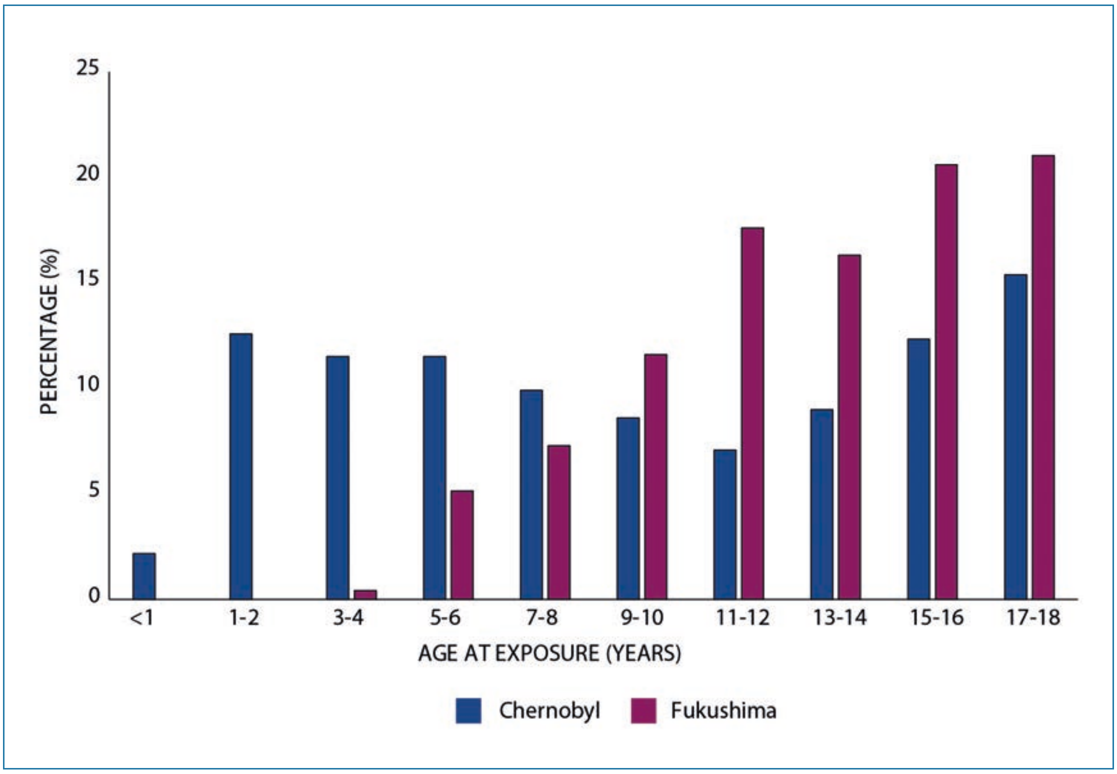
(c) Both in studies following the Chernobyl accident [T35] and following external radiation exposure [L12], a strong increase in thyroid cancer incidence was seen in those exposed in early childhood (aged less than 5-years old). In the Japanese Life Span Study of atomic bombing survivors, the greatest risk of thyroid cancer was seen among those exposed in early childhood [F23]. Beyond the minimum latency period after the Chernobyl and FDNPS accidents, there was a remarkable difference in the distribution of thyroid cancers by age at exposure: numerous cases associated with radiation occurred in the Chernobyl children exposed at ages 0 to 4 years [T35, U15], while only one case occurred in children exposed at ages 0 to 4 years in Fukushima in the first four rounds of screening (see figure XXI) [F7]. Since early childhood is a time of high susceptibility to thyroid cancer from radiation exposure, the comparatively low numbers of early childhood cancers imply that the Fukushima cancers are primarily related to attained age rather than to radiation exposure;

(d) A study conducted in three Japanese prefectures that had no radiation exposure resulting from the FDNPS accident, using the equivalent ultrasound equipment and diagnostic protocol as that used by FHMS [H11], found prevalences of thyroid cysts and nodules as high as those found in the first round of FHMS screening, albeit for a smaller study size and absolute numbers of cases. Other thyroid cancer screening results of young people in Japan without radiation exposure were also similar to those in the FHMS cohort [N3], as were estimated background (unexposed) rates in a screening programme of children from the Chernobyl area [W8];

(e) The molecular biology of the thyroid cancers found in the FHMS screening programme has not confirmed a radiation aetiology [M32]. Some studies had reported a higher than expected frequency

of rearrangements of the *RET*[39] gene in post-Chernobyl thyroid cancer, as did studies of the more highly exposed Japanese atomic bombing survivors [H2, K27, N11], suggesting that some *RET* rearrangements might be regarded as a marker for radiation exposure. In contrast, the FHMS-detected thyroid cancers had a low frequency of *RET* rearrangements and a predominance of *BRAF*[40] mutations. *BRAF* mutations are characteristic of sporadic (spontaneous) thyroid cancers in older patients. However, other studies that used age-matched unirradiated control groups have suggested that *RET* rearrangements are characteristic of thyroid cancer occurring at early ages, but are not indicative of radiation exposure [F3, P5]. The low frequency of *RET* rearrangements and predominance of *BRAF* mutations in Fukushima children thus may reflect that the cancers were largely diagnosed in adolescence and early adulthood [S51], rather than in early childhood. In any event, the pathological findings provide no indication of a radiation aetiology in Fukushima thyroid cancer cases.

Figure XXI. Percentage of the total number of thyroid cancers observed in children[a] (percentage distribution) by age at exposure to radioactive material: in Belarus, the Russian Federation and Ukraine in the first 10 years after the Chernobyl accident,[b] and in Fukushima[c] within about 8 years after the Fukushima accident



[a] The total numbers of thyroid cancers observed in children in these time periods are 1,567 for Chernobyl and 233 for Fukushima.

[b] Data were provided for this tabulation by representatives of the respective countries [U16]. The figure includes data from both the initial “prevalence” screening and any subsequent “incidence” screenings.

[c] In the 17 to 18 age group in Fukushima, the percentage may be an underestimate of the actual thyroid cancer frequency because of a significant decrease in the percentage of individuals who received thyroid screening once they reached an attained age of about 18 years.

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[39] *RET* is an abbreviation for “rearranged during transfection”. The human *RET* gene provides instructions for producing a protein that is involved in signalling within cells.

[40] The human *BRAF* gene encodes a protein called B-Raf which is involved in sending signals inside cells directing cell growth.

227. Within the FHMS screening programme (designed with a uniform screening protocol), several investigators have compared thyroid cancer rates across Fukushima regions or municipalities with different estimated external exposure levels to look for evidence of a relationship between exposure and thyroid cancer incidence. The results are summarized in table 16. Most investigators have found no statistically significant increases in thyroid cancer rates with increased exposure level [O7, O9, O10, S52, W8]. Nakaya et al. [N8] employed a spatial analysis of FHMS-detected thyroid cancer by municipality of residence that avoided arbitrary divisions of exposure levels, and also addressed uncertainties associated with detected nodules that did not undergo confirmatory testing. They found no statistical association of geographic location with thyroid cancer prevalence.

228. Kato [K8], on the other hand, reported a marginally significant trend for combined thyroid cancer prevalence and incidence by estimated municipality external exposure levels (see table 16), though their methodology has been criticized [O8, O11]. Yamamoto et al. [Y6] also reported a statistically significant positive radiation exposure-related trend for thyroid cancer prevalence or incidence in the first two rounds of FHMS screening, based on estimated average external exposure levels and numbers of screened individuals and thyroid cancer cases for each of the 59 municipalities in Fukushima Prefecture. The study has several weaknesses: for example:

(a) It was based on only municipality radiocaesium deposition densities and failed to take into account evacuations or variations in radioiodine deposition;

(b) There was dose-related confounding across municipalities in the fractions who received fine needle aspiration cytology and confirmation of malignancy [O12];

(c) It failed to take into account the substantial variability in personal doses, so that the regression analysis intervals were too narrow, and the “significant” results should be viewed circumspectly.

A recent study found no association across municipalities of external radiation measurements and thyroid cancer prevalence in the first round of screening, soon after the accident, but reported a positive association for the later second round. However, there was no association of soil measurements of ^{131}I levels and thyroid cancer rates for either round of thyroid screening [T33].

Table 16. Summary of studies of the relative risk of thyroid cancer found in the Fukushima Health Management Survey screening programme in relation to estimated external radiation exposure levels

Odds ratio estimates of relative risk (95% CI)[a]					*Reference*
Reference group (lowest exposure)	*Next higher exposure level*	*Next higher exposure level*	*Next higher exposure level*	*Next higher exposure level*	
1.00[b]	1.7 (0.81, 4.1)	1.5 (0.63, 4.0)			[T45]
1.00[b]	1.21 (0.80, 1.82)	1.08 (0.60, 1.96)			[W8]
1.00[c]	1.00 (0.67, 1.50)	1.49 (0.36, 6.23)			[O7]
1.00[d]	0.76 (0.43, 1.35)	0.24 (0.03, 1.74)			[O7]
1.00[e]	1.19 (0.58, 2.43)	1.21 (0.64, 2.3)	1.22 (0.55, 2.70)		[S52]
1.00[f] (a) 1.00 (b)	1.08 (0.58, 2.01) 0.55 (0.24, 1.26)	1.05 (0.53, 2.09) 0.93 (0.45, 1.93)	1.44 (0.75, 2.75) 0.73 (0.33, 1.60)	0.95 (0.48, 1.88) 0.59 (0.24, 1.47)	[O9]
1.00[g,h]	1.03 (0.58, 1.83)	1.23 (0.68, 2.23)	1.31 (0.77, 2.23)		[K8]
1.00[i] (a)	1.02 (0.36, 2.86)	2.20 (0.82, 5.93)	2.32 (0.86, 6.24)	1.62 (0.59, 4.46)	[O10]

Odds ratio estimates of relative risk (95% CI)[a]					*Reference*
Reference group (lowest exposure)	*Next higher exposure level*	*Next higher exposure level*	*Next higher exposure level*	*Next higher exposure level*	
1.00 (b)	1.19 (0.32, 4.41)	2.24 (0.63, 8.03)	1.30 (0.32, 5.19)	0.91 (0.22, 3.80)	
1.00 (c)	0.81 (0.27, 2.46)	1.68 (0.57, 4.94)	1.92 (0.65, 5.67)	1.27 (0.42, 3.85)	
1.00[j] (a)	1.22 (0.43, 3.49)	1.12 (0.43, 2.95)	1.60 (0.59, 4.33)		[O12]
1.00 (b)	1.66 (0.47, 5.86)	0.54 (0.12, 2.45)	0.26 (0.03, 2.42)		

[a] Except as noted, the analyses in the various studies have been adjusted for sex and age at screening. The odds ratio shows the relative risk in each exposure level group compared with the risk in the lowest exposure (reference) group. The exposure levels of the groups in the table were selected by the authors using various metrics and cutpoints for surrogates of external radiation dose, so the numbers in the respective groups are not identical across studies. Furthermore, the data included in the various studies differed, so the studies are not strictly comparable and caution should be used in the interpretation. Definitions of the exposure levels in the various studies (reference group and successively higher groups) are given below for each study.

[b] Tsuda et al. [T45] did not report estimated exposure levels, but compared their "middle" and "nearest" areas to one segment of the "least contaminated" area. Wakeford et al. [W8] used the exposure-level breakdown from [T45], but calculated odds ratios based on the entire "least contaminated" area. Neither the Tsuda et al. nor Wakeford et al. analyses were adjusted for sex and age.

[c] Ohira et al. [O7] used a breakdown of estimated external doses <1 mSv, 1 to <2 mSv, and ≥2 mSv, respectively.

[d] Ohira et al. [O7] used a breakdown of estimated personal external doses <1 mSv, 1 to <2 mSv, and ≥2 mSv, respectively for those for whom they were available.

[e] Suzuki et al. [S52] used a breakdown by Fukushima areas, namely Aizu, Iwaki and Soma, Nakadori, and the evacuation zone, respectively.

[f] For reference groups marked with (a), Ohira et al. [O9] used a breakdown of municipalities by estimated per cent of people screened with external doses ≥1 mSv: <0.67%, 0.67% to <5.7%, 5.7% to <55.4%, 55.4% to <66%, ≥66%, respectively, based on 115 cases among 300,473 in the first round of screening (P for trend = 0.69). For reference groups marked with (b), they tabulated by quintiles of estimated personal external doses, with 56 cases among 129,181 screened; the quintiles had median values of 0.2, 0.3, 0.7, 1.3 and 1.9 mSv, respectively (P for trend = 0.52).

[g] Kato [K8] used a breakdown of municipalities by per cent of people screened with estimated external doses ≥1 mSv (estimated mean doses given in parentheses): <0.80% (0.20 mSv), 0.80% to <5.7% (0.50 mSv), 5.7% to <55.4% (0.74 mSv), and ≥55.4% (1.37 mSv), respectively.

[h] Kato [K8] claimed that the Ohira et al. [O9] numbers for screening in the first round were incorrect, made an alternate "corrected" tabulation, and further added municipality results for screening in the second round to extend follow-up to 6 years. There was no indication of adjustment for age and sex. For the first and second rounds of screening combined, Kato showed a marginal association (P for trend = 0.07). The result was interpreted to indicate that the marginally significant trend was attributable to the second round screening data. However, the correctness of the disparate, dose-based municipality groupings by Kato versus Ohira et al. (see footnote *f*) is unclear.

[i] Ohira et al. [O10] analysed 70 thyroid cancers among 241,832 people screened in the second round of FHMS screening. The quintiles of municipalities based on proportions of residents with estimated external doses ≥1 mSv were <0.67%, 0.67% to <5.7%, 5.7% to <55.4%, 55.4% to <66% and ≥66%, respectively. Reference groups marked with (a) are for all thyroid cancers >5 mm; reference groups marked with (b) are for only the thyroid cancers >10 mm in diameter (n = 34); and reference groups marked with (c) are for all thyroid cancers >5 mm, where quintiles are based on the proportions of residents with estimated external doses ≥2 mSv. Proportions with ≥2 mSv were <0.05%, 0.05% to <0.25%, 0.25% to <8.8%, 8.8% to <12.2%, and ≥12.2%, respectively.

[j] Ohira et al. [O12] divided the 59 municipalities into quartiles according to the first year combined internal and external thyroid doses according to the UNSCEAR 2013 Report [U10]. They evaluated thyroid cancer risk in the second round of FHMS thyroid screening, examining those screened at ages 6–14 (reference group marked (a)) and ≥15 (reference group marked (b)) separately. The UNSCEAR 2013 Report upper estimates of dose were used for each municipality. Relative risks were adjusted for sex, age and year of examination. Neither test for trend by dose category was statistically significant.

229. Two caveats to the above studies are of note. First, the FHMS screening programme has been conducted primarily as a health-supportive programme rather than a rigorous scientific study that aimed to control for all sources of data bias. Thus, it was observed in the second round of screening that, in the

less-exposed municipalities, comparatively lower percentages of suspect nodules/cysts tended to have confirmatory examinations and fine needle aspiration cytology; comparison of the rates of confirmed thyroid cancer in the more-exposed to the less-exposed municipalities may therefore be upwardly biased [O10, O11]. Second, patterns of external exposure do not necessarily reflect total absorbed doses to the thyroid. All except the last study reported in table 16 [O12] used external doses to define the dose categories; only the last study used estimated absorbed doses to the thyroid from both internal and external exposure. Few personal measurements of internal thyroid exposures were made, so comparisons between regional/municipality levels of internal thyroid exposure and thyroid cancer rates are complex and uncertain. For the second round of screening, Ohira et al. [O10] analysed risk according to the estimates of absorbed dose to the thyroid from internal exposure developed by Kim et al. [K15]. For municipalities for which the estimated 90th percentiles of absorbed doses to the thyroid from internal exposure were 10 to 20 mGy and >20 mGy, the relative risks compared to the baseline group (<10 mGy) were 1.50 (95% CI: 0.71, 3.16) and 0.63 (95% CI: 0.31, 1.27), respectively, thereby providing no indication of a progressive trend in thyroid cancer risk by internal dose level. Similarly, Toki et al. [T33] reported no significant association between municipality measured soil levels of ^{131}I and thyroid cancer incidence. In any case, the limited information on absorbed doses to the thyroid from internal exposure should temper the interpretation of the studies in table 16.

(b) *Other health conditions among Fukushima residents*

230. To date, there are no reports of an excess in the incidence of childhood or adult leukaemia among Fukushima residents. This is in accord with the view expressed in the UNSCEAR 2013 Report [U10] that any increase in leukaemia was not expected to be discernible. Since the UNSCEAR 2013 Report, additional information has become available regarding excess leukaemia risk after childhood radiation exposure. Recent high-quality studies [B4, L11, M20] have been reviewed by the Committee and the Committee has concluded [U17] that the studies support risk estimates for leukaemia consistent with those used in the UNSCEAR 2013 Report. Statistical power analyses of lifetime doses and risks were conducted for the cancer endpoints of leukaemia and breast cancer that are known to be especially susceptible to radiation exposure, plus all solid cancer (see attachment A-23 for further details). The Committee found that, for all those evacuated and for residents of municipalities in Fukushima Prefecture that were not evacuated, as well as for the subset with effective doses over 5 mSv, excess risks of breast cancer would not be discernible (see attachment A-23).

231. The expected lifetime excess risk of leukaemia in the Fukushima Prefecture population is also small. For instance, in the subgroup from in utero up to 5 years of age at the time of the FDNPS accident, who are expected to be the most sensitive group for leukaemia, about 10 to 50 excess incident cases of leukaemia during their lifetime could be inferred, depending on the model assumed, from the estimated dose levels to the red bone marrow. The baseline number (in the absence of radiation exposure from the FDNPS accident) is about 640 cases with a 95% confidence interval of 590 to 690. Furthermore, this range does not include possible variations in background rates among geographic localities, changes in rates over calendar time, etc. Even 50 potential excess cases would probably not be discernible among 640 expected cases, given the estimated range of uncertainty in the baseline risk. Since leukaemia risk tends to be expressed at early ages after childhood exposure, statistical power analyses were also conducted for up to either 30 or 40 years of age; these indicated that any excess in the incidence of leukaemia would probably not be discernible for most subpopulations. The greatest statistical power was for those initially exposed at ages in utero up to 5 years of age and observed up to 40 years of age. Including both sexes, and depending on the risk model assumed, about 10 to 40 cases could be inferred from the estimated radiation exposure, compared to about 160 baseline cases in the absence of radiation exposure, with an estimated range of uncertainty in the baseline estimate of about 50 cases. In summary, because of the low estimated doses to the child and young adult populations, excess cases of leukaemia

attributable to radiation exposure are generally not discernible, although a possibility exists of discernible risk among those aged 5 years and under at the time of the accident.

232. When rates of various adverse pregnancy outcomes were compared in the months before and after the FDNPS accident, the post-accident incidences were not found to be elevated for stillbirth or preterm delivery [F9]. There also was no reported increase in congenital anomalies overall, or for specific types of anomalies, such as cryptorchidism (undescended testes) [F9, K34]. Rates of preterm deliveries, low birthweight and congenital anomalies were uninfluenced by the nuclear accident and were similar to those observed throughout Japan [K48, Y14]. In contrast, both Scherb et al. [S17] and Körblein and Küchenhoff [K39], conducted spatiotemporal regression analyses of perinatal mortality data that included Fukushima Prefecture and four or five neighbouring prefectures in comparison to the remainder of Japan, and reported increased rates in perinatal mortality of 15% and 10%, respectively, in Fukushima and neighbouring prefectures after the accident. However, Körblein and Küchenhoff [K39] acknowledged that their data unexpectedly showed no excess perinatal mortality in those conceived 1 to 3 months after the accident, and that the highly aggregated results also had appreciable temporal variability and might be due to other non-radiation factors. The large 10% to 15% estimated increases in perinatal mortality reported for the groups of prefectures are not considered plausible, given the estimated effective doses of only 0.2 to 4.3 mSv [K39, S17].

233. In the UNSCEAR 2013 Report [U10], the Committee could not exclude that a small number of pregnant women may have received absorbed doses to the uterus of about 20 mGy, but concluded that any increase of the risk would not lead to a discernible increase in the incidence of childhood leukaemia or other childhood cancers, because of the relatively small number of pregnant women involved and the rarity of childhood cancer. The study of Japanese atomic bombing survivors found that the risk of solid cancers among the prenatally exposed group was nominally smaller than, but statistically compatible with, the risk among those exposed at postnatal ages 0 to 5 years [P6]. The Southern Urals studies of children with in utero irradiation when mothers worked at the Mayak Production Association (median prenatal dose of about 19 mGy) [T36] or were exposed to radioactive material released to the Techa River (mean prenatal dose about 4 mGy) did not show a risk of solid cancer due to prenatal exposure [A9, K40]. There was mixed evidence regarding an increased risk of leukaemia in that cohort (mean prenatal dose about 30 mGy) [K40, S19]. The Committee's revised estimates of absorbed doses to those exposed in utero (red bone marrow dose) are that average doses were less than about 2 mGy, with 95% upper bound on the average dose of about 3.5 mGy. The Committee has assessed the resulting excess risk of childhood leukaemia up to age 20 and found that the excess risk would not be discernible (see attachment A-23). The Committee therefore still does not expect any discernible increase in the incidence of childhood leukaemia or other childhood cancers as a result of prenatal exposure.

234. A variety of reports have indicated an increased prevalence of obesity, dyslipidemia, glucose intolerance, diabetes mellitus, liver and renal dysfunction, high blood pressure, atrial fibrillation and polycythaemia among evacuees after the FDNPS accident [E2, H5, K48, K53, S48, Y10]. Prevalences of hypertension, dyslipidemia and diabetes mellitus increased after the accident among evacuees, but did not increase among non-evacuees, suggesting the effects were associated with evacuation rather than radiation exposure [O6]. There was little evidence of an increase in acute myocardial infarction after the accident [Y5]. The observed differences appear to reflect changes in lifestyle and psychological stresses following the disaster and evacuation, rather than effects of radiation exposure. There is little likelihood of a discernible excess incidence of cardiovascular diseases attributable to radiation at the levels of exposure estimated for members of the public. Likewise, no excess incidence of cataracts is expected to be discernible among the public.

235. Various adverse effects on mental health in Fukushima Prefecture were associated with the disaster-related stresses and radiation risk perceptions [F15, M2]. Psychological effects were especially evident

among those who were evacuated, and included excess anxiety, depression, problem drinking, and adverse psychological health effects among children and their mothers. However, several studies have reported no association of these effects with radiation exposure levels [F15, G5, M8, O3]. The frequency of reported psychological health effects has also decreased with time [K48]. In addition, further studies have provided evidence that evacuation may have increased mortality among those in elderly care [N14, Y22].

2. Health implications for workers engaged in emergency work

236. No deterministic health effects or deaths have been observed among workers engaged in emergency work that could be attributed to radiation exposure. Studies suggest little risk for hypothyroidism below thyroid doses of one or more gray [D1, I32, I39, S22]. Given that the 13 workers with the highest estimated absorbed doses to the thyroid are now estimated to have received doses in the range of 2 to 32 Gy (see chapter VI), the Committee cannot preclude the possibility of hypothyroidism in these more exposed workers, although it continues to consider the likelihood of such effects to be low.

237. Whether there is a discernible risk of cataracts is uncertain; some estimates of dose to the lens of the eye have become available, but they rely on assumptions about the wearing of full-face masks, when there is evidence that those workers who would have received the highest exposures of the eye lens may not have been wearing such equipment. Another issue is uncertainty in the level of a dose-effect threshold for cataracts, if any. ICRP [I20] has indicated there may be a dose threshold of 0.5 Gy, but with substantial uncertainty. Several [A20, L9, W19], though not all [L7], large studies among radiation workers suggest a dose-related risk of detectable lens opacities (cataracts), although two large studies of radiation workers did not find a dose-related risk of clinically significant cataracts requiring surgery [A21, L9]. No associations of radiation exposure with glaucoma or macular degeneration have been observed in other occupational studies [B9, L10].

238. For most workers, the effective doses in the first year received as a result of the accident were low, with an average dose of about 13 mSv,[41] and with 64% receiving an effective dose within the first year of less than 10 mSv [S25]. The Committee therefore expects no discernible increase in health effects among the overall group of emergency workers that could be attributed to their radiation exposure. A small proportion of workers (174 workers, about 0.8%) received effective doses within the first year of 100 mSv or more, with an average of about 140 mSv [S25]. Among this group, a small increased risk of cancer could be inferred over the lifetime: risk estimates for this subgroup correspond to about two to three additional cases of cancer in addition to about 70 cases that would occur spontaneously [E7]. The Committee therefore considers that it is unlikely that an increased incidence of cancer due to irradiation would be discernible, because the normal variability in baseline rates of cancer incidence is much larger than the inferred radiation-associated cancer rates.

239. In the UNSCEAR 2013 Report [U10], the Committee acknowledged that there was potentially an enhanced risk of thyroid cancer for the group of 13 workers who received the largest absorbed doses to the thyroid (now estimated to be in the range of 2 to 32 Gy). However, the Committee continues to consider that the number of workers exposed at these high absorbed doses to the thyroid is likely too small to discern an increased incidence in thyroid cancer. Similarly, it does not consider that the dose distribution and size of the group of 1,757 emergency workers thought to have had absorbed thyroid doses exceeding 100 mGy to be sufficient to discern an increased incidence. This is because of the low

[41] Doses to workers have generally been reported in terms of effective dose. The two main contributors are the broadly uniform exposure of the whole body from external radiation and internal exposure of the thyroid from intakes of radioiodine. The average absorbed doses in most organs of the body other than the thyroid in the first year was 11 mGy [I5].

susceptibility of adults to radiation-induced thyroid cancer [K23, L2], the relatively small number of workers with higher thyroid doses, and the normal statistical fluctuations in background incidence.

240. IAEA reported [I6] the interim results of a survey involving ultrasound examinations of the thyroid of 627 emergency workers engaged at FDNPS with absorbed doses to the thyroid of more than 100 mGy and 1,437 with lower thyroid doses. No significant differences between the incidence of thyroid diseases in the two groups were found, consistent with the relatively low doses received by these adults and the short time interval between exposure and examination. The negative finding is also in accord with three large studies of thyroid cancer in over 350,000 radiation workers that did not find a radiation dose-associated excess after several decades of follow-up [H12, K23, L2].

241. Regarding leukaemia risk, the Committee estimated absorbed doses to the red bone marrow for the small group of 37 most highly exposed workers to be up to about 200 mGy, but again did not expect any increase in incidence of leukaemia to be discernible because of the small number of workers in this group. The magnitude of leukaemia risk seen in other radiation workers is compatible with this expectation [S29].

242. MHLW is sponsoring a study of the FDNPS emergency worker cohort with a comprehensive health assessment, including cancer incidence and mortality, a clinical study of general health parameters, laboratory blood and urine tests, and special substudies of thyroid cancer, cataract, psychological status, radiobiological mechanistic markers, and physical and biological reconstruction of personal doses [J4, K24, M23, Y18]. Statistical power analysis conducted as part of this study confirmed the Committee’s findings (as set out in more detail in attachment A-23) that the inferred 60-year incidence of all solid cancer among the workers would not achieve adequate statistical power to be discernible [J4]. The study expands upon the health monitoring now required of nuclear operators in Japan [Y20]. Questionnaire information is being obtained on potential confounding factors, such as, medical history, medical radiation exposures, lifestyle and sociodemographic data, psychological stresses, and exposure to other toxic agents. Blood samples will be stored, and linkage with mortality and cancer databases will be implemented. To date, the clinical infrastructure of the study has been established, 7,270 workers have agreed to participate and clinical examinations have been conducted on 5,748 (by December 2019) [K24, M23]. This study has led to the reassessment of the absorbed doses to the thyroid of six of the workers with the highest doses [K54].

243. Up to the end of 2018, the Japanese Government has awarded compensation to a total of six occupationally-exposed nuclear power station workers who were employed at FDNPS following the accident and accumulated part of their exposure at the FDNPS site. Three of these workers were diagnosed with leukaemia [M24, M25, M26], two with thyroid cancer [M24] and one with lung cancer [M24]. The Committee has informed on the elements of scientific attribution of malignancies to radiation exposure (see annex A of the UNSCEAR 2012 Report [U12]). Scientific attribution is not equivalent to legal imputation in an occupational context. Therefore, the granting of these awards (and, likewise, others granted previously or in the future to occupationally-exposed workers) does not imply a scientifically proven cause-effect relationship between radiation exposure and any particular case of cancer. Rather, it is the result of the application of a scheme,[42] developed several decades ago by the Japanese Government,

[42] In 1976, the Japanese Government established the basis for the award of compensation to occupationally-exposed workers through the Industrial Accident Compensation Insurance scheme [M36]. The initial focus of the scheme was leukaemia. According to this scheme, leukaemia may be deemed eligible for medical compensation by a medical review panel if the dose was at least 5 mSv times the number of years between (first) exposure and diagnosis of the malignancy. A similar scheme applies for certain other lympho-haematopoietic malignancies with modification based on their comparative radiosensitivity. Up to the end of 2018, some 16 nuclear power station workers in Japan had been granted compensation under this scheme for lympho-haematopoietic malignancies, of which about half were leukaemia. Three of these 16 workers worked at FDNPS. Solid cancer may be deemed eligible for medical compensation by a medical review panel if the effective dose was at least 100 mSv, the time between (first) exposure and diagnosis of the malignancy was five years or more, and there was no other aetiology than radiation. These criteria are kept under continuing review and may be revised in light of new scientific evidence.

for industrial accident compensation insurance [M36]; knowledge and understanding of the effects of radiation has since improved considerably.

C. Summary

244. In the years since the UNSCEAR 2013 Report [U10] no adverse health effects among Fukushima Prefecture residents have been documented that are directly attributable to radiation exposure from the FDNPS accident. There have been some modest changes in the Committee’s updated estimates of doses to members of the public compared with the Committee’s previous estimates (see chapter V). In addition, estimated baseline cancer risks have undergone a modest amount of change, and new data have become available to update estimates of radiation risk for various cancer endpoints. The Committee has therefore carried out reanalyses of lifetime risks for particularly radiosensitive malignancies: leukaemia, thyroid cancer and female breast cancer, as well as all solid cancers (excluding thyroid cancer and nonmelanoma skin cancer).

245. The Committee’s updated statistical power analyses suggest that excess thyroid cancer risk that could be inferred from radiation exposure was most likely not discernible in any of the age groups considered. For thyroid cancer incidence taking account of the thyroid screening being carried out in FHMS, analyses of children did not indicate that excess thyroid cancer would likely be discernible up to either age 30 or 40. For those exposed in utero, the Committee similarly found that the statistical power was too low to discern an excess risk of thyroid cancer.

246. A substantial number of thyroid cancers have been detected among exposed children. However, the excess does not appear to be associated with radiation exposure, but rather a result of the application of highly sensitive ultrasound screening procedures. Other features of the thyroid cancer occurrence do not fit well with a radiation aetiology: *(a)* no excess of thyroid cancer has been observed in those exposed before age 5, in contrast to the large excess observed in the same age group exposed as a result of the Chernobyl accident; and *(b)* thyroid cancers were observed within 1 to 3 years after exposure following the FDNPS accident rather than beginning 4 to 5 years after exposure as in Chernobyl and other radiation studies. Nevertheless, because the natural progression of thyroid cancer based on the possible causes in young patients remains unknown, there is a need for further research into the biological mechanisms (in general, and not necessarily related to radiation exposure) that lead to thyroid cancer at young ages.

247. While the updated estimated doses to the red bone marrow have not increased, the Committee’s estimate of leukaemia risk per mGy has increased somewhat compared to the UNSCEAR 2013 Report [U10]. However, for risk models based on the experience of the Japanese atomic bombing survivors or on the broadest, multi-study risk data, any increased incidence of leukaemia is still unlikely to be discernible among Fukushima Prefecture residents of any ages, although there would be some possibility of detecting risk if the true average doses were actually at the estimated upper bound of uncertainty. The Committee has assessed the excess risk of childhood leukaemia up to age 20 resulting from its revised estimates of absorbed doses to the red bone marrow for those exposed in utero and found that the excess risk would not be discernible. Likewise, the levels of exposure of members of the public have been too low for the Committee to expect discernible increases in the incidence of breast cancer or other solid cancers.

248. There has been no credible evidence of excess congenital anomalies, stillbirths, preterm deliveries or low birthweights related to radiation exposure. Increases in the incidence of cardiovascular and metabolic conditions have been observed among those evacuated following the accident but are probably associated with concomitant social and lifestyle changes and are not attributable to radiation exposure.

Excess psychological distress also occurred in the aftermath of the combined earthquake, tsunami and FDNPS accident.

249. The health of the FDNPS emergency workers is being monitored. Because the majority of workers had low exposures with effective doses within the first year of less than 10 mSv, and only a small fraction of workers received effective doses within the first year of 100 mSv or more, an increase in the incidence of cancers is unlikely to be discernible for leukaemia, total solid cancers or thyroid cancer. The Committee has insufficient information to reach an informed judgement on the risk of cataracts among workers. The Japanese Government recently updated its plan for health monitoring of nuclear power station workers [Y20]. In addition, a detailed investigation of health parameters of the FDNPS emergency workers is underway.

250. Care is needed in interpreting the results from sensitive ultrasound thyroid screening following radiation exposure after a major radiological accident. There is compelling evidence that sensitive ultrasound screening detects many more cases of thyroid cancer than would be detected following the presentation of clinical symptoms. The consequential over-diagnosis of thyroid cancers has the potential to cause anxiety among those screened and might lead to unnecessary treatment.

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

A. Introduction

251. The Committee had assessed exposures of non-human biota and associated effects in general in its scientific annexes to the UNSCEAR 1996 Report and UNSCEAR 2008 Report [U6, U8]. The benchmarks[43] set out and used in those annexes, and in the UNSCEAR 2013 Report [U10], were based on a large synthesis of information derived primarily from radiobiological literature spanning many decades of experimental work and (to a limited extent) including analyses of field observations from earlier accidents. The benchmarks were 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. The Committee has examined the impact of the FDNPS accident on non-human biota inhabiting terrestrial, freshwater and marine ecosystems. It has considered estimated radiation exposures, including contributions from short-lived radionuclides such as ^{131}I, in terms of the intermediate phase after the accident (approximately the first two months) and the late phase (months to years). The methodology, including detailed descriptions of the geographical areas and the timescales considered, and the basis for the benchmarks applied are provided in the UNSCEAR 2013 Report.

[43] Benchmarks in this context are dose rates below which non-human biota populations are unlikely to be significantly harmed based on current knowledge; they have been used to assess the likelihood that adverse effects occurred as a result of exposures. Benchmarks have often been established using information from chronic, stationary or quasi-stationary, exposures and, as such, were not fully compatible with a quickly changing, post-accidental situation. The interpretation of the dose rates reported for early and late periods after the accident was thus not straightforward and a balance was required between maintaining consistency with earlier UNSCEAR publications and relating effects of radiation exposure to the time-integrated dose, correcting for dose rate effects, where appropriate.

B. Overview of current understanding

1. Estimates of levels of radionuclides in various biota

252. In the UNSCEAR 2013 Report [U10], the Committee used measurements of radionuclides in organisms and in the environment and applied suitable models to estimate levels of radionuclides in selected reference organisms. Numerous studies published since the UNSCEAR 2013 Report provide updated information on levels of radionuclides in non-human biota and processes influencing radionuclide transfer within ecosystems [U11, U13, U14]. Fuma et al. [F22] reported that fungi, ferns, and mosses accumulated high amounts of radiocaesium, from areas in close proximity to FDNPS, with ^{134}Cs and ^{137}Cs concentrations of 10^4 to 10^6 Bq/kg fresh mass (FM). Earthworms, amphibians, and the soft tissue of snails also had levels as high as 10^4 to 10^5 Bq/kg FM of ^{134}Cs and ^{137}Cs. Small mammals with maximum ^{134}Cs and ^{137}Cs concentrations in excess of 10^5 Bq/kg FM have also been captured in the exclusion zone [K46]. The highest reported concentration of ^{134}Cs and ^{137}Cs in marine fish muscle, sampled in the FDNPS port and reported by Johansen et al. [J5], was 740,000 Bq/kg FM in an *Hexagrammos otakii* (greenling; sampled in February 2013). Concentrations in fish are generally orders of magnitude lower than this level tens of kilometres offshore [S23].

253. These levels are generally consistent with the data used in the UNSCEAR 2013 Report [U10], but some reported radionuclide levels warranted more detailed consideration. The study of Qiu et al. [Q1] indicated that substantial bioaccumulation of ^{110m}Ag in marine crustaceans may have occurred in some locations near to FDNPS: a ^{110m}Ag/^{137}Cs ratio in excess of one (one or two orders of magnitude higher than the ratio found in coastal sediments) was reported for a Fukushima coastal location (although radionuclide levels were generally low, rarely exceeding 100 Bq/kg FM). Silver has a relatively high concentration ratio for fish, so it is plausible that ^{110m}Ag was more important than assumed in the UNSCEAR 2013 Report.[44] Horiguchi et al. [H26] similarly measured relatively elevated levels of ^{110m}Ag in shellfish, although the ^{110m}Ag/^{137}Cs ratios were considerably higher in this study.

2. Estimates of doses for reference organisms

254. In the UNSCEAR 2013 Report [U10], the Committee estimated that total (internal and external) absorbed dose rates, including contributions from very short-lived ^{132}Te and ^{132}I, may have been as high as 1,000 µGy/h for some terrestrial organisms over short periods (hours to days). In the intermediate phase (i.e., the first two months), dose rates of 300 µGy/h may have been possible for soil-dwelling organisms in areas of high deposition density (such as Okuma Town, where the maximum deposition density of ^{137}Cs was about 15 MBq/m^2). For aquatic ecosystems, maximum exposures were calculated from estimated concentrations in seawater to be more than 20,000 µGy/h for aquatic macroalgae for locations closest to the discharge point (Fukushima North Channel), with the contribution from ^{131}I being dominant, and 140 µGy/h for marine fish. Macroalgae dose rates were estimated to have fallen rapidly, in line with the 8-day half-life of ^{131}I. From measured radionuclide concentrations in biological samples, corresponding to the late phase of the accident, terrestrial mammals and birds were estimated to have been exposed to total dose rates between 1.2 µGy/h and 2.2 µGy/h in areas encompassing an indicative range of ^{137}Cs deposition densities (between 50 and 500 kBq/m^2), and dose rates to marine organisms were estimated to be in the range of 0.10 to 0.25 µGy/h.

[44] In terms of levels and effects of radiation exposure for non-human biota.

255. The IAEA report [I6] similarly included estimates of total absorbed dose rates for non-human biota. Estimates were derived:

(a) From time-integrated concentrations of radionuclides in soil, freshwater and seawater for "early" (first 30 days), "intermediate" (31–90 days), and "late" (91 days to 1 year) periods after the accident;

(b) From directly measured radionuclide concentrations in biota, generally for the "late" period.

Estimates of the doses and dose rates based on measurements of radionuclide levels in biota were of a similar order of magnitude to those presented in the UNSCEAR 2013 Report [U10], with maximum dose rates for terrestrial systems of around 80 µGy/h for wild grass and around 8 µGy/h for a large mammal.

256. Fuma et al. [F22] estimated total absorbed dose rates, mainly for the period May 2011 to March 2012, to herbaceous plants (up to 44 µGy/h), amphibians (up to a maximum of 76 µGy/h), insects (up to a maximum of 23 µGy/h), and earthworms (up to a maximum of 40 µGy/h) for areas close to FDNPS. Kubota et al. [K45] estimated the average total absorbed dose rate to small mammals (rodents), from an area with relatively high deposition levels around 4 km west of FDNPS (Ottozawa, Okuma Town, where deposition densities of ^{137}Cs exceeded 1 MBq/m^2), at approximately 52 µGy/h (in December 2013). These and other exposure estimates [F14], for periods within approximately the first two years of the accident, are similar to the estimates made earlier in the UNSCEAR 2013 Report [U10], providing support for the assessment approach used in that report and the validity of the associated exposure calculations.

257. For the marine environment, evidence of the persistence of elevated concentrations in benthic marine fish [S23] indicates that longer term (>1 year post accident) exposures may have been higher than might be inferred from the estimates made in the UNSCEAR 2013 Report [U10]. Johansen et al. [J5] estimated a maximum dose rate of about 130 µGy/h in early 2013, similar to the Committee's estimate for marine fish in 2011. This discrepancy may have numerous causes, including not taking sufficient account of accumulation of radionuclides in sediment and sediment-associated food chains in the UNSCEAR 2013 Report, and/or the continued (and unforeseen) importance of diffuse sources of releases to the marine environment (see chapter III). Further work has continued to refine marine biota transfer and dose modelling (see, for example, [K41, V2, V3]).

3. Predicted and observed effects

258. In the UNSCEAR 2013 Report [U10], the Committee had inferred the effects due to the estimated radiation exposures by applying its generic evaluations of dose-effects relationships. It had concluded that exposures of both marine and terrestrial non-human biota following the accident had been, in general, too low for acute effects to be observed, although some exceptions had been considered possible because of local variability. It had further concluded that, in general, population-relevant effects on non-human biota in the marine environment would have been confined to areas close to where highly radioactive water was discharged and released into the ocean.[45] Although the Committee had been unable to exclude a risk of effects to individuals of certain terrestrial species, in particular mammals, it had considered observable

[45] Predicted exposures for macroalgae at locations very close to the discharge point of around 20 mGy/h are within the range of 10–100 mGy/d considered to cause potential effects on reproduction and growth rate, with 3-month integrated doses of 6.8 Gy signalling potential acute effects [I18], at least in theory. Therefore, the calculated exposures for macroalgae could have been at a level where acute impact could have occurred; however, these exposures were transient and the Committee had concluded in the UNSCEAR 2013 Report that there would not be lasting population level effects.

effects at the population level to be unlikely. Any radiation effects would have been constrained to a limited area, in the terrestrial environment, where the deposition density of radioactive material was greatest, and, beyond this area, the potential for effects on biota was considered insignificant.

259. Since the UNSCEAR 2013 Report [U10], deleterious effects in non-human biota have been observed in the field, although not all of these would be expected to impact on populations. There have been numerous studies in which cytogenetic, physiological and morphological effects have been observed in areas of enhanced radiation levels following the FDNPS accident. These include: chromosomal aberrations in splenic lymphocytes of two species of Japanese field mice (*Apodemus speciosus*) [K9, K46]; DNA (single- and double-strand) breaks in earthworms [F12]; lowered blood neutrophil, monocyte and lymphocyte counts in fish [S53]; haematological changes in monkeys [O1]; and morphological abnormalities in gall-forming aphids [A8]. Significant increases in morphological abnormalities have been observed in coniferous trees, such as Japanese red pine (*Pinus densiflora*) [Y26] and Japanese fir (*Abies firma*) [W11] in areas with elevated radionuclide deposition densities following the FDNPS accident. Although Watanabe et al. [W11] considered that there was no decisive evidence that any single factor was causally related to these increased morphological effects, the authors also concluded that the positive correlation between ambient dose rates and the frequencies of such negative changes was indicative of ionizing radiation being a potentially important factor. Indeed, accumulated doses in vegetation in areas with relatively high levels of deposited radionuclides were estimated in the UNSCEAR 2013 Report to be similar to those at which disturbances in growth, reproduction and morphology of conifers had been observed following the Chernobyl accident [S39].

260. There have also been studies in which no significantly elevated effects have been observed despite there being relatively enhanced exposure levels. Such studies include: no clear abnormalities, from histological analysis, in the reproductive tissues of frogs (where internal concentrations of ^{137}Cs exceeded 47 kBq/kg FM) [M16]; no increases in the frequencies of morphologically abnormal sperm in Japanese field mouse (*Apodemus speciosus*) [O20]; no increase in epigenetic markers (methylation of DNA) in Brassicaceae plants within the exclusion zone with increasing radiation levels [H25]; no significant effects on the blood cell counts in cattle [S8]; no impact on chromosomal inversion frequency on fruit flies (*Drosophila melanogaster*) [I40]; no significant effects of the exposure to ionizing radiation on Japanese tree frog (*Hyla japonica*) body condition or tissue carotenoid concentration [G3]; and an absence of higher levels of genetic damage in bird nestlings, despite the conclusion, in the same paper, that lower survival and reproduction and/or fledging rate prevailed [B6].

261. The observations of sublethal effects (including cytogenetic damage and morphological effects) are not inconsistent with the findings of the UNSCEAR 2013 Report [U10]. In contrast, several studies have also suggested that there have been substantial (non-human biota) population impacts. The abundance of forest and grassland avian species has been observed to be lower in areas with enhanced exposure levels (ambient dose rate equivalents around 40 µSv/h) [M42], although concerns have been expressed regarding some of the conclusions drawn within these studies [B2, B3], e.g., problems with field dosimetry, low power statistics, and implying causation from correlation in the presence of confounding factors. Some of these concerns have been addressed in subsequent rigorous dose reconstructions of some of the underpinning data sets [B1, G2], albeit that this dose reconstruction work itself has been subject to criticism [S30]. Mousseau and Møller [M46] reported that butterflies and cicadas exhibited lower abundances with increasing radionuclide deposition densities, despite such declines not being observed for bumblebees, dragonflies or grasshoppers. Arachnids were stated to exhibit a statistically significant increase in abundance at sites with high levels of radionuclide deposition, attributed to the decrease in the number of (insect-eating) birds reported within these areas. The Committee has reviewed numerous, mainly field-based, studies on the impact of the FDNPS accidental releases upon the pale grass blue butterfly (*Zizeeria maha*) [U9, U11, U13]. The studies have generally concluded that artificial radionuclides from FDNPS were the cause of genetic and physiological damage to this species of insect

and that the cumulative effects of exposures could have caused a deterioration in the population [H23, H24]. In follow-up studies from the same group [G8], involving the feeding of butterfly larvae with artificial diets incorporating relatively high levels of ^{137}Cs, no effects on endpoints including pupation, eclosion and survival rates were observed. This led these authors to the conclusion that biological effects in the field may be mediated through ecological systems and cannot be estimated solely based on radiation doses. In contrast to the above-mentioned studies inferring population-level impacts on biota, Lyons et al. [L13] concluded, based on data analysed from a network of remote cameras in the Fukushima exclusion zone, that effects of radiological exposure on mid- to large-sized mammals did not appear to manifest in a population-level response. Furthermore, confounding factors, including the removal of human management activities, can have substantial negative impacts on populations of some insect species such as bees [Y27], and need to be accounted for in assessments of stressor impacts.

262. An assessment by IAEA [I6] considered impacts for all ecosystems. This assessment used a somewhat different methodology to that adopted by the Committee in the UNSCEAR 2013 Report [U10] (which incorporated dynamic transfer models, enabling the estimation of maximum dose rates occurring over shorter time periods). But the overall results were largely consistent, given the substantial uncertainties associated with assessment models. IAEA concluded that, based on current knowledge, no impacts on populations and the ecosystems (both terrestrial and marine environments) were expected and that long-term effects were not expected. IAEA also noted that knowledge of the impacts of radiation exposure on non-human biota needed to be strengthened by improving the assessment methodology and understanding of radiation induced effects on biota populations and ecosystems.

263. The Committee reviewed over 20 years of research on radiation impacts in the Chernobyl exclusion zone [U8] and found no adverse radiation induced effects reported in plants and animals exposed to a cumulative dose of less than 0.3 Gy during the first month after the Chernobyl accident (i.e., <10 mGy/d, on average). For the most contaminated areas, a few years were needed for recovery from the major radiation-induced adverse effects on plants and animals [U8]. Studies in the Chernobyl exclusion zone that are still ongoing provide tentative evidence that organisms in their natural environment may be more sensitive to radiation than those tested under laboratory conditions [G1]. Furthermore, studies on high levels of biological organization (e.g., population, ecosystem function) are still scarce and very few of them consider the impact on ecology and evolution of species.

264. The Committee continues to consider it unlikely that there would be severe, regional population-level impacts on non-human biota as a result of the FDNPS accident, although it acknowledges the results of the studies in which substantial population impacts have been observed for some types of organisms. The cause of these results remains to be identified definitively and the observations need to be followed up.

4. Uncertainties

265. Overall uncertainties associated with the types of models applied in the Committee’s assessment, particularly when the approach involves a biological transfer component, are large: estimations of exposures to non-human biota using different models often differ from one another by more than one order of magnitude (see, e.g., [V4]). A further substantial uncertainty is associated with exposures from short-lived radionuclides in the initial phases of releases, such as doses to the mammalian thyroid from ^{131}I, as discussed in [S38].

266. The benchmarks used by the Committee to assess effects on non-human biota constituted the best insight that could be achieved into the doses at which biological effects were likely. However, the benchmarks were largely based on exposures of small groups of individuals, maintained in isolation and

under controlled laboratory conditions.[46] There will clearly be some limitations to the applicability of this information when extrapolating to infer effects for ecosystems. Disturbances induced by stressors cannot be entirely understood from knowledge of the stressor's effects on individual organisms, considering that such effects may act as triggers of perturbation, which propagate through higher levels of biological organization within ecosystems [B8]. This view appears to be supported by recent meta-analysis of effects data, partly involving findings from Chernobyl exclusion zone, and suggesting that organisms in their natural environment may be more sensitive to radiation than those tested under laboratory conditions [B1, G1]. Nonetheless this contention has been questioned [S30] and requires further testing and verification. Confounding factors render interpretation of environmental impacts from radiation exposure challenging. For example, IAEA [I6] contended that the severe earthquake and tsunami caused significant environmental stress to the terrestrial and marine environments along the north-eastern coast of Honshu, that was considered to be far in excess of that caused by radiation exposure.

C. Summary

267. The Committee continues to consider that regional impacts on wildlife populations, with a clear causal link to radiation exposure resulting from the FDNPS accident, would have been unlikely although detrimental effects on individual organisms might have been possible. Indeed, various cytogenetic, physiological and morphological (sublethal, individual level) effects in some plants and animals have been observed in areas of enhanced radiation levels following the FDNPS accident, in the absence of any reported wide-scale group impacts. However, such studies remain scarce and current conclusions strongly depend on the studied organism. A few studies have indicated substantial population impacts on selected wildlife groups, but, given the wealth of underpinning radiobiological evidence to the contrary, the findings of these studies and their robustness, regarding reproducibility and adequate account being taken of confounding factors, remain subject to some doubt. However, assessed uncertainties are large and understanding is far from complete, and it is possible that current assessment methodologies are inadequate. Further analysis would be useful of the impacts of radiation exposure on non-human biota under field conditions, such as those present in the exclusion zone of FDNPS, as was done in the Chernobyl exclusion zone. Moreover, further research would be useful to investigate the dose response at the population level, and higher levels of biological organization, within natural environments, taking account of elements of ecosystem function and structure.

IX. CONCLUSIONS

268. The Committee has assessed and summarized the information available at the time of the UNSCEAR 2013 Report [U10] and the new information that has become available to the Committee since the completion of that report. The significant amount of new information that has become available has enabled the Committee to carry out a higher quality and more robust assessment of the levels and

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[46] Furthermore, the benchmarks commonly used pertain to chronic exposures under current and existing exposure situations whereas values dedicated to acute exposures, which are scarce in the literature, may be more appropriately applied. In this respect, an acute threshold value proposed at the ecosystem level for the marine environment (see [S38]), also considered by the Committee [U7] (i.e., value of 4.84 Gy), may be applicable.

effects of radiation exposure due to the FDNPS accident than set out in the UNSCEAR 2013 Report. From its assessment, the Committee has concluded the following:

(a) The total releases to the atmosphere of ^{131}I and ^{137}Cs ranged generally between about 100 to about 500 PBq and 6 to 20 PBq, respectively. The ranges correspond to about 2% to 8% of the total inventory of ^{131}I and about 1% to 3% of the total inventory of ^{137}Cs in the three operating units (Units 1–3) from which the releases occurred at the time of the accident. The releases of less volatile radionuclides (e.g., ^{90}Sr and ^{239}Pu) were negligible. About 80% of the total amount released was dispersed over and deposited on to the Pacific Ocean;

(b) For the purposes of estimating concentrations of radionuclides in the environment where measurements do not exist or can no longer be made, the Committee recommends the use of the latest in a series of estimates of the temporal pattern of release (or the so called “source term”) developed at JAEA. The most recent estimate is that of [T28] and the Committee has used it in revising its estimates of doses to the public from airborne radionuclides. The total releases of ^{131}I and ^{137}Cs to the atmosphere in this source term are 120 and 10 PBq, respectively;

(c) Releases of radionuclides into the Pacific Ocean occurred directly and indirectly and still continue, albeit at decreasing rates. They comprise: *(i)* direct releases in the first three months (in leakage and deliberate release of water containing radionuclides), amounting to about 10 to 20 PBq of ^{131}I and about 3 to 6 PBq of ^{137}Cs; *(ii)* deposition of radionuclides on to the ocean surface following their release to, and dispersion in, the atmosphere, amounting to about 60 to 100 PBq of ^{131}I and 5 to 8 PBq of ^{137}Cs; *(iii)* direct release of about 60 TBq of ^{137}Cs in ground water draining from the site up to October 2015, when measures were taken to reduce these releases, and about 0.5 TBq per year thereafter; and *(iv)* continuing indirect releases of about 5 to 10 TBq of ^{137}Cs per year via rivers draining catchment areas on to which radioactive material released to the atmosphere was deposited;

(d) The material released to the Pacific Ocean was rapidly dispersed and diluted in seawater: by 2012, the concentrations of ^{137}Cs, even in the coastal waters off the FDNPS site, were little above the levels prevailing before the accident. Concentrations of ^{137}Cs in marine foods have declined rapidly: 41% of samples caught off the coast of Fukushima Prefecture in 2011 exceeded the long-term limit established by the Japanese Government, decreasing to 17% in 2012, and, from the beginning of 2015, to just four samples out of 9,000;

(e) A large body of Japan-specific information has been accumulated on the levels and transfer of radionuclides released to the atmosphere through terrestrial and freshwater environments. Radiocaesium has been found to be more strongly bound to soils in Japan than in many soils affected by the Chernobyl accident, resulting in its reduced transfer to crops and its reduced rate of downward migration into soil, with implications for doses via ingestion and from external radiation from deposited radionuclides. Concentrations of radionuclides in most monitored foodstuffs have declined rapidly following the accident. Since 2015, no samples of livestock and crop products, and less than a few per cent of most monitored wild food and freshwater fish products, have exceeded the limit established by the Japanese Government;

(f) The levels of radiation exposure and concentrations of radionuclides in the environment following the accident at FDNPS have been extensively characterized through measurements and monitoring campaigns. They provide a broadly sufficient basis for making realistic estimates of doses to the Japanese population for most pathways of exposure. The exception is exposure from the inhalation of airborne radionuclides for which measurements are relatively sparse. The Committee had, therefore, to rely on a model to estimate concentrations of radionuclides in air over the Japanese land mass and used the source term and associated ATDM by Terada et al. [T28] for this purpose;

(g) The Committee has used information available to it on measurements made on people largely for the purposes of validating the approaches and models it has used to estimate doses. These measurements comprised WBC, levels of radioiodine in the thyroid and personal dosimetry campaigns. The Committee had access to measurements made on people reported in the published literature and requested further information from national, regional and municipal authorities in Japan. Notwithstanding the large amount of measurements that have been and continue to be made in Japan that were not yet publicly available, in particular personal dosimetry campaigns and WBC, the only information made available to the Committee was data from personal dosimetry campaigns undertaken by Minamisoma City and Naraha Town. Access to the wider body of measurements in Japan would have enabled the Committee to further refine and/or enhance the validation of its models. Broad agreement was found between the Committee's dose estimates and those derived from the available measurements made on people. This has provided support for the validity of the improved models used for estimating doses from intakes into the body of radioiodine and radiocaesium and external doses from radionuclides deposited on the ground. Of particular note, in this respect, is the improved and validated approach for estimating doses from ingestion of radionuclides that has resulted in doses from this exposure pathway that are lower by at least ten times than those estimated in the UNSCEAR 2013 Report;

(h) The estimated municipality- and prefecture-average effective doses to infants in the first year are in the range of about 0.2 to 8 mSv for municipalities that were evacuated, in the range of about 0.1 to 5 mSv in other municipalities of Fukushima Prefecture, in the range of about 0.1 to 1 mSv in neighbouring prefectures, and from 0.005 to 0.5 mSv for prefectures in the rest of Japan. The average effective doses to children and adults were estimated to be about 80% and 70%, respectively, of the doses to infants. In the first 10 years after the accident, these effective dose estimates would increase by between two and three times, and over a lifetime (up to age 80 years) by about four times. In 2021, average annual effective doses have been estimated to be less than 0.5 mSv in all non-evacuated municipalities in Fukushima Prefecture and below 0.1 mSv elsewhere in Japan. In the evacuated communities where evacuation orders have been lifted, average annual effective doses in 2021, taking account of remediation work completed in these areas, are generally less than 1 mSv;

(i) The estimated municipality- and prefecture-average absorbed doses to the thyroid for infants in the first year are in the range of about 2 to 30 mGy for municipalities that were evacuated, in the range of about 1 to 20 mGy for other municipalities in Fukushima Prefecture, in the range of about 0.6 to 6 mGy in neighbouring prefectures, and in the range of about 0.09 to 0.7 mGy for prefectures in the rest of Japan. The average absorbed doses to the thyroid for children and adults are estimated to be about 80% and 50%, respectively, of the doses to infants. The estimated absorbed dose to the thyroid over a lifetime for infants at the time of the FDNPS accident is about twice the dose in the first year;

(j) The greater amount and better quality of information now available has enabled the Committee to make quantitative, and less subjective, estimates of the distributions of individual doses in each municipality of Fukushima Prefecture, for the prefecture as a whole, and for other prefectures. The distributions take account of uncertainties in the estimated doses and variability between individuals resulting from where they live and work, their lifestyle, and other habits. The estimated doses have been presented in terms not only of the average, but also of the 5th and 95th percentiles of the distribution. In general, 90% of the individuals in each population group were estimated to have received doses within a range from about three times lower than the average dose to about three times higher. Individuals within each population group are estimated to be more likely to have received effective doses lower than the average than higher than the average. The distribution of individual effective doses in the first year within Fukushima Prefecture, for example, shows that nearly all individuals were estimated to receive an effective dose between about ten times lower and three times higher than the average for the prefecture;

(k) Compared with the estimates in the UNSCEAR 2013 Report, the Committee's revised estimates of average effective doses in the first year are considerably lower (by more than an order of magnitude) for municipalities or prefectures with lower doses and up to about 30% lower for those with higher doses. For absorbed doses to the thyroid, the Committee's revised estimates of average doses in the first year are similarly much lower for municipalities or prefectures with lower doses and up to about two times lower for those with higher doses. The reductions in the doses are attributable to: *(i)* more realistic assessment of intakes of radionuclides by ingestion; *(ii)* account being taken of lower concentrations of radionuclides inside buildings; and *(iii)* the use of Japan-specific dose coefficients for the intake of radioiodine. These reductions have been counterbalanced by modest increases in doses from external exposure resulting from the use of an improved and validated model. The use of a different source term and ATDM for estimating doses from the inhalation of radionuclides has led to increases in doses at some locations and decreases in others;

(l) The Committee's revised estimates of doses to the public and their associated uncertainties provide a more realistic assessment of the exposure of the public resulting from the accident at FDNPS compared with the UNSCEAR 2013 Report. While the uncertainties in the estimated doses remain large, the Committee is of the view that further research is unlikely to reduce them significantly, or change the central estimates, other than in specific circumstances (e.g., to take account of further information on the efficacy of remediation). The measurements made in the environment and on people in the immediate aftermath of the accident cannot be repeated, and estimates of doses using these measurements cannot go beyond the limitations of this information, however much research is conducted subsequently;

(m) The Committee has taken account of the impact of remediation activities on its estimates of doses to evacuees if they return to their homes. It has not taken account of the impact of remediation activities completed across wider areas of Japan, although the effect of the resulting overestimate of doses after the completion of this work is likely to be small in comparison with other uncertainties in its dose estimates. Further information is needed about the effect of the remediation work in reducing individual doses as measured on people to make more precise estimates of doses following remediation;

(n) The average effective dose to the more than 20,000 emergency workers involved in mitigation and other activities at the FDNPS site from March 2011 to the end of March 2012 was about 13 mSv. About 36% of the workforce received an effective dose of more than 10 mSv and about 0.8% (174 workers) have been assessed to have received more than 100 mSv over that period. Annual effective doses have been considerably lower since April 2012, with average annual effective doses declining from about 6 mSv in the year to the end of March 2013 to about 2.5 mSv in the year to the end of March 2020. No worker has received an annual effective dose of more than 50 mSv since April 2013;

(o) Absorbed doses to the thyroid of six emergency workers who received the highest doses have recently been reassessed, in particular using individual-specific measurements of thyroid size. The largest assessed committed absorbed dose to the thyroid due to internal exposure from inhalation of ^{131}I is now 32 Gy. There is no evidence to suggest that using standard reference values for thyroid mass or volume is not appropriate for the Japanese population in general; but the Committee has noted that further individual-specific reassessments of thyroid dose are foreseen. For workers whose individual absorbed dose to the thyroid is to be reassessed for the purposes of epidemiology or health risk assessment, measurement of thyroid volume, subject to ethical approval, would be beneficial as part of the reassessment. Beta dose to the lens of the eye of workers was identified as a research need in the UNSCEAR 2013 Report but an assessment of these doses has yet to be reported;

(p) Timely monitoring (e.g., WBC, thyroid measurements, personal dosimetry) of representative groups of workers and the public at the earliest opportunity after an accident would greatly enhance

the quality and informativeness of any assessment of doses to workers and the public following a radiological or nuclear accident. If appropriate human measurements are not made in the immediate aftermath of an accident, doses to people can only be assessed using models together with other measurements that may be available, for example, in the facility where the accident occurred and/or in the wider environment. Experience has shown that the use of such models often leads to conservative estimates of doses;

(q) No adverse health effects among Fukushima residents have been documented that are directly attributable to radiation exposure from the FDNPS accident. The Committee's revised estimates of dose are such that future radiation-associated health effects are unlikely to be discernible. The Committee believes that, on the balance of available evidence, the large increase, relative to that expected, in the number of thyroid cancers detected among exposed children is not the result of radiation exposure. Rather, they are the result of ultrasensitive screening procedures that have revealed the prevalence of thyroid abnormalities in the population not previously recognized. An increase in the incidence of cancers is unlikely to be discernible in workers for leukaemia, total solid cancers or thyroid cancer. The Committee has insufficient information to reach an informed judgement on the risk of cataracts;

(r) Care is needed over the widespread use and interpretation of sensitive ultrasound thyroid screening following radiation exposure as a result of events such as the FDNPS accident. There is compelling evidence that sensitive ultrasound screening detects many more cases of abnormalities and cancer in the thyroid than would be detected following the presentation of clinical symptoms. The consequential over-diagnosis of thyroid cancers, many of which may never result in clinical symptoms, has the potential to cause considerable anxiety among some of those screened and to lead to unnecessary treatment, the detrimental effects of which may outweigh those of the radiation exposure itself, especially if the thyroid doses are relatively low. If such screening is to be carried out, perhaps including even further advances in thyroid assessment equipment and techniques, as well as determining evidence of a dose-response, an unexposed control group needs to be studied at the same time and using an equivalent protocol and technical equipment. These safeguards will reduce the risk that cancers diagnosed following any future accident are attributed wrongly to exposure to radiation;

(s) The Committee continues to consider that regional impacts on wildlife populations with a clear causal link to radiation exposure resulting from the FDNPS accident would have been unlikely, although detrimental effects on individual organisms might have been possible, and some effects have been observed in plants and animals in the absence of any wide-scale group impacts. A few studies have indicated substantial population impacts on selected wildlife groups, but these findings remain subject to some doubt. It is possible, however, that current assessment methodologies are not adequate and further analysis of impacts under field conditions could be valuable. Further research could also be useful on the impacts of radiation exposure on non-human biota under field conditions that are able to take account of higher levels of biological organization, within natural environments, and elements of ecosystem function and structure.

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Coordination expert group

Project manager: N. Kelly (United Kingdom); *Senior technical advisors*: W. Weiss (Germany) and M. Akashi (Japan).

Expert group

Coordinating lead writer: N. Kelly (United Kingdom); *Members and lead writers*: S. Solomon (Australia), C. Estournel (France), F. Gering (Germany), P. Strand (Norway), M. Balonov (Russian Federation), G. Etherington (United Kingdom), B. Howard (United Kingdom) and R. Shore (United States).

Task group public exposure

Leader: M. Balonov (Russian Federation); *Members*: D. Broggio (France), L. Chipiga (Russian Federation), V. Berkovskyy (Ukraine) and V. Drozdovitch (United States); *Observers*: S. Kinase* (Japan) and A. Ulanowski (IAEA).

Task group atmospheric dispersion

Leader: F. Gering (Germany); *Members*: A. Mathieu (France), D. Quelo (France), T. Aono (Japan), M. Chino (Japan), Y. Moriguchi (Japan), H. Nagai (Japan), P. Bedwell (United Kingdom) and S. Leadbetter (United Kingdom).

Japanese Working Group

Members: K. Akahane (Japan), M. Akashi (Japan), T. Aono (Japan), M. Chino (Japan) and K. Ozasa (Japan).

Critical reviewers

G. Hirth (Australia), H. Vandenhove (Belgium), J. Chen (Canada), S. Charmasson (France), J-R. Jourdain (France), R. Michel (Germany), S. Shinkarev (Russian Federation), A. Wojcik (Sweden), J. Brown** (United Kingdom), R. Wakeford (United Kingdom), N. Harley (United States), B. Napier (United States) and D. Pawel (United States).

* Until May 2019 (IAEA observer) and later (Japan).
** As of 2019 (IAEA observer).

Other contributing experts

M. Cook (Australia), B. Orr (Australia), T. Hamburger (Germany), J. Brown (Norway), C. Robinson (Norway) and G. Ratia (Ukraine).

APPENDIX A. ASSESSMENT OF DOSES TO THE PUBLIC

I. INTRODUCTION

A1. This appendix summarizes the information available (as at the end of 2019)[1] of relevance to the assessment of the doses received by members of the public as a result of the Fukushima Daiichi Nuclear Power Station (FDNPS) accident. It describes the analyses that have been carried out using this information to develop improved methodologies for assessing doses to the public and presents the results of their application, i.e., updated estimates of doses.

A2. In the UNSCEAR 2013 Report [U10], the Committee's aim was to make realistic estimates of doses. However, information that has become available since the completion of that report demonstrated that some of the doses presented in the report were overestimates, in a few cases by a considerable margin. In particular, as identified in its subsequent reviews of information published since the UNSCEAR 2013 Report [U11, U13, U14], the Committee considered that doses to the public from ingestion were likely to have been much lower than those estimated from the limited information then available in the UNSCEAR 2013 Report. This possibility had even been recognized in the UNSCEAR 2013 Report itself from the emerging information from measurements made directly on people. As the Committee acknowledged in the UNSCEAR 2013 Report, the tendency to make cautious assumptions is "an inevitable consequence" when the information available is incomplete.

A3. In addition, much more information has since become available to enable more quantitative and less subjective assessments to be made of the uncertainties and individual variability in the estimates of doses. For example, because of a lack of measurement information about concentrations of radionuclides in the air, estimates of doses from inhalation of radionuclides in the air were largely based on concentrations derived from an assumed source term for the release of radionuclides into the atmosphere and atmospheric transport, dispersion and deposition modelling (ATDM). At any particular location, such estimates are associated with considerable uncertainty. In addition, the Committee had to make numerous assumptions, for example, about the chemical forms in which iodine was released and was present in the environment. Only very broad and subjective estimates of some of the uncertainties were presented in the UNSCEAR 2013 Report, and some may have been underestimates. Much more measurement information is now available, particularly on concentrations of radiocaesium and radioiodine in the air, on the chemical form of iodine, on radionuclides consumed in foodstuffs, etc. These have enabled better estimates of the release of radionuclides into the atmosphere and of how the released material was transported, dispersed and deposited in the environment as a function of time, and of doses from the ingestion of food. As a result, the Committee has been able to make not only more realistic estimates of doses, but also more quantitative and less subjective estimates of their uncertainties and the range of variability among individuals within the population.

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[1] The Committee has, exceptionally, taken account of information that became available after this date, where it would affect the findings of the report.

A4. The Committee considers that sufficient new information is now available to support revised estimates of doses to the public that avoid, to the extent practicable, the conservative assumptions made in its previous assessment and provide more quantitative and less subjective assessments of uncertainties and variabilities. To the extent practicable, the Committee has aimed to base its revised dose estimates on measurements, firstly those made on people directly and secondly those made in the environment, and to make greater use of these measurements in validating its updated dose estimates. It has also placed greater reliance on dose assessments made by other researchers and published in the peer-reviewed literature, rather than developing its own models and making its own predictions. For ease of comparison with the UNSCEAR 2013 Report [U10], dose estimates have been made for the same age groups (20-year-old adult, 10-year-old child and 1-year-old infant) and the same dosimetric endpoints (the absorbed dose to selected organs – the thyroid, red bone marrow, colon and female breast – and the effective dose). In addition, estimates have been made of the average absorbed doses to the fetal thyroid over the 30-week development period of the fetus and of the average absorbed dose in utero to the red bone marrow over the 40-week term of pregnancy. Estimates have also been made of doses in the first year after the accident, over the first 10 years and until an attained age of exposed individuals of 80 years, and of annual doses in the year 2021.

A. Exposure pathways

A5. For the radioactive material released to the atmosphere, the principal pathways by which members of the public can be exposed are:

(a) External exposure to radionuclides in the air;

(b) External exposure to radionuclides deposited from the air on to the ground surface by either wet or dry deposition;

(c) Internal exposure from inhalation of radionuclides in the air;

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

These were the pathways considered in the UNSCEAR 2013 Report [U10] and have again been considered in the dose assessment reported here. Members of the public could also have been exposed to radioactive material released to the marine environment, through ingestion of fish and other seafood and exposure to radionuclides in the ocean or on sediments. The former exposure pathway has been included in the estimation of internal exposure from ingestion of radionuclides in food; the latter pathway has not been included because it was not expected to be a significant contributor in view of the inaccessibility of the ocean and sediments within the 20-km evacuation zone established around the FDNPS site.

B. Overview of dose assessment in UNSCEAR 2013 Report

A6. In general, measurements made on people, either of exposures or of radionuclides in the body, provide a more direct source of information for estimating doses. At the time of the UNSCEAR 2013 Report [U10], information on such measurements covered only a limited number of people and locations and was insufficient to make comprehensive estimates of doses to the public and was only used as one means of checking the validity of the Committee’s dose assessment.

A7. The dose assessment in the UNSCEAR 2013 Report [U10] was accordingly largely based on measurements of radioactive material in the environment, combined with models describing how people were exposed to this material. Data were available regarding the radiation levels and deposition densities of radioactive material in every prefecture in Japan, concentrations in foodstuffs, and, to a more limited extent, public exposure. Many of these data were provided by official government agencies in Japan; and 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 and the Committee also considered data made available by several non-governmental organizations. All data were evaluated to determine their suitability for the assessment. Most of the scientific information used in the UNSCEAR 2013 Report was limited to that published or disclosed by the end of October 2012.

A8. In the UNSCEAR 2013 Report [U10], models were used, inter alia, for estimating:

(a) The levels of radionuclides deposited on the ground where insufficient measurement information was available (generally only in the evacuated areas during the periods of the evacuations, where time dependent information is needed), where the Committee's chosen source term was used with ATDM;

(b) Concentrations of radionuclides in the air, where the source term and ATDM were used, either directly for the period of evacuation and for radionuclides which were not deposited on the ground, or to derive air concentrations from measured deposition densities;

(c) The variation, as a function of time, of the external dose rate from deposited radionuclides;

(d) Levels of radionuclides in food beyond the first year after the accident, for which measurements were not available, where the Committee used a modified version of the FARMLAND model [B12] for estimating the transfer of radionuclides through terrestrial food chains.

A9. The Committee took account of the measures implemented by the Japanese authorities to protect the public, including the precautionary evacuation of approximately 78,000 residents within the 20-km area around the FDNPS site and some nearby areas, which took place between 11 and 15 March 2011, and the deliberate evacuation, based on environmental measurements, of about 10,000 residents of several municipalities to the north-west of the FDNPS site, which took place between March and June 2011. About a further 30,000 people were also included among those evacuated: these included some of the people living within the "evacuation prepared area" between 20 km and 30 km from the FDNPS site, who were advised to begin voluntary evacuation on 25 March 2011, as well as some living outside the 30-km radius. In addition, foodstuffs and drinking water containing more than prescribed concentrations of radioactive material were prohibited from sale. The Committee did not take account of other protective measures including directives to shelter in place during the main releases and to take stable iodine, as sufficiently precise information had not been available. Nor was the Committee able to take account of the large land remediation programmes that were being implemented in some of the more affected parts of Fukushima Prefecture due to the lack of detailed information at the time of the UNSCEAR 2013 Report [U10] about the scale and efficacy of the implemented remediation actions.

A10. The Committee's updated estimates of public doses have been compared with the estimates made in the UNSCEAR 2013 Report [U10] in section IV.H of this appendix.

II. INFORMATION FOR DOSE ASSESSMENT

A11. The Committee's revised estimates of doses to the public from internal and external exposure described in this appendix make use of information collected for the UNSCEAR 2013 Report [U10], together with new information that has become available since (up to the end of December 2019).[2] This includes measurement data on people[3] (in particular, personal dosimeters, whole-body counting (WBC) and thyroid measurements), and new measurements of concentrations of radionuclides in the air during the release and on the ground, as well as new information on radionuclides in foodstuff as consumed, occupancy factors, dose reduction factors (location factors) and information on protective measures, including evacuation scenarios.

A12. Chapters II, III and IV have provided summaries of the information now available on releases to the atmosphere and to the ocean, on the distribution of the released radioactive material in the air, on the ground and in the sea and on transfers through the terrestrial, freshwater and marine environments to foodstuffs. More measurement-based information is available on the levels of released radionuclides deposited on to the ground surface and on concentrations of radionuclides in air, more information is available on the transfer of radionuclides through the terrestrial environment in Japanese conditions, and more measurements are available, over a longer period of time, on the levels of radionuclides in foods.

A. Information from measurements made on people within Japan

1. Measurements of individual doses from external exposure

A13. Numerous measurement campaigns have been carried out to assess individual doses from external exposure through surveys of daily activity patterns of residents, measurements of ambient dose rates and individual measurements using personal dosimeters. The most significant of such measurement campaigns (some thousands of measurements per year) were carried out by municipalities, including, for example, Minamisoma City, Date City, Fukushima City, Naraha Town and some others [F18, M31]. The results of these large-scale measurement campaigns have been made widely available to the public and professionals. In addition, the municipalities of Minamisoma and Naraha provided the Committee with anonymized data on personal external doses measured between 2014 and 2019. The large-scale measurements of individual doses [F18, M31, N13, N15, T40, T41] were usually carried out using glass dosimeter badges worn for a period of months, which were subsequently read in laboratories. In smaller-scale scientific studies, either electronic dosimeters with silicon detectors, that provided data on both personal doses and dose rates, or optically stimulated luminescence dosimeters made from aluminium oxide and worn on a strap around the neck were used [H4]. Annual natural background radiation doses of between 0.54 and 0.63 mSv have been subtracted from the measurements as appropriate.

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[2] New information that has become available after December 2019 has been taken into account exceptionally, where it may have a significant impact on the estimates of doses.

[3] These measurement data are described further in section II.A and are examined in detail in attachments A-1, A-2 and A-3. The measurement data can be described in terms of log-normal distributions, giving the Committee confidence in the quality of these data (see the International Atomic Energy Agency (IAEA) report [I5] for a more detailed discussion of the useful role played by analysis of measurement data in terms of log-normal distributions).

A14. Several authors (for example [T40, T41]) have analysed sample data from the large-scale measurement campaigns to study the patterns of external exposure of Japanese people of different ages and different occupations and to test dosimetric models.

A15. Other authors (for example [H4, N13, N15, T10, T42]) carried out measurements of the individual doses on smaller numbers of participants (some tens to some hundreds of people), often accompanied by behaviour surveys and measurements of dose rates in air, with the aim of developing dosimetric models.

A16. The Committee has made use of some of these data and other scientific results published in peer-reviewed journals to validate its estimates of doses from external exposure and in the development of a revised model (M2020) to apply to the wider population. Further details can be found in attachment A-1.

2. Thyroid measurements

A17. Thyroid monitoring to measure directly the ^{131}I content in the thyroid of members of the public provides the most direct source of information on thyroid doses from internal exposure, although estimating doses to the thyroid from measurements requires some assumptions and modelling and is subject to both measurement and modelling uncertainties. Thyroid monitoring began in March–April 2011, on evacuees, permanent residents of Fukushima Prefecture, and residents of Tokyo Metropolitan Area, covering in total more than 1,500 persons of various ages and both sexes. The studies and their results are summarized in table A1. In general, personal interviews were not carried out with those on whom the measurements were made, so assumptions were needed about where those monitored resided, about their consumption of foodstuffs and whether they had been administered stable iodine.

Table A1. Summary of thyroid monitoring studies

Reference	*Measurement dates*	*Location*	*Number of people monitored*	*Method*	*Results*
[H30, K14, K17]	26–30 March 2011	Iwaki City, Kawamata Town, Iitate Village	1 080 (children aged 1–15)	Hand-held NaI(Tl) scintillator survey	598 individuals with measurements at or below measured background; 858 individuals with net exposure rate ≤0.1 μSv/h
[T34]	12–16 April 2011	Evacuees from Namie Town (Tsushima), coastal area of Minamisoma City	62 (aged 0–83 years)	NaI(Tl) scintillation spectrometer	^{131}I detected in 46 people

Reference	*Measurement dates*	*Location*	*Number of people monitored*	*Method*	*Results*
[M11, M45]	15 March–April 2011	Evacuees and short-term visitors to Fukushima	173	Whole-body counter calibrated using bottle manikin absorption phantom	^{131}I detected in 55 people (with minimum detection level (MDL) 30 Bq); and in further 49 people in continued measurements
[U20]	8–20 April 2011	Tokyo and suburbs	268 Russian embassy staff, members of their families, and other Russian citizens (mainly adults with a few children)	Spectrometric measurements	3 adults exceeded MDL of 100 Bq of ^{131}I, with the highest measurement being 130 Bq. Each person was interviewed at the time of measurement

A18. The Committee has used the results of most of these thyroid measurements to validate its estimates of doses to the thyroid from internal exposure. Further details of the methods used and the estimates of doses derived from the thyroid measurement information can be found in sections III.D and IV.G below and in attachments A-2 and A-4.

3. Whole-body monitoring data

A19. Whole-body monitoring campaigns have been carried out by national institutes, such as the Japan Atomic Energy Agency (JAEA) and the National Institute of Radiological Sciences (NIRS), and by universities, hospitals and municipalities. In most cases, subjects have been monitored with fixed whole-body counters equipped with large NaI(Tl) detectors scanning the body for a few minutes, the recorded spectrum enabled either to measure the radiocaesium body content through proper calibration, or to put an upper limit on the content in the case of measurements below MDL.

A20. The results of these campaigns that are publicly available are summarized in table A2. The large-scale measurements began in July 2011 for evacuees and in October 2011 for residents, i.e., four and seven months after the accident, respectively, and long after the first intakes may have occurred. The measured levels of radiocaesium in the body can be used to estimate doses from its intake by inhalation and ingestion; but such estimates depend on knowledge or assumptions about the temporal pattern of intake before the measurements were made and the rate at which radiocaesium is excreted from the body. Further information about the data and the estimates of doses from internal exposure due to intakes of radiocaesium that can be derived from the whole-body monitoring data is set out in attachment A-3.

A21. There have also been whole-body measurement campaigns carried out where the results have not been made publicly available. For example, the Fukushima prefectural government began carrying out whole-body measurements on residents in June 2011 and had screened more than 100,000 residents by 2013 [H9]. The Committee has not had access to information from these campaigns.

Table A2. Summary of whole-body monitoring campaigns carried out following the Fukushima Daiichi Nuclear Power Station accident

Reference	*Measurement dates*	*Target population*	*Measurement programme*	*Age group*	*Number of people monitored*	*Findings*
[M11, M45]	March–April 2011	Adult evacuees and first responders	WBC	Adults	173	– 39% of measurements of ^{134}Cs above MDL (33 Bq) – 32% of measurements of ^{137}Cs above MDL (33 Bq)
[M43]	11 July 2011–31 January 2012	Evacuees from 11 municipalities of Fukushima Prefecture	JAEA fixed WBC in Tokai-Mura JAEA mobile units in Fukushima Prefecture	Adults Children (<17 years)	3 128 6 799	– 80% of measurements below MDL = 300 to 370 Bq – $^{137}Cs/^{134}Cs$ ratio is between 1.12 and 1.26 – No correlation between committed effective dose of children and parents – Maximum body burden: 2.7 kBq (<8-years old), 14 kBq (adults) – Dose calculation based on acute inhalation
[K16]	27 June–28 July 2011	Evacuees from various municipalities of Fukushima Prefecture	NIRS fixed WBC	Adults Children (<15 years)	125 49	– Detection rate: 47% (^{134}Cs, MDL = 320 Bq), 26% (^{137}Cs, MDL = 570 Bq) – $^{137}Cs/^{134}Cs$ = 1.1 – Committed effective dose based on acute intake on 15 March 2011 – Data compare well with JAEA estimates – ^{134}Cs body burden adult: ~550 Bq/body (mean), 300 Bq/body (median), 7 kBq/body (max) – Committed effective dose based on the most conservative scenario – No significant difference in committed effective dose for adults and children

Reference	*Measurement dates*	*Target population*	*Measurement programme*	*Age group*	*Number of people monitored*	*Findings*
[H10]	11 July–29 July 2011	Evacuees from Minamisoma City who had subsequently returned	Anzai chair-type WBC	Adults (≥16 years)	566	– Complex and indirect corrections had to be applied to the measurements for shielding by the body – Average body burden of ^{134}Cs in July 2011 was 825 ± 360 ± 110 Bq
[H9]	October 2011–February 2012	Residents of Fukushima Prefecture (73%), Ibaraki Prefecture (23%)	Fixed WBC at Hirata Central Hospital	Adults Children (<15 years)	4 716 6 310	– Some measurements might have been affected by external contamination – ^{137}Cs detection rate maximum in November–December 2011 (15% for all population), then decreases below 5% after February 2012 (MDL = 300 Bq) – ^{137}Cs body burden, whole population: ~12 Bq/kg (mean), ~9.5 Bq/kg (median), 77 kBq/kg (max)
[T38]	October 2011–March 2012	Residents of Minamisoma City	Fixed WBC at Minamisoma Municipal General Hospital	Adults Children (<15 years)	8 066 1 432	– Children detection rate = 16.4%, median body content = 590 Bq (for positive measurements) – Adults detection rate = 38%, median body content = 744 Bq (^{134}Cs and ^{137}Cs, for positive measurements) – MDL = 210 Bq for ^{134}Cs, 250 Bq for ^{137}Cs in adults – Difference in exposure between adult and children is statistically significant

Reference	*Measurement dates*	*Target population*	*Measurement programme*	*Age group*	*Number of people monitored*	*Findings*
[S40]	October 2011–March 2012	Residents of Minamisoma City	Fixed WBC at Minamisoma Municipal General Hospital	Adults Children (<15 years)	7 214 1 067	– ^{134}Cs or ^{137}Cs detected in 40% of adults (MDL = 210 Bq for ^{134}Cs, 250 Bq for ^{137}Cs) and 9% of children – For positive measurement of ^{134}Cs and ^{137}Cs median body burden was 11 Bq/kg for adults and 8.5 Bq/kg for children – Contains an analysis of risk factors (food consumption and habits) related to Cs detection, not detailed here
[T38]	April 2012–March 2013	Residents of Minamisoma City	Fixed WBCs at Minamisoma Municipal General Hospital and Hirata Central Hospital	Median age 14 years Age range 2–97 years	30 622	– ^{137}Cs detected in 612 participants (6.1%) from Minamisoma Hospital (MDL = 210 Bq for ^{134}Cs, 250 Bq for ^{137}Cs) and 144 participants (0.7%) from Hirata Hospital (MDL = 300 Bq for ^{134}Cs and ^{137}Cs) – >50 Bq/kg ^{137}Cs detected in 9 participants – Median ^{137}Cs content in body of these 9 participants 4 830 Bq (69.6 Bq/kg); range 2 130 to 15 918 Bq (50.7 to 216.3 Bq/kg) – All 9 participants consumed homegrown produce and wild mushrooms

B. Environmental monitoring data

A22. There have been extensive measurements of the levels of radioactive material in the environment across Japan following the FDNPS accident. JAEA has collected environmental monitoring data published by various organizations related to the accident, including dose rate in air (from airborne and deposited radionuclides), and radionuclide concentrations (ground surface, soil, seawater, marine sediments, river water, river sediment, groundwater, and food). These data sets form the Environment Monitoring Database (EMDB) which is available to the public through an online website [J3].

A23. A total of 62 data sets related to the measurement of dose rate in air, radionuclide ground deposition density, and radionuclide concentrations in air and in food and drinking water were downloaded from EMDB by the Committee over the period between August and October 2018. These data sets reported the results of over 200 radiation surveys carried out in Japan between March 2011 and March 2018 by government bodies and other organizations. Only a small subset of these EMDB data sets were used for this dose reassessment. These are listed in table A3.

A24. The Committee systematically catalogued these downloaded EMDB data sets, with the files renamed to reflect the source and type of data in the data files. The full collection comprised over 16 GB of measurement data and over a thousand files. A full list of the downloaded EMDB data sets is provided in attachment A-5. The Committee undertook a process of quality assurance, including extensive checks to determine whether the measurements were scientifically sound and fit for purpose, consistent with the processes undertaken in the preparation of the UNSCEAR 2013 Report [U10].

A25. The downloaded EMDB data sets and any derived data sets were categorized into three data set types: "original", "primary" and "derived", reflecting the nature of the data analysis and the quality assurance processes. Original data sets were as downloaded from a trusted website at a specific time or provided by a trusted source as per an official request or similar. Aside from a possible renaming of the file, the content in the original downloaded data set files was un-modified. Primary data sets were produced from the original data sets by adding additional quality assurance, metadata and workflow worksheets to the spreadsheet. Finally, derived data sets were produced from one or more primary data sets, through a combination of information at the same location or the addition of additional information such as demographic data. These were subjected to independent checking and testing before use by the Committee.

A26. Consistent with the approach in the UNSCEAR 2013 Report [U10], the recorded latitude and longitude of the sampling locations for the EMDB radionuclide ground deposition data sets were used to allocate the updated deposition measurements to the corresponding cell in the Japan 1 km grid to allow combination with the population data. The Japanese Government has divided Japan into a grid for the purposes of reporting relevant geospatial information, including population data. The dimensions of these grid cells were approximately 10 by 10 km. A third-order grid was obtained by equally dividing the second-order grid cells into further 10 by 10 cells. The horizontal and vertical distances of the third-order grid cells were approximately 1 by 1 km.

A27. Two data sets, in particular, the 2,200-location soil deposition data set and the data set with ^{131}I deposition densities derived from analysis of measurements of ^{129}I [M50] formed the basis for the assessment of external exposure from deposition in municipalities within Fukushima Prefecture, and the derived tables are provided in attachments A-6 and A-7. The two data sets were combined with other population and demographic data to produce a derived data set provided in attachment A-8. In the data set used for the UNSCEAR 2013 Report [U10], ^{131}I was detected at approximately 400 locations out of the more than 2,200 locations at which soil was sampled; the updated data set in attachment A-8 now includes ^{131}I deposition densities at approximately 800 locations.

Table A3. Japan Atomic Energy Agency Environment Monitoring Database data sets used in the update of doses to the public

Data set title	*Website data set description*	*Organization*	*Period covered*
Results of the radionuclide analysis of soil sampling at 2 200 locations in Fukushima Prefecture and neighbouring prefectures	Ambient dose equivalent rates were measured, and soil samples collected from 6 June to 8 July 2011 for areas within 100 km from FDNPS. From FDNPS out to 80 km these were undertaken on 2 km × 2 km grids. Between 80 km and 100 km from FDNPS they were divided into 10 km × 10 km grids. Ambient dose equivalent rates were measured at a height of 1 m above the ground surface at one location in each of these divided grids (nearly 2 200 locations in total), and soil samples were collected at five points at each location. Around 11 000 soil samples were taken; deposition densities of five gamma-emitting radionuclides (^{110m}Ag, ^{129m}Te, ^{131}I, ^{134}Cs and ^{137}Cs) were measured using Germanium Semiconductor Detectors. JAEA conducted the survey with cooperation of various universities and research institutes. Ministry of Education, Culture, Sports, Science and Technology (MEXT) was responsible for the coordination of the measurement data and assessment of validity [S1]	MEXT	Decay correction: 14 June 2011
Radioactivity concentration analysis of iodine in the distribution survey of radioactive substances	This series of data was created to derive deposition density of ^{131}I using the deposition density of ^{129}I. This data set was prepared from published results of ^{129}I deposition densities obtained in the soil samples where ^{131}I was measured in the first distribution survey. A part of the soil sample was used to measure ^{127}I (stable iodine) by Inductively Coupled Plasma Mass Spectrometry. The ratio of ^{129}I atomicity to ^{127}I atomicity was measured by accelerator mass spectrometry. The concentration (Bq/kg) of ^{129}I in the soil sample was derived using concentration of ^{127}I and the (^{129}I)/(^{127}I) ratio. The ^{129}I deposition density (Bq/m^2) was derived from the mass and volume of the relevant soil sample [M17, M49]	MEXT, and the Secretariat of the Nuclear Regulation Authority	Fiscal year 2011–Fiscal year 2013

Table A4. Other environmental monitoring data sets used in the assessment of doses to the public

Data set title	*Website data set description*	*Organization*	*Period covered*
Measured concentrations in soils	These data were officially provided by the Government of Japan for the UNSCEAR 2013 Report [U10]. There are 3 422measurements of ^{134}Cs and ^{137}Cs in cultivated soils in 15 prefectures in eastern Japan (Fukushima, Iwate, Miyagi, Yamagata, Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, Kanagawa, Niigata, Yamanashi, Nagano and Shizuoka), based on samples collected from 26 April 2011 to 3 February 2012. The cultivated soil activities were adjusted to a reporting date of 5 November 2011. The original data sets were supplied as pdf files, data were converted and cross-checked to produce data in spreadsheet format. The Committee reviewed this data set and considered it acceptable and fit for purpose	Japanese Ministry of Agriculture, Forestry and Fisheries	26 April 2011 to 3 February 2012 Decay corrected – 5 November 2011

A28. In the UNSCEAR 2013 Report [U10], the Committee's focus was on estimating exposures of individuals considered to be representative of different subsets of the Japanese population. Dose estimates were presented as population-weighted averages for different geographical areas, either municipalities, or prefectures, depending broadly on distance from FDNPS. In the updated data sets, the spatial coverage in prefectures neighbouring and nearby Fukushima Prefecture was different and this has led to some changes in the groupings of prefectures compared with the UNSCEAR 2013 Report.

A29. Measurements of concentrations of radionuclides in air over Japan while the release was happening were rather limited, in particular, in the early stages of the accident and in the areas devastated by the tsunami. New data on the concentrations of radionuclides in airborne aerosols have become available for seven locations within the Japanese mainland for each hour of the period from 12 March to 11 May 2011 [D7]. The data were derived from measurements on samples collected by the United States Department of Defense (DoD) and the United States Department of Energy (DOE) at or near locations where DoD-affiliated individuals worked or lived. Further information about the levels of radionuclides in the air and deposited on the ground has come from reanalysis of monitoring data collected at the time of the accident by the application of some novel analysis methods. Specifically, concentrations of different radionuclides in the air in the early stage of the FDNPS accident have been estimated at several monitoring posts in Fukushima and Ibaraki Prefectures from gamma spectrometry using sodium iodide scintillation detectors [H17, M44, T29]. In addition, concentrations of ^{137}Cs and ^{129}I (from which levels of ^{131}I can be inferred) in air at ground-level in the Fukushima and Kanto areas are being derived from an analysis of filter-tapes of air pollution stations (for monitoring suspended particulate matter) [E1, O25, T50, T51], although it should be noted that only iodine in particulate form will have been collected on the filter-tapes. The latest version of the data set produced by this work, which includes information on ^{137}Cs levels for 101 locations and on ^{131}I for 4 locations, has provided an important input into the detailed analyses described in this appendix. These new sources of information on concentrations of radionuclides in air are summarized in table A5.

Table A5. Summary of measurements of concentrations of radionuclides in air over Japan

Reference	*Measurement type*	*Location*	*Radionuclides*
[H16]	$LaBr_3$ scintillation detector	Fukushima Prefecture, 6 measurement points (Abukuma-kogen service area, Adatara service area, Funehiki-Miharu interchange, Koriyama-higasi interchange, Miharu parking area, Motomiya interchange)	^{132}Te, ^{131}I, ^{132}I, ^{133}Xe, ^{136}Cs, ^{134}Cs
[H17]	NaI(Tl) scintillation spectrometer in automated monitoring station	Fukushima Prefecture, 9 monitoring stations (Fukushima City Momijiyama, Futaba Town Koriyama, Futaba Town Yamada, Hirono Town Futatsunuma, Naraha Town Matsudate, Okuma Town Minamidai, Okuma Town Mukaihata, Okuma Town Oono, Okuma Town Ottozawa)	^{131}I
[H18]	NaI(Tl) scintillation spectrometer in automated monitoring station	Fukushima Prefecture, 8 monitoring stations (Fukushima City Momijiyama, Futaba Town Yamada, Hirono Town Futatsunuma, Naraha Town Matsudate, Okuma Town Minamidai, Okuma Town Mukaihata, Okuma Town Oono, Okuma Town Ottozawa)	^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{135}Xe, ^{133}Xe, ^{135m}Xe
[K12]	NaI(Tl) scintillation spectrometer in automated monitoring station	Fukushima Prefecture, 8 monitoring stations (Fukushima City Momijiyama, Futaba Town Yamada, Hirono Town Futatsunuma, Naraha Town Matsudate, Okuma Town Minamidai, Okuma Town Mukaihata, Okuma Town Oono, Okuma Town Ottozawa)	^{131}I
[T29]	NaI(Tl) scintillation spectrometer in automated monitoring station	Ibaraki Prefecture, 6 monitoring stations (Ajigaura, Araji, Ishikawa, Muramatsu, Ohnuki, Sugaya)	^{133}Xe, ^{132}Te, ^{131}I, ^{132}I, ^{133}I, ^{137}Cs, ^{134}Cs, ^{136}Cs
[M44]	NaI(Tl) scintillation spectrometer in automated monitoring station	Ibaraki Prefecture, 21 monitoring stations (Ajigaura, Araji, Ebisawa, Funaishikawa, Hiroura, Hitachinaka, Horiguchi, Ishigami, Ishikawa, Isobe, Kadobe, Kuji, Mawatari, Muramatsu, Ohba, Ohnuki, Oshinobe, Sugaya, Toyooka, Tsukuriya, Yokobori)	^{133}Xe, ^{132}Te, ^{131}I, ^{132}I, ^{133}I
[F17]	Gamma-spectrometric measurement with Germanium detectors	Fukushima Prefecture, 14 monitoring stations (very few measurements each)	^{132}Te, ^{131}I, ^{132}I, ^{137}Cs, ^{134}Cs
[T51]	Filter samples	Fukushima Prefecture, 2 suspended particulate matter monitoring stations (Futaba Town, Naraha Town)	^{137}Cs, ^{134}Cs

Reference	*Measurement type*	*Location*	*Radionuclides*
[O25]	Filter samples measured with Germanium detectors	Several prefectures, 99 suspended particulate matter monitoring stations	^{137}Cs, ^{134}Cs
[E1]	Filter samples analysed with accelerator mass spectrometry	Tokyo Metropolitan Area, 4 monitoring stations (Institute of Physical and Chemical Research, Kakinoki-zaka, Tokyo Metropolitan Industrial Technology Research Institute, Tokyo Metropolitan University)	^{129}I, ^{131}I, ^{137}Cs
[D7]	Filter samples analysed with gamma-spectrometry systems	4 monitoring stations (Ishinomaki (City of Ishinomaki), Misawa Air Base, Sendai (Sendai Airport), Yokota Air Base)	^{140}Ba, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{131}I, ^{133}I, ^{140}La, ^{86}Rb, ^{99}Mo, ^{99m}Tc, ^{129}Te, ^{129m}Te, ^{131m}Te, ^{132}Te
[A10]	Filter samples analysed with gamma-spectrometry systems	Chiba Metropolitan Area, 1 monitoring station (JCAC)	^{134}Cs, ^{136}Cs, ^{137}Cs, ^{131}I, ^{132}I, ^{133}I, ^{132}Te
[D4]	Filter samples analysed with gamma-spectrometry systems	Tsukuba, 1 monitoring station (NIES)	^{131}I, ^{133}I ^{132}Te, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{129m}Te, ^{99}Mo
[J2]	Filter samples analysed with gamma-spectrometry systems	Filter samples, 3 monitoring stations	^{131}I, ^{133}I, ^{132}Te, ^{134}Cs, ^{136}Cs, ^{137}Cs, ^{129m}Te

C. Monitoring of food and drinking water

A30. In the UNSCEAR 2013 Report [U10], the Committee estimated doses from ingestion using the Food and Agriculture Organization/IAEA food database, which included measurement data for over 500 types of foodstuffs sampled in all 47 prefectures in Japan, and data on concentrations of radionuclides in drinking water provided by the Japanese Ministry of Health, Labour and Welfare. The food measurement data used were for foodstuffs as marketed and information about how much of particular foodstuffs were consumed per capita of the population was based on surveys carried out in Japan.

A31. In addition to the food and drinking water monitoring data in the JAEA EMDB data sets listed in attachment A-5, new sources of information available that are relevant to estimating the dose from ingestion include measurements of the radiocaesium content in the whole daily diet sampled by the duplicate-diet or market-basket methods. These methods generally take account of intakes from both food and drinking water. In the available literature, six publications contained data of this type collected in 2011–2013 in Fukushima Prefecture, four neighbouring prefectures (Ibaraki, Iwate, Miyagi and Tochigi) and eight distant prefectures (Hokkaido, Kanagawa, Kochi, Nagasaki, Niigata, Osaka, Saitama and Tokyo) located in various parts of Japan. These studies are summarized in table A6.

Table A6. Summary of sources of information for estimating intakes of radiocaesium in the daily diet

Reference	*Measurement dates*	*Location*	*Number of samples*	*Method*	*Results*
[K33]	July 2011	Iwaki, Soma, Nihonmatsu and Fukushima cities	10–25 daily food sets in each city	Market-basket (grocery stores)	Average daily intakes of each of ^{134}Cs and ^{137}Cs: 3 Bq/d (Soma City) to 0.4 Bq/d (Fukushima City) Average daily intake for Fukushima Prefecture (55 samples) 1.1 ± 1.5 Bq/d
[T53]	September 2011	Tokyo, Miyagi Prefecture, Fukushima City	14 food sample groups in three study areas	Market-basket (local food markets)	Daily intake rate of ^{137}Cs estimated at 0.4 Bq/d (Tokyo), 3 Bq/d (Miyagi Prefecture), 3.3 Bq/d (Fukushima City)
[S12]	November 2011–March 2012 and June–September 2012	Kenpoku and Kenchu areas of Fukushima Prefecture	200	Duplicate-diet (100 families)	Mean concentration in daily meals of ^{134}Cs 0.27 ± 0.45 Bq/kg, and of ^{137}Cs 0.37 ± 0.61 Bq/kg
[H3]	4 December 2011	Fukushima Prefecture and neighbouring prefectures	53	Duplicate-diet	Mean dietary intake of each of ^{134}Cs and ^{137}Cs: 4.5 ± 2.6 Bq/d (Fukushima Prefecture)
[H4]	August 2012	Three municipalities (Kawauchi Village, Soma City and Minamisoma City) of Fukushima Prefecture	125	Duplicate-diet	Average daily intake of ^{134}Cs and ^{137}Cs combined: 1.1 Bq/d (Kawauchi Village) to 3.5 Bq/d (Tamano area, Soma City)
[U2]	Winter 2012, autumn 2012, winter 2013	Three regions (Hamadori, Nakadori and Aizu) of Fukushima Prefecture, four neighbouring prefectures and eight distant prefectures	939	Market-basket and duplicate-diet	Daily intake of ^{134}Cs and ^{137}Cs combined (market-basket method): 0.17–1.7 Bq/d (winter, 2012), 0.15–0.68 Bq/d (autumn, 2012), 0.15–1.3 Bq/d (winter, 2013) Intake rate was higher in Fukushima Prefecture and neighbouring prefectures than in distant areas and decreased with time in most areas

A32. Intakes from food and drinking water have been assessed in a number of studies by Japanese researchers [H15, K10, M34, M47]. Murakami and Oki [M47] made estimates of the doses from ingestion of food and drinking water containing ^{131}I, ^{134}Cs and ^{137}Cs, based on food monitoring data. They used data from a wider range of sources than was available to the Committee when preparing the UNSCEAR 2013 Report [U10] and took account of the regional trade in foods (specifically, of the shares of foods from different parts of Japan arriving at food markets, where most Japanese citizens purchase food). The studies by Hirakawa et al., Kawai et al. and Miyatake et al. [H15, K10, M34] have focused on the early period after the FDNPS accident. They have provided evidence based on surveys that, because of the after-effects of the earthquake and tsunami and the resulting collapse in supply chains, very little, if any, food potentially containing elevated levels of radioactive material released as a result of the accident was consumed, particularly in the municipalities that were evacuated, even before food restrictions were put in place. Most of the food that evacuees consumed immediately after the accident was sourced from either stockpiles prepared before the accident or relief supplies from outside the affected area. As a result, the majority of intakes from ingestion in this early period, certainly for evacuees, would have been from drinking water. Measurements of radionuclides in drinking water began shortly after the accident and were used in the UNSCEAR 2013 Report to estimate doses from ingestion of drinking water. However, measurements of the shorter-lived radionuclides, specifically ^{131}I, were relatively limited and estimates of doses from ingestion of ^{131}I in tap water have therefore generally made use of models, complemented by measurements where available.

D. Radiation measurements outside of Japan

A33. In the UNSCEAR 2013 Report [U10], the 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, supported by the extensive measurements and dose assessments carried out by Member States. The Committee has made a further review of the literature published since the UNSCEAR 2013 Report. These are summarized in section IV.E of this appendix together with the Committee's latest assessment of doses in countries neighbouring, or in close proximity to, Japan.

III. METHODOLOGY FOR ASSESSING DOSES TO THE PUBLIC

A34. There is considerably more good quality measurement information available than was available to the Committee at the time of preparation of the UNSCEAR 2013 Report [U10], including measurements made on people, in the environment and in foodstuffs as consumed by members of the public. As well as this additional measurement information, Japanese researchers have carried out many detailed assessments of doses and published the results in the literature. The Committee has made use of all of this information in its revised assessment of doses to members of the public. Where possible, the Committee has placed greater reliance on the results of studies published in the literature rather than carrying out its own modelling. However, it still needed to make use of some models for a full dose assessment comparable with that in the UNSCEAR 2013 Report. The approaches used by the Committee, including the models applied, are described briefly in this section, with further detail provided in attachments. The Committee has also used the additional information that has become available since the UNSCEAR 2013 Report to test and refine its models, reducing and providing a better estimation of uncertainties and variabilities; the measurements made on people, in particular, have proved valuable in validating the models that had to be used for estimating doses in the wider population.

A. Regions considered for dose estimation

A35. In order to estimate doses to members of the public in Japan, the Committee again focused on four groups of geographical areas (see table A7):

- Group 1 included locations in Fukushima Prefecture from which members of the public were evacuated in the days to months after the accident according to 40 evacuation scenarios;
- Group 2 included all municipalities and parts of municipalities in Fukushima Prefecture that were not evacuated;
- Group 3 included selected prefectures (Ibaraki, Miyagi, Tochigi and Yamagata) in eastern Japan that were neighbouring Fukushima Prefecture;
- Group 4 included all the remaining 42 prefectures of Japan.

Table A7. Population groups considered

Population group	*Geographical areas*	*Spatial resolution*
1	Locations where people were evacuated in the days to months after the accident	Representative areas were used for each location identified in 40 evacuation scenarios
2	Municipalities[a] and parts of municipalities of Fukushima Prefecture[b] not evacuated	Municipality level for external and inhalation pathways, based on the estimates for each of the 1-km grid points, averaged over the municipality Prefecture level for ingestion pathway
3	Selected prefectures (Ibaraki, Miyagi, Tochigi and Yamagata) in eastern Japan that are neighbouring to Fukushima Prefecture	Municipality level for external and inhalation pathways, based on the estimates for each of the 1-km grid points, averaged over the municipality Average for the four prefectures (Ibaraki, Miyagi, Tochigi and Yamagata) for ingestion pathway
4	All remaining prefectures of Japan	Prefecture level for external and inhalation pathways Average of the rest of Japan (i.e., the 42 prefectures, excluding Fukushima, Ibaraki Miyagi, Tochigi and Yamagata) for ingestion pathway

[a] Each prefecture of Japan (see below) is divided into municipalities. A municipality is a local administrative unit; the municipalities are used primarily in the Japanese addressing system to identify the relevant geographical areas and collections of nearby towns and villages. The term “municipality” has been used in this report in place of the term “district” in the UNSCEAR 2013 Report [U10].

[b] Japan comprises of 47 prefectures. In Japanese the word “prefecture” is used for translating references to “ken” in Japanese.

A36. The spatial resolution adopted for assessing the doses in each of these groups was dependent on the available data:

– Estimates for Group 2 were made at the municipality level for the external exposure and inhalation pathways, and at the prefecture level for the ingestion pathway;

– The selection of the four prefectures in Group 3 was based on the spatial coverage of the available measurement information on deposition densities. Estimates of dose for Group 3 were made at the municipality level for a number of municipalities (where the spatial resolution allowed) for the external exposure and inhalation pathways. The dose from ingestion for all four of these prefectures in Group 3 (Ibaraki, Miyagi, Tochigi and Yamagata) was based on the average for these four prefectures;

– Doses for all Group 4 prefectures were assessed at prefectural level for the external exposure and inhalation pathways, and on the basis of an average for the remaining 42 prefectures together for the ingestion pathway.

B. Source term and atmospheric transport, dispersion and deposition modelling for Japan

A37. While there is more information available on the concentrations of radionuclides in the air and deposited on to the ground and other surfaces than was available for the UNSCEAR 2013 Report [U10], all of the information now available is not sufficient to allow estimates of doses based solely on measurements and some modelling has been necessary. In particular, in order to estimate doses from radioactive material in the air, both from external exposure to this material and from internal exposure from its inhalation, modelling was needed to obtain estimates of concentrations of radionuclides in air at all locations of interest, as measurements remain sparse. The approach used in the UNSCEAR 2013 Report has again been used. Nonetheless, the greater amount of measurement information now available has been used to test this approach and provide greater assurance about its validity.

A38. Accordingly, exposures from radioactive material in the air at specific times and locations have been estimated from the assumed time sequence of the release of the more significant radionuclides and their transport through the atmosphere using ATDM. In this report, the Committee has used the latest source term developed by the group of researchers at JAEA [T28]. This source term [T28] has been developed from all of the measurement information on levels of radionuclides in the air and deposited on the ground using improved ATDM simulation with an optimization method based on Bayesian inference, as well as information on events occurring on-site as the accident progressed. It represents a further refinement of the series of source terms estimated by the same group of researchers (e.g., [C3, K6, K30, T27]) and has been optimized using various measurements, such as air concentration, surface deposition, and newly released hourly air concentrations of ^{137}Cs derived by analysing suspended particulate matter collected at air pollution monitoring stations [O25, T51]. Further details about this source term and ATDM and how its results compare with measurement information are provided in attachment A-9.

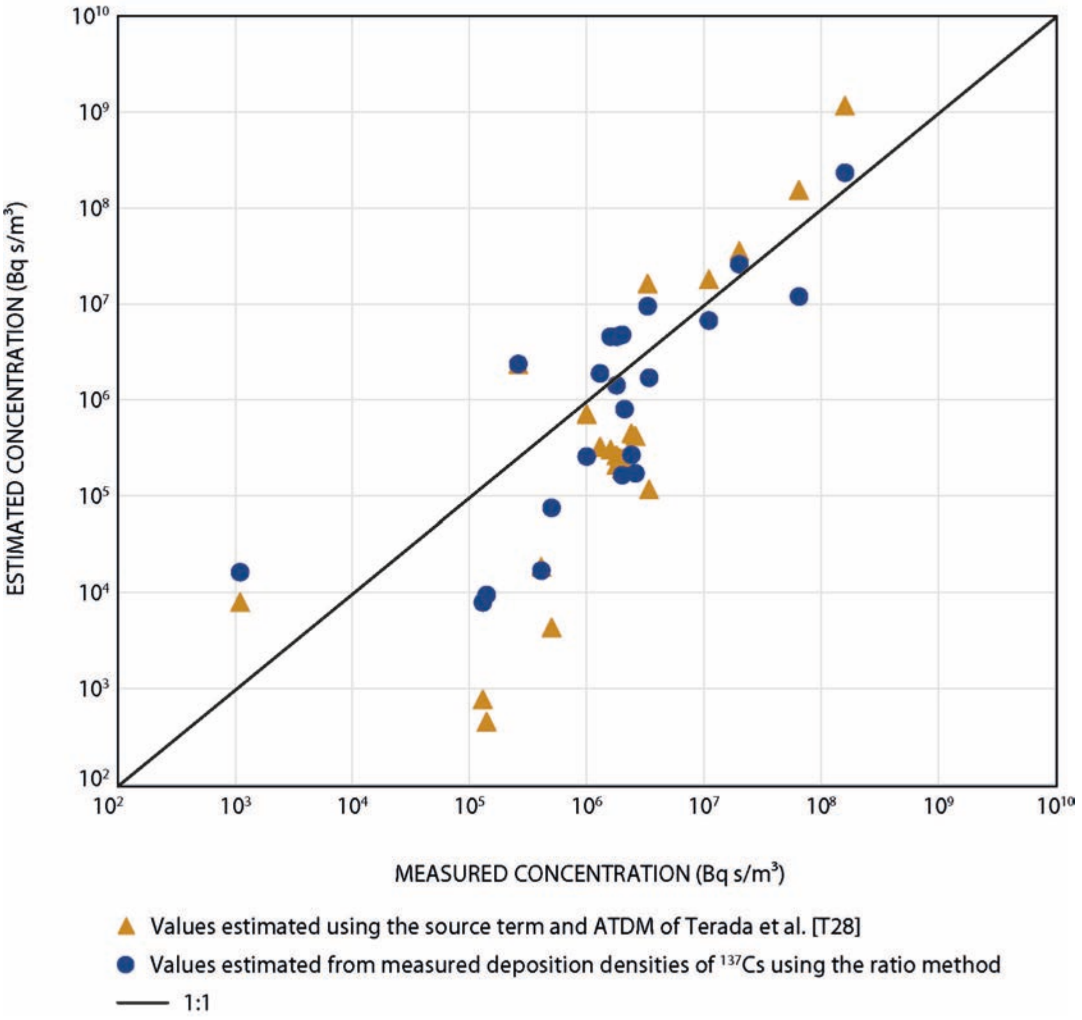
A39. Terada et al. [T28] have used the same ATDM (Worldwide version of System for Prediction of Environmental Emergency Dose Information – WSPEEDI) with this source term to estimate the time-dependent concentrations in air and deposition densities of the radionuclides ^{132}Te (and therefore of its daughter radionuclide, ^{132}I, with which it is assumed to be in equilibrium), ^{131}I, ^{134}Cs and ^{137}Cs. For ^{131}I (and the other radioiodines), three chemical forms have been considered: inorganic particulate, elemental vapour, and organic, using the constant ratios, based on experimental and other evidence, of 0.5 for $^{131}I_{particulate}/^{131}I_{total}$, 0.2 for $^{131}I_{elemental}/^{131}I_{total}$ and 0.3 for $^{131}I_{organic}/^{131}I_{total}$. This ATDM includes a new meteorological model (Weather Research and Forecasting Model), better modelling of deposition, and an improved data assimilation method [T28]. The ATDM results have been provided by JAEA to the Committee for two nested grids:

- The finer grid covering most of Fukushima Prefecture with a horizontal resolution of 1 km;
- The coarse grid covering Fukushima Prefecture and all neighbouring prefectures with a horizontal resolution of 3 km [T28].

A40. Terada et al. did not include the short-lived radionuclide ^{133}I and the Committee has therefore estimated the concentration of ^{133}I in air from the calculated concentrations of ^{131}I in air by applying a time-dependent ratio of the two radioisotopes based on the ratio at 14:46 JST on 11 March 2011 [N12], adjusted for their half-lives. Terada et al. also did not include ^{133}Xe, and the Committee has not included this radionuclide in its estimates of doses. Xenon-133 would have contributed significantly to the dose from external exposure to airborne radioactive material, adding about 30% to the estimated effective doses from this pathway. However, the estimated effective dose from this pathway is typically only about 1% to 3% of the estimated effective dose from internal exposure from inhalation of airborne radioactive material, so the contribution of ^{133}Xe to the estimated total effective doses from airborne material would have been less than 1%, which is small compared with uncertainties in these estimates (see attachment A-10 for further details). The details of the ATDM model and the outputs used for the Committee's assessments are described in attachment A-9.

A41. As in the UNSCEAR 2013 Report [U10], the ATDM estimates of concentrations of radionuclides in the air as a function of time have been used directly to estimate doses to evacuees from external exposure to the airborne radionuclides and doses from internal exposure from inhaled radionuclides. At locations where members of the public were not evacuated, the ATDM estimates of deposition density and of time integrated concentration of each radionuclide in air have been used to calculate ratios by which measured deposition densities have been scaled to infer a time integrated air concentration from which external exposure to airborne radionuclides and internal exposure from inhalation have been derived. As the Committee stated in the UNSCEAR 2013 Report, while estimates of radionuclide concentrations in air and deposition densities provided by the assumed source term and ATDM simulations at any specific location are uncertain, the ratios of these two estimates are, in general, likely to be much less so. For the revised source term and ATDM adopted by the Committee in this report, the time-integrated air concentrations estimated directly from the ATDM and those derived by scaling the measured deposition density by the ratio method have been compared with the available measurements of time integrated air concentration in figure A-I. The figure shows that, using the ratio method around 50% of the estimates are within a factor of about 2 of the measurements and almost all estimates are within a factor of about 10; and that estimates are distributed both above and below the corresponding measured values. On the other hand, using the source term and ATDM to estimate time integrated air concentrations, results in estimates that are less close to the measurements and, at the higher air concentrations, generally higher than the measured values. At lower air concentrations neither method provides a good fit with the measurements, with estimated values being generally below the measurements.

Figure A-I. Comparison[a] of the measured time integrated concentration of ^{137}Cs in air with estimated values



[a] The straight line shown in the figure indicates where the modelled air concentration and the measured air concentration would be equal. Data points above this line indicate measured air concentrations where the modelled air concentrations overestimate the measurements; data points below this line indicate where the modelled air concentrations underestimate the measurements.

A42. These comparisons provide support to the method being used by the Committee to estimate time integrated air concentrations of radionuclides and the resulting doses to residents (i.e., those not evacuated).

C. Assessment of external exposure

1. External exposure from deposited material

(a) *Doses for residents*

A43. In the UNSCEAR 2013 Report [U10], the Committee assessed doses from external exposure to radionuclides deposited on the ground and other surfaces from the measurement data on deposition densities of radionuclides using models for:

(a) The estimation of the air kerma rate in free-in-air condition at a reference site;

(b) Time-dependent location factors that take account of where people were located and their size and of shielding provided by buildings, as well as radionuclide migration in the environment owing to weathering, cleaning and other factors;

(c) Occupancy factors that take account of the amounts of time spent by different population groups in different types of location;

(d) Coefficients to convert air kerma rate to absorbed dose rate in a particular organ or effective dose rate.

Location factors made use of information on house types typical of Japan but were largely based on post-Chernobyl experience and parameters determined for areas in the Russian Federation and Ukraine. Occupancy factors were derived based on available data from Japanese national surveys at that time. The dose rate coefficients used were based on the computational phantom for adults specified by the International Commission on Radiological Protection (ICRP) [I19] and other voxel phantoms for different age groups with account taken of growth [G4, P2].

A44. Since the UNSCEAR 2013 Report [U10], further information has become available relating to the deposition densities of ^{131}I and to the dynamics of ambient dose rates in the environment specific to Japanese conditions. Extensive measurements of individual dose from external exposure made directly on people have also become available. In addition, ICRP has developed new dosimetric data relevant for assessing dose from external exposure in a post-accident situation [I22]. The Committee has taken account of these developments to derive an improved model (M2020) for assessing doses from external exposure to deposited radionuclides and made comparisons with the measurements made on people to provide more robust testing and validation of this model. Details of the improved model and its validation can be found in attachment A-1.

A45. In the UNSCEAR 2013 Report [U10], to derive deposition densities where measurements for some radionuclides were lacking (e.g., ^{131}I), the measured deposition density of ^{137}Cs (which was measured in all samples) was scaled by the average ratio of the deposition density of the radionuclide to that of ^{137}Cs for samples where both were measured. Different ratios were used for the South trace (Hirono Town, Iwaki City, Naraha Town and Tomioka Town in Fukushima Prefecture, and Kitaibaraki City and Takahagi City in Ibaraki Prefecture) because the ratios for ^{129m}Te and ^{131}I were significantly elevated there in comparison with elsewhere. In its revised assessment, the Committee has used a similar approach with the same ratios, apart from those for ^{131}I, ^{132}Te (and its daughter ^{132}I) and ^{129m}Te. For these radionuclides, the available measurement data are more consistent with ratios based on non-linear relationships with the deposition densities of ^{137}Cs rather than constant values, and approximate empirical relationships have been derived from the data. Table A8 provides a summary of the ratios applied.

Table A8. Initial ratios at 15 March 2011 used, where measurements were lacking, to estimate deposition densities of the shorter-lived radionuclides from the initial deposition density of ^{137}Cs

Area	*Deposition density ratios for radionuclide (dimensionless)*						
	^{137}Cs	^{134}Cs	^{136}Cs	^{131}I	^{129m}Te	^{132}Te (^{132}I)[a]	^{110m}Ag
All of Japan excluding the South trace	1.0	1.0	0.17	8.3–37[b]	1.1–1.9[b]	7.6–13[b]	0.0028
The South trace[c]	1.0	1.0	0.17	25–250[b]	1.7–28[b]	12–190[b]	0.0028

[a] Activity of the daughter ^{132}I was assumed equal to activity of the parent ^{132}Te at the time of deposition.

[b] Non-linear relationships were applied for isotopic activity ratios. See attachment A-1 for more details.

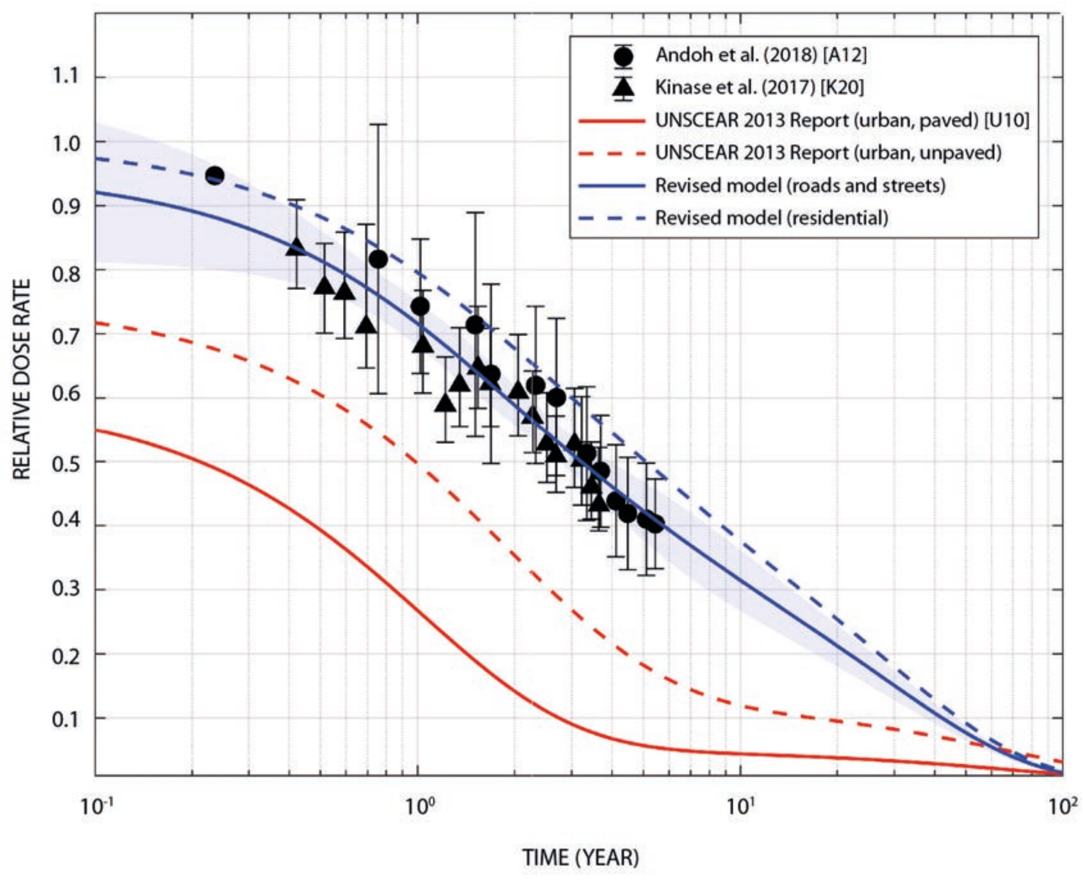
[c] Hirono Town, Iwaki City, Naraha Town and Tomioka Town of Fukushima Prefecture, Kitaibaraki City and Takahagi City of Ibaraki Prefecture.

A46. As indicated above, ICRP has developed revised dose rate coefficients for air kerma and ambient dose equivalent at 1 m above an infinite planar source at a mass depth of 0.5 g/cm^2 in soil [I22]. It has also presented dose rate coefficients for effective dose and sex-specific organ dose equivalents for six reference ages. While these revisions do not greatly affect the estimates of doses, the Committee has used these ICRP dose rate coefficients rather than the dose rate coefficients used in the UNSCEAR 2013 Report [U10], because they represent the current state of knowledge and are consistent with its aim to make realistic estimates of doses.

A47. Extensive monitoring studies in Fukushima and neighbouring prefectures have been published since the UNSCEAR 2013 Report [U10] on the effects of natural migration in soil, weathering and run-off processes [M30]. These studies have enabled the development of a model for the time-dependent location factor (i.e., the factor by which the air kerma rate in free-in-air condition is reduced according to where those exposed are located) that is more representative of undisturbed locations in Japan. In particular, the revised model predicts a slower reduction in dose over the first 15 years due to natural redistribution of radionuclides in undisturbed soil than the model used in the UNSCEAR 2013 Report, in better agreement with observations in Japan.

A48. Additional studies [S2] have examined the different changes with time in dose rate measurements in populated and, especially, urbanized areas made in airborne and car-borne surveys and those carried out on foot. The Committee has used the results to develop a dose rate reduction model that takes account of the fact that Fukushima Prefecture has a high population density with almost all flatland being used or involved in anthropogenic activities and provides a better fit with the most representative survey data (car-borne for roads and streets; surveys carried out on foot for residential areas including unpaved areas). The results comparing the car-borne survey data and the data from the surveys carried out on foot with the revised model and the model used in the UNSCEAR 2013 Report [U10] are illustrated in figure A-II. They demonstrate the improved estimates provided by the revised model for both “roads and streets” and “residential” areas, again showing the slower reduction in the dose rate with time compared with the model used in the UNSCEAR 2013 Report.

Figure A-II. The external dose rate reduction factors for populated places as *(a)* derived from the car-borne surveys [A12, K20] and shown as solid symbols; *(b)* calculated for paved and unpaved areas using the model used in the UNSCEAR 2013 Report [U10] (red lines); and *(c)* fitted to the data and implemented in the revised model (blue lines)



A49. The Committee has used the same house types and shielding factors as used in the UNSCEAR 2013 Report [U10] as they are consistent with recent observations made by Japanese authors (e.g., Matsuda et al. [M13]). Similar occupancy factors representing the time spent by different population groups in different locations have also been assumed. Further details can be found in attachment A-4.

A50. Several personal dosimetry surveys have been carried out to measure doses from external exposure directly, typically using optically stimulated luminescence dosimeters or radio-photoluminescence dosimeters, as described in section II.A.1 of this appendix. These measurements have been compared with the predictions from the new model and that used in the UNSCEAR 2013 Report [U10]. Full details are provided in attachment A-1. A summary of the comparisons is provided in section IV.G of this appendix.

(b) *Doses for evacuees*

A51. As part of the response of the Japanese authorities to the FDNPS accident, there was widespread evacuation of residents living nearby at different times to reduce radiation exposures. Most of the residents of the municipalities of Futaba Town, Hirono Town, Kawauchi Village, Naraha Town, Okuma Town and Tomioka Town, as well as those residents of the municipalities of Katsurao Village, Minamisoma City, Namie Town and Tamura City living within a 20-km radius of FDNPS, were evacuated as a precaution between 12 March and 15 March 2011. The residents of the whole of the municipality of Iitate Village, as well as parts of the municipalities of Katsurao Village, Kawamata Town and Namie Town, to the north-west of the FDNPS site, were subsequently evacuated between April and June 2011, based on environmental measurements.

A52. In the UNSCEAR 2013 Report [U10], the assessment of doses to residents of these evacuated communities for the period before and during the evacuation was based on the results from a questionnaire survey to ascertain the locations and movements of these people. NIRS used the results of this survey to define 18 scenarios representative of the movements of residents local to FDNPS, following the accident [A6].

A53. In a recent study, Ohba et al. [O5] have refined these evacuation scenarios by conducting a hierarchical clustering analyses of 100 to 300 randomly sampled behavioural questionnaire responses from each of the seven municipalities in the evacuation area. This analysis resulted in 37 new representative evacuation scenarios. These 37 evacuation scenarios did not include those evacuated from the municipalities of Hirono Town and Katsurao Village, and the Committee has additionally included three of the original 18 evacuation scenarios which represent those evacuated from these locations. The resulting 40 evacuation scenarios which the Committee has used to assess doses to evacuees are summarized in table A9. Ohba et al. used their new scenarios for the purposes of comparing doses estimated using models with doses reconstructed from thyroid measurements carried out in March 2011. As a result, these scenarios only consider the movements of the evacuees up to midnight on 25 March 2011. Where people were evacuated after this date (e.g., some residents of the municipality of Iitate Village), their evacuation date and final destination are not shown in the table, but their evacuation at a later date and their final destination have been taken into account in accordance with scenarios used in the UNSCEAR 2013 Report [U10]. Information on the numbers of evacuees by evacuation scenario is provided in attachment A-11.

A54. Within these 40 evacuation scenarios, the Committee has considered four types of human activities: normal living conditions; preparing for evacuation; evacuation; and sheltering. For normal living conditions, the Committee has made the same assumptions about human behaviour as were made for residents, who were not evacuated. For the evacuation preparation, evacuation, and sheltering activities, the Committee assumed occupancy factors that reflected the nature of activities being undertaken. Because of a lack of measurement data for this early period after the accident, the Committee assessed external doses during evacuation using estimated concentrations of radionuclides deposited on the ground derived from the assumed source term and ATDM. Ohba et al. [O5] used the same source term and ATDM in their dose assessment for 37 scenarios, although the Committee's assessment is based on a finer spatial and temporal resolution.

Table A9. Evacuation scenarios considered

Ohba et al. [O5] (scenarios 01–37) and NIRS survey [A6] (scenarios 38–40)

Scenario	*Location at 11 March 2011*	*Start > Route > Destination*	*Timing*[a,b]
01(FT1)	Futaba Town	Futaba > Kawamata > OOP[c]	AM2 on 12 March
02(FT2)	Futaba Town	Futaba > Iwaki > OOP	PM1 on 12 March
03(FT3)	Futaba Town	Futaba > Odaka > Fukushima > OOP	AM2 on 12 March
04(FT4)	Futaba Town	Futaba > Haramachi> Koriyama	PM2 on 12 March
05(FT5)	Futaba Town	Futaba > Namie > Kawamata > OOP	PM1 on 12 March
06(TM1)	Tomioka Town and Kawauchi Village[d]	Kawauchi > OOP	PM1 on 15 March
07(TM2)	Tomioka Town	Tomioka > Ono > OOP	PM1 on 12 March
08(TM3)	Tomioka Town	Tomioka > Kawauchi > Koriyama > OOP	AM2 on 12 March
09(TM4)	Tomioka Town	Tomioka > Iwaki	PM1 on 12 March
10(NR1)	Naraha Town	Naraha > Iwaki > OOP	AM2 on 12 March
11(NR2)	Naraha Town	Naraha > Iwaki > OOP	AM2 on 12 March
12(NR3)	Naraha Town	Naraha > Iwaki	AM2 on 12 March
13(NR4)	Naraha Town	Naraha > Hirono > Aizu > OOP	AM2 on 12 March
14(NR5)	Naraha Town	Naraha > Iwaki > OOP > Iwaki	AM2 on 12 March
15(OK1)	Okuma Town	Okuma > Tamura > Aizu	PM1 on 12 March
16(OK2)	Okuma Town	Okuma > Tamura	AM2 on 12 March
17(OK3)	Okuma Town and Futaba Town[d]	Futaba > Kawamata > Iwaki > OOP	AM2 on 12 March
18(OK4)	Okuma Town and Tamura City[d]	Tamura	(no further evacuation)
19(OK5)	Okuma Town	Okuma Town > Odaka > Haramachi > Sukagawa > OOP	AM1 on 12 March
20(NM1)	Namie Town	Namie > Haramachi > OOP	AM2 on 12 March
21(NM2)	Namie Town	Namie > Soma	PM1 on 12 March
22(NM3)	Namie Town	Namie > Tsushima > Koriyama	AM2 on 12 March
23(NM4)	Namie Town and Tsushima[d]	Tsushima > Nihonmatsu	AM2 on 16 March
24(NM5)	Namie Town	Namie > Kawamata > OOP	AM2 on 13 March
25(IT1)	Iitate Village	Iitate > Koriyama	AM2 on 16 March
26(IT2)	Iitate Village	Iitate > Kawamata > Fukushima > Aizu	AM2 on 15 March
27(IT3)	Iitate Village	Iitate > OOP	AM2 on 19 March
28(IT4)	Iitate Village	Iitate > Fukushima City	22 June

Scenario	*Location at 11 March 2011*	*Start > Route > Destination*	*Timing*[a,b]
29(OD1)	Odaka ward of Minamisoma City	Odaka > Haramachi > Iwaki > OOP	PM2 on 12 March
30(OD2)	Odaka ward of Minamisoma City	Odaka > Kawamata > Aizu > OOP	PM1 on 12 March
31(OD3)	Haramachi ward of Minamisoma City	Haramachi > Date > Haramachi > OOP	AM2 on 12 March
32(OD4)	Odaka ward of Minamisoma City	Odaka > Haramachi > Fukushima > OOP	PM2 on 12 March
33(OD5)	Odaka ward of Minamisoma City	Odaka > Haramachi > Soma > OOP	PM1 on 12 March
34(HK1)	Haramachi ward of Minamisoma City	Haramachi > Fukushima > OOP	PM1 on 17 March
35(HK2)	Iitate Village	Iitate > Koriyama > OOP	AM1 on 12 March
36(HK3)	Kashima ward of Minamisoma City	Kashima > Haramachi > Iitate > OOP	AM2 on 12 March
37(HK4)	Haramachi ward of Minamisoma City	Haramachi > Soma	PM1 on 18 March
38 (10 in [U10])	Hirono Town	Hirono > Ono Town Office	12 March
39 (12 in [U10])	Katsurao Village	Katsurao > Azuma General Gymnasium	14 March
40 (14 in [U10])	Katsurao Village Office	Katsurao > Azuma General Gymnasium	21 March

[a] AM1, AM2, PM1, PM2 refer to early morning, late morning, early afternoon and late afternoon, respectively.

[b] The focus of Ohba et al. [O5] was on evacuation before 26 March 2011. The timings of later evacuations (in particular, of the municipalities of Iitate Village and parts of Tamura City in May and June 2011, are as set out in the UNSCEAR 2013 Report [U10].

[c] OOP denotes out of prefecture and indicates that the destination was a prefecture other than Fukushima Prefecture.

[d] In these scenarios, people were evacuated from the first named location to the second named location on the day of the earthquake (11 March 2011).

A55. The assessment of doses to those evacuated also included doses received at their evacuation destinations, either in less affected areas of Fukushima Prefecture or in other prefectures, and it was assumed, as in the UNSCEAR 2013 Report [U10], that evacuees remained at these destinations subsequently. Projected external doses from deposited radionuclides have also been assessed for the evacuated locations, as described above for residents, in order to determine the dose averted by evacuation.

(c) *Effects of environmental remediation and doses following population return*

A56. Experimental studies and tests of environmental remediation technologies started in the affected areas of Japan in summer 2011. They included technologies for remediation of inhabited areas, countermeasures in agriculture (e.g., top soil removal and additional fertilization) and in forestry. These studies and tests in Fukushima Prefecture continued until 2013. Since 2013, large scale remediation of the evacuated municipalities started in a special decontamination area (SDA), with the support of the Government of Japan. In some affected areas beyond the SDA (the intensive contamination survey area

(ICSA)), local authorities initiated remediation activities, mostly focused on public areas and especially on children's facilities (kindergartens, schools, hospitals, etc.), but also including household plots.

A57. There is detailed information available about the technologies used and the scale of the environmental remediation actions that have been carried out, and about the resulting reductions in ambient dose rates. This has been summarized in chapter IV. The measured reductions included the effects of radioactive decay and other natural processes, such as migration of radionuclides in the soil. Based on a large number of ambient dose rate measurements taken before and after remediation, the Ministry of the Environment (MOE) used a model to estimate the average reduction in the effective dose to the public as a result of remediation in the SDA and ICSA (i.e., having subtracted the contributions from natural processes) [M38]. The average reductions estimated by the MOE correspond to dose reduction factors (DRFs – the ratio of the dose before remediation to the dose after remediation assessed with the contribution of radioactive decay and radionuclide migration in the soil subtracted) of about 1.4 for the SDA and 1.3 for the ICSA. Comparison with some measurements of individual external dose on people in a municipality in the ICSA suggest slightly lower DRFs of 1.1–1.2 in the ICSA [M48, T43]. The Committee has accordingly judged that remediation has resulted in a DRF of about 1.3 in the SDA and of about 1.1 to 1.2 (depending on initial dose rate and remediation timing) in the ICSA. Further details are provided in attachment A-1. While these dose reduction factors can be used to provide an indication of the benefits of the remediation work, more reliable estimates of the doses to the public taking account of remediation require much more extensive information from post-remediation measurements of individual doses on people. The results of such post-remediation monitoring have not yet been published or provided to the Committee.

2. External exposure from radionuclides in the air

A58. There were insufficient measurements of gamma dose rate and of the concentration of radionuclides in air during the passage of the plumes of released material for an assessment to be made of external exposure from these radionuclides in air based solely on environmental measurements. External exposures due to radionuclides in air were therefore calculated from estimated concentrations of radionuclides in air based on the assumption that the plume could be represented by a semi-infinite cloud, an appropriate assumption where the distribution of radionuclides in air can be considered uniform over hundreds of metres. Estimates of radionuclide concentrations in air were averages for the approximately 1 km squares and were derived from the assumed source term and ATDM, as described in section III.B of this appendix.

A59. In estimating doses from radionuclides in air for residents, the same assumptions as in section III.C.1(a) of this appendix (i.e., for external doses from deposited radionuclides) were adopted for the fraction of the time spent indoors and the shielding provided by buildings. Full details of the methods of calculation of external exposures from radionuclides in air and related parameter values using the ATDM results are given in attachment A-10. For evacuees, external exposures from radionuclides in the air were estimated according to the evacuation scenarios and the four types of human activity described in section III.C.1(b) of this appendix.

D. Assessment of internal exposure

1. Dose coefficients for radioiodine intakes

A60. The Japanese population traditionally has an iodine-rich diet containing up to tens of thousands of micrograms of stable iodine a day [K5, L3, N2, Z6, Z7]. Stable iodine comes mainly from seafood, and particularly algae, which is a traditional component of the Japanese diet: typically, kelp (algae seaweed) contributes up to 90% of the total iodine intake in Japan [K4]. In contrast, the reference ICRP biokinetic model [I12, I13] assumes a moderate level of dietary intake of stable iodine at about 200 µg/d for adults.

A61. As a result of this iodine-rich diet, the fractional uptake of radioiodine into the thyroid following intake via ingestion or inhalation among the Japanese population can be expected to be lower than the reference ICRP value of 30%. For example, Kusuhara and Maeda [K61] obtained a mean value of the fractional uptake of 16.1% ± 5.4% for 15 Japanese male subjects from Nagasaki with normally functioning thyroid glands, and a similar study in Tokyo resulted in the value of 12.8% ± 5.7% [K52].

A62. In the UNSCEAR 2013 Report [U10], assessments of doses from intakes of radioiodine were based on the current set of ICRP reference dose coefficients for members of the public [I14]. These age-dependent dose coefficients were derived by ICRP with the use of a reference three-compartmental iodine biokinetic model [I13] and reference dosimetric models [I14]. In 2017, ICRP adopted a new more detailed model of iodine biokinetics in adults [I21] that is based on the model of Leggett [L3]. This new model has been used to calculate dose coefficients for inhalation of various physico-chemical forms of radioiodine (particulate aerosols with Type F absorption and activity median aerodynamic diameter (AMAD) = 1 µm, methyl iodide vapour and elemental iodine vapour) and for ingestion of ^{131}I, ^{132}I, ^{133}I and ^{132}Te, for three types of diet that may be more appropriate for the Japanese population:

- A typical Japanese diet (with fractional uptake of radioiodine (*U)* of 15%);
- A kelp-rich diet (*U* = 5%);
- A Western pattern diet (*U* of about 30%), that is popular among some groups of the Japanese population.

The dose coefficients were developed for dose to the thyroid, red bone marrow, female breast and colon, as well as for effective dose.

A63. The indicative dose coefficients for intake by inhalation and ingestion have been calculated for an adult female, an adult male, and for a 10-year-old child and a 1-year-old infant. Additionally, the dose coefficients for in utero exposure have been assessed for acute intake at the 35th week of pregnancy in terms of the fetus absorbed thyroid dose and fetus effective dose per maternal exposure.

A64. Further details of the model and its parameter values can be found in attachment A-2 and of the resulting dose coefficients can be found in attachment A-4. The Committee has used the dose coefficients for a typical Japanese diet in estimating doses from intakes of radioiodine; these dose coefficients result in doses from intakes of radioiodine lower by about a factor of two than the dose coefficients used in the UNSCEAR 2013 Report [U10].

2. Assessment of internal doses from inhalation of radionuclides

A65. The assessment of internal exposures from the inhalation of radionuclides required information on the concentrations of radionuclides in air, the age-dependent breathing rates and the dose coefficients for intake via inhalation. As described in section III.B above, concentrations of radionuclides in air have been estimated from the results of the assumed source term and ATDM derived by Terada et al. [T28]. Full details of the methods of calculation of internal exposures from inhalation of radionuclides in air and related parameter values using the ATDM results are given in attachment A-10.

A66. For residents, the time-integrated concentrations of radionuclides in air have been derived from measured deposition densities of radionuclides, by scaling according to the ratio of the modelled time integrated concentration in air of each radionuclide to its modelled deposition density.

A67. The Committee used reference (i.e., ICRP) values of the age-dependent breathing rates and dose coefficients for ^{134}Cs and ^{137}Cs for absorbed doses to the thyroid, red bone marrow, female breast and colon, and for effective dose [I16, I17]. These dose coefficients for intake by inhalation were derived using a default particle size (AMAD of 1 µm) and assuming Type F absorption for radiocaesium. Thyroid dose coefficients specific to the Japanese population for each of the three physico-chemical forms of iodine considered have been used as described in section III.D.1. The inhalation rates applied were the average rates over a day from the ICRP model of the respiratory tract [I16].

A68. In the UNSCEAR 2013 Report [U10], the Committee made no allowance for any reduction in the dose from inhalation (as a result of the filtering effects of buildings) for people being indoors during the passage of the plumes of released material, in the absence of more specific information. Hirouchi et al. [H22] has presented new information about the factor by which doses from inhalation may be reduced through being indoors, which was experimentally derived for Japanese houses. The reduction factors ranged from less than 0.1 to approximately 1. The Committee has accordingly used a reduction factor of 0.5 (with an uncertainty described by a triangular distribution with minimum = 0.1, peak = 0.5 and maximum = 0.95, as proposed by Ohba et al. [O5]) for assessing doses from inhalation of radionuclides when people were indoors. For residents, the same occupancy factors as described in section III.C.1(a) of this appendix have been applied to account for the amount of time different groups of people spent indoors.

A69. For evacuees, the concentrations of radionuclides in air to which they were exposed before and during evacuation were determined from the estimates of the time dependent concentrations of the released radionuclides in air as assessed by Terada et al. [T28] using the assumed source term and ATDM. Time integrals of air concentration were estimated for each of the 40 evacuation scenarios listed in section III.C.1(b) of this appendix. Doses were estimated from these air concentrations using the same dose coefficients as for residents. No allowance, however, was made for any reduction in dose that may have occurred while in buildings or vehicles during evacuation (i.e., owing to the filtering effects of buildings/vehicles). This may have resulted in an overestimate of inhalation doses to evacuees that, in the absence of more detailed information on how the evacuations were conducted, is difficult to quantify; but any overestimate is unlikely to be large.

3. Assessment of internal doses from ingestion

A70. In the UNSCEAR 2013 Report [U10], the Committee estimated doses from ingestion from measurements of ^{131}I, ^{134}Cs and ^{137}Cs in a wide variety of foods and in drinking water in Japan. From emerging information from whole-body monitoring, the Committee was aware, at the time of preparation of the report, that these estimates were likely to be substantial overestimates. Possible reasons for this identified in the UNSCEAR 2013 Report included that the food monitoring measurements used, particularly in the first year, were not based on random sampling, but on samples aimed at identifying foods containing high concentrations of radionuclides. In addition, where measurement results were below the limit of detection, a constant concentration of 10 Bq/kg, the nominal limit of detection, was assumed for ^{131}I, ^{134}Cs and ^{137}Cs, although for ^{131}I this was only for the first four months.

A71. Further relevant information has since become available:

- For radiocaesium, this includes: WBC measurements made on people; measurements made on food actually consumed by people, either from market-basket or from duplicate-diet surveys; and detailed assessments carried out by Japanese researchers based on measured levels in food;

- For radioiodine, this includes: measurements of the radioiodine content of thyroids; and detailed assessments carried out by Japanese researchers based on measured levels in food and drinking water.

Each source of information, in particular its strengths, weaknesses and limitations in respect of estimating or validating doses to the public, is considered in more detail below.

A72. Making use of these different sources of information to estimate doses is complicated by factors such as the timing of the measurements, and the different routes of intake and the different radionuclides included:

- Estimates of exposures made from measurements on people, either whole-body or thyroid monitoring, reflect combined intakes from ingestion and inhalation, are based on one measurement made at a specific time, and focus on intakes of specific radionuclides (radiocaesium or radioiodine, respectively);

- Estimates made from market-basket or duplicate-diet survey measurements are not informative for intakes that occurred before the survey samples were taken and generally reflect intakes from ingestion of caesium radionuclides only (because iodine radionuclides were generally not measurable by the time the surveys started);

- Estimates made using models separately consider each intake route (inhalation, ingestion of food and ingestion of drinking water) and can include all significant radionuclides but need to rely on many modelling assumptions.

The resulting approach used by the Committee in updating its assessment of doses from ingestion is described in section III.D.3(c) of this appendix. Further details of the measurements and studies underpinning the Committee’s approach can be found in attachments A-2 and A-3.

(a) *Intakes of caesium radionuclides*

Whole-body counting data

A73. Data available from WBC campaigns, summarized in table A2, provide information on the whole-body content of radiocaesium from as early as June 2011. Some of these campaigns, for example, the campaigns of measurements at the Municipal General Hospital of Minamisoma City and at Hirata Central Hospital, begun in October 2011, have continued into the longer term. In the campaign at the

Municipal General Hospital of Minamisoma, radiocaesium was detected in the body in 40% of the adults and 9% of the children in autumn 2011, but these proportions had fallen to around 15% of the adults and 1% of the children in spring 2012. By spring 2013, radiocaesium was no longer detected in children, and was detected in only around 3% of the adults, this proportion falling to just 1% in spring 2014.

A74. The strength of the whole-body monitoring data for estimating doses is that they are from direct measurements on people. However, the estimation of realistic doses from such measurements is not straightforward and relies on knowledge about the temporal pattern of intake, not only for intakes before the measurement, but also for any intakes that may occur after the measurement up to the end of the period of interest (e.g., the end of the first year). In all of the whole-body monitoring studies, there was generally insufficient knowledge about this temporal pattern of intake. There were also uncertainties associated with the measurement methods used and other factors, such as possible external contamination of clothing, and how representative those measured were of the wider population. A further weakness and a potential source of uncertainty, was the low, and rapidly declining, fraction of measurements found above MDL, which required assumptions to be made about how to treat the larger, and rapidly increasing, fraction of measurements below the MDL. As a result, much of these data (particularly measurements carried out at longer times after the accident) are only informative in putting an upper limit on the magnitude of the doses. There are also the additional complications that the doses estimated are from total intakes, and therefore that some apportionment has to be made between intakes from inhalation and intakes from ingestion in order to estimate or validate doses from ingestion, with further assumptions likely to be needed for estimating doses to the wider population.

A75. In light of these qualifications to dose estimates derived from the WBC studies, the Committee has concluded that these estimates are best used to provide validation of doses estimated by other methods. Further details of the whole-body monitoring studies, estimates of the doses from intakes of radiocaesium to various population groups that can be derived from these studies, and comparisons between these estimates and those derived using other approaches are provided in attachment A-3. A summary of the comparison between doses derived from whole-body monitoring studies and those estimated using the methods adopted by the Committee in this report is given in section IV.G.3 below.

Market-basket and duplicate-diet studies

A76. Data on daily intakes of radionuclides from market-basket and duplicate-diet samples of food and drinking water have been collected between July 2011 and winter 2013. The studies are summarized in table A6. The studies indicate that, during the first year after the accident, daily intakes of ^{134}Cs and ^{137}Cs were each of the order of 1–5 Bq/d in Fukushima Prefecture, around 3 Bq/d in neighbouring prefectures, and around 0.4 Bq/d in distant prefectures. These intake estimates provide a further indication of the likely overestimate of doses from ingestion made in the UNSCEAR 2013 Report [U10]: based on the per capita food intakes used in the UNSCEAR 2013 Report, the minimum intakes of each of ^{134}Cs and ^{137}Cs from food alone in the first year would have been more than 10 Bq/d because of the assumption that the concentration of ^{134}Cs and ^{137}Cs in food should be set to 10 Bq/kg if the measured concentration was below the MDL.

A77. The results of these market-basket and duplicate-diet studies enable more realistic estimates to be made of doses to both adults and children from ingestion of ^{134}Cs and ^{137}Cs in food and drinking water over the first few years after the accident. They are based on measurements made on the food as consumed by people, and, in some cases, take account of factors such as losses during food preparation and cooking. They therefore represent a more realistic basis for estimating doses from ingestion than the approach used in the UNSCEAR 2013 Report [U10].

A78. The strength of these studies is that they provide more direct estimates of doses from ingestion, the only additional knowledge required being (in the case of the duplicate-diet studies) the dose coefficient (i.e., the dose per unit intake) of the radionuclide(s) ingested, for which ICRP reference values are available, and also (in the case of the market-basket studies) information about food consumption rates. Weaknesses include that they are not informative of doses from ingestion before the first studies were carried out (July 2011) and that they may not be representative of the wider region (e.g., a whole prefecture) to which the estimated doses may need to be applied.

Dose estimates using food monitoring data and other survey results

A79. Murakami and Oki [M47] made estimates of the doses in the first year from ingestion of food and drinking water containing ^{131}I, ^{134}Cs and ^{137}Cs based on food monitoring data, a similar approach to that used in the UNSCEAR 2013 Report [U10]. However, Murakami and Oki used data from a wider range of sources than was available to the Committee when preparing the UNSCEAR 2013 Report and took account of the regional trade in foods (specifically, of the shares of foods from different parts of Japan arriving at food markets, where most Japanese citizens purchase food). They have provided estimates, with uncertainties, by age and sex, of equivalent dose to the thyroid and effective dose from ^{131}I intakes and of effective dose from ^{134}Cs and ^{137}Cs intakes for residents of Fukushima City, Tokyo and Osaka. They estimated average doses in these three locations as well as doses to agricultural workers (about 4% of the population) in Fukushima City who may have preferentially consumed locally produced vegetables and evaluated the effect of countermeasures to restrict the distribution of food, voluntarily withhold rice, and provide bottled water instead of tap water for infants. They compared their estimates of the effective dose from ingestion of ^{134}Cs and ^{137}Cs in food and drinking water with the estimates of Koizumi et al. [K33] and Harada et al. [H3], which were derived from market-basket and food-duplicate surveys in five periods from July 2011 to March 2012, and found general agreement within a factor of about two.

(b) *Intakes of iodine radionuclides*

Thyroid monitoring

A80. Measurements were made between 26 and 30 March 2011 of ^{131}I in the thyroid glands of 1,080 children in three locations in Fukushima Prefecture (Iitate Village, Iwaki City and Kawamata Town) and the results have been most recently reported by Kim et al. [K18]. Additional measurements of ^{131}I in the thyroid are available from other studies on smaller numbers of people, including adults [K55, T34, U1, U20]. The Committee has analysed these measurements and made its own estimates of absorbed doses to the thyroid from internal exposure to ^{131}I at several locations in Fukushima Prefecture. Further detail on the methodology used by the Committee, including the corrections made for background radiation and the treatment of the large proportion of measurements of dose rate that were equal to or less than the background dose rate, is given in attachment A-2. Assumptions were also needed about where the individuals who were measured were, and their habits, during the passage of radioactive plumes, and where they subsequently lived, as this information was generally lacking. While dose estimates derived from these measurement data have the advantage of being based on direct measurements on people, they have similar weaknesses to those described above for the whole-body measurements and are not informative about thyroid doses to the wider population. The resulting reconstructed doses to the thyroid have therefore been used for validation of the estimates of absorbed dose to the thyroid from intakes of ^{131}I made using models for intakes via inhalation and intakes via ingestion of food and drinking water (see section IV.G. below).

Estimates of radioiodine intakes from drinking water

A81. Miyatake et al. [M34] used models to supplement the measurement data on drinking water and make estimates of the doses from ^{131}I intakes from ingestion of tap water to people in the 12 municipalities of the evacuation area. The authors based the estimates on the results of earlier survey work by Hirakawa et al. [H15] that identified that consumption of drinking water was likely to be the only important source of radionuclide intakes by ingestion by evacuees. Miyatake et al. [M34] used the same assumed source term and ATDM [T28] as used by the Committee in this report. However, the authors used a simpler set of evacuation scenarios and the ICRP dose coefficients for intakes of radioiodine. Miyatake et al. found good agreement between their estimates of ^{131}I concentration in tap water and measurements. They accounted for the different sources of tap water at different locations along the evacuation routes, and presented estimates of equivalent doses to the thyroid for adults, 10-year-old children and 1-year-old infants for 12 municipalities for median, mean and 95th percentile intakes of drinking water. They gave separate, detailed consideration to the water supply at Iitate Village, including the relative amounts supplied by three water purification plants and by well or spring water.

(c) *Approach used by the Committee to estimate doses from ingestion*

A82. In view of the quality and detailed nature of the study by Murakami and Oki [M47], the validation of its results against the market-basket and duplicate-diet studies described above, and its inclusion of estimates of doses from ^{134}Cs, ^{137}Cs and ^{131}I, the Committee has based its estimates of doses from ingestion in the first year to both adults and children on the estimates of Murakami and Oki. Murakami and Oki's dose estimates have been adjusted to account for the dose coefficients for radioiodine intakes specific to Japanese people. The dose estimates derived from this study have been compared with the results of the thyroid monitoring studies and the whole-body monitoring studies as described in detail in attachments A-2 and A-3 and summarized in section IV.G. The estimated doses for Fukushima City have been considered representative of doses from ingestion of food and drinking water to residents of Fukushima Prefecture as a whole; this is a plausible assumption given food distribution and purchasing practice in Japan. Doses in other prefectures in the first year have been estimated from doses estimated by Murakami and Oki for Fukushima City by scaling according to the ratios of the average radiocaesium concentrations monitored in foods for neighbouring prefectures and for the rest of Japan to that in Fukushima Prefecture. The resulting doses from ingestion in neighbouring prefectures and in the rest of Japan estimated by the Committee are consistent with the estimates made by Murakami and Oki for the Tokyo and Osaka Metropolitan Areas [M47].

A83. For evacuees, doses from ingestion of food before and during evacuation have been assumed to be negligible, based on survey results [H15, K10]. Doses from drinking water estimated by Miyatake et al. [M34] for 12 evacuated municipalities have been used, with adjustment for the specific dose coefficients for iodine intakes for Japanese people (see section III.D.1 of this appendix). For doses after evacuation, the same approach as used for residents has been adopted.

A84. For time periods after the first year, the Committee has used as its starting point estimates of doses to adults and children from ingestion of radiocaesium derived from the market-basket and duplicate-diet studies for Fukushima and other prefectures, and then used the model developed by Smith et al. [S33] to estimate how intakes of radiocaesium from food and drinking water change over the longer term. This model was developed from an analysis of long-term measurement data collected annually from 1963 to 2008 on the ^{137}Cs content of food products and in the whole diet in Japan resulting from fallout of radiocaesium from atmospheric nuclear weapons testing. The observed annual concentrations of ^{137}Cs in food products and in the whole diet were described by Smith et al. in terms of coefficients representing a fast decline in concentrations after deposition, a slow decline as a result of soil fixation processes, and the very long-term component which declines due to vertical migration, erosion and further slow reductions in bioavailability. The initial fast decline in the model is not relevant for intakes more than a year after deposition, but the slow and long-term declines from the model have been applied to intakes derived from market-basket and duplicate-diet measurements in various prefectures of Japan from March 2012 onwards. The model takes no account of food restrictions, but the proportion of monitored food found to be above the limit (of 100 Bq/kg) established by the Japanese Government was low (generally below 1%) by the second quarter of 2012. Further details of the model of Smith et al. [S33] and its implementation can be found in attachment A-3.

E. Microparticles

A85. As indicated in chapter II, several studies have identified radiocaesium in the environment associated with water-insoluble “glassy spherules”. The fraction of the radiocaesium deposited on to the ground in the form of such microparticles varies from a few per cent at distances of up to 30 km from FDNPS to up to about 80% at large distances (more than 200 km) [I29, U19]. Radiocaesium in the form of such microparticles would be expected to migrate more slowly into the soil and have lower transfer to plants and animals. The effect of such microparticles on estimated doses is complex, resulting in higher doses from one exposure pathway and lower doses from another, than as assumed in the models used in this report. While the presence and behaviour of radiocaesium in the environment in the form of microparticles is worthy of further scientific investigation, the Committee judges that it will have no material impact on the overall levels of dose to the public estimated in this report.

F. Assessment of variabilities and uncertainties

A86. The Committee’s aim throughout has been to make realistic estimates of the average radiation exposures of members of the public in defined population groups (see table A7). Among the individual members in each group, there will be some variability between the radiation exposures of each person, and this variability may be significant. In addition, any method of estimating doses will be associated with uncertainty, whether the estimated doses have been derived from direct measurements on people or from indirect measurements in the environment coupled with modelling. In light of the additional information that has become available since the UNSCEAR 2013 Report [U10], the Committee has made more quantitative and less subjective assessments of the variabilities and uncertainties in its estimates of public doses, enabling it to report distributions of individual doses in municipalities and prefectures, and the 5th and 95th percentiles of the distributions, as well as municipality- and prefecture-averages. The Committee’s approach to its assessment of the variabilities and uncertainties in its estimates of doses is set out in further detail in attachment A-12.

G. Assessment of collective doses

A87. The collective dose to the general public is a quantity intended primarily for the optimization of protection, comparing technologies or protection measures. Comparisons have been made of the collective dose integrated over a defined time period with those from other events associated with radionuclide releases to the environment (such as the Chernobyl accident). As in the UNSCEAR 2013 Report [U10], the Committee has estimated the collective effective dose and the collective absorbed dose to the thyroid over the first year, the first 10 years and up to age 80 years, for the population of Japan.

These time periods were chosen, as in the UNSCEAR 2013 Report, to indicate the annual collective dose in the first year and to illustrate the temporal accumulation of the collective dose commitment.

A88. The collective dose due to external exposure was reassessed using the same assumptions about population sizes, age and social composition, dwelling types and occupation as in the UNSCEAR 2013 Report [U10]. However, for residents of Fukushima Prefecture, the Committee has used different values for the proportions of people living in different dwelling types: 37% of the population were assumed to live in wooden one-to-three storey houses, 42% in wooden fireproof houses, and 21% in multi-storey concrete buildings [M27]. The values used in the UNSCEAR 2013 Report were the average values for the whole of Japan (30%, 30% and 40%, respectively) and have again been assumed for other prefectures.

A89. The collective dose from internal exposure includes doses from inhalation and ingestion. The collective inhalation dose (both effective and thyroid dose) has been assessed by summation of inhalation doses over the first year of exposure for all localities of Fukushima Prefecture and other prefectures of Japan. The collective ingestion dose (both effective and thyroid dose) in the first year has been assessed from the estimated doses from ingestion for the different population groups in the first year integrated over the population of Japan, taking account of the age distribution. For subsequent years the ingestion dose has been estimated by means of time integrals over 1–10 years and 11–80 years of the radiocaesium intake in food and drinking water from the market-basket and duplicate-diet studies with decreases over time from the model of Smith et al. [S33], and with subsequent integration over the population of Japan (see section IV.C. below).

IV. RESULTS

A90. The methodologies described in section III of this appendix have been used to derive detailed estimates of the doses by age group (20-year-old adult, 10-year-old child and 1-year-old infant) for:

(a) Municipalities in Fukushima Prefecture that were evacuated or partially evacuated according to the 40 evacuation scenarios (Group 1);

(b) The municipalities and parts of municipalities within Fukushima Prefecture that were not evacuated (Group 2);

(c) The selected four prefectures in eastern Japan neighbouring Fukushima Prefecture (Group 3);

(d) The rest of Japan (Group 4).

A detailed dose assessment was conducted for all municipalities in Fukushima Prefecture and some municipalities of the Group 3 prefectures[4] of Ibaraki, Miyagi, Tochigi and Yamagata. Additional estimates of dose were made for those municipalities that were in the evacuation zones and for those municipalities that were partially evacuated. For ease of comparison, the estimated doses are presented in a similar way to that used in the UNSCEAR 2013 Report [U10]. As well as estimates of the average doses in each municipality or prefecture for the population groups considered in this report, estimates are also provided of the uncertainties in these values and of the distribution of individual doses within each of the population groups (see section IV.F of this appendix).

[4] The Committee has used a slightly different reporting of results for prefectures in its revised assessment because of changes in the spatial coverage of the deposition density data. The previous Group 3 prefectures of Gunma, Chiba and Iwate were not analysed at the municipality level and are now included in Group 4.

A91. Following a review of more recent information on estimates of doses to members of the public in countries neighbouring, or in close proximity to, Japan, the Committee has revisited its estimates of such doses in the UNSCEAR 2013 Report [U10] (see section IV.E).

A. Estimates of doses in Japan in the first year

1. Effective dose

A92. Table A10 summarizes the ranges of municipality- or prefecture-average effective doses estimated for the first year following the accident, for the representative 20-year-old adult,[5] 10-year-old child and 1-year-old infant residing in the non-evacuated municipalities of Fukushima Prefecture (Group 2), the selected neighbouring prefectures (Group 3) and the remaining prefectures in Japan (Group 4). The doses are summed over the main exposure pathways and are intended to be characteristic of the municipality- or prefecture-average doses received by people living in each municipality or prefecture. The estimates in table A10 reflect the range of average doses across the municipalities within prefectures, not the ranges of doses received by individuals within the populations at these locations (i.e., the variability in the doses between individuals). The relative contribution of each main pathway to the total estimated doses varied between municipalities and prefectures reflecting the levels of radionuclides in the environment and exposure conditions. Detailed results for each municipality and age group including the 5th and 95th percentiles of the distributions of individual effective doses are provided in attachment A-13.

A93. Comparison with the equivalent table C6 in the UNSCEAR 2013 Report [U10] indicates that the Committee's revised estimates of the ranges of effective dose from external exposure and inhalation pathways taken together are broadly comparable (within a few tens of per cent) with those in that report. This apparent similarity is, however, masking much larger differences in the average dose estimates for each municipality and in the average doses from these two pathways when considered separately (see section IV.H below and attachment A-13). The revised estimated doses from ingestion are much lower, however, by about 10 to 30 times, reflecting the more realistic approach adopted that is supported by the whole-body measurements made on people (see section IV.G) and the market-basket and duplicate-diet studies that measured intakes from the food actually bought or consumed.

A94. Figure A-III shows the estimated average effective dose for infants for each municipality of Fukushima Prefecture that was not evacuated; municipalities that were partly evacuated are also included in the figure. The highest estimated doses were to individuals in the municipalities with high levels of deposition density (Date City, Fukushima City, Koriyama City, Nihonmatsu City, Koori Town and Otama Village). The municipality-average total effective doses to infants in these municipalities were in the range of 3.6 to 5.3 mSv in the first year. The contribution of external exposure from deposited radionuclides to the total effective dose was dominant. Adults were estimated to have received average effective doses in the first year, about 70% of those received by infants.

[5] Average doses to adults who were indoor workers have been chosen to be representative of adults as a whole. The variability of the effective doses and absorbed doses to the thyroid among the population, including whether adults were indoor or outdoor workers, or retired has been considered in section IV.F of appendix A.

Table A10. Ranges of estimated municipality- or prefecture-average effective doses in the first year following the accident for residents of Japan for locations that were not evacuated

Geographical area	*Ranges of average effective dose by pathway[a] (mSv)*								
	Adult[b]			*10-year-old*			*1-year-old*		
	External + inhalation	*Ingestion[c]*	*Total*	*External + inhalation*	*Ingestion[c]*	*Total*	*External + inhalation*	*Ingestion[c]*	*Total*
GROUP 2[d] – FUKUSHIMA PREFECTURE									
Municipalities not evacuated	0.043–3.7	0.036	0.079–3.8	0.051–4.5	0.051	0.10–4.5	0.061–5.3	0.055	0.12–5.3
GROUP 3[e] – NEIGHBOURING PREFECTURES									
Ibaraki Prefecture	0.14–0.81	0.009	0.15–0.81	0.17–0.98	0.013	0.18–0.99	0.20–1.1	0.015	0.21–1.2
Miyagi Prefecture	0.18–0.91	0.009	0.19–0.91	0.22–1.1	0.013	0.23–1.1	0.26–1.3	0.015	0.27–1.3
Tochigi Prefecture	0.28–0.92	0.009	0.29–0.92	0.33–1.1	0.013	0.35–1.1	0.39–1.3	0.015	0.41–1.3
Yamagata Prefecture	0.093–0.13	0.009	0.10–0.14	0.11–0.16	0.013	0.13–0.18	0.13–0.19	0.015	0.15–0.21
GROUP 4[f] – REST OF JAPAN									
42 remaining prefectures	0.0[g]–0.36	0.004	0.004–0.36	0.0[g]–0.43	0.005	0.005–0.43	0.0[g]–0.50	0.005	0.005–0.51

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

[b] Adult indoor workers have been considered to be representative of adults.

[c] Doses to a subgroup of the population (agricultural workers) who preferentially consumed local vegetables may be larger by a factor of about 4 to 5.

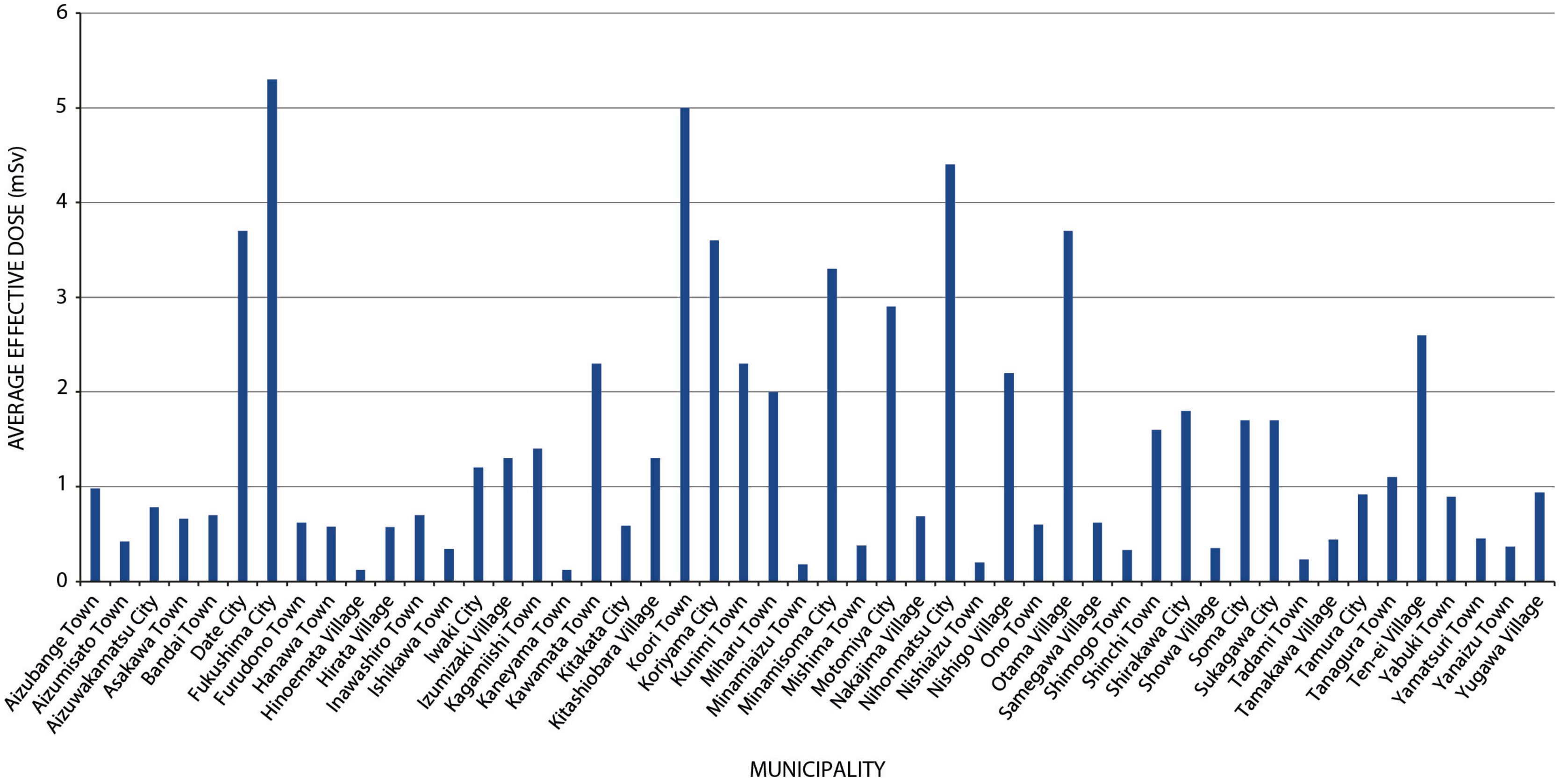
[d] Group 2: Members of the public living in the non-evacuated municipalities of Fukushima Prefecture.

[e] Group 3: Members of the public living in the neighbouring prefectures of Ibaraki, Miyagi, Tochigi and Yamagata.

[f] Group 4: Members of the public living in the remaining prefectures of Japan, including the previous Group 3 prefectures of Chiba, Gunma and Iwate.

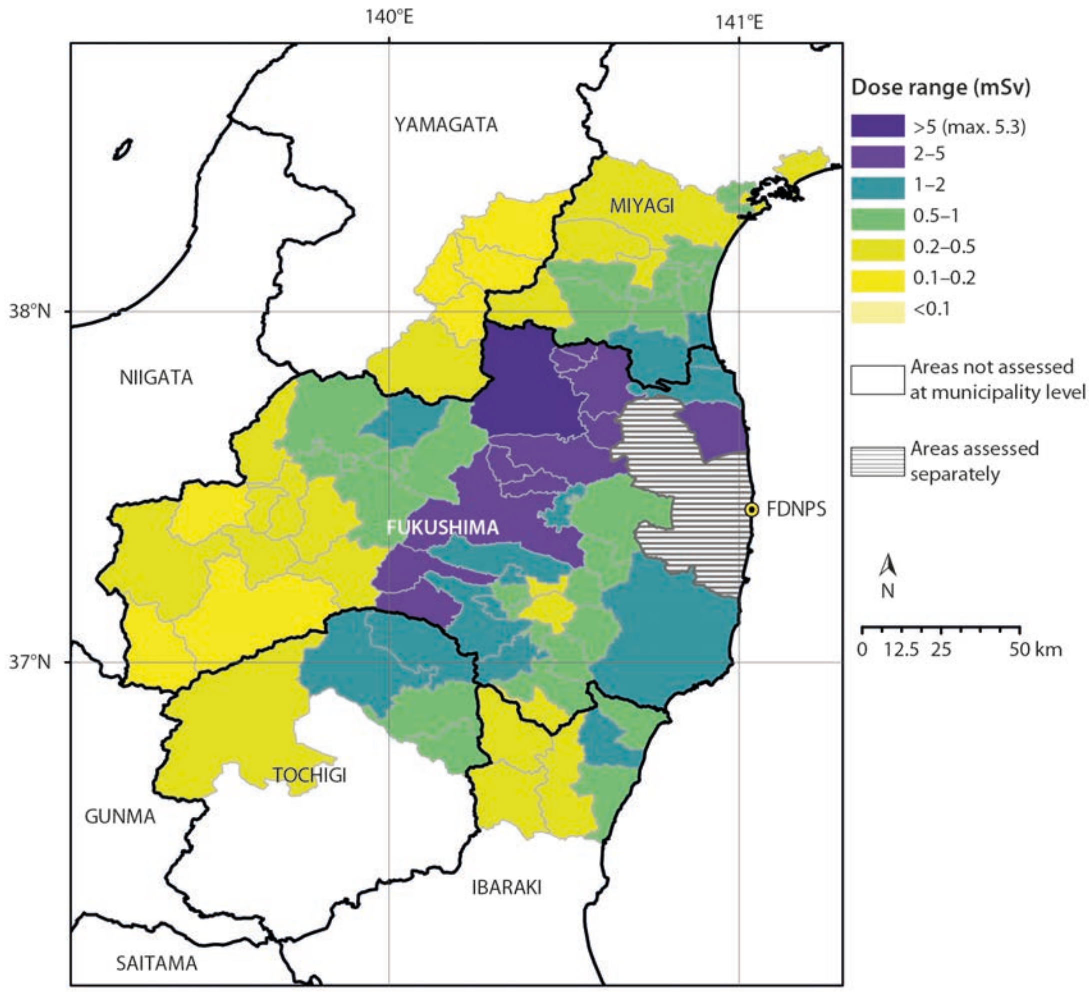
[g] Estimated doses that are very much less than 1 μSv have been assigned a value of 0.0.

Figure A-III. Estimated average effective dose in the first year to infants in each municipality of Fukushima Prefecture apart from those that were evacuated



A95. Figure A-IV shows the municipality-average effective doses in the first year following the accident for infants living in municipalities of Fukushima Prefecture that were not evacuated and some municipalities of the Group 3 prefectures. The spatial distribution in the estimated doses shown in this figure reflects the pattern of the releases and depositions of radionuclides in the different municipalities in the area.

Figure A-IV. The average effective dose in the first year following the accident for infants living in municipalities of Fukushima Prefecture that were not evacuated and some municipalities of Group 3 prefectures



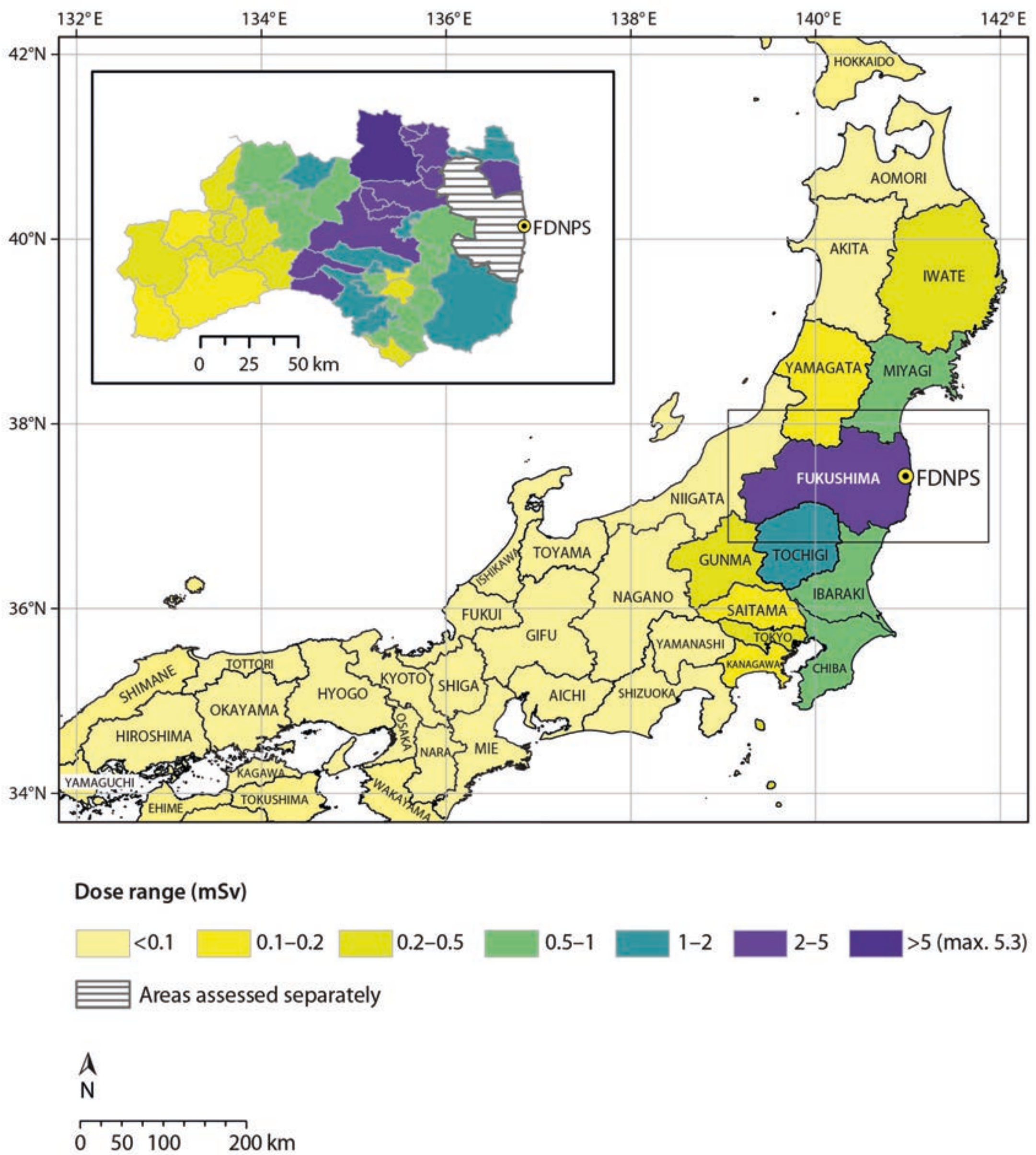
The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

A96. For municipalities of the Group 3 prefectures (Ibaraki, Miyagi, Tochigi and Yamagata), the municipality-average effective doses to infants were in the range of 0.15 to 1.3 mSv in the first year, with the dominant contribution again being generally from external exposure to deposited radionuclides. The prefecture-average effective doses to infants for the prefectures in the remainder of Japan were in the range 0.005 to 0.51 mSv, with external exposure from deposited radionuclides making the dominant contribution to the higher average doses in this range.

A97. Figure A-V shows the prefecture-average effective doses in the first year to infants in the rest of Japan. Prefecture-average doses in other prefectures were lower than those in Fukushima Prefecture and were considerably lower in the more distant prefectures, where the dose estimates were less than the variation in background doses from natural sources of radiation [O21].

Figure A-V. Estimated average effective doses to infants in the first year following the accident

The main map shows the prefecture-average effective dose. Fukushima Prefecture average only includes municipalities that were not evacuated. The inset map shows the municipality-average doses for municipalities in Fukushima Prefecture that were not evacuated



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

A98. All of the estimated doses are representative of the average doses to the population in the respective municipalities for Group 2 and Group 3 prefectures and in the respective prefectures for Group 4. These average doses are subject to uncertainties in the measurement data and in the models used to estimate the doses, and the doses to individuals in the population group will vary about the average depending on location within the municipality or prefecture and individual habits, such as the amount of time spent indoors. The Committee has estimated the 5th and 95th percentiles of the distributions of effective doses to individuals in the first year in each population group, taking account of all the major sources of individual variability as well as the uncertainties, and these are presented in attachment A-13. The 5th percentiles are around half the average effective dose and the 95th percentiles are around twice the average. Example distributions of individual effective doses are presented and discussed in section IV.F.

A99. In the Committee's revised dose estimates, external exposure to deposited radionuclides is generally the dominant contributor to effective dose in the first year (except in areas largely unaffected by dispersion of the released radioactive material, where the doses are comparatively low and ingestion is the dominant pathway). This contrasts with the effective doses estimated in the UNSCEAR 2013 Report [U10], where the relative contribution from ingestion of food was much larger. The Committee's revised estimates of effective doses from ingestion are based on a more realistic assessment of this pathway and are 10–30 times lower than assessed in the UNSCEAR 2013 Report.

2. Estimates of organ doses in non-evacuated areas in the first year

A100. Ranges of first-year average absorbed doses to the thyroid of various age groups for all of the municipalities of Fukushima Prefecture that were not wholly evacuated, most municipalities of the Group 3 prefectures and for the rest of Japan (Group 4) are presented in detail in attachment A-14 and summarized in table A11. Most of the absorbed dose to the thyroid was estimated to have been received over the first months after the accident. Comparison with the equivalent table C10 in the UNSCEAR 2013 Report [U10] again shows that revised estimates of doses from ingestion are significantly lower than estimated in the UNSCEAR 2013 Report. The revised ranges of the average absorbed doses to the thyroid from the external exposure plus inhalation pathways are very similar to those estimated in the UNSCEAR 2013 Report. The detailed breakdown in attachment A-14 shows, however, that this apparent similarity is the net result of many competing factors. These factors and their effects on the Committee's revised dose estimates in comparison with the dose estimates in the UNSCEAR 2013 Report are considered in further detail in section IV.G below.

A101. Figure A-VI shows the estimated average absorbed dose to the thyroid of infants in each municipality of Fukushima Prefecture that was not evacuated. The highest municipality-average doses to the thyroid were in the municipalities of Minamisoma City, Date City, Fukushima City, Soma City and Koori Town. The highest municipality-average absorbed dose to the thyroid was estimated to have been 21 mGy for infants living in the municipality of Minamisoma City, with more than 80% of this due to inhalation, more than 10% due to external exposure to deposited radionuclides, and about 5% to ingestion. The estimated absorbed doses to the thyroid for adults and children in the first year were about 60% and 85%, respectively, of those for infants.

Table A11. Ranges of estimated municipality- or prefecture-average absorbed doses to the thyroid in the first year following the accident for residents of Japan for locations that were not evacuated

Geographical area	*Ranges of absorbed dose to thyroid[a,b] (mGy)*								
	Adult[c]			*10-year-old*			*1-year-old*		
	External + inhalation	*Ingestion[d]*	*Total*	*External + inhalation*	*Ingestion[d]*	*Total*	*External + inhalation*	*Ingestion[d]*	*Total*
GROUP 2[e] – FUKUSHIMA PREFECTURE									
Municipalities not evacuated	0.051–10	0.43	0.48–11	0.061–16	0.95	1.0–17	0.070–20	1.1	1.2–21
GROUP 3[f] – NEIGHBOURING PREFECTURES									
Ibaraki Prefecture	0.22–2.0	0.11	0.33–2.2	0.30–3.0	0.25	0.55–3.2	0.35–3.5	0.31	0.66–3.9
Miyagi Prefecture	0.39–3.2	0.11	0.50–3.3	0.55–4.9	0.25	0.80–5.2	0.64–6.0	0.31	1.0–6.3
Tochigi Prefecture	0.30–1.2	0.11	0.41–1.3	0.35–1.4	0.25	0.60–1.7	0.40–1.7	0.31	0.72–2.0
Yamagata Prefecture	0.20–0.90	0.11	0.31–1.0	0.26–1.4	0.25	0.52–1.7	0.31–1.6	0.31	0.62–1.9
GROUP 4[g] – REST OF JAPAN									
42 remaining prefectures	0.0[h]–0.45	0.034	0.034–0.48	0.0[h]–0.56	0.073	0.073–0.63	0.0[h]–0.65	0.087	0.087–0.74

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

[b] Detailed estimates are not tabulated here for doses to the fetus but can be found in attachment A-14. Ranges of average fetal absorbed doses to the thyroid over the 30-week development period of the fetus are about 70% to 80% of the tabulated adult thyroid doses.

[c] Adult indoor workers have been considered to be representative of adults.

[d] Doses to a subgroup of the population (agricultural workers) who preferentially consumed local vegetables may be larger by a factor of about 3.

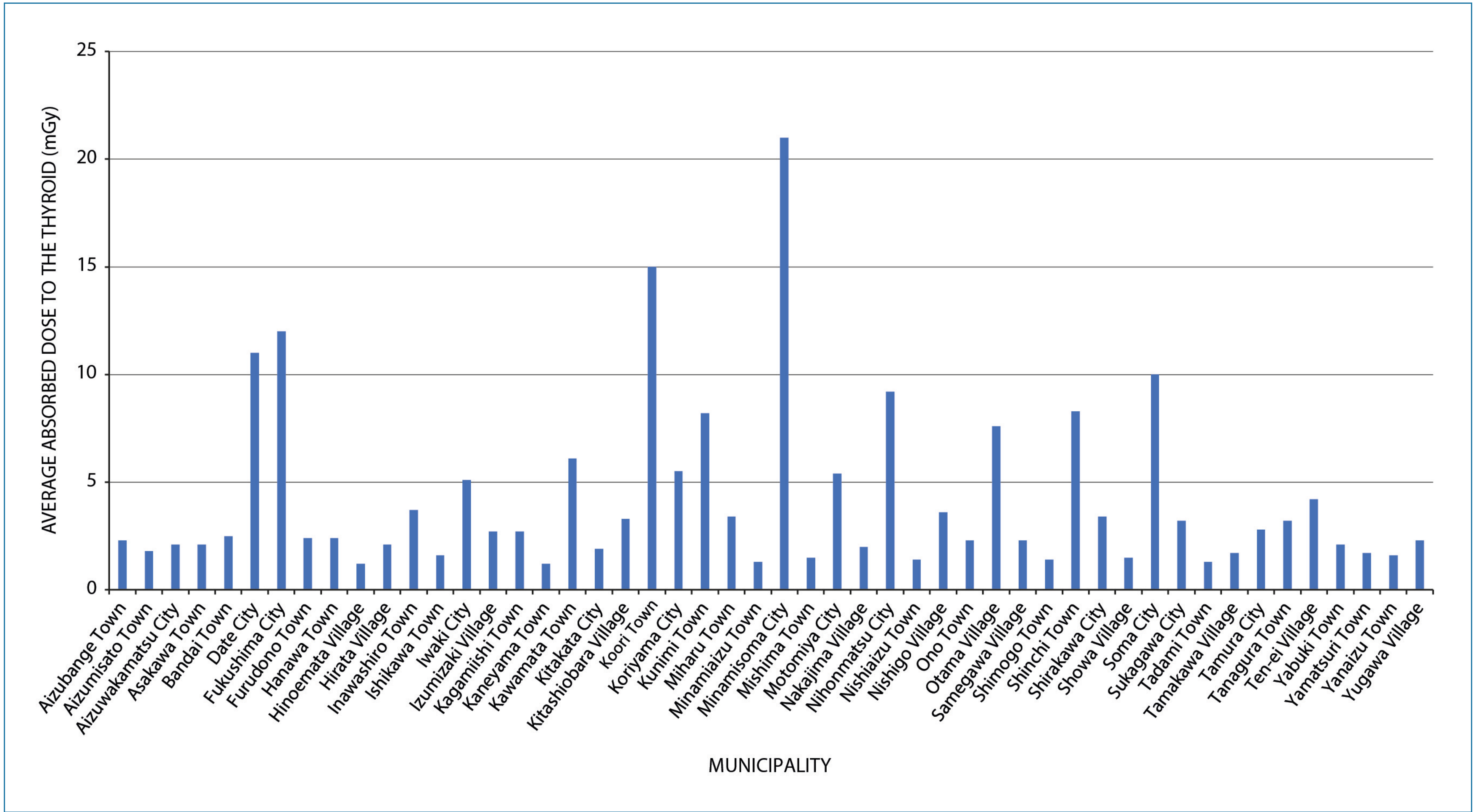
[e] Group 2: Members of the public living in the non-evacuated municipalities of Fukushima Prefecture.

[f] Group 3: Members of the public living in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata. These prefectures were grouped together to calculate the dose from ingestion in these prefectures.

[g] Group 4: Members of the public living in the remaining prefectures of Japan, including the previous Group 3 prefectures of Chiba, Gunma and Iwate.

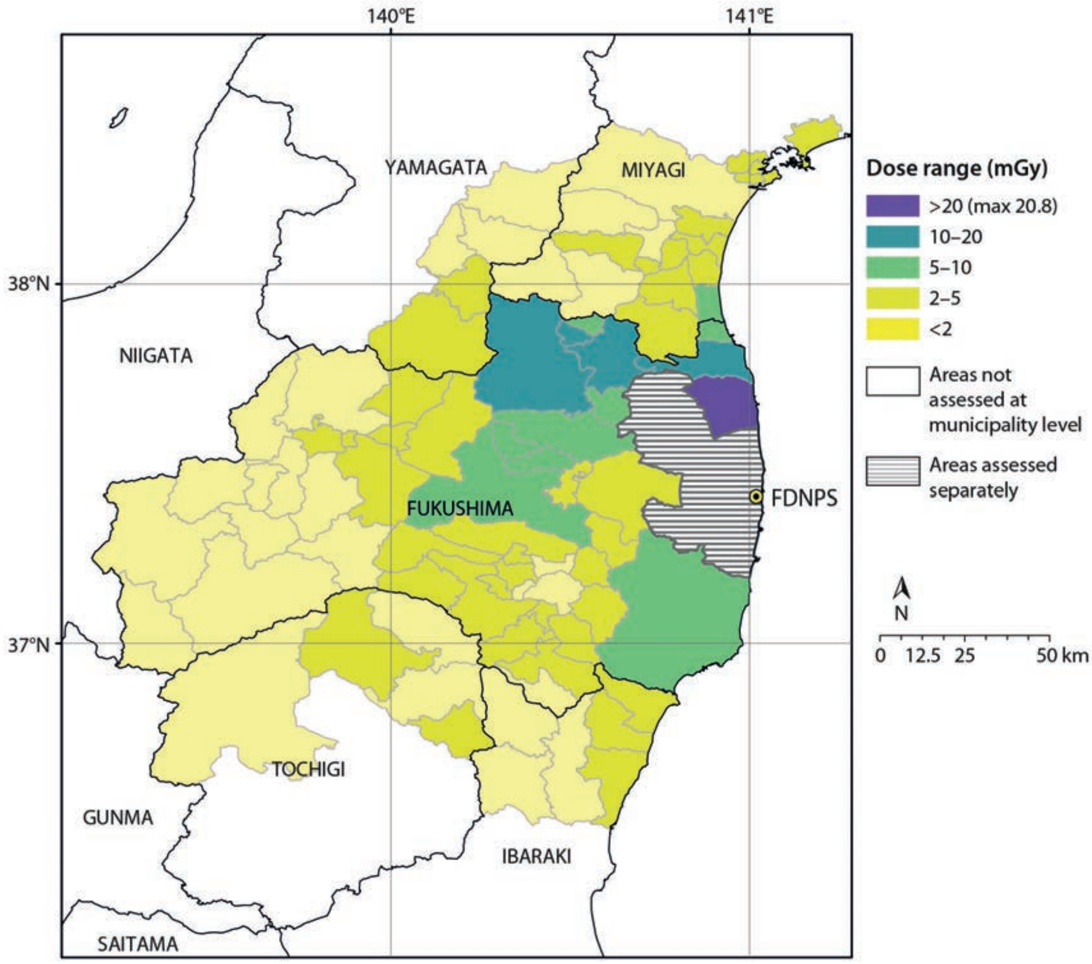
[h] Estimated doses that are less than 1 µGy have been assigned a value of 0.0.

Figure A-VI. Estimated average absorbed dose to the thyroid in the first year to infants in each municipality of Fukushima Prefecture apart from those that were evacuated



A102. Figure A-VII shows the estimated average absorbed doses to the thyroid of infants in the first year by municipality for Fukushima Prefecture and parts of the Group 3 neighbouring prefectures. For the Group 3 prefectures (Ibaraki, Miyagi, Tochigi and Yamagata), the average absorbed doses in the thyroid of infants were estimated to be in the range of 0.62 to 6.3 mGy, with the dominating exposure pathway again being inhalation. In the other prefectures of Japan, the prefecture-average absorbed doses in the thyroid of infants were estimated to have been up to about 0.7 mGy, with the dose from ingestion being the dominant exposure pathway in most prefectures, but with external exposure to deposited radionuclides and inhalation pathways making significant contributions (up to about 60% and 20%, respectively) to the total in some prefectures (specifically, Chiba, Gunma and Iwate).

Figure A-VII. The average absorbed dose to the thyroid in the first year following the accident for infants living in municipalities of Fukushima Prefecture that were not evacuated and some municipalities of Group 3 prefectures



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

A103. The Committee has estimated the distributions of individual absorbed doses to the thyroid in each municipality and prefecture and the 5th and 95th percentiles of the distributions are presented in attachment A-14. The 5th and 95th percentiles are generally up to around 2–3 times lower and 2–3 times higher than the average absorbed doses to the thyroid, although they can be more than 4 times lower and higher, respectively, in municipalities where internal exposure from inhalation of radionuclides makes the largest contribution to the total dose. Example distributions of individual absorbed doses to the thyroid are presented and discussed in section IV.F below.

A104. Estimates have also been made of the absorbed doses to the fetal thyroid. For the municipalities of Fukushima Prefectures that were not evacuated, the municipality-average fetal absorbed dose to the thyroid over the 30-week development period of the fetus ranged from about 0.4 to 8 mGy. Generally, the municipality-average fetal absorbed doses to the thyroid were estimated to be about 70% to 80% of the corresponding adult thyroid dose in the first year.

A105. For the municipalities and parts of municipalities within Fukushima Prefecture that were not evacuated, the municipality-average absorbed doses to the different organs: *(a)* red bone marrow; *(b)* colon; and *(c)* female breast in the first year were all estimated to be in the range of 0.06 to 3.9 mGy for adults, 0.06 to 4.5 mGy for children, and 0.06 to 5.2 mGy for infants. The municipality-average in utero absorbed doses to the red bone marrow over the 40-week term of pregnancy range from about 0.05 to 2.1 mGy (i.e., about half the adult red bone marrow dose in the first year). For municipalities of Group 3 prefectures (Ibaraki, Miyagi, Tochigi and Yamagata), the municipality-average absorbed doses to the red bone marrow, colon and the female breast in the first year were all estimated to be in the range of: *(a)* 0.08 to 0.98 mGy for adults; *(b)* 0.09 mGy to 1.1 mGy for children; *(c)* and 0.10 mGy to 1.3 mGy for infants. In the remaining 42 prefectures of Japan, the prefecture-average absorbed doses in the red bone marrow, the colon and the female breast in the first year were estimated to have been less than about 0.5 mGy for adults, children and infants. The estimated absorbed doses to the red bone marrow, the colon and the female breast for the different age groups in the first year following the accident for all of the municipalities of Fukushima Prefecture, most municipalities of the Group 3 prefectures and the rest of Japan (Group 4) are presented in detail in attachments A-15, A-16 and A-17, respectively.

3. Effective doses and organ doses for evacuees

A106. The evacuations undertaken to protect the public from the releases from FDNPS reduced the radiation exposures that would otherwise have been received. Doses were estimated for 40 groups of people who were evacuated at different times and moved to different locations (see table A9). The doses were assessed for the period before and during the evacuation. The last evacuation occurred on 22 June 2011 from Iitate Village. The dose estimates for the period before and during the evacuation[6] were based on the ATDM results for radionuclide concentration in air and deposition density in the days following the accident, and estimates from Miyatake et al. [M34] of doses from ingestion of drinking water. The estimated average effective doses to adults in these groups are summarized in table A12. The estimates of average effective dose to adults over the periods of these evacuations were generally less than around 1 mSv, apart from the last evacuees from Iitate Village, who were estimated to have received an average effective dose before evacuation of 3.6 mSv.

A107. The estimated average effective doses in the first year to those who were evacuated are the sum of the doses received before and during evacuation and the doses received during the remainder of the year at the location to which they were evacuated. These doses are also summarized in table A12. The average effective doses to adults were estimated to be generally less than about 4 mSv in the first year. The one exception is again the last evacuees from Iitate Village who were estimated to have received an

[6] For most scenarios. For scenario IT4, where people were not evacuated until 22 June, these assumptions applied up to midnight on 25 March, after which doses were estimated based on the same assumptions as for residents up to 22 June 2011.

average effective dose in the first year of 5.5 mSv. Children and infants were estimated to have received average effective doses in the first year about 20% to 30% and 40% to 60% higher, respectively, than those for adults. Table A12 also shows the 95th percentiles of the distribution of individual doses among those evacuated according to each scenario. The 5th and 95th percentiles are generally 2–3 times lower and higher, respectively, than the average effective doses. Detailed results of the estimates of effective doses to the evacuees and parameters of the distributions of individual doses are provided in attachment A-18.

Table A12. Estimated effective doses to adults evacuated from municipalities of Fukushima Prefecture

The doses calculated are effective doses for each evacuation scenario, before and during evacuation, and for the first year following the accident. The dose estimates are intended to be characteristic of the average effective doses received by groups of people evacuated from each locality. The 95th percentile indicates the upper bound of the distribution of individual doses

Locality	*Scenario No.*	*Destination*	*Effective dose to adults (mSv)*					
			Evacuation[a]	*Destination*[b]	*Total first year*[c]		*Projected*[d]	*Averted*[e]
			Mean	*Mean*	*Mean*	*95th percentile*		
Futaba	01(FT1)	Saitama City	0.27	0.084	0.35	1.1	43	43
Futaba	02(FT2)	Ibaraki Prefecture	0.50	0.29	0.79	2.0	43	43
Futaba	03(FT3)	Ibaraki Prefecture	0.30	0.29	0.58	1.4	43	43
Futaba	04(FT4)	Koriyama City	0.56	1.9	2.5	4.3	43	41
Futaba	05(FT5)	Tochigi Prefecture	0.078	0.53	0.61	1.0	43	43
Kawauchi	06(TM1)	Niigata City	0.041	0.005	0.046	0.072	1.6	1.5
Tomioka	07(TM2)	Chiba City	0.25	0.25	0.50	1.1	18	17
Tomioka	08(TM3)	Chiba City	0.13	0.25	0.38	0.67	18	17
Tomioka	09(TM4)	Iwaki City	0.39	0.39	0.77	1.8	18	17
Naraha	10(NR1)	Nasushiobara City	0.14	0.64	0.78	1.3	2.7	1.9
Naraha	11(NR2)	Chiba City	0.22	0.25	0.47	0.97	2.7	2.2
Naraha	12(NR3)	Iwaki City	0.39	0.39	0.77	1.8	2.7	1.9
Naraha	13(NR4)	Tochigi Prefecture	0.069	0.53	0.60	1.0	2.7	2.1
Naraha	14(NR5)	Iwaki City	0.27	0.39	0.66	1.4	2.7	2.0
Okuma	15(OK1)	Aizuwakamatsu City	0.32	0.33	0.65	1.5	37	37
Okuma	16(OK2)	Tamura City	0.34	0.46	0.80	1.7	37	37

Locality	*Scenario No.*	*Destination*	*Effective dose to adults (mSv)*					
			Evacuation[a]	*Destination*[b]	*Total first year*[c]		*Projected*[d]	*Averted*[e]
			Mean	*Mean*	*Mean*	*95th percentile*		
Okuma	17(OK3)	Shinjuku Ward	0.23	0.10	0.33	0.86	43	43
Okuma	18(OK4)	Tamura City	0.71	0.46	1.2	3.2	0.64	–
Odaka	19(OK5)	Nasushiobara City	0.30	0.64	0.94	1.7	2.2	1.3
Namie	20(NM1)	Shinjuku Ward	0.15	0.10	0.25	0.57	16	16
Namie	21(NM2)	Soma City	0.44	0.69	1.1	2.3	16	15
Namie	22(NM3)	Koriyama City	0.34	1.9	2.3	3.8	16	14
Tsushima	23(NM4)	Nihonmatsu City	0.85	2.3	3.1	5.7	16	13
Namie	24(NM5)	Yonezawa City	0.31	0.058	0.37	1.3	16	16
Iitate	25(IT1)	Koriyama City	0.64	1.9	2.6	4.5	12	10
Iitate	26(IT2)	Aizu Region	0.083	0.33	0.41	0.68	12	12
Iitate	27(IT3)	Saitama City	0.28	0.084	0.36	0.99	12	12
Iitate	28(IT4)	Iitate Village	3.6	1.9	5.5	9.1	12	6.6
Odaka	29(OD1)	Shinjuku Ward	1.0	0.10	1.1	3.9	2.2	1.1
Odaka	30(OD2)	Tsuruoka City	0.027	0.078	0.11	0.18	2.2	2.1
Haramachi	31(OD3)	Yokohama City	0.17	0.054	0.22	0.58	2.3	2.1
Odaka	32(OD4)	Shinjuku Ward	0.61	0.10	0.72	2.3	2.2	1.5
Odaka	33(OD5)	Saitama City	0.43	0.084	0.52	1.6	2.2	1.7
Haramachi	34(HK1)	Yokohama City	0.26	0.054	0.31	0.91	2.3	2.0
Iitate	35(HK2)	Yamagata City	0.13	0.078	0.21	0.44	12	12
Kashima	36(HK3)	Yokohama City	0.54	0.52	1.1	2.4	1.6	0.55

Locality	*Scenario No.*	*Destination*	*Effective dose to adults (mSv)*					
			Evacuation[a]	*Destination*[b]	*Total first year*[c]		*Projected*[d]	*Averted*[e]
			Mean	*Mean*	*Mean*	*95th percentile*		
Haramachi	37(HK4)	Soma City	0.55	0.69	1.2	2.7	2.3	1.1
Hirono Town	10 (old)	Ono Town Office	0.46	0.30	0.75	2.1	1.9	1.2
Katsurao Village	12 (old)	Azuma Gymnasium	0.17	2.7	2.9	4.8	7.4	4.5
Katsurao Village	14 (old)	Azuma Gymnasium	1.2	2.7	3.9	7.4	7.4	3.5

[a] The effective dose for the evacuation is an estimate of the dose that people received before and during evacuation.

[b] The effective dose at destination is an estimate of the dose that people received for the remainder of the first year following evacuation.

[c] The total first-year effective dose is an estimate of the dose in the first year that people received before and during evacuation and at destination for the remainder of the year.

[d] The effective dose that is projected is an estimate of the dose that people would have received in the first year if they had not been evacuated.

[e] The effective dose that is averted is an estimate of the dose that people avoided by being evacuated. In some cases, this can be estimated to be a small negative value, because of the assumption that people were outdoors during the passage of the plume of radioactive material during evacuation, but would have been indoors if not evacuated. These cases are indicated by “–”.

Table A13. Estimated absorbed doses to the thyroid of infants evacuated from municipalities of Fukushima Prefecture

The doses calculated are absorbed doses to the thyroid for each evacuation scenario, before and during evacuation, and for the first year following the accident. The dose estimates are intended to be characteristic of the average absorbed doses to the thyroid received by groups of people evacuated from each locality. The 95th percentile indicates the upper bound of the distribution of individual doses

Original location	*Scenario No.*	*Destination*	*Absorbed dose to the thyroid of infants (mGy)*					
			Evacuation[a]	*Destination*[b]	*Total first year*[c]		*Projected*[d]	*Averted*[e]
			Mean	*Mean*	*Mean*	*95th percentile*		
Futaba	01(FT1)	Saitama City	3.7	0.19	3.9	7.8	490	490
Futaba	02(FT2)	Ibaraki Prefecture	14	0.68	15	47	490	480
Futaba	03(FT3)	Ibaraki Prefecture	10	0.68	11	33	490	480
Futaba	04(FT4)	Koriyama City	12	3.7	15	43	490	480
Futaba	05(FT5)	Tochigi Prefecture	2.8	1.0	3.8	6.4	490	490
Kawauchi	06(TM1)	Niigata City	3.5	0.087	3.5	5.9	7.4	3.9
Tomioka	07(TM2)	Chiba City	5.3	0.43	5.7	11	99	94
Tomioka	08(TM3)	Chiba City	4.7	0.43	5.1	9.3	99	94
Tomioka	09(TM4)	Iwaki City	10	1.6	12	33	99	87
Naraha	10(NR1)	Nasushiobara City	3.5	1.2	4.6	8.2	12	7.6
Naraha	11(NR2)	Chiba City	6.1	0.43	6.5	16	12	5.7
Naraha	12(NR3)	Iwaki City	9.5	1.6	11	32	12	1.1
Naraha	13(NR4)	Tochigi Prefecture	2.7	1.0	3.7	6.1	12	8.4
Naraha	14(NR5)	Iwaki City	6.3	1.6	7.9	20	12	4.2
Okuma	15(OK1)	Aizuwakamatsu City	5.4	1.5	6.9	17	320	310
Okuma	16(OK2)	Tamura City	5.9	1.7	7.6	19	320	310

Original location	Scenario No.	Destination	Absorbed dose to the thyroid of infants (mGy)					
			Evacuation[a]	Destination[b]	Total first year[c]		Projected[d]	Averted[e]
			Mean	Mean	Mean	95th percentile		
Okuma	17(OK3)	Shinjuku Ward	5.3	0.23	5.5	13	490	490
Okuma	18(OK4)	Tamura City	3.7	1.7	5.4	10	2.8	–
Odaka	19(OK5)	Nasushiobara City	7.4	1.2	8.5	21	21	12
Namie	20(NM1)	Shinjuku Ward	5.7	0.23	5.9	15	120	120
Namie	21(NM2)	Soma City	12	2.0	14	45	120	110
Namie	22(NM3)	Koriyama City	2.6	3.7	6.3	11	120	120
Tsushima	23(NM4)	Nihonmatsu City	9.0	4.2	13	34	120	110
Namie	24(NM5)	Yonezawa City	12	0.37	13	44	120	110
Iitate	25(IT1)	Koriyama City	12	3.7	16	39	57	41
Iitate	26(IT2)	Aizu Region	4.2	1.5	5.7	9.6	57	51
Iitate	27(IT3)	Saitama City	8.3	0.19	8.5	18	57	48
Iitate	28(IT4)	Iitate Village	14	2.5	16	30	57	41
Odaka	29(OD1)	Shinjuku Ward	30	0.23	30	100	21	–
Odaka	30(OD2)	Tsuruoka City	1.8	0.38	2.2	3.6	21	19
Haramachi	31(OD3)	Yokohama City	3.9	0.15	4.0	6.6	21	17
Odaka	32(OD4)	Shinjuku Ward	23	0.23	23	76	21	–
Odaka	33(OD5)	Saitama City	14	0.19	15	44	21	6.2
Haramachi	34(HK1)	Yokohama City	7.0	0.15	7.1	17	21	14
Iitate	35(HK2)	Yamagata City	5.3	0.41	5.7	9.7	57	51
Kashima	36(HK3)	Yokohama City	12	0.78	12	34	20	7.6

Original location	*Scenario No.*	*Destination*	*Absorbed dose to the thyroid of infants (mGy)*					
			Evacuation[a]	*Destination*[b]	*Total first year*[c]		*Projected*[d]	*Averted*[e]
			Mean	*Mean*	*Mean*	*95th percentile*		
Haramachi	37(HK4)	Soma City	16	2.0	18	56	21	2.4
Hirono Town	10 (old)	Ono Town Office	3.2	1.5	4.7	9.8	10	5.1
Katsurao Village	12 (old)	Azuma Gymnasium	0.77	4.7	5.5	9.2	30	25
Katsurao Village	14 (old)	Azuma Gymnasium	8.8	4.7	14	36	30	17

[a] The absorbed dose to thyroid for the evacuation is an estimate of the dose that people received before and during evacuation.

[b] The absorbed dose to thyroid at destination is an estimate of the dose that people received for the remainder of the first year following evacuation.

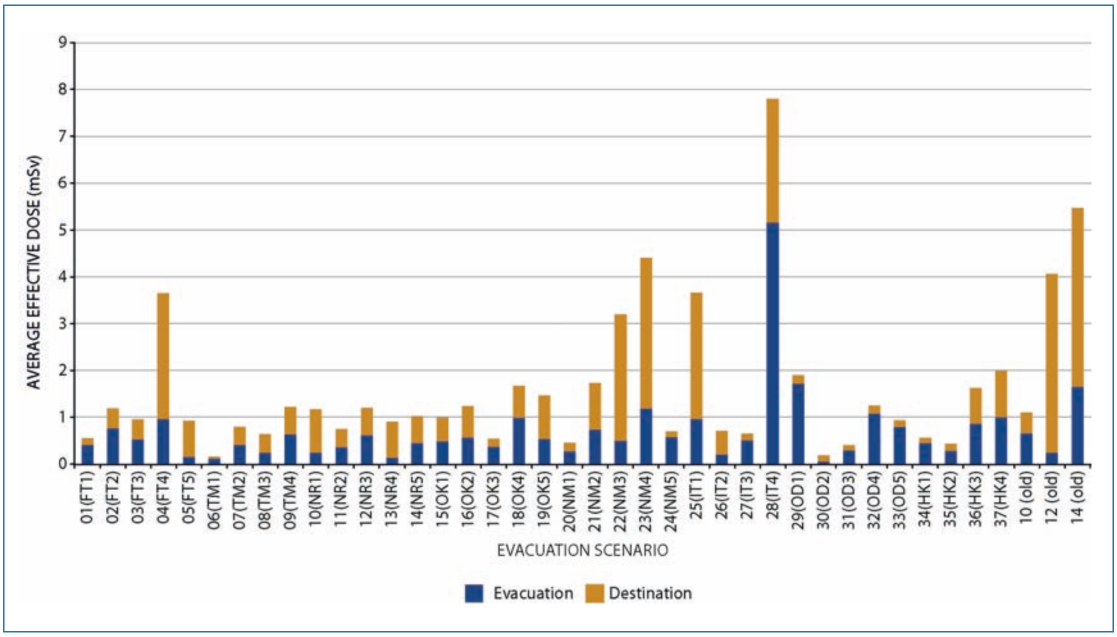
[c] The total first-year absorbed dose to the thyroid is an estimate of the dose in the first year that people received before and during evacuation and at destination for the remainder of the year.

[d] The absorbed dose to thyroid that is projected is an estimate of the average dose that people would have received in the first year if they had not been evacuated.

[e] The absorbed dose to thyroid that is averted is an estimate of the average dose that people avoided by being evacuated. In some cases, this can be estimated to be a small negative value, because of the assumption that people were outdoors during the passage of the plume of radioactive material during evacuation, but would have been indoors if not evacuated. These cases are indicated by "–".

A108. The average effective dose in the first year to infants for each evacuation scenario is shown in figure A-VIII. The figure shows the contribution of the effective dose over the period of the evacuation and of the effective dose at the destination. For several scenarios, effective doses received at the destination exceed those received before and during evacuation. The largest average annual effective dose to infants is again for the late evacuees from Iitate Village. Comparison with figure A-III shows that (apart from this one scenario) the doses to evacuees were generally comparable with those for municipalities of Fukushima Prefecture that were not evacuated.

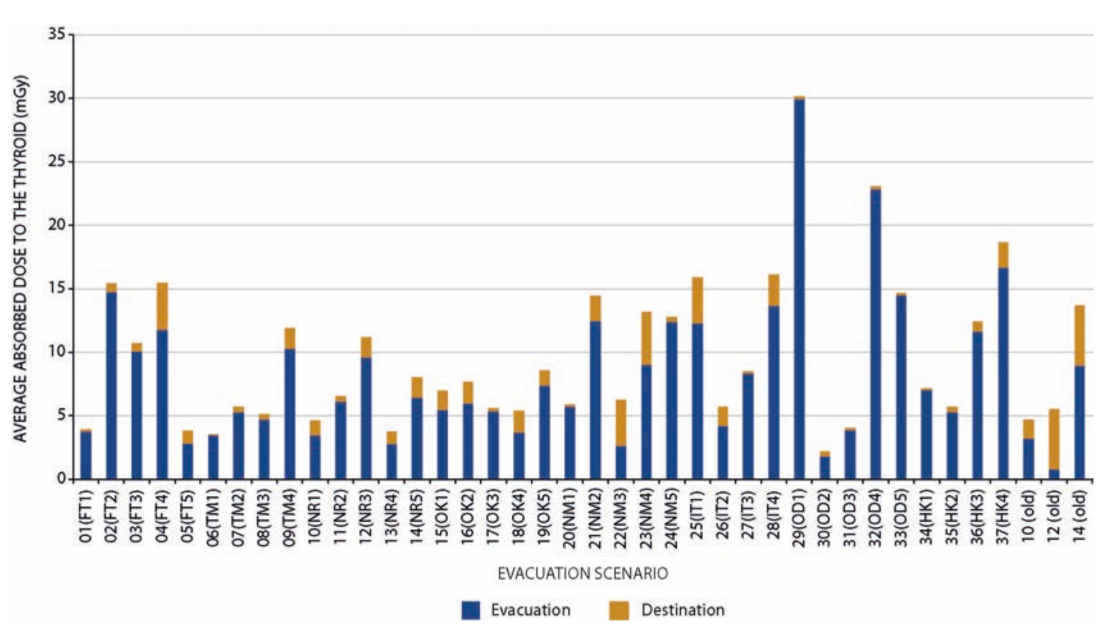
Figure A-VIII. Average effective dose in the first year to infants for each evacuation scenario



A109. The estimates of average absorbed doses to the thyroid for those evacuated are shown in table A13, where the doses presented are those to infants. The average absorbed doses to the thyroid of infants for the period before and during the evacuations were estimated to be up to about 30 mGy. These values are consistent with those obtained in a recent assessment of absorbed doses to the thyroid of infant evacuees that used a similar methodology [O5] (see attachment A-22). The doses were principally from inhalation during the passage of the airborne radioactive material through the affected areas in the early days of the accident, with a smaller contribution from ingestion of drinking water. The average absorbed doses to the thyroid for the first year for infants who were evacuated (including doses before and during the evacuation and doses during the remainder of the year at the destination) also ranged up to about 30 mGy. The absorbed doses to the thyroid of children and adults are about 80% and 40%, respectively, of those to infants. The Committee has estimated the distribution of doses to individuals within each population group and the 95th percentiles of the distribution for each scenario are also shown in table A13. The 5th and 95th percentile absorbed doses to the thyroid are between about two and four times lower and about two to three times higher, respectively than the average dose. Detailed results of the estimates of average absorbed doses to the thyroid for those who were evacuated, including estimates for adults and children, are provided in attachment A-18.

A110. Estimates have also been made of the absorbed doses to the fetal thyroid. Generally, the fetal absorbed doses to the thyroid over the 30-week development period of the fetus were estimated to be about 70% to 80% of the adult thyroid dose in the first year reported in attachment A-18.

Figure A-IX. Average absorbed dose to the thyroid in the first year to infants for each evacuation scenario



A111. Figure A-IX shows the average absorbed dose to the thyroid for infants in the first year for each of the evacuation scenarios, with the contribution of the dose for the period of the evacuation and the dose at the destination separately indicated. For the absorbed dose to the thyroid, much more of the total in the first year was contributed by the period before and during the evacuation than was the case for the effective dose. Detailed results of the estimates of average absorbed dose to the thyroid of the evacuees are provided in attachment A-18. The protective effect of iodine blocking possibly implemented by some residents was not taken into account in the assessment. However, the general iodine-rich diet of the Japanese people has been reflected in the dose coefficients used.

A112. Comparisons with the doses to evacuees estimated in the UNSCEAR 2013 Report [U10] indicate that the Committee's revised estimates of average effective doses in the first year are about a few tens of per cent lower, but that the revised estimates of absorbed dose to the thyroid in the first year are between three and four times lower. This reduction is largely a reflection of the lower Japan-specific dose coefficients for intakes of radioiodine and the much lower destination doses from ingestion.

A113. The evacuation of municipalities was estimated, on average, to have averted effective doses to adults of up to about 40 mSv and absorbed doses to the thyroid of infants of up to about 500 mGy. In several scenarios, the average doses estimated to have been received by the evacuees were similar to those estimated to have been received had they stayed in place.

A114. For the small number of hospital and nursing-home patients, residents and other individuals in the 20-km zone for whom the 40 evacuation scenarios were not applicable, higher doses could not be ruled out. The doses that were averted, when added to the estimates of dose received before and during the evacuation, can be used as estimates of the doses to people who might have stayed in the evacuation zone, and as an upper bound for any individual who might have gained long term access to the zone.

B. Estimation of doses in Japan over longer time periods

A115. Estimates have also been made of municipality- and prefecture-average doses accumulated over the first 10 years after the accident and up to age 80 years. The doses from external exposure were assessed with similar methods as for the first year but taking account of the reduction in dose rate due to radioactive decay and the model described in section III.C.1 and attachment A-1. Table A14 shows the dependence of doses from external exposure on the exposure duration and location for various age groups of the Japanese population. Compared with the equivalent table C13 in the UNSCEAR 2013 Report [U10], the doses from external exposure are generally higher, by factors varying by population group, exposure duration and location between a few per cent and a factor of about two. The differences reflect the different model used (see attachment A-1 for further details). No account was taken of the possible reduction in exposure as a consequence of remediation in these estimates of doses. The effect of the resulting overestimation of doses for time periods after the completion of remediation work in areas that have been remediated on the doses presented in tables A14, A15 and A16 would generally have been small in comparison with the uncertainties in these dose estimates.

Table A14. Dependence of the effective dose from external exposure normalized by deposition density of ^{137}Cs on the exposure duration

Exposure duration	*Effective dose from external exposure per unit deposition density[a] (mSv per 0.1 MBq/m^2 as of June 2011)*			
	Age/population group (as of 2011)			
	1-year-old	*10-year-old*	*Adult outdoor worker*	*Adult indoor worker*
ENTIRE JAPAN EXCEPT FOR SOUTH TRACE[b]				
1 year	2.3	1.9	2.6	1.6
10 years	6.3	5.4	7.6	4.7
Lifetime[c]	8.5	7.6	10.8	6.7
SOUTH TRACE[b]				
1 year	2.9	2.4	3.2	2.0
10 years	6.9	5.9	8.2	5.1
Lifetime[c]	9.1	8.1	11.5	7.1

[a] No account was taken of the reduction in exposure as a consequence of remediation in some areas.

[b] Hirono Town, Iwaki City, Naraha Town and Tomioka Town of Fukushima Prefecture, and Kitaibaraki City and Takahagi City of Ibaraki Prefecture.

[c] Time up to age 80, assuming 20-year-old adult at time of the accident.

A116. For doses from the ingestion of radionuclides for time periods after the first year, the Committee has used estimates of doses to adults and children from ingestion of caesium radionuclides derived from the market-basket and duplicate-diet studies as its starting point, and then used the model developed by Smith et al. [S33] to estimate how intakes of radiocaesium from food and drinking water change over the longer term. The estimated municipality-average or prefecture-average effective doses for adults, children and infants, integrated over 10 years after the accident and up to age 80 years are provided in attachment A-19 together with the parameters of the distributions of doses to individuals in each population group. Ranges of the average total effective doses within different municipalities or prefectures from external and internal exposures are summarized in table A15. Compared with the equivalent table C14 in the UNSCEAR 2013 Report [U10], the estimated average effective doses accumulated over the first 10 years and up to the age of 80 years at the upper end of the ranges are generally within a few tens of per cent of those estimated in the UNSCEAR 2013 Report (although the differences for the Group 4 prefectures are larger due to the different prefecture groupings used in this report); at the lower end of the ranges, they are up to 10 or 20 times lower. The 95th percentile of the distribution of effective doses over a lifetime to individuals in each population group due to uncertainties and variabilities is generally less than a factor of two greater than the average dose.

Table A15. Ranges of estimated municipality- or prefecture-average effective doses to adults, children and infants (as of 2011) over the first year and first 10 years and to age 80 years

Age group in March 2011	*Ranges of municipality- or prefecture-average effective dose[a] (mSv)*		
	Group 2[b]	*Group 3[c]*	*Group 4[d]*
1-YEAR EXPOSURE			
Adult	0.079–3.8	0.10–0.92	0.004–0.36
10-year-old	0.10–4.5	0.13–1.1	0.005–0.43
1-year-old	0.12–5.3	0.15–1.3	0.005–0.51
10-YEAR EXPOSURE			
Adult	0.16–11	0.25–2.5	0.009–1.0
10-year-old	0.19–12	0.30–2.9	0.008–1.2
1-year-old	0.22–14	0.34–3.4	0.007–1.3
LIFETIME EXPOSURE TO AGE 80 YEARS			
Adult	0.22–15	0.32–3.6	0.010–1.4
10-year-old	0.24–17	0.38–4.0	0.009–1.6
1-year-old	0.27–19	0.43–4.5	0.008–1.8

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

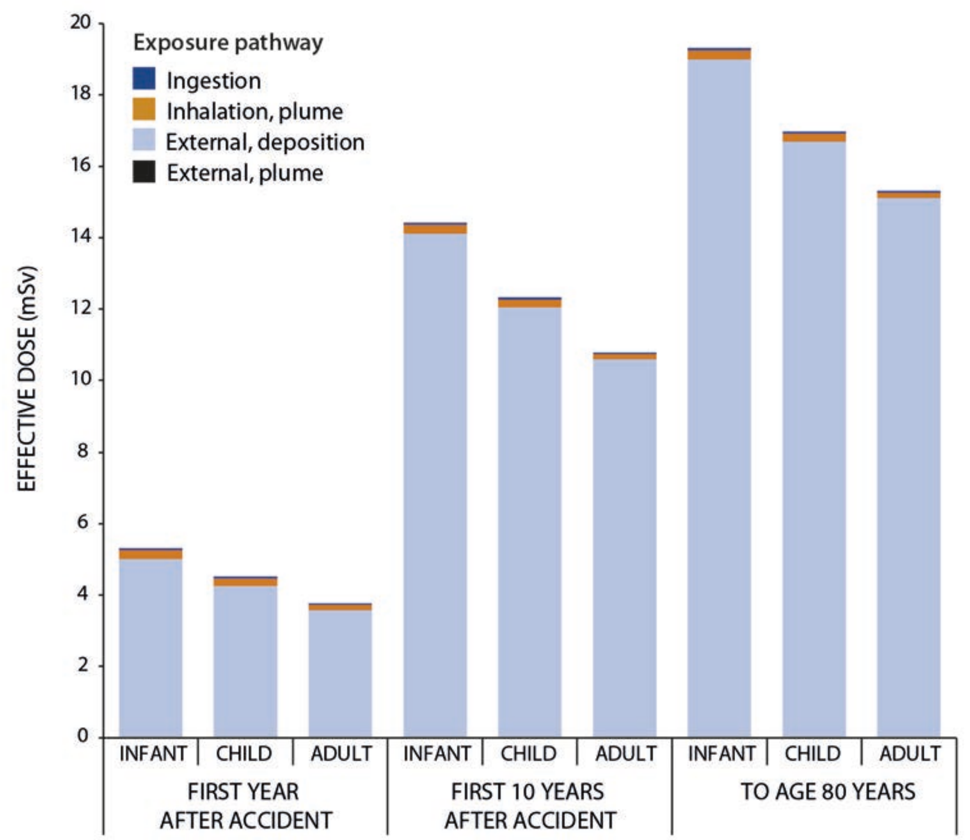
[b] Municipalities of Fukushima Prefecture that were not wholly evacuated.

[c] Members of the public living in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata.

[d] Members of the public living in the remaining prefectures of Japan, including the previous Group 3 prefectures of Gunma, Chiba and Iwate.

A117. Figure A-X shows the estimated average effective dose as a function of age group for the different integration times for people living in Fukushima City. The estimated average effective doses over the 10-year-exposure period and the average effective doses up to age 80 years are larger by factors of up to 2.5 and 4, respectively, than those received in the first year. External exposure to deposited radionuclides is by far the dominant pathway.

Figure A-X. Estimated average effective dose as a function of age group (as of 2011) for the different integration times for people living in Fukushima City



A118. Most of the absorbed dose to the thyroid of residents of Japan was received during the first year from inhalation of radioiodine. Continued exposure from the longer-lived radioisotopes of caesium (from external radiation from deposited radionuclides and intake by ingestion) is estimated to result in an absorbed dose to the thyroid up to age 80 years about twice that received in the first year.

C. Estimation of current levels of exposure

A119. To provide an indication of current levels of exposure resulting from the accident, table A16 sets out the ranges in the estimated municipality- or prefecture-average annual effective doses in 2021 in the non-evacuated municipalities of Fukushima Prefecture (Group 2), the Group 3 prefectures and the remaining prefectures in Japan (Group 4). The estimated average annual effective doses are all less than 0.5 mSv in Fukushima Prefecture (Group 2) and below 0.1 mSv elsewhere in Japan. The estimated average dose in each municipality or prefecture and the parameters of the distribution of individual doses, as well as the contributions from the pathways of external exposure to deposited radionuclides and internal exposure from ingestion are provided in attachment A-19. The 5th and 95th percentiles of the distributions of individual doses are about two to three times lower and two times higher than the average doses, respectively. External exposure to deposited radionuclides generally accounts for more than 95%

of the total dose. Figure A-XI shows the estimated average annual effective dose to infants in 2021 by municipality for Fukushima Prefecture and parts of the Group 3 neighbouring prefectures. It includes the municipalities in Fukushima Prefecture that were evacuated (apart from the “Areas where Returning is Difficult”), assuming that residents have returned, and takes account of remediation in the SDA (see paragraph A120 below).

Table A16. Ranges of estimated municipality- or prefecture-average effective doses to adults, children and infants in the year 2021

Geographical area	*Ranges of municipality- or prefecture-average annual effective dose[a] (mSv)*		
	Adult	*10-year-old*	*1-year-old*
GROUP 2[b] – FUKUSHIMA PREFECTURE			
Municipalities not evacuated	0.004–0.31	0.004–0.36	0.004–0.42
GROUP 3[c] – NEIGHBOURING PREFECTURES			
Ibaraki Prefecture	0.009–0.037	0.010–0.043	0.012–0.051
Miyagi Prefecture	0.010–0.067	0.011–0.079	0.013–0.093
Tochigi Prefecture	0.010–0.070	0.011–0.082	0.013–0.097
Yamagata Prefecture	0.005–0.008	0.006–0.009	0.006–0.011
GROUP 4[d] – REST OF JAPAN			
42 remaining prefectures	<0.001–0.028	<0.001–0.033	<0.001–0.039

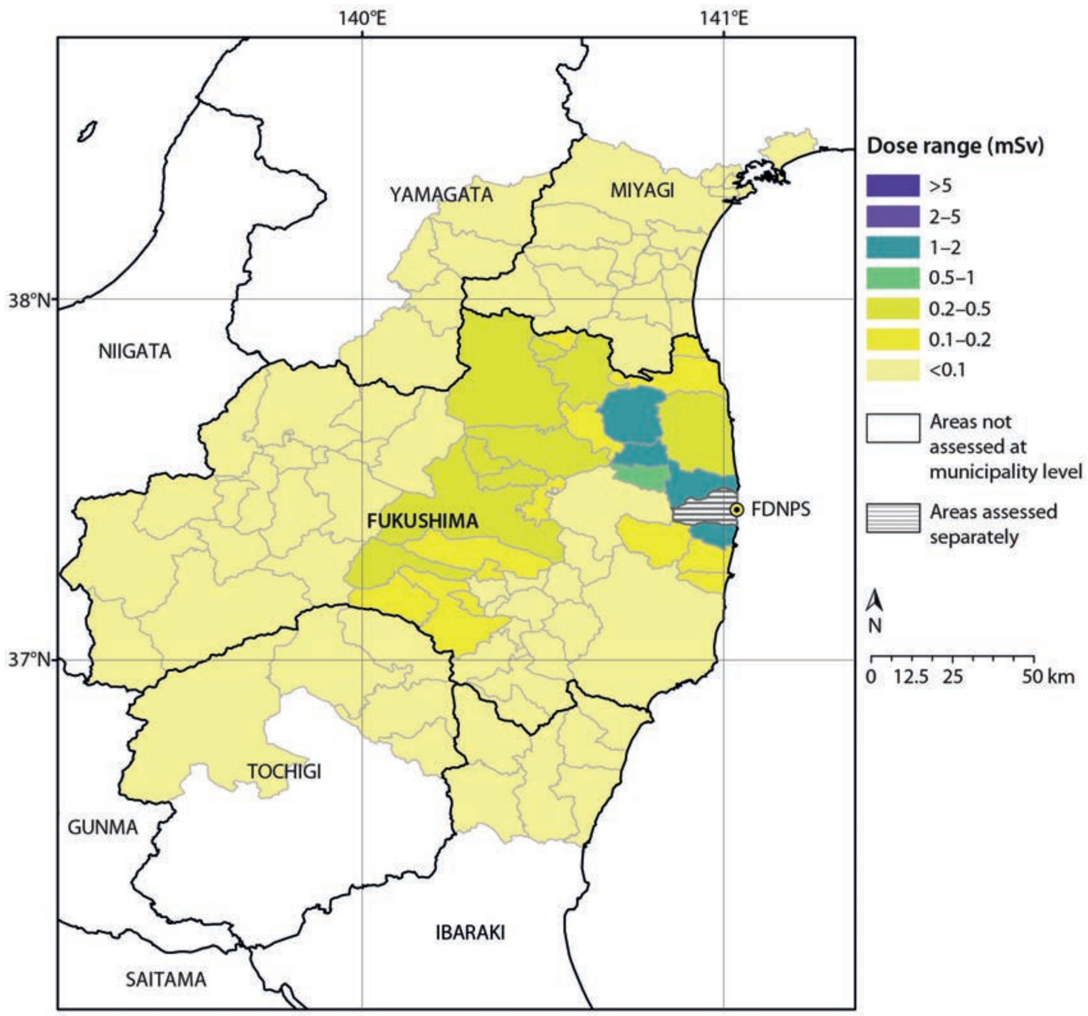
[a] The reported doses are ranges of the municipality-averaged doses for the Group 2 and Group 3 prefectures and the prefecture-average doses for the Group 4 prefectures. These estimates of dose are representative of the average doses received by people living at different locations and do not reflect the range of doses received by individuals within the population at these locations. The doses are in addition to doses from natural background radiation and other sources of exposure and are for the people in the specified age groups in 2021. The adult doses are for indoor workers as representative of adults as a whole.

[b] Municipalities of Fukushima Prefecture that were not evacuated.

[c] Members of the public living in the prefectures of Ibaraki, Miyagi, Tochigi and Yamagata.

[d] Members of the public living in the remaining prefectures of Japan.

Figure A-XI. The estimated average annual effective dose in 2021 for infants living in municipalities of Fukushima Prefecture and some municipalities of Group 3 prefectures



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations (Source: Adapted from Japan administrative level 0-2 boundaries, Japanese prefecture governments).

A120. The completion of remediation work in the SDA has allowed the removal of most evacuation orders and the gradual return of people to remediated areas. Estimates of the annual external doses received in the period 2019–2021 and up to the age of 80 years by those who were evacuated if they returned to their homes and regular lifestyles are shown in table A17 for those who were 20-year-old adults or 1-year-old infants in 2011. These estimates include a DRF of 1.3 to take account of the effect of remediation in the SDA.

Table A17. Estimated annual average and lifetime effective doses from external exposure for adults and infants at the time of the accident if they were to return to municipalities from which they were evacuated

Municipality	*Effective dose from external exposure (mSv)*							
	Annual doses and doses up to age 80 years for those who were adults at the time of the accident				*Annual dose and dose up to age 80 years for those who were infants at the time of the accident*			
	2019	*2020*	*2021*	*Lifetime*	*2019*	*2020*	*2021*	*Lifetime*
Futaba Town[a]	2.6	2.4	2.1	38	3.3	2.9	2.6	40
Hirono Town	0.090	0.080	0.080	1.3	0.12	0.10	0.090	1.4
Iitate Village	0.94	0.83	0.75	13	1.2	1.0	0.93	14
Katsurao Village	0.58	0.52	0.46	7.7	0.72	0.64	0.57	8.5
Kawamata Town	0.12	0.11	0.090	1.7	0.15	0.13	0.12	1.8
Kawauchi Village	0.12	0.10	0.090	1.5	0.14	0.12	0.11	1.8
Minamisoma City (Odaka)	0.15	0.13	0.12	2.0	0.18	0.16	0.15	2.2
Namie Town	1.2	1.1	0.95	16	1.5	1.3	1.2	18
Naraha Town	0.15	0.14	0.12	2.2	0.19	0.17	0.15	2.4
Okuma Town[a]	2.3	2.1	1.9	32	2.9	2.5	2.3	35
Tamura City	0.050	0.040	0.04	0.69	0.050	0.050	0.050	0.69
Tomioka Town	1.2	1.1	0.99	18	1.5	1.4	1.2	19

[a] Municipality entirely within "Areas where Returning is Difficult" and not included in figure A-XI (Iitate Village, Katsurao Village, Namie Town and Tomioka Town, also contain some "Areas where Returning is Difficult" but are included in the figure).

D. Estimation of collective doses

A121. The collective effective doses[7] and the collective absorbed doses to the thyroid from the major exposure pathways (external exposure, inhalation and ingestion) were estimated for the first year, 10 years and to age 80 years following the accident[8] for Fukushima Prefecture, neighbouring prefectures and the rest of Japan, and are summarized in table A18. Further details can be found in attachment A-20.

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[7] The Committee has used the quantity, collective (effective) dose, for many years to compare the radiation exposures of populations from different sources of ionizing radiation, or following different protection measures. The collective (effective) dose is always estimated for a defined population over a specified period of time. It is the product of the mean effective dose to a specified population from a particular source, and the number of people in that population, integrated over a defined period of time. Importantly, calculated doses are recommended only for comparative purposes and not for estimations related to health effects. Collective dose is not intended as a tool for epidemiological risk assessment. Moreover, the aggregation of very low individual doses over extended time periods is inappropriate for use in risk projections and, in particular, the calculation of numbers of cancer deaths from collective doses based on individual doses that are well within the variation in background exposure should be avoided.

[8] In this report, the Committee has used the terms "collective effective dose" and "collective absorbed dose to the thyroid" and described them as being for different time periods. This follows the approach used in the UNSCEAR 2013 Report. Strictly, the correct terms are "collective effective dose commitment" and "collective absorbed dose commitment to the thyroid" (for the time-integrated quantity), and the descriptions should make clear that the dose commitment (time-integrated) has been truncated at the different time periods. The Committee has retained the same terms as used in the UNSCEAR 2013 Report for ease of comparison with that report and for simplicity.

External exposure from deposited radionuclides makes the largest contribution to the collective effective dose for all exposure durations. For exposure durations of more than a few years, external exposure from deposited radionuclides also makes the largest contribution to the collective absorbed dose to the thyroid, although ingestion of radionuclides in food makes a greater contribution to the collective absorbed dose to the thyroid in the first few years. The estimates of the collective doses to the population of Japan can be compared with estimates for populations of European countries exposed to radiation following the 1986 Chernobyl accident (see appendix B). The collective effective dose to the population of Japan due to a lifetime exposure following the FDNPS accident is approximately 10% to 15% of the corresponding value for European populations exposed to radiation following the Chernobyl accident, and the collective absorbed dose to the thyroid is approximately 3% of that due to the Chernobyl accident. For further perspective, the annual collective effective dose to the population of Japan from natural background radiation can be estimated to be about 280,000 man Sv (about 20 times the collective effective dose in the first year after the FDNPS accident).

Table A18. Collective effective doses and collective absorbed doses to the thyroid for the population of Japan (128 million in 2010)

Exposure pathway	*Exposure duration*		
	First year	*10 years*	*Lifetime (up to age 80 years)*[a]
COLLECTIVE EFFECTIVE DOSE (thousand man Sv)			
Inhalation	0.27	0.27	0.27
External	11	30	42
Ingestion	0.64	1.2	1.4
Total	12	32	44
COLLECTIVE ABSORBED DOSE TO THE THYROID (thousand man Gy)			
Inhalation	5.7	5.7	5.7
External	11	31	43
Ingestion	7.1	7.6	7.8
Total	24	44	57

[a] The collective dose over a lifetime (up to age 80 years) represents more than 97% of the collective dose commitment in each case.

E. Radiation exposure outside of Japan

A122. In the UNSCEAR 2013 Report [U10] the Committee concluded that the effective doses and equivalent doses to the thyroid for individuals living outside of Japan were less than 0.01 mSv in the first year following the accident. This was based on an analysis of estimates in the published peer-reviewed literature, the results of World Health Organization preliminary dose estimation [W13] and dose assessments carried out by Member States of the United Nations (see table C15 in the UNSCEAR 2013 Report).

A123. The Committee has reviewed literature, published since the UNSCEAR 2013 Report [U10], on assessments made of doses in countries neighbouring, or in relatively close proximity to, Japan including the Republic of Korea, the Russian Federation, the People's Republic of China, and Taiwan Province of

China. The estimated doses in these more recent publications are summarized in table A19 and mostly relate to doses from ingestion of food either grown in the countries themselves or imported from Japan. In light of the studies summarized in the UNSCEAR 2013 Report and in table A19, the Committee sees no reason to revise its conclusion that the effective doses and equivalent doses to the thyroid for people living outside of Japan were less than 0.01 mSv in the first year following the accident.

Table A19. Estimated doses reported for countries neighbouring, or in close proximity to, Japan

Location [Reference]	*Committed effective dose in the first year from intakes of radiocaesium (mSv)*	*Comments*
Asia-Pacific [P4]	7×10^{-3}	Realistic estimate based on consumption of fish caught in the open North West Pacific Ocean (includes a conservative estimate of the contribution from ^{90}Sr of about 10% of the total)
Taiwan Province of China [L8]	5.7×10^{-3}	Based on consumption of contaminated imported food. Doses were estimated for a "worst-case scenario" from measurements
People's Republic of China [S21]	3×10^{-5}	Based on environmental monitoring where activity concentrations in vegetables, milk and drinking water were below detection limits
People's Republic of China [W20]	9×10^{-6}	Based on environmental monitoring and atmospheric modelling
People's Republic of China [Y12]	1.4×10^{-5}–2.2×10^{-5}	Based on measurements of seafood and algae; measured levels not significantly different from those before the accident
Russian Federation [R1]	2.7×10^{-3}	Based on measurements and environmental monitoring of levels in milk

F. Distributions of doses in the population

A124. The Committee's dose estimates for residents and for evacuees set out in this appendix are intended to be characteristic of the average doses received by people living in each municipality or prefecture, or represented by each evacuation scenario. The ranges of doses indicated in the tables above reflect how the average doses vary between municipalities or between prefectures rather than the range of doses received by individuals within a given municipality or prefecture.

A125. The Committee has, in addition, made estimates of the distributions of individual doses in each municipality and prefecture taking account of uncertainties and of numerous factors that may influence how doses may vary between individuals (e.g., concentrations of radionuclides in air and on the ground where they live and work, their diet, lifestyle (e.g., fraction of the time spent indoors/outdoors), shielding provided by buildings). The dose distributions were estimated using a Monte Carlo approach, where the uncertainties and variabilities were described by assigning probability distributions to the input parameters. These probability distributions were either estimated based on available data or by expert judgement. See attachment A-12 for further details.

A126. The 5th and 95th percentiles of the distributions of individual doses have been provided with estimates of the average doses in attachments A-13 to A-19. Distributions of individual doses (both effective and absorbed dose to the thyroid) in the first year and over a lifetime are provided in attachment A-21 for municipalities in Fukushima Prefecture that were not evacuated, for subgroups of the population that were evacuated, and for the non-evacuated municipalities of Fukushima Prefecture as a whole and evacuees as a whole. Examples of these distributions are presented in figures A-XII to A-XVII for:

(a) Effective doses in the first year in Fukushima Prefecture as a whole;

(b) Absorbed doses to the thyroid in the first year in Fukushima City;

(c) Effective doses in the first year among evacuees;

(d) Absorbed doses to the thyroid in the first year among evacuees;

(e) Absorbed doses to the thyroid in the first year in Fukushima Prefecture as a whole;

(f) Effective doses over a lifetime in Fukushima Prefecture as a whole.

The average dose and the median dose are shown for each distribution.

A127. The first example in figure A-XII (the distribution of effective doses in the first year in Fukushima Prefecture) shows that most individuals were estimated to have received an effective dose within about ten times lower and three times higher than the average dose in the prefecture (around 2 mSv). A small proportion (around a thousand) of the population of about 2 million people were estimated to have received effective doses less than 0.1 mSv and an even smaller proportion were estimated to have received doses more than 10 mSv. The distribution shows one peak centred around an annual effective dose of about 1 mSv and a second centred around an annual effective dose of 2 to 3 mSv. This is likely to be due to the dominance of the contribution from external exposure to deposited radionuclides to the total dose and differences in the deposition densities of radionuclides in the main population centres in Fukushima Prefecture.

A128. The second example in figure A-XIII (the distribution of absorbed doses to the thyroid in the first year in Fukushima City) shows a similar pattern, although the distribution is a little narrower: most individuals in Fukushima City received an absorbed dose to the thyroid within the range of three times lower and three times higher than the average dose for Fukushima City (around 9 mGy), with more individuals receiving a dose lower than the average than higher than the average.

A129. The third example in figure A-XIV (distribution of effective doses in the first year for evacuees) shows that most evacuees were estimated to have received effective doses between about 0.1 and 5 mSv, and more were estimated to have received doses less than the average than above the average effective dose (of around 0.9 mSv). Compared with the previous distributions in figures A-XII and A-XIII, the distribution shows a larger difference (of about a factor of nearly two) between the average dose and the median dose (P50), reflecting greater asymmetry.

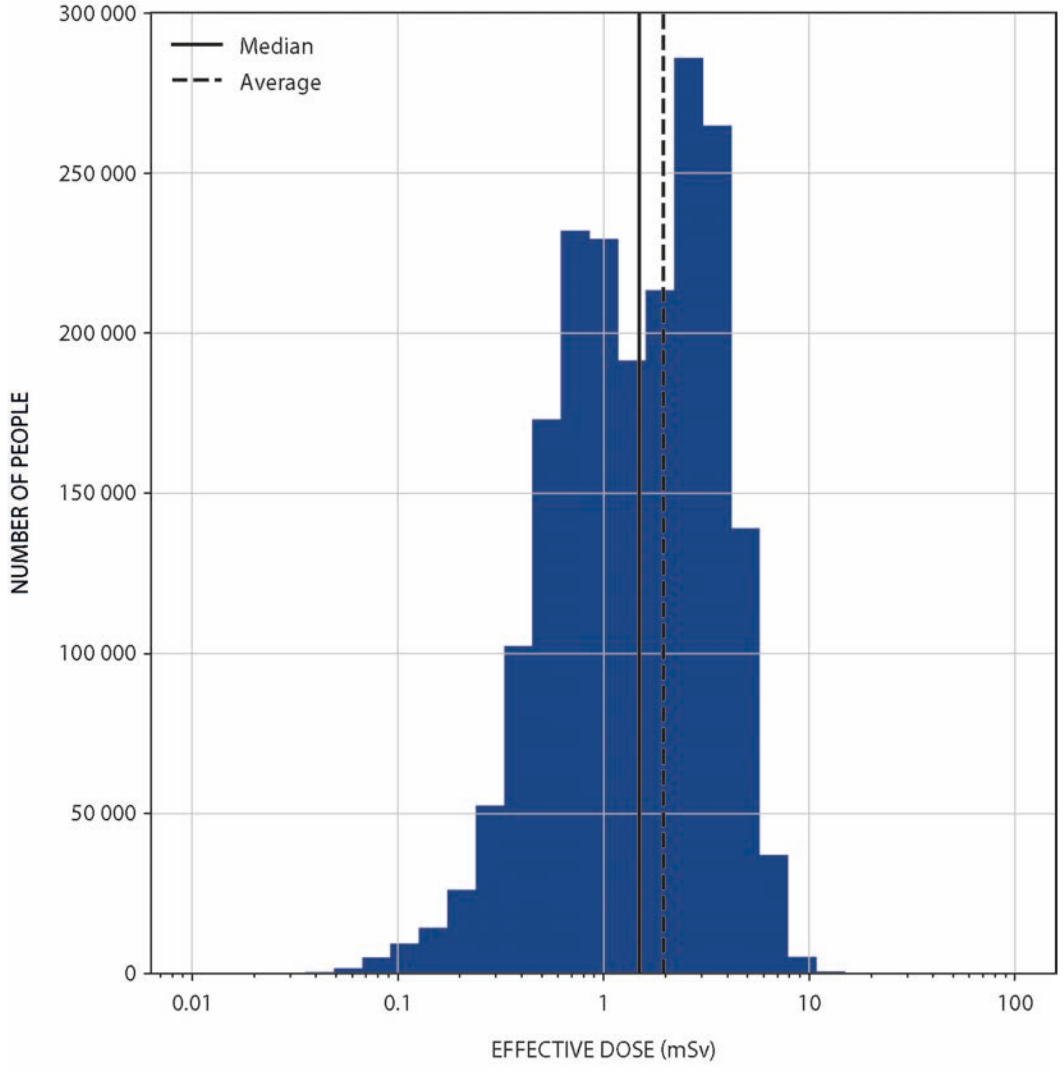
A130. The fourth example in figure A-XV (distribution of absorbed doses to the thyroid in the first year for evacuees) shows that nearly all of the evacuees were estimated to have received doses between five times lower and about three times higher than the average of about 4.5 mGy. There is again a comparatively large difference between the median dose and average dose. About 15% of the evacuees were estimated to have received absorbed doses to the thyroid of about 1 mGy or less, and around 0.2% were estimated to have received more than 100 mGy.

A131. The fifth example in figure A-XVI (distribution of absorbed dose to the thyroid in the first year in Fukushima Prefecture) shows the distribution of absorbed dose to the thyroid in the first year in the non-evacuated municipalities of Fukushima Prefecture. Most individuals in Fukushima Prefecture were estimated to have received absorbed doses to the thyroid in the first year between about six times lower and three times higher than the average for the prefecture as a whole of about 5 mGy. Only about 1% of the population were estimated to have received doses lower than 0.5 mGy or greater than 20 mGy.

A132. The final example in figure A-XVII (distribution of effective doses over a lifetime for Fukushima Prefecture) shows the doses ranging over about two orders of magnitude, with nearly all of the individuals in Fukushima Prefecture estimated to have received effective doses over a lifetime between ten times lower and four times higher than the average dose for the prefecture (of about 7 mSv). This distribution shows a clear double peak (similar to, but more pronounced than, that apparent in figure A-XII), with a large proportion of the population (about 40%) estimated to have received doses in a distribution centred around an effective dose of about 2 mSv, and a second large proportion (just over 40%) estimated to have received doses in a distribution centred around an effective dose of about 10 mSv. This pattern is again likely to be a consequence of the dominance of the pathway of external exposure to deposited material and the different deposition densities of released radionuclides in areas where most people in Fukushima Prefecture live.

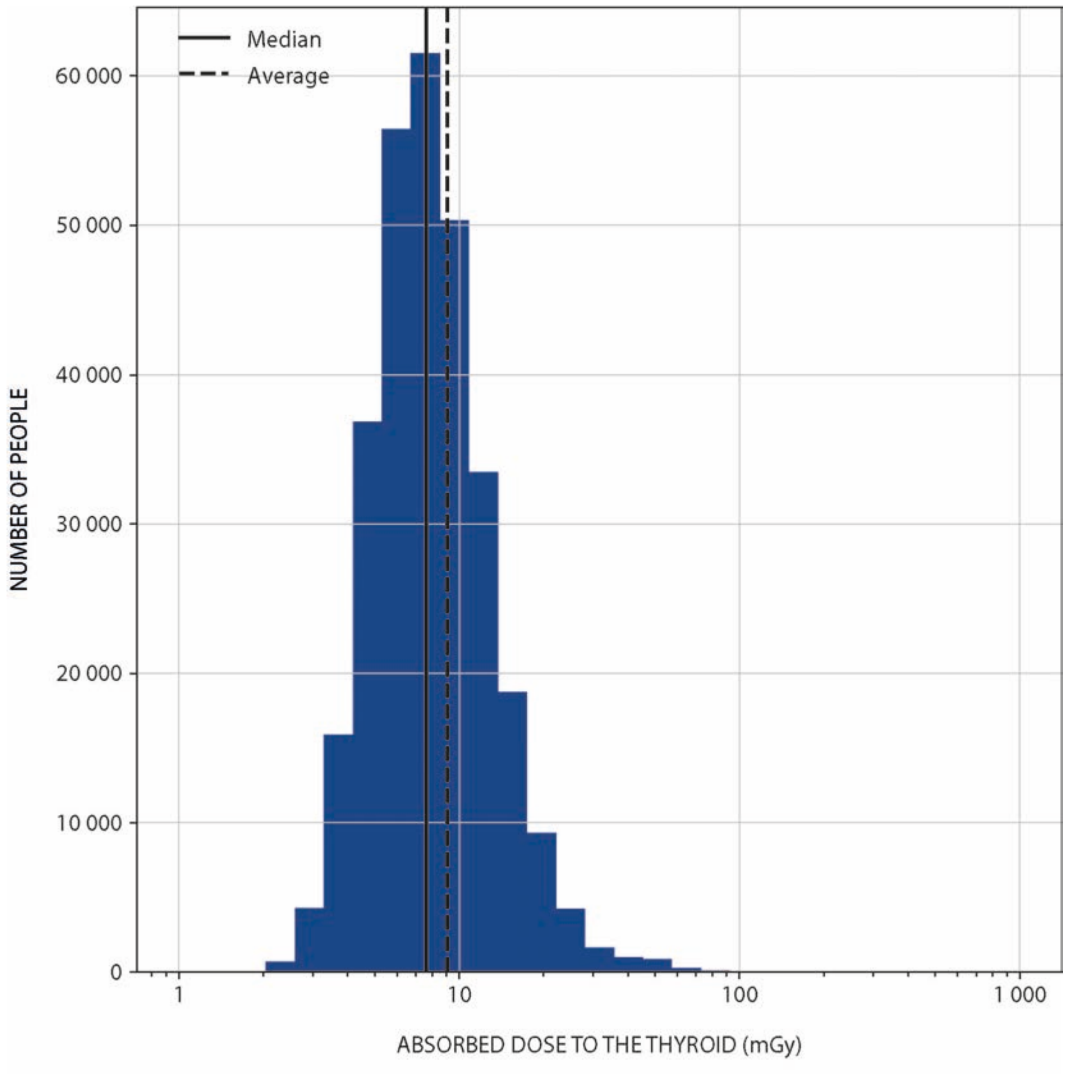
A133. Finally, figure A-XVIII (cumulative distribution of doses in the first year in Fukushima Prefecture) provides examples of an alternative presentation of the distributions of dose in the form of cumulative distributions. The figure shows the fraction of the population of Fukushima Prefecture estimated to have received an effective dose in the first year and an absorbed dose to the thyroid in the first year above the level indicated.

Figure A-XII. Distribution of effective dose in the first year in Fukushima Prefecture[a]



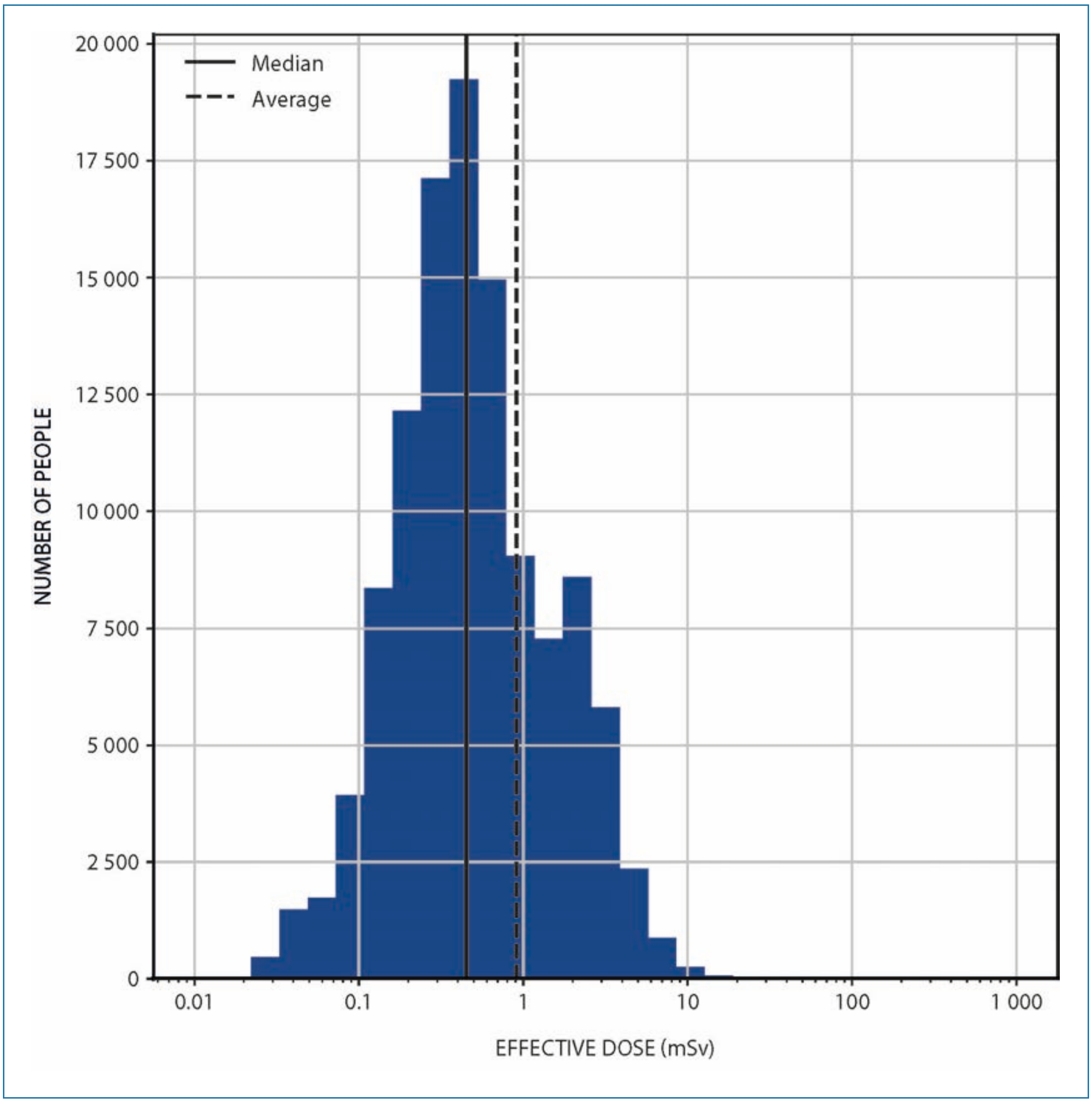
[a] Includes all age groups.

Figure A-XIII. Distribution of absorbed dose to the thyroid in the first year in the municipality of Fukushima City[a]



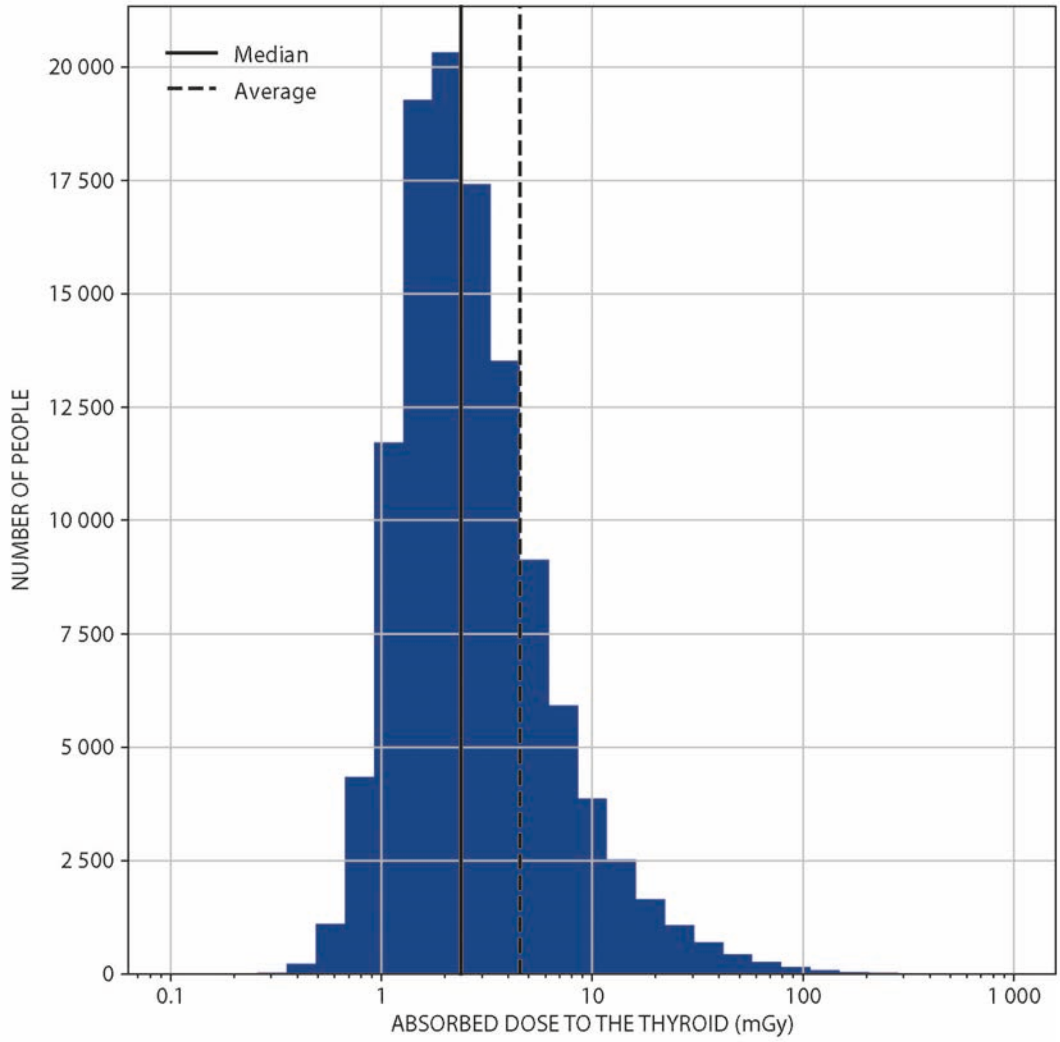
[a] Includes all age groups.

Figure A-XIV. Distribution of effective dose in the first year for evacuees[a]



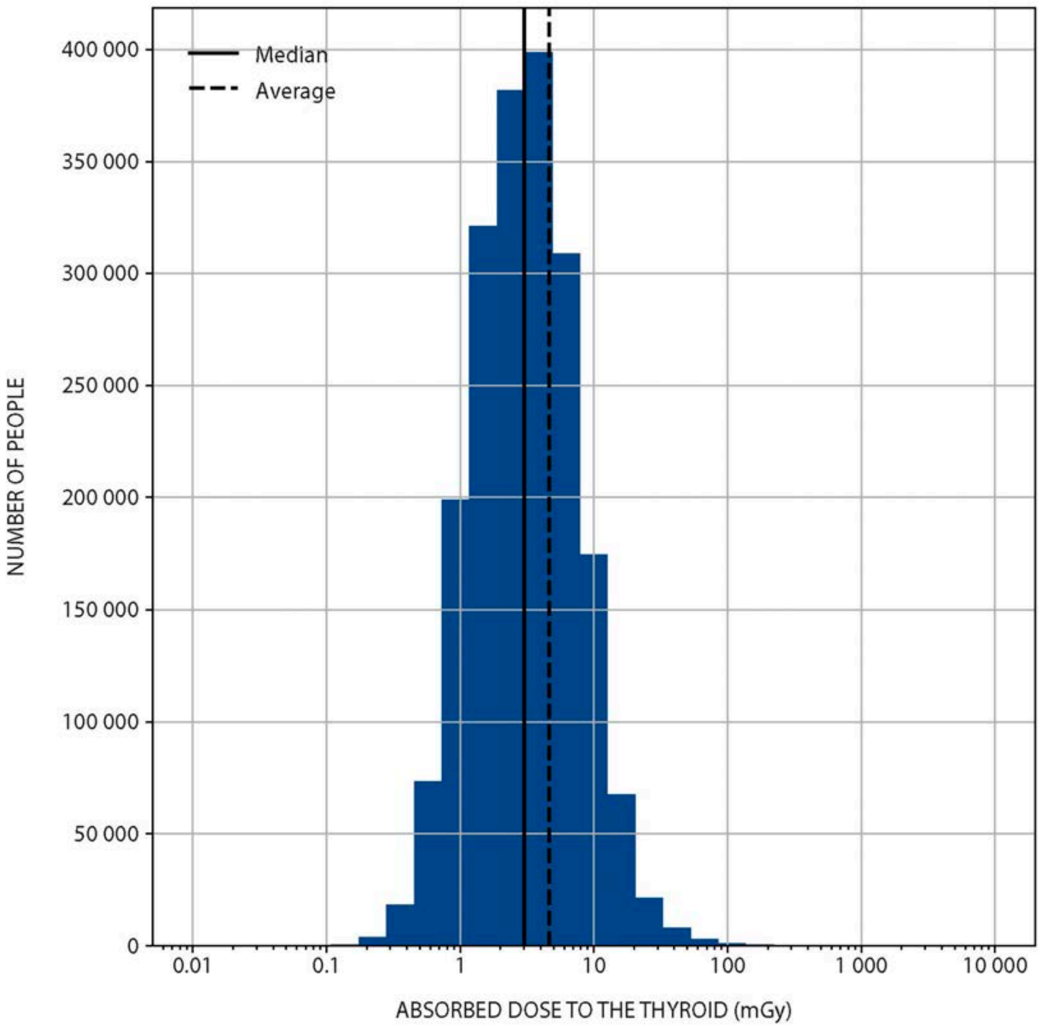
[a] Includes all age groups.

Figure A-XV. Distribution of absorbed dose to the thyroid in the first year for evacuees[a]



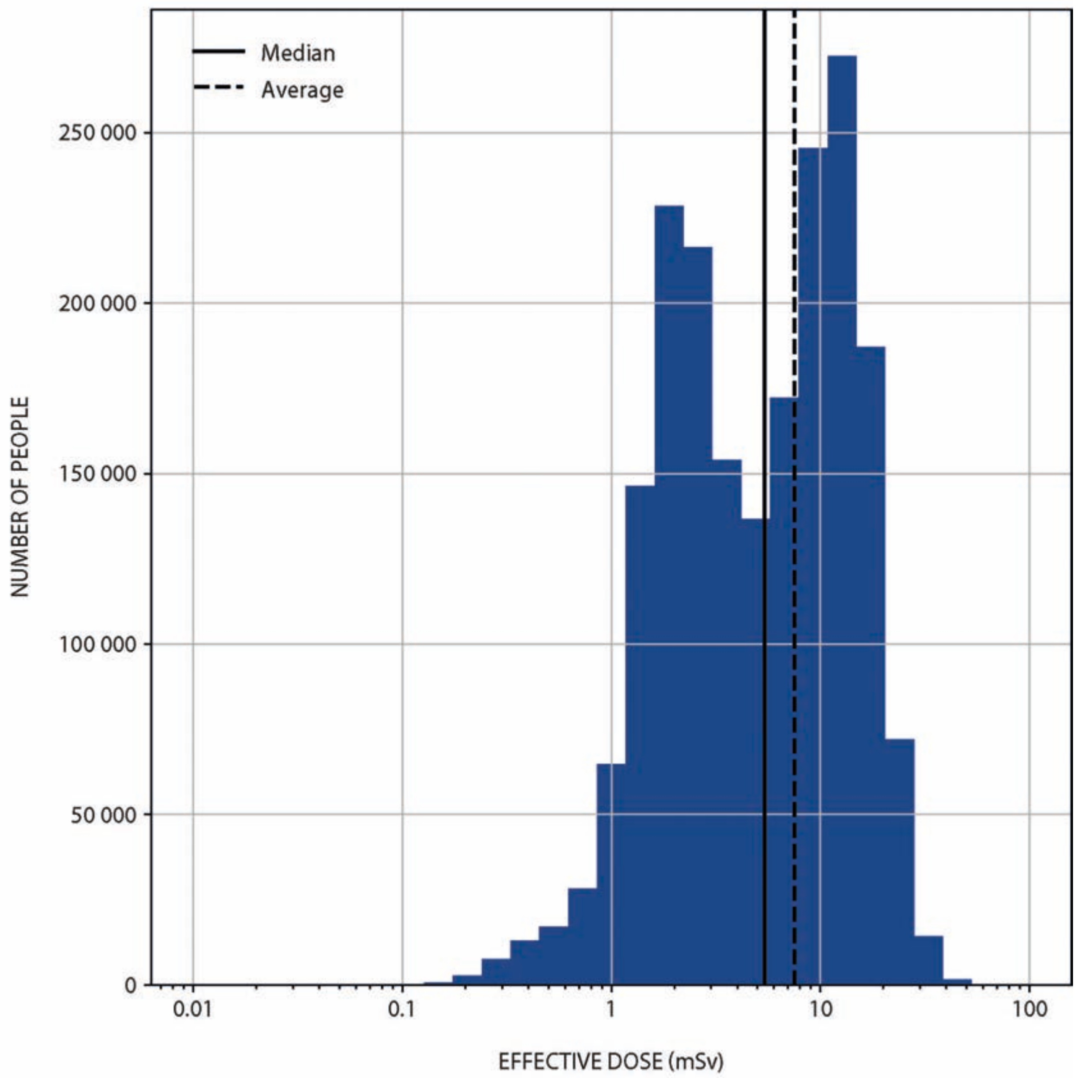
[a] Includes all age groups.

Figure A-XVI. Distribution of absorbed dose to the thyroid in the first year in Fukushima Prefecture[a]



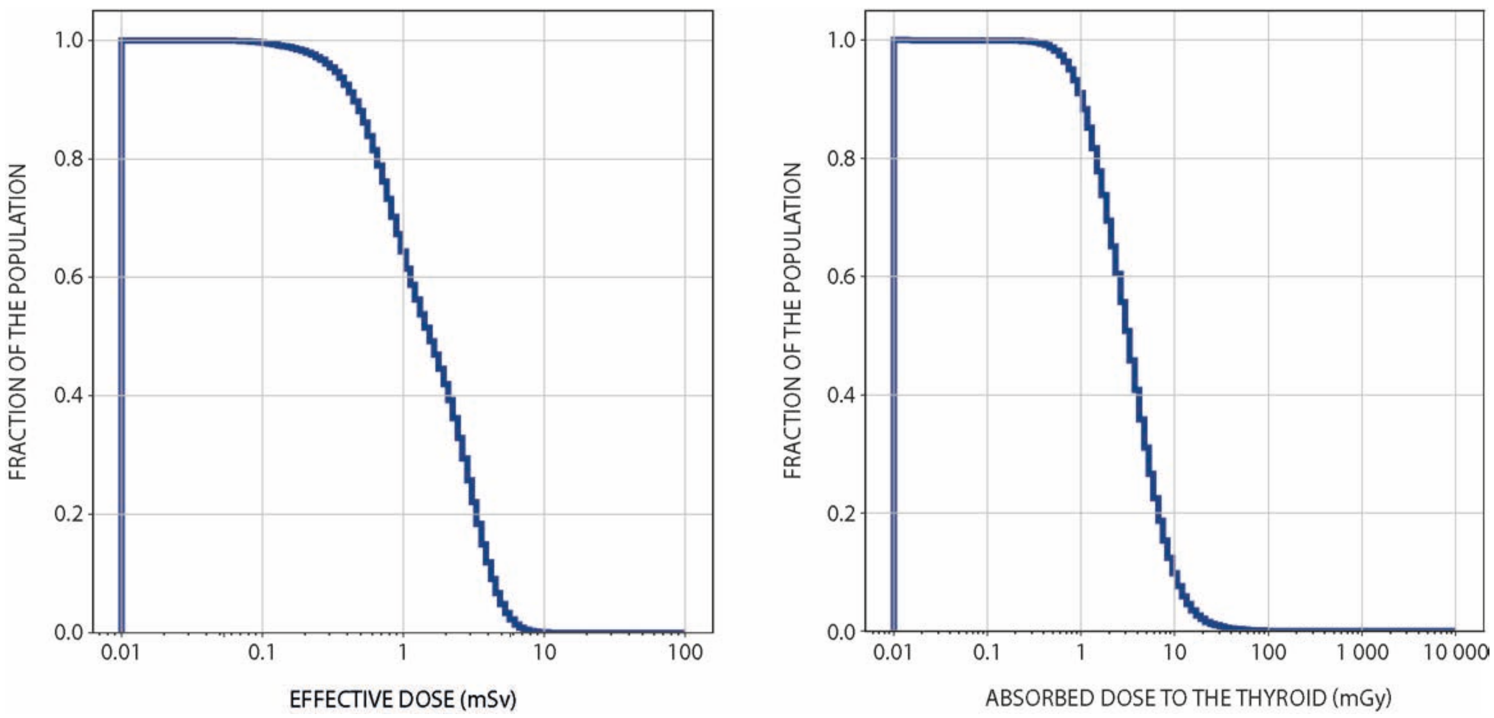
[a] Includes all age groups.

Figure A-XVII. Distribution of effective doses over a lifetime in Fukushima Prefecture[a]



[a] Includes all age groups.

Figure A-XVIII. Reverse cumulative distribution of doses in the first year in Fukushima Prefecture (the fraction of the population estimated to have received a dose above the indicated level)[a]



[a] Includes all age groups.

G. Comparison of modelled and measured doses

1. Effective dose from external exposure

A134. Several personal dosimetry surveys have been carried out to measure doses from external exposure directly, typically using luminescence dosimeters. The surveys included those carried out in Kawauchi Village, the Tamano area of Soma City and the Haramachi area of Minamisoma City [H4], on school children in Minamisoma City [N13, N15], on adults from Fukushima City and neighbouring municipalities [T10], on children from Minamisoma City [T40], children in Soma City [T41], and adults in Minamisoma City [T42]. In addition, the municipalities of Minamisoma and Naraha provided the Committee with anonymized data on personal external doses measured between 2014 and 2019 using luminescence dosimeters. These measurements have been compared with the predictions from the new (M2020) model and that used in the UNSCEAR 2013 Report [U10]. The new model provides a better fit to the measurements for all these surveys, apart from that of Harada et al. [H4], where both models give dose estimates systematically lower than the reported measured values. Taken together, the measurements span a time period of eight years after the FDNPS accident. For this whole period, the new model provides dose estimates that are within a factor of two of the measured doses, indicating that the new model adequately addresses the observed dynamics of the ambient dose rate over an extended period. Full details are provided in attachment A-1.

2. Absorbed doses to the thyroid

A135. The measurements made on the thyroids of 1,143 individuals at various locations in Fukushima Prefecture between 26 March and 16 April 2011 have been analysed and the Committee has estimated absorbed doses to the thyroid from them. The majority of the measurements (1,080) were made between 26 and 30 March 2011 on children at locations in Iitate Village (299), Iwaki City (134) and Kawamata Town (647). Background measurements were made at the time of the thyroid measurements on these 1,080 children, but in 598 cases (55%), the measured exposure rate was less than or equal to background. A lower limit of exposure rate was derived for each of these cases. Age-dependent calibration coefficients for the measuring device derived by Kim et al. [K18] have been used. Further details of the dose reconstruction methods used can be found in attachment A-2.

A136. Some of the measurements were carried out in locations that had been evacuated, and there is a lack of published information about where those monitored were in the period before the measurements were made. Information was also not available about other factors such as whether the individuals consumed locally produced foodstuffs and whether they changed clothes before the measurement. Such information does exist, but it was not available to the Committee. Nevertheless, some, albeit less informative, comparisons can be made on the assumption that those measured at a particular location were representative of those who had been evacuated from or had remained at that location in accordance with the evacuation scenarios relevant to that location as defined by Ohba et al. [O5] (see section III.C.1(b) of this appendix). The Committee has accordingly estimated absorbed doses to the thyroid for comparison with the doses derived from thyroid measurements ("measured"), and the results are presented in table A20; more detailed information can be found in attachment A-2. The comparison shows very good agreement between the estimated and "measured" doses (the ratio of modelled to "measured" varies from about 0.4 to 1.3), providing some confidence in the Committee's updated estimates of thyroid doses and, more generally, in the approach used by the Committee to estimate doses from intakes by inhalation and ingestion. This comparison is, however, based on a small number of measurements in a limited geographical area, and both modelled and "measured" doses are associated with significant uncertainty (with 5% and 95% confidence intervals spanning wide ranges – see attachment A-2).

Table A20. Comparison of modelled and "measured" thyroid doses

The number of people measured in each group is given in parentheses

Locality	*Median absorbed dose to the thyroid (mGy)*					
	Adult		*10-year-old*		*1-year-old*	
	Modelled	*"Measured"*	*Modelled*	*"Measured"*	*Modelled*	*"Measured"*
Iwaki City	1.2		2.2	1.8 (79)	2.6	4.6 (55)
Kawamata Town	0.95		1.8	2.6 (361)	2.1	4.5 (286)
Iitate Village	1.4		2.3	3.6 (220)	2.8	7.1 (79)
Namie Town[a]	22	21 (6)	36		41	
Minamisoma City[a]	5.8	6.5 (15)	9.9		12	10 (1)
Tamura City	0.50	1.2 (1)	1.1		1.2	

[a] Excluding persons evacuated shortly after the accident.

A137. Ohba et al. [O5] also found good agreement between their modelled doses and measurements of people known to have been evacuated. Their comparison is more informative than that of the Committee in that it was limited to evacuees whose whereabouts before and after the accident were known to the authors (based on behaviour questionnaire survey sheets – information that was not available either publicly or to the Committee). The comparison of Ohba et al. provides added confidence (albeit by proxy) in the validity of the approach used by the Committee to estimate doses to the thyroid (and, by association, doses from intakes by inhalation and ingestion, more generally). The approach used by Ohba et al. to estimate doses by inhalation was essentially the same as that of the Committee (i.e., based on the Terada et al. [T28] source term, the related ATDM data base and the evacuation scenarios listed in table A9). The only difference was in the use of different spatial and temporal resolutions in the respective computations. The doses estimated by the Committee are compared with those for Ohba et al. in attachment A-22 and are broadly comparable within their respective uncertainties.

3. Effective doses from intakes of radiocaesium

A138. In the UNSCEAR 2013 Report [U10], the Committee referred to estimates of effective dose derived from whole-body measurements made on evacuees and residents beginning in July 2011 [H9, M43]. Including further information now available from these and other WBC measurements (see table A2), the Committee has made estimates of the effective dose from intakes of ^{134}Cs and ^{137}Cs for both evacuees and non-evacuees (residents) of Fukushima Prefecture for comparison with doses estimated by other methods.

A139. To assess annual doses from these whole-body measurements, assumptions needed to be made about when and how the intake of the radionuclides measured in the body took place and whether further intakes occurred before the end of the year in question. In three of the studies [K16, M43], the authors assumed that the intake was by inhalation over a short period. For the other two studies [H9, T38], the Committee has assumed that the intakes were by inhalation (over a few hours to a few days) and ingestion (over a few weeks). The Committee has also adopted a simplifying assumption that all measurements below the MDL were equal to half of that MDL. The Committee has only reconstructed doses from the measurements made on adults because of the lower detection rate and greater uncertainties associated with the measurements made on children. The resulting committed effective doses from intakes of ^{134}Cs and ^{137}Cs for each of the groups measured, as reconstructed from the whole-body measurements are summarized in table A21. These estimates of committed effective dose are compared in table A21 with committed effective doses estimated for the same population groups of the different studies using the models adopted by the Committee in this study.

Table A21. Committed effective doses to adults from intakes of ^{134}Cs and ^{137}Cs in the first year estimated from whole-body measurements compared with corresponding doses estimated using the models adopted by the Committee in this report

Population measured using WBC	*WBC (all intakes)*		*Using models adopted in this report*		
	Committed effective dose up to time of measurement (µSv)		*Average committed effective dose from intakes within first year (µSv)*		
	Average	*Median*	*Inhalation*	*Ingestion*	*All intakes*
Minamisoma City[a] [T38]	~50[f]		~42[k]	~19[p]	~61
Minamisoma City[b] [H10]	~80[g]		13[l]	~19[p]	~32
Hirata Central Hospital[c] [H9]	~50[h]		~5.1[m]	~19[p]	~24
Evacuated municipalities[d] [M43]		~25[i]	~7.8[n]	~19[p]	~27
Evacuated municipalities[e] [K16]		~30–70[j]	~4.8[o]	~19[p]	~24

[a] Adult residents of Minamisoma City.

[b] Hayano et al. [H10] reported only on measurements made of those who lived in “the most contaminated zone”, about 85% of whom had been evacuated at different times during March 2011, but had returned in July 2011.

[c] Seventy-three per cent from Fukushima Prefecture, 23% from Ibaraki Prefecture with the remainder from Tochigi and Miyagi Prefectures. No information available on where, within the prefectures, those measured were at the time of the accident or where they lived subsequently within the respective prefectures.

[d] Adult evacuees from Futaba Town, Hirono Town, Iitate Village, Katsurao Village, Kawamata Town, Kawauchi Village, Minamisoma City, Naraha Town, Namie Town, Okuma Town and Tomioka Town.

[e] Adult evacuees from the same municipalities as in footnote *d* above apart from Minamisoma City and inclusion of Tamura City. Median doses only estimated for Futaba Town, Iitate Village and Namie Town.

[f] Estimated by the Committee assuming short term intake with all measurements less than the MDL assumed to be equal to half the MDL.

[g] Estimated by [H10] assuming acute inhalation of radiocaesium in March 2011.

[h] Estimated by the Committee assuming short-term intake with all measurements less than the MDL assumed to be equal to half the MDL. The Committee has used the measurement data in the first year after the accident at FDNPS, although the authors restricted their analyses to measurements made after March 2012 because of possible surface contamination of clothes before this date.

[i] Estimated by the authors by extrapolating to the 50th percentile assuming a log-normal distribution and assuming acute inhalation of radiocaesium in March 2011. The median dose takes no account of potential bias consequent upon a fraction of the measurements being affected by contamination on clothes. The authors also presented dose distributions for each of six evacuated municipalities, with the doses varying from about a factor of two lower, to a few tens of percent higher, than those for all municipalities.

[j] Estimated by the authors assuming a log-normal distribution and an acute intake by inhalation on 12 March. The quoted values are the range of median doses of those measured in Namie Town (26 μSv), Iitate Village (27 μSv) and Futaba Town (68 μSv), which are not necessarily the median dose in the whole population of the evacuated municipalities.

[k] Estimated by the Committee as the average dose for residents of Minamisoma City from air concentrations predicted by scaling measured deposition densities by ratios derived from ATDM.

[l] Estimated by the Committee as the average dose for evacuees from Kashima and Haramachi wards of Minamisoma City (who comprised 82% of those measured) based on predicted air concentrations using source term and ATDM.

[m] Estimated by the Committee as the average dose to residents in Fukushima Prefecture based on predicted air concentrations derived by scaling measured deposition densities by ratios derived using source term and ATDM.

[n] Estimated by the Committee as the average dose for all evacuees from Fukushima Prefecture based on predicted air concentrations using source term and ATDM.

[o] Estimated by the Committee as the average dose for evacuees, with account taken of where those measured were evacuated from, based on predicted air concentrations using source term and ATDM.

[p] Estimated by Murakami and Oki [M47] from measured concentrations in food and drinking water in Fukushima City. The Committee has assumed this estimate to be applicable to the whole of Fukushima Prefecture while recognizing that there will be some variation with location.

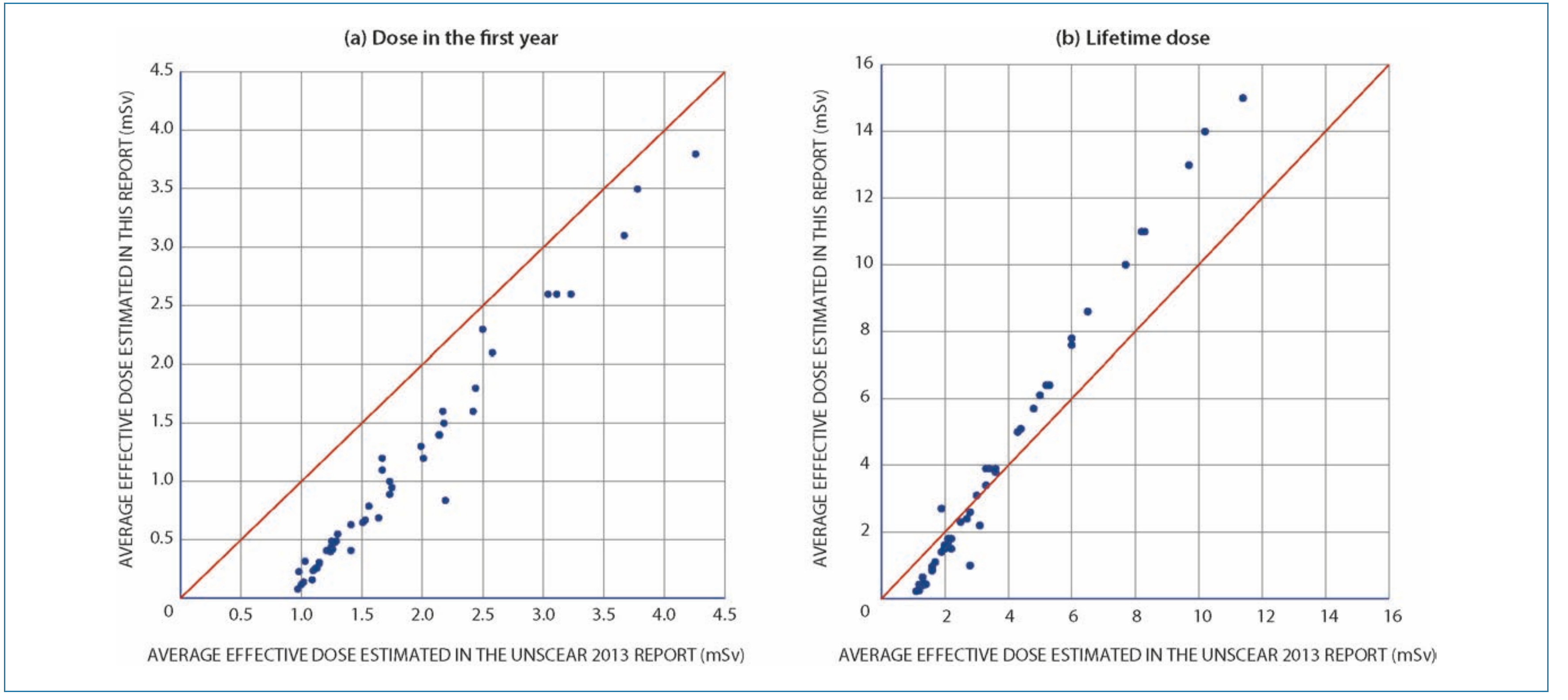
A140. The values presented in table A21 are subject to large uncertainties and are, in many cases, not directly comparable. Estimates of the uncertainties in the values presented and discussion of the limitations on the comparisons are set out in detail in attachment A-3. Nevertheless, the sums of the doses from inhalation and ingestion intakes estimated using the models the Committee has adopted in this report are broadly in agreement with the committed effective doses estimated from the WBC measurements. This indicates that the modelling approaches used by the Committee are able to provide estimates of doses comparable with the measurements made on people. The estimates given in table A21 also indicate that average effective doses from intakes of radiocaesium are low (both in absolute terms and relative to the total doses from all radionuclides and all exposure pathways), ranging from a few tens of µSv to about 100 µSv for those population groups for which whole-body measurements were made. While intakes of radiocaesium by inhalation and ingestion may make only a small contribution to the overall doses, the comparison provides some assurance that the methodology used by the Committee for estimating doses via inhalation and ingestion more generally are broadly valid. Further details are provided in attachment A-3.

H. Comparisons with dose estimates in UNSCEAR 2013 Report

A141. To illustrate the differences between the doses estimated in this report with those estimated in the UNSCEAR 2013 Report [U10], figures A-XIX and A-XX show scatter plots comparing estimates in the two reports. Figure A-XIX compares estimates of the municipality-average effective dose in the first year and over a lifetime to an adult for each of the municipalities in Fukushima Prefecture. The diagonal line in each figure indicates where the doses would be equal; points below the line are where current estimates of doses are lower than in the UNSCEAR 2013 Report, and points above the line are where current estimates of doses are higher than in the UNSCEAR 2013 Report. The comparison for the municipality-average effective dose in the first year to adults shows that the current estimates are systematically lower than those in the UNSCEAR 2013 Report for all municipalities by an amount that increases with decreasing estimated dose (from a few tens of per cent for municipalities with the higher doses to a factor of several for municipalities with lower doses). Over a lifetime, however, the effective doses to adults estimated in this report are similar to those estimated in the UNSCEAR 2013 Report in many municipalities, but higher (by up to 30%) for municipalities with higher doses. The general reduction in the current estimates of effective doses in the first year compared with those in the UNSCEAR 2013 Report are largely due to the more realistic and lower estimates of doses from ingestion; in the UNSCEAR 2013 Report, the dose from ingestion dominated the total dose in municipalities where the doses from other pathways were low. Other factors that have led to a decrease in the current estimates of effective dose in the first year include the reduction in the dose from inhalation because account has been taken of filtration inside buildings, and the dose coefficients used that are specific to the Japanese population. Over the longer term, these decreases in the estimated effective doses are counterbalanced by an increase in the estimated dose from external exposure to deposited radionuclides (see section III.C.1(a) of this appendix).

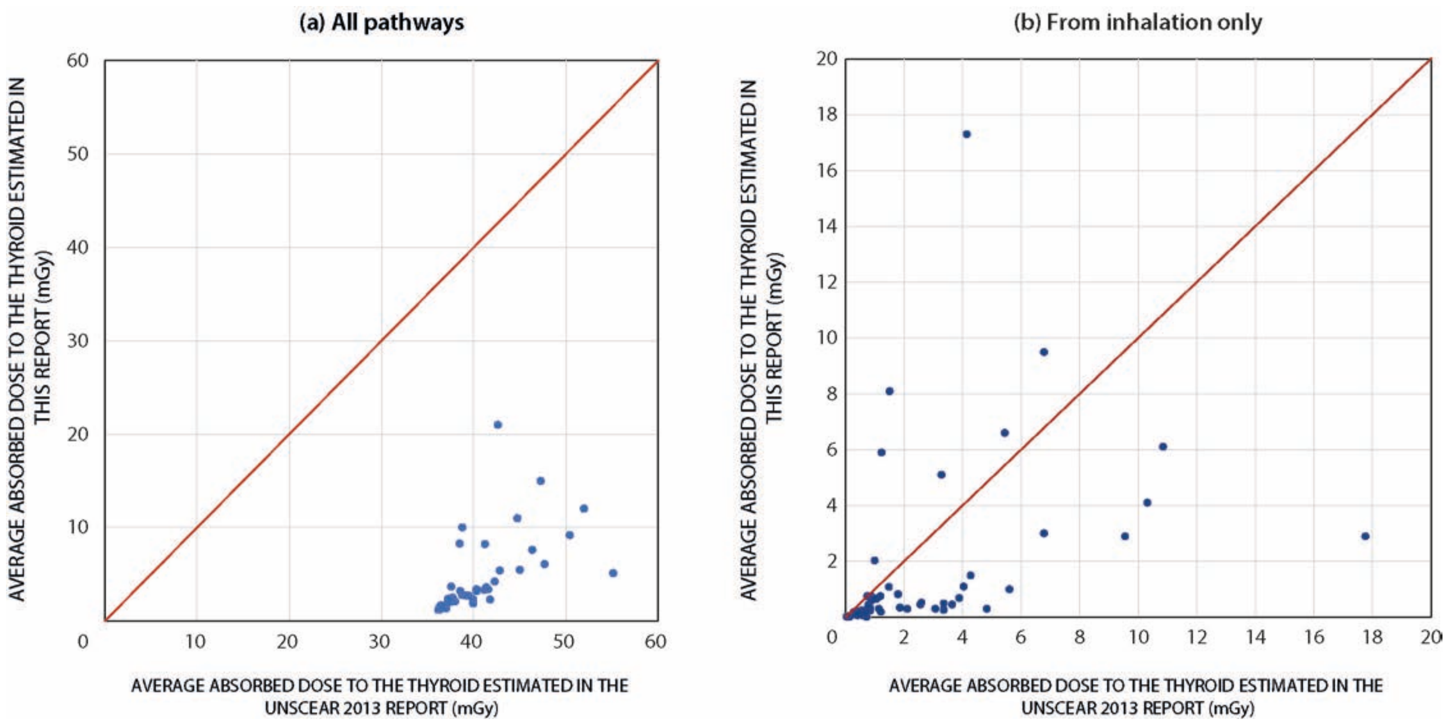
A142. Figure A-XX compares estimates of the municipality-average absorbed doses to the thyroid in the first year to infants from all pathways and from inhalation only, again for each of the municipalities in Fukushima Prefecture. The comparison for the municipality-average absorbed dose to the thyroid from all pathways shows very clearly that the current estimates are consistently, and considerably (by up to an order of magnitude or more in some cases), lower than those in the UNSCEAR 2013 Report [U10]. This large difference can be attributed to the dose from ingestion having been overestimated in that report because of the unduly cautious assumptions made. Consideration of inhalation dose only shows that, for most municipalities, the dose estimates in this report are lower as a result of using Japanese specific dose coefficients for intakes of radioiodine, and because account has been taken of filtering by buildings in reducing the concentrations of radionuclides indoors. However, the different source term and ATDM used in this report has also introduced additional scatter. The Committee considers that, as a result of using more realistic estimates of doses from ingestion and taking due account of filtering by buildings and of the iodine-rich Japanese diet, the estimates made in this report are much more realistic.

Figure A-XIX. Scatter plot of the effective dose *(a)* in the first year and *(b)* over a lifetime to adults estimated in this report compared with that estimated in the UNSCEAR 2013 Report[a]



[a] The straight line indicates the 1:1 relationship (i.e., where the dose estimates would be equal).

Figure A-XX. Scatter plot of the absorbed dose to the thyroid in the first year to infants *(a)* from all pathways and *(b)* from inhalation only estimated in this report compared with that estimated in the UNSCEAR 2013 Report[a]



[a] The straight line indicates the 1:1 relationship (i.e., where the dose estimates would be equal).

V. ACKNOWLEDGEMENTS OF ORGANIZATIONS THAT PROVIDED DATA

Country	*Organization*
Belarus	Belarusian State Medical University
Japan	Hirosaki University Minamisoma City Naraha Town National Institute of Radiological Sciences of the National Institutes for Quantum and Radiological Science and Technology
Russian Federation	Federal Medical Biological Agency
Ukraine	National Research Centre for Radiation Medicine National Academy of Medical Sciences of Ukraine

APPENDIX B. COMPARISON BETWEEN VARIOUS ATTRIBUTES AND CONSEQUENCES OF THE ACCIDENTS AT CHERNOBYL AND FUKUSHIMA DAIICHI NUCLEAR POWER STATIONS

B1. The main features or attributes of the accidents that occurred at Chernobyl Nuclear Power Station (CNPS) and Fukushima Daiichi Nuclear Power Station (FDNPS) from peer reviewed literature are summarized in the table below together with estimates of the resulting exposures of, and health effects in, workers and the public. The consequences of the accident at FDNPS were much lower than those at CNPS (e.g., for the FDNPS accident, estimated average effective doses to adult evacuees were less than about 6 mSv and average absorbed doses to the thyroid were less than about 15 mGy, compared with around 30 mSv and 500 mGy for the CNPS accident). These lower consequences were due to the following main reasons (see table B1):

(a) A much larger fraction of the more significant radionuclides (isotopes of iodine and caesium) in the fuel of the respective reactors (also referred as units) was released to the environment from CNPS than FDNPS. The reactors at FDNPS had purpose-built containments within which most of the radionuclides released from the molten fuel were retained; by contrast, the reactor at CNPS did not have a containment and the core was directly exposed to the atmosphere as a result of the explosion that occurred at the beginning of the accident;

(b) The explosion at CNPS resulted in a fire on the roof of the reactor and turbine buildings that had to be extinguished to minimize the risk of the accident escalating and propagating to other reactor units. In this process more than a hundred emergency workers were exposed to high levels of radiation (exposure of the whole body to external radiation and of the skin to beta radiation) that resulted in acute radiation syndrome (ARS);

(c) The radionuclides released to the atmosphere from CNPS were dispersed and largely deposited over the land mass of Europe. By contrast, some 80% of the release to the atmosphere from FDNPS was dispersed and largely deposited over the Pacific Ocean, where the consequences (in terms of doses to and effects on humans) were considerably less than for radionuclides dispersed and deposited over land. Beyond the evacuation area, deposition densities were also much lower from Fukushima compared with Chernobyl;

(d) The accident at FDNPS occurred earlier in the agricultural growing season than that at CNPS (11 March compared with 26 April) with the result that a much lower fraction of deposited radionuclides was transferred to foodstuffs;

(e) The binding or fixation of radiocaesium in many soils in Japan and in the former Soviet Union is broadly comparable, as is its bioavailability. However, much enhanced and sustained uptake of radiocaesium occurred from some poor agricultural soils (sandy, organic) that occurred in affected regions of Belarus, the Russian Federation and Ukraine around CNPS and in highly organic and upland soils in Western Europe. There is no evidence of such enhanced uptake from Japanese soils;

(f) Agricultural practice and animal husbandry differ between Japan and the former Soviet Union (i.e., in Japan by far the majority of cattle are housed in barns and do not graze pasture) with the result that the transfer of radionuclides to milk and meat following the accident at FDNPS was much lower;

(g) Protective measures (in respect of people, e.g., precautionary evacuation, and foodstuffs) were implemented more effectively following the accident at FDNPS than at CNPS, resulting in a larger fraction of the potential doses being averted;

(h) The failure to inform the population, in particular in more rural areas, of the need to restrict or avoid the consumption of potentially affected foodstuffs especially milk, following the accident at CNPS resulted in very large doses to the thyroids of many people and an increased incidence, attributable to radiation exposure, of thyroid cancer, in particular among those who were children at the time;

(i) The restrictions imposed in Japan on the concentrations of radionuclides in foodstuffs that were marketed for consumption were much lower than in the former Soviet Union, resulting in lower doses from ingestion.

Table B1. Main attributes and features of the accidents at Chernobyl and Fukushima Daiichi Nuclear Power Stations

	Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
REACTOR CHARACTERISTICS AND SOURCE TERM		
Reactor type	RBMK[a]	BWR[b]
Electric power	1 000 MWe	460, 784 and 784 MWe
Location	Inland site	Coastal site
Containment	No	Yes
Date of accident	26 April 1986	11 March 2011
Origin/s of the accident	Uncontrolled nuclear chain reaction occurred during a safety test to demonstrate that cooling water circulation could be maintained following an electric power outage pending back up power becoming available. This resulted in: a rapid and large increase of energy that vaporized superheated cooling water; a steam explosion; melting of the fuel and other core components; reactor building extensively damaged; reactor core exposed to the atmosphere and on fire for about 10 days (burning of the graphite moderator and other core materials); and fragments of the core (fuel, graphite moderator, control rods and other core components) ejected from the building in the initial explosion Little retention of fission and activation products released from the molten fuel in the absence of a containment system and the core being exposed directly to the atmosphere. Release of less volatile elements (e.g., Sr, actinides) larger than would have been expected on account of their volatility alone – a result of the fragmentation of the fuel during the explosion and physical generation of aerosols and particles containing less volatile elements. Releases occurred over an extended period with most occurring within the first 10 days after the accident	Extended loss of off-site and on-site power and heat removal capacity as result of the great east-Japan earthquake and the associated tsunami. Fuel overheated/melted with hydrogen generated from water-fuel cladding (Zr) reactions. Fission and activation products released from the fuel, the relative amounts depending on their volatility High volatility (low vapour pressure) elements (e.g., noble gases, I, Te, Cs) released almost totally from the fuel; percentage release from the fuel of moderate volatility elements (e.g., Ba, Sb, Nb, Sr) were a few orders of magnitude lower than elements of high volatility; and percentage release of refractory elements (e.g., La, actinides) was even smaller Most of the fission products (apart from noble gases) released from the fuel were retained in the reactor pressure vessel and/or the primary containment as a result of condensation, plate out on various surfaces and scrubbing. A fraction was released to the atmosphere though breaches in the reactor pressure vessel and primary containment and/or by deliberate venting, hydrogen explosions, etc. Releases occurred over an extended period, with most occurring in the period from 12 to the end of March 2011

		Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
Release (PBq) to the atmosphere[c] (% of core inventory)	^{133}Xe	6 500 (≈100%)	7 300 (≈61%)
	^{131}I	≈1 760 (≈60%)	120 (≈2%)
	^{134}Cs	≈47 (≈30%)	10 (≈1.3%)
	^{137}Cs	≈85 (≈30%)	10 (≈1.3%)
	^{90}Sr	≈10 (≈4%)	<0.01 (<0.001%)[d]
	^{239}Pu	≈0.013 (≈1.5%)	Very small[e]
Pattern of release		Dispersed and largely deposited over the land mass of Europe	≈80% of the release dispersed and largely deposited over the Pacific Ocean
Direct release (PBq) to the sea[f] (% of core inventory)	^{3}H	Not applicable[g]	0.3–0.7
	^{131}I		11–18 (≈0.2%)
	^{134}Cs		3.5–5.6 (≈0.6%)
	^{137}Cs		3.5–5.6 (≈0.6%)
	^{90}Sr		0.04–1 (not applicable)
Indirect release (PBq) to the sea[h] (deposited from the atmosphere onto the sea surface)		Black Sea – ≈2.8 (^{137}Cs) Baltic Sea – ≈3.0 (^{137}Cs)	Pacific Ocean ^{131}I: ≈ 57–100 ^{134}Cs: 5–11 ^{137}Cs: 5–11

	Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
	EMERGENCY RESPONSE[i]	
Number of people evacuated	116 000 (in 1986)	Precautionary evacuation of 78 000 from within 20 km zone Deliberate evacuation of 10 000 on the basis of measurements Voluntary evacuation of 30 000 from 20–30 km evacuation prepared zone
Number of people relocated	220 000 (in 1989–1992) plus those evacuated in 1986 (i.e., ≈340 000 in total)	Those evacuated (i.e., 118 000 in total, as indicated above)
Iodine prophylaxis	Not implemented in a timely or effective manner (except for evacuees from Pripyat)	Iodine tablets were issued but their distribution/issue was neither consistent nor uniform. They were not distributed to evacuees within the 20 km zone despite this being the intent. They were distributed (on or after 14 March 2011) to everyone younger than 40 years living within the Fukushima Prefecture between about 20 and 50 km of FDNPS (about 1 million tablets were distributed)
Food restrictions	Various countermeasures applied (e.g., evacuation of animals from 30 km zone, supply of clean feed, controlling levels of radionuclides in food, converting milk to storable products, etc.). The focus was on collective farms. The population was not adequately informed of the need for protective actions, in particular the private farming sector prevalent in rural areas. Countermeasures in some areas were not applied or were delayed with the result that contaminated milk and vegetables were consumed that should, otherwise, have been restricted; milk consumption resulted in large (and avoidable) doses to the thyroids of many people	Countermeasures relating to food, drinking water and agriculture implemented generally in a timely and effective manner along with arrangements for informing the public. “Provisional regulation values” (replaced in April 2012 by “standard limits”) established controlling the levels of radionuclides in food and drinking water, and extensive monitoring campaigns were implemented
	TRANSFER IN THE TERRESTRIAL ENVIRONMENT	
Fixation and bioavailability of radiocaesium in soil	Radiocaesium is strongly bound to many soils in the former Soviet Union and most European countries, which limits its bioavailability. Fixation, however, in poor quality agricultural soils (sandy, organic) present in some affected areas of Belarus, Russian Federation and Ukraine and highly organic and upland soils in Western Europe is much lower (and bioavailability much higher); this resulted in sustained and relatively high uptake of radiocaesium from such soils	The fixation and bioavailability of radiocaesium in Japanese soils are broadly comparable with many soils in the former Soviet Union. No evidence, however, of enhanced and sustained uptake of radiocaesium as experienced in poor quality agricultural soils in areas affected by the CNPS accident

		Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
Agricultural practice and animal husbandry		Larger fraction of cattle grazing pasture at the time of the accident in the former Soviet Union – resulting in high transfer of deposited radionuclides to meat and milk (especially in rural areas)	Majority of cattle housed in barns with only a small fraction grazing pasture – resulting in much lower transfer of radionuclides to meat and milk
DOSES TO EMERGENCY/RECOVERY WORKERS[i]			
Number of emergency and recovery workers		Emergency workers: ≈ 600 Recovery workers: ≈530 000	About 21 000 in the first year and varying within a range of ≈14 000 to 21 000 in each subsequent year
Workers with acute radiation syndrome	Number diagnosed	134	None
	Doses	Bone marrow doses ranged from 0.8 to 16 Gy Skin doses 10 to 30 times greater	
Other emergency and recovery workers	Effective dose	Average individual dose: ≈120 mSv	Average annual dose: 13 mSv in first year (declining in subsequent years within a range from ≈6 to ≈2 mSv in the year ending 31 March 2020) Maximum annual dose: 680 mSv in first year (declining in subsequent years within a range from ≈50 to ≈20 mSv in the year ending 31 March 2020) 168 and 6 workers, respectively with doses >100 mSv and 250 mSv in first year
	Thyroid dose		Maximum absorbed dose in first year – 32 Gy About 180 workers with thyroid equivalent dose >100 mSv
	Collective effective dose	61 000 man Sv[j]	≈860 man Sv[k] up to March 2020
Iodine prophylaxis		Stable iodine tablets administered to emergency workers and to some personnel operating other reactors at CNPS	About 17 500 stable iodine tablets issued to about 2 000 workers during the accident although records of their issue are incomplete

	Chernobyl Nuclear Power Station (Unit 4)					*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*				
DOSES TO PUBLIC[i]										
Measurements of radioiodine in thyroid	400 000[l]					1 200				
Average individual doses to residents in different regions, municipalities or prefectures	*Group*	*Time period*	*Number (thousands)*	*Thyroid dose[m] (mGy)*	*Effective dose[m,n] (mSv)*	*Group (adults)*	*Time period*	*Number (thousands)*	*Thyroid dose[m] (mGy)*	*Effective dose[m] (mSv)*
	Evacuees	First year	115	≈500	≈50	Evacuees	First year	118	≈0.8–15	≈0.05–6
	"Contaminated areas"[o] in Belarus, Russian Federation[p] and Ukraine	First year for thyroid dose 1986-2005 for effective dose	6 400	≈100	≈13	Municipalities in Fukushima Prefecture	First year for thyroid dose First ten years for effective dose	1 900	≈0.5–10	≈0.2–10
	Belarus, Russian Federation[p] and Ukraine		98 000	≈20	≈2	Municipalities in neighbouring prefectures		17 000	≈0.3–3	≈0.3–3
	Rest of Europe		500 000	≈1	≈0.4	Prefectures in rest of Japan		110 000	≈0.03–0.5	≈0.009–1
Ranges of individual doses	Absorbed doses to the thyroids of evacuees ranged from <50 mGy to >5 Gy, with several hundred evacuees receiving doses in excess of 5 Gy Absorbed doses to the rest of the population of Belarus, Russian Federation and Ukraine (98 million) varied over a wide range, with most receiving thyroid doses <50 mGy and about 1% doses >200 mGy					Absorbed doses to the thyroids of evacuees varied over a wide range (5th to 95th percentile) from less than about 1 mGy to about 15 mGy Absorbed doses to the thyroids of non-evacuees range up to about 15 mGy (95th percentile) with about 1% >20 mGy				

		Chernobyl Nuclear Power Station (Unit 4)				*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
Collective doses[q]		*Group*	*Number (thousands)*	*Thyroid[r] (thousand man Gy) in the first year*	*Effective[r,s] (thousand man Sv) in the period 1986–2005*	Collective doses to the whole of the Japanese population (128 million) in the first ten years Effective: 32 thousand man Sv Thyroid: 44 thousand man Gy (24 thousand man Gy in the first year)
		Evacuees (first year)	115	57	≈6	
		"Contaminated areas"[o] in Belarus, Russian Federation[p] and Ukraine	6 400	650	85	
		Belarus, Russian Federation[p] and Ukraine	98 000	1 600	≈200	
		Rest of Europe	500 000	660	≈160	
HEALTH EFFECTS IN EMERGENCY AND RECOVERY WORKERS[t]						
Early	ARS	134				None
	Deaths attributable to ARS[u]	28				None
Late	ARS survivors	Skin injuries and radiation induced cataracts. Some increases in other diseases probably due to ageing and other factors not attributable to radiation				Not applicable
	Other emergency and recovery workers	Evidence of a dose related increase in the incidence of leukaemia and cataracts among those who received higher doses; no evidence of other health effects that can be attributed to radiation exposure				None to date (Nuclear Emergency Workers Study ongoing)

	Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
HEALTH EFFECTS IN, AND SCREENING OF, THE PUBLIC[v]		
Screening	Systematic screening of thyroids of a large number of young people (as of 1986) using ultrasound Lower resolution (compared with Fukushima) ultrasound equipment used for screening with lower sensitivity to detect thyroid abnormalities	Systematic screening of thyroids of about 600 000 young people using ultrasound High resolution ultrasound equipment used for screening with greater sensitivity to detect thyroid abnormalities
Thyroid cancer	Substantial fraction of the 19 000 thyroid cancers observed (up to 2016) among people who were children or adolescents at the time of the accident attributable to radiation exposure	Greater incidence of thyroid cancer and abnormalities observed in those screened than were expected based on national statistics – most likely the result of using high resolution ultrasound in the screening. Increasing body of evidence that the observed thyroid cancers are not attributable to radiation exposure
Other effects (e.g., other cancers, birth defects, fetal deaths, non-cancer diseases, etc.)	No persuasive evidence of any other health effect attributable to radiation exposure at CNPS or FDNPS	
Social/psychological impact	Increases observed in a wide range of health conditions following both accidents but no evidence that any are directly attributable to radiation exposure; rather, they are the result of changes in lifestyle (e.g., following evacuation/relocation), psychological stress, social stigma, etc., associated with the accident. Also, in the case of the accident at FDNPS, the wider impacts of the earthquake and associated tsunami	
DOSES AND EFFECTS ON NON-HUMAN BIOTA[w]		
Maximum accumulated doses (first months post deposition)	Pine trees = >100 Gy (4 km^2 zone near CNPS) Mammals = 110 Gy (first 5 months, gamma-radiation)	Pine trees = 0.5 Gy (first month) Mammals = 0.2 Gy (first month)
Effects in terrestrial plants (within the first years post-accident)	Complete death of pine trees was observed over an area covering 4 km^2 and sublethal effects in conifers including death of meristems occurred over and area of 38 km^2. The colour of dead pine stands, appearing during the summer of 1986, resulted in the forest being referred to as the “red forest”	No confirmed instances of forest die off attributable to the accident at Fukushima have been published although some sublethal, morphological aberrations in conifers have been documented

	Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
Effects in invertebrates (within the first years post-accident)	Population level effects in invertebrates were observed in the most contaminated areas. The number of invertebrates within 3–7 km was reduced by a factor of 30 and reproduction was strongly impacted, i.e., larvae and nymphs were absent	Sublethal damage in invertebrates has been observed including genetic damage in earthworms, and morphological aberrations in aphids and butterflies. Impacts on populations linked to these sublethal effects have been inferred as opposed to directly observed and the few studies suggesting significant populations impacts have not been corroborated
Effects in other animals (within the first years post-accident)	Substantial impacts in terrestrial animals were observed. The number of rodents (autumn 1986) in highly contaminated areas had decreased by a factor of 2–10 times. Chronic radiation effects were observed in autopsied larger animals including reduced body mass and the presence of haematomas in organs. Cattle suffered severe impacts on their thyroids connected with disruption of the hormonal balance and reproductive failure and in some cases death	No population level impacts on animals in the impacted areas have been corroborated. There have been observations of sublethal cytogenetic and haematological impacts on various groups including chromosomal aberrations in mice and low blood cell counts in Macaque. The few studies where population impacts have been inferred, notably for birds, remain unsubstantiated

[a] RBMK – graphite moderated, water cooled reactor.
[b] BWR – boiling water reactor.
[c] Values taken from [I2] and/or [U8] for CNPS and from [T28] or [U10] for FDNPS unless otherwise stated; inventory and percentages released from CNPS taken from [I1].
[d] Three to four orders of magnitude less than radiocaesium [I8].
[e] No notable increase in levels present from global fallout from the testing of nuclear weapons in the atmosphere prior to the accident [I8].
[f] Values from this annex (see table 2).
[g] CNPS sited inland so no direct release to the sea.
[h] Values for CNPS from [U8]; those for FDNPS from this annex (see table 2).
[i] Values taken from [U8] for CNPS and from this annex for FDNPS.
[j] For the period 1986 to 2005.
[k] On-site workers at FDNPS; about 40% of the collective dose up to the end of March 2020 was received in the first year after the accident.
[l] Direct measurements of thyroids in Belarus, Russian Federation and Ukraine [U20].
[m] Rounded values (one significant figure) generally quoted.
[n] Including the contribution to effective dose from internal exposure due to intake of ^{131}I.
[o] “Contaminated” areas in Belarus, Russian Federation and Ukraine designated as those with ^{137}Cs deposition in excess of 37 Bq/m^2 (1 Ci/km).
[p] Nineteen affected regions of the Russian Federation.
[q] Note that the doses reported for CNPS and FDNPS may not be directly comparable (i.e., different population groups and time periods over which doses integrated).
[r] Rounded to one or two significant figures.
[s] From [U8], vol. 2, table 2. Collective effective dose includes the contribution from internal exposure due to intake of ^{131}I.
[t] Values for Chernobyl from [U8] (effects up to 2006).
[u] Deaths within 4 months – other deaths occurred later for those diagnosed with ARS but in general the cause of death was not attributable to radiation exposure.
[v] Values for Chernobyl from [U15] (effects up to 2016) and those for FDNPS from this annex.
[w] From [U8] and [U10].

SUPPLEMENTARY INFORMATION

A number of attachments are cited in this annex that provide supplementary information on the detailed analyses that have been made of doses to the public and their outcomes.

The attachments cited in this annex are electronically available for download from http://www.unscear.org/unscear/en/publications/2020_2021_2_Attachments.html.

They comprise the following:

A-1 The estimation of external doses from deposited radionuclides following the accident at the Fukushima Daiichi Nuclear Power Station and their validation

A-2 The estimation of thyroid doses resulting from the accident at the Fukushima Daiichi Nuclear Power Station and their validation

A-3 The estimation of whole-body doses from the intake of radiocaesium following the accident at the Fukushima Daiichi Nuclear Power Station

A-4 Japan-specific data

A-5 Data sets downloaded from the Japan Atomic Energy Agency Environment Monitoring Database

A-6 MEXT survey of ground deposition: results of the radionuclide analysis of soil sampling at 2,200 locations in Fukushima Prefecture and neighbouring prefectures

A-7 MEXT survey of ground deposition: radioactivity concentration analysis of iodine in the distribution survey of radioactive substances

A-8 MEXT survey of ground deposition combined with demographic data

A-9 Atmospheric transport, dispersion and deposition modelling of air concentration over Japan

A-10 Methodology for estimating external doses from the plume and internal doses from inhalation of radionuclides in the plume

A-11 Evacuation scenarios and number of evacuees

A-12 Approach for assessing uncertainties and variability in estimated doses

A-13 Estimates of effective dose to people in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-14 Estimates of absorbed dose to the thyroid of people in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-15 Estimates of absorbed dose to the red bone marrow of people in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-16 Estimates of absorbed dose to the colon of people in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-17 Estimates of absorbed dose to the breast of people in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-18 Estimates of effective dose and absorbed dose to the thyroid of evacuees in Japan for the first year after the accident at the Fukushima Daiichi Nuclear Power Station

A-19 Estimates of the effective dose to people in Japan over longer periods

A-20 Estimates of collective dose for the Japanese population resulting from the accident at the Fukushima Daiichi Nuclear Power Station

A-21 Distributions of doses in municipalities and evacuation groups

A-22 Estimation of thyroid doses to evacuees from inhalation of radioiodine and comparison with those derived from measurements of people and estimated by Ohba et al.

A-23 Power calculations for epidemiological detection of health effects from the accident at the Fukushima Daiichi Nuclear Power Station

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GLOSSARY

Absorbed dose	Fundamental dosimetric quantity defined as the energy imparted by ionizing radiation in unit mass of matter; measured in grays (Gy); 1 gray is equal to 1 joule per kilogram (J/kg).
Activity	The rate at which spontaneous transformations occur in a given amount of radioactive material. (Strictly, the expectation value of the number of nuclear transformations occurring in a given quantity of material per unit time). It is measured in becquerels (Bq); 1 becquerel equals one transformation per second.
Acute exposure	Exposure received within a short time period (see also protracted exposure).
Adjustment	The process of statistically accounting for effects of differences between groups or populations under comparison in order to control confounding. Adjustment is frequently performed when estimating effect measures from epidemiological data, for example by stratification or multivariate regression analysis.
Attained age	Age at observation or during the follow-up, usually refers to age as time-dependent characteristic in a cohort study.
Baseline risk	Baseline risk refers to the probability that an event of interest (e.g., diagnosis of cancer) will occur in an individual among an unexposed population over a given time period (e.g., lifetime following exposure).
Bayesian inference	The method of inference that quantifies the degree of belief (or the analyst's state of knowledge) of a true value or sets of values of a quantity of interest by combining their prior knowledge about these quantities with recent measurements, observations, or estimates. The degree of belief of the quantity of interest is often described by a subjective probability distribution representing possibly true values for that quantity. The distribution resulting from Bayesian inference is called a posterior distribution.
Becquerel (Bq)	The SI unit of activity, equal to one transformation per second. As the unit is so small, multiples are frequently used such as megabecquerels (MBq) which is 10^6 or a million becquerels (1 GBq is 10^9 Bq; 1 TBq is 10^{12} Bq; and 1 PBq is 10^{15} Bq).
Bias	A statistical estimation procedure is "biased" if the expected value of the estimate of the quantity of interest is not equal to the true value of the quantity. The "bias" of the procedure is the difference between the expected and true values.
Biodosimetry	The use of biological (or chemical, physiological) markers of exposure to reconstruct acute or protracted radiation doses.
Biokinetic model	A mathematical model for the behaviour of radionuclides in the body which takes account of the movement, retention and excretion of a radionuclide as a function of time.
Chronic exposure	Exposure persisting in time. (See also: "Acute exposure" or "Protracted exposure".)

Cold shutdown	Defined in the context of this report by TEPCO and the Nuclear Emergency Response Headquarters as the state where the coolant water temperatures of Units 1–3 were less than 100ºC, the pressure inside the reactor vessels was the same as the outside air pressure, and where any further releases would not result in dose rates greater than 1 mSv per year at the site boundary.
Collective dose	The total radiation dose incurred by a population (that is the sum of all the individual doses); measured in man–sievert (man Sv) or man–gray (man Gy).
Committed dose	The integral, over a defined period of time, of the dose rate in a particular tissue or organ that will be received following the intake of radioactive material into the body.
Confidence interval	In "frequentist inference", a confidence interval is an interval defined in terms of the sampling distribution of a statistic of interest (i.e., the distribution of estimates of the statistic that would arise from repeated—generally hypothetical—realizations of data generated from the same underlying distribution as the observed data) such that, for example, the probability that a 95% confidence interval for a given parameter contains the true value of that parameter is 0.95. (Compare this with "Credible intervals" used in "Bayesian inference".)
Confounding factor or confounder	A confounding factor is a variable that is correlated with both the exposure (e.g., radiation exposure or dose) and the outcome variable (e.g., risk of lung cancer) and, if not controlled for analytically, may distort the conclusions. For example, occupation may be a confounding factor in a study of the relation between lung cancer incidence among non-smokers (dependent variable) and medical radiation exposure (independent variable). For instance, air crew are exposed to higher levels of radiation due to their employment (correlation with radiation exposure) while staff working in certain recreation industries are often occupationally exposed to cigarette smoke (correlation with outcome lung cancer). This confounding might be controlled by introducing into the analysis an indicator for the occupational group.
Decontamination	The complete or partial removal of contamination by a deliberate physical, chemical or biological process.
Deterministic effect	A health effect of radiation exposure for which a threshold level of dose generally exists, above which the severity of the effect is greater for a higher dose.
Dose	A measure of the energy deposited by radiation in a target. Dose can be used as a shorthand for absorbed dose and effective dose when the context is clear.
Dose coefficient/dose per unit intake	The committed effective dose or committed absorbed or equivalent dose in a tissue or organ resulting from an intake, by a specified means (usually ingestion or inhalation), of unit activity of a specified radionuclide in a specified chemical form.
Dose rate	Dose delivered or received per unit time. Measurements are usually made in terms of the dosimetric quantity, ambient dose equivalent rate, H*(10), in units of μSv/h.
Effective dose	Fundamental dosimetric quantity for the purposes of radiological protection defined as the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the body; measured in sieverts (Sv).

Equivalent dose	Fundamental dosimetric quantity for the purposes of radiological protection defined as the product of the absorbed dose in the tissue or organ and the appropriate radiation weighting factor for the type of radiation giving rise to the dose; measured in sieverts (Sv).
Error	The difference between an observed or estimated value and the true (but unknown) value. Since the true value is unknowable, error cannot be quantified. Error can be contrasted with uncertainty, which can be estimated by repeated measurements or Bayesian inference.
Evacuation	The rapid, temporary removal of people from an area to avoid or reduce short-term radiation exposure in an emergency.
Excess risk/rate	A measure of the statistical relationship between a given risk factor and a specific outcome. Depending on the context it can refer to some characterization of the influence on rates such as the “relative risk”, “excess relative risk”, or “excess (absolute) rate”, or, perhaps most appropriately, to estimates of the risk over some period of time (lifetime risk) associated with an exposure of interest. The excess rate is strictly a statistic calculated from observed frequencies/rates, while the excess risk is a prospective estimate inferred from the observations and reasoning.
Exposure	The act or condition of being subject to irradiation. External exposure is exposure to radiation from a source outside of the body. Internal exposure is exposure to radiation from a source within the body.
External dose	Dose from an external radiation source; obtained from being within a radiation field.
Frequency (of occurrence of disease)	The number of new cases of the disease under study divided by the number of people in a population over a defined time period.
Gene	The fundamental physical and functional unit of heredity. A gene is an ordered sequence of nucleotides located in a particular position on a particular chromosome that encodes a specific functional product.
In vivo measurement	A procedure used to determine the nature, activity, location or retention of radionuclides in the body by direct measurement.
Inference	The process of drawing conclusions from scientific observations, evidence and reasoning in the presence of uncertainty. While this report is focussed on prospectively inferring risk, note that estimating an assigned share (or probability of causation) is also inference, but retrospective.
Internal dose	Dose from radioactive material deposited in the body.
Latency (period)	The period between exposure and manifestation of a health effect. This is also the period after which statistically significant increases in frequency of occurrence of the health effect in a population have been seen; theoretically, there might be an undetectable increased frequency of occurrence of the health effect in an exposed population during the presumed latency period, but this possibility becomes vanishingly small in the period shortly after exposure because there is a finite time required for damaged cells to replicate in an uncontrolled manner and manifest as a cancerous growth.

Lifetime risk	Probability that a disease occurs from a given point of time (e.g., at exposure) until the end of life. The lifetime baseline risk refers to the probably of a disease occurring over a lifetime without exposure additional to the background from natural and other sources of radiation. Lifetime risk due to exposure is the additional probability of a disease occurring over a lifetime due to additional radiation exposure.
Likelihood	Generally, the state or fact of being likely or probable. The term may also be used to express a defined statistical concept. Specifically, given a set of data and a statistical model that describes the distribution of the data in terms of some parameters, the statistical concept of "likelihood" is a function of the model parameters that is proportional to the probability density function for the data (given the parameter values). For independent observations, the likelihood of the data is the product of the likelihood values for each observation. Likelihood functions play a central role in both "frequentist inference" and "Bayesian inference" (albeit with different interpretations). Frequentist inference often proceeds by finding parameters that maximize the likelihood given the data (maximum likelihood estimation) and using (asymptotic) properties of the maximized (log-) likelihood as the basis for inference.
Monte Carlo analysis	Computation of a probability distribution of an output of a model on the basis of repeated calculations using random sampling of values of uncertain input variables specified as probability distributions. The numerical sampling strategy used may be Simple Random Sampling, or a form of stratified sampling such as Latin Hypercube Sampling.
Pooled analysis	A combined analysis of original data from two or more data sets bearing on a common question of interest. The analysis may include parameters that distinguish between the different data sets. (Contrast with "*meta-analysis*".)
Protracted exposure	Exposure persisting in time (see also acute exposure).
Radionuclide	A radioactive isotope of an element. Different isotopes of an element have the same number of protons but different numbers of neutrons and hence different atomic masses. If there are too many or too few neutrons, the nuclei of the isotope tend to be unstable and transform into the nuclei of another element and in the process emit radiation.
Relative risk	Ratio of the risk for two groups, estimated from the relative rates of disease between, for example, an exposed group and an unexposed group.
Remediation	Any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.
Shielding	The absorbing property of material between a radiation source and a receptor which results in reduced exposure.
Sievert (Sv)	Unit of equivalent dose and of effective dose, equal to 1 joule per kilogram (J/kg).

Source term	Mathematical expression used to denote information about the actual or potential release of radiation or radioactive material from a given source. Here this term includes the release rate, radionuclide composition, physico-chemical form and their changes over time of the radionuclides released.
Statistical power	The expected probability of being able to detect an effect of a specified magnitude, estimated before the start of a study. It depends on study size, baseline risk and effect size. Statistical power reflects only random error in outcome occurrence, while ignoring measurement error and typically assumes no bias in the study.
Stochastic effect	A radiation-related health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of which (if it occurs) is independent of dose.
True dose	The true but unknown value of dose for a specific individual. The state of knowledge about this unknown true value can be characterized by measurements and estimates that produce a distribution representing state of knowledge about possibly true values. In an epidemiological cohort, there will be a unique set of unknown true doses.
Uncertainty	Expression of having doubt, or being unsure about study results, hypotheses, model-based estimations or results of measurements, and specifically the true value of a quantity of interest. This may be due to lack of complete knowledge about true values for an individual or to a lack of complete knowledge of factors explaining the inter-individual variability of true values in a defined subgroup or population. Unlike error, uncertainties can be quantified. Estimates of uncertainty represent the amount or percentage by which an observed or calculated value might differ from its true value. For a quantity of interest that has a true fixed value, uncertainty is defined here as a degree of belief probability distribution comprising many realizations of possibly true values. For a quantity of interest that is a group or population of true values, uncertainty can be characterized as many alternative realizations of sets of true values.
Variability	Heterogeneity, diversity or a range which characterizes variation in estimated, measured, or true values of a quantity of interest. The term variability is often used to describe differences in measured or true values among individuals in a population or cohort. Examples include inter-individual differences in body weight and/or dose or inter-cohort differences in exposure–response due to differences in sensitivity to a hazardous agent. Further study cannot reduce variability, but may provide additional information to explain reasons why some of this variability occurs. This additional information can reduce the fraction of inter-individual variability initially treated as stochastic.

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This publication contains:

VOLUME II

Scientific annex with appendices

Annex B: Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report

EVALUATING RADIATION SCIENCE FOR INFORMED DECISION-MAKING

In 1955 the United Nations General Assembly established the Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in response to concerns about the effects of ionizing radiation on human health and the environment. At that time fallout from atmospheric nuclear weapons tests was reaching people through air, water and food. UNSCEAR was to collect and evaluate information on the levels and effects of ionizing radiation. Its first reports laid the scientific grounds on which the Partial Test Ban Treaty prohibiting atmospheric nuclear weapons testing was negotiated in 1963.

Over the decades, UNSCEAR has evolved to become the world authority on the global levels and effects of exposure to ionizing radiation. UNSCEAR's independent and objective evaluations of the science are to provide for—but not address—informed policymaking and decision-making related to radiation risks and protection.

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