APPENDIX C. ASSESSMENT OF DOSES TO THE PUBLIC

I. INTRODUCTION

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

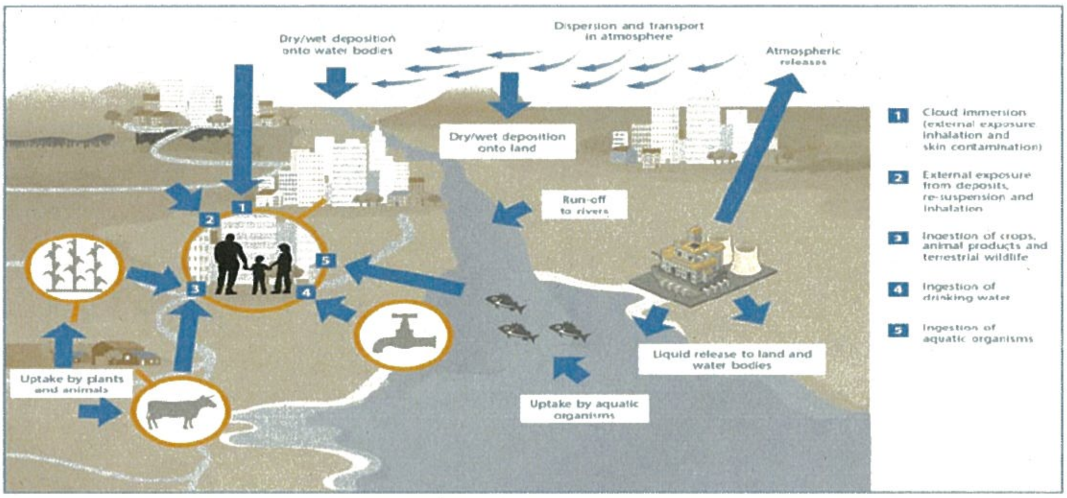
C2. The assessment considered the more important pathways by which people were exposed to radiation following the accident, with the main focus being on estimating exposures of individuals considered to be representative (i.e. having typical habits, such as food intake and behaviour) of the different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

A. Exposure pathways

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

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

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



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

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

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

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

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

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

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

B. Data for dose assessment

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

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

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

1. Radiation measurements within Japan

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

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

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

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

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

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

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

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

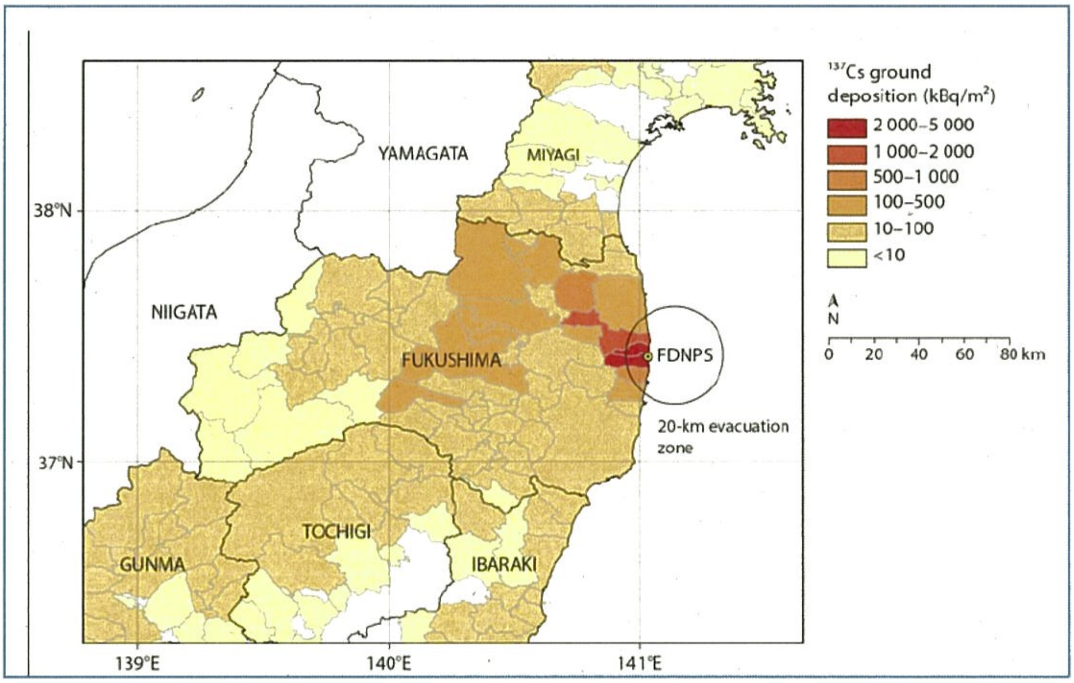
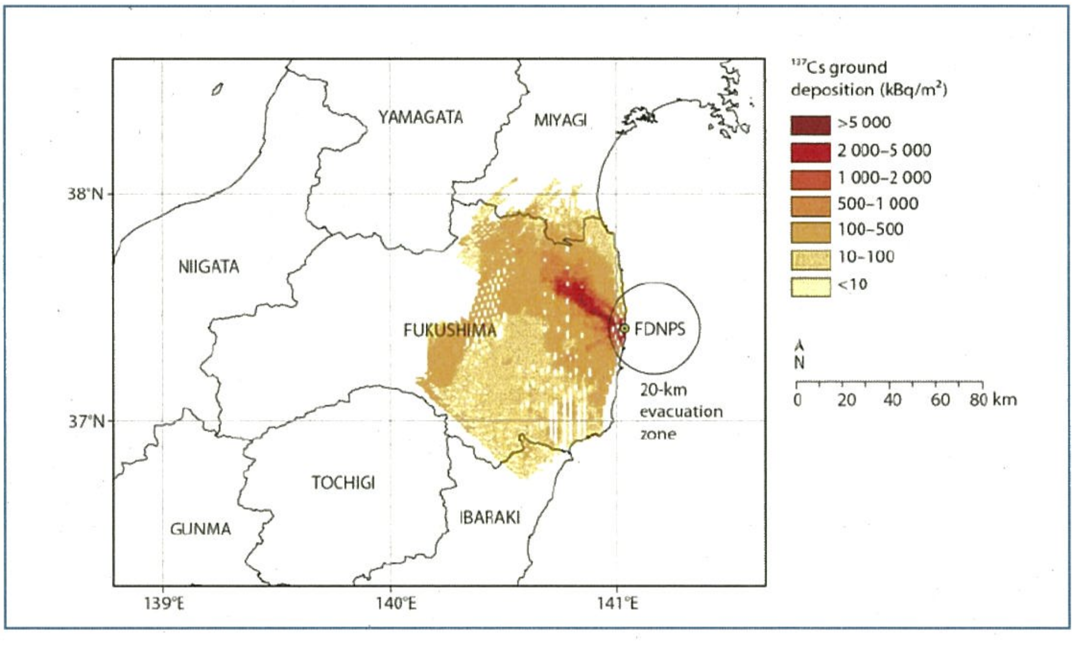


Figure C-III. Deposition density of ^{137}Cs in Fukushima Prefecture based on measurement data from the airborne radiometric surveys adjusted to 30 June 2011 [U17]



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

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

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

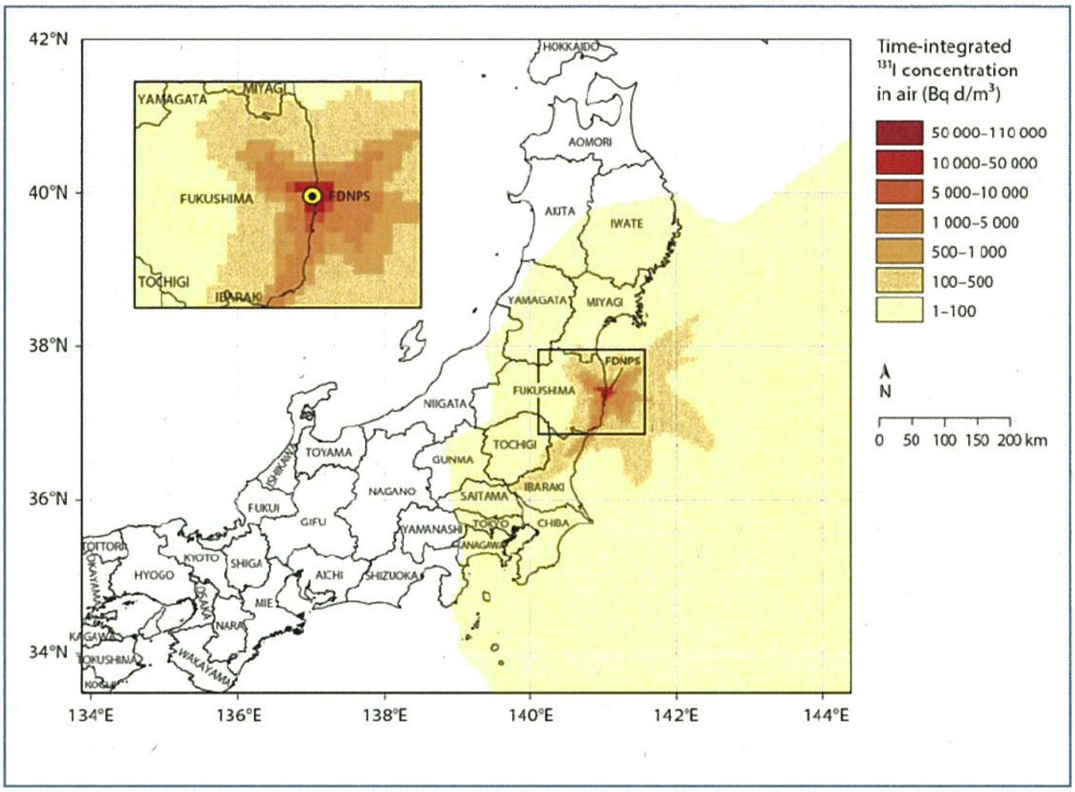
2. Atmospheric transport, dispersion and deposition modelling for Japan

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

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

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

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



3. Radiation measurements outside of Japan

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

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

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

4. Protective actions

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

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

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

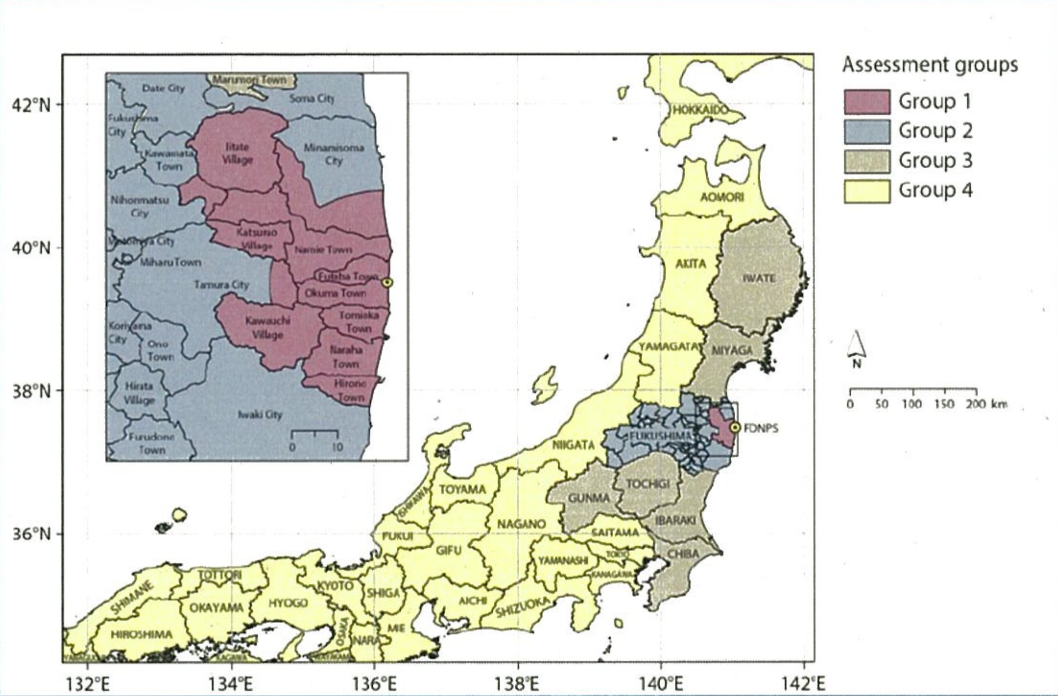
II. METHODOLOGY

A. Regions considered for dose estimation

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

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

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



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

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

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

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

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

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

B. Assessment of external exposure in non-evacuated areas

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

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

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

1. External exposure from deposited material

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2. External exposure from radionuclides in the air

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

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

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

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

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

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

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

D. Assessment of doses from ingestion of radionuclides

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

E. Assessment of doses to residents of evacuated communities

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

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

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

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

Table C5. Eighteen evacuation scenarios based on the NIRS survey

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

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

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

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

F. Assessment of collective doses

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

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

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

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

III. RESULTS

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

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

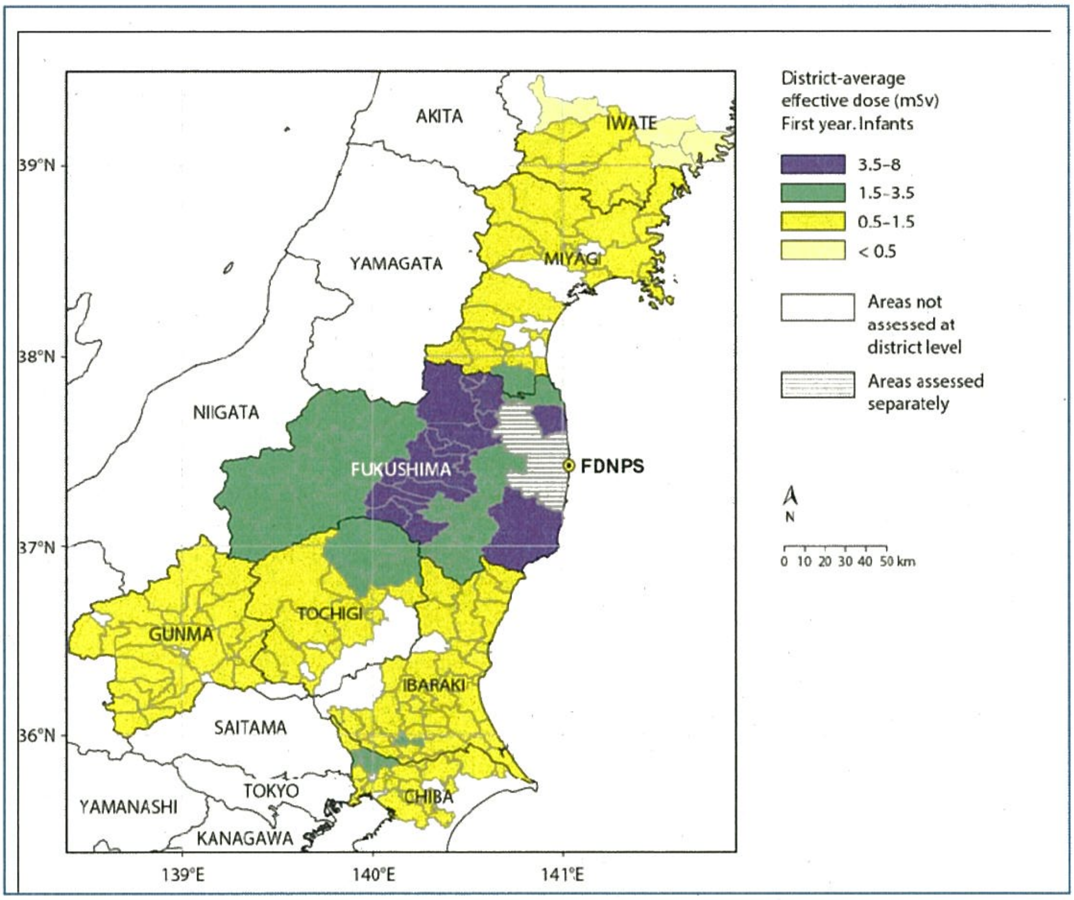
A. Estimates of doses in Japan in the first year

1. Effective dose

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

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

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



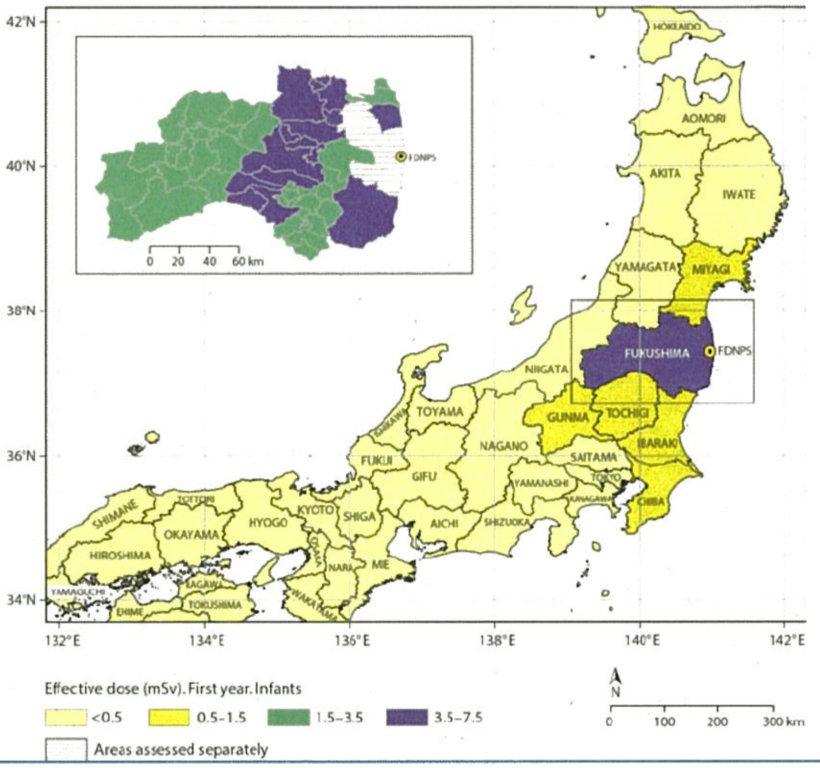
C77. The highest estimated doses were to those individuals who were not evacuated in Fukushima Prefecture, the districts that partly fall within the 20-km evacuation zone (Minamisoma City) and those with high levels of deposition density (the cities of Fukushima, Nihonmatsu, Date, Motomiya and Koriyama,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

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

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

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

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



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

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

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

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

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

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

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

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

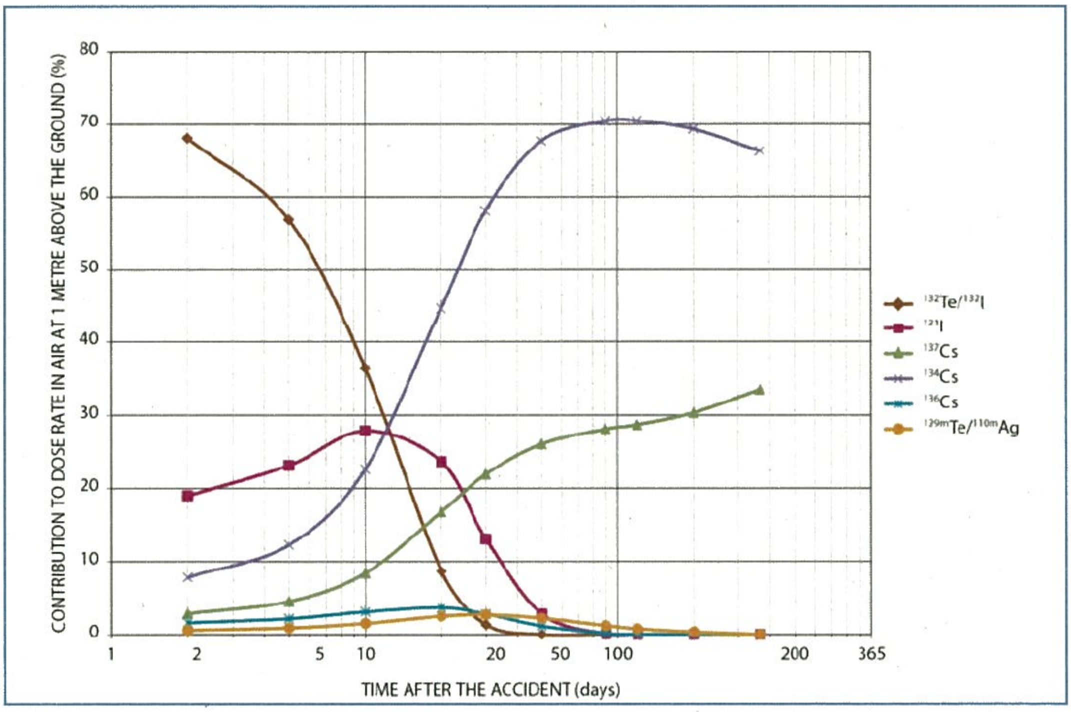
[d] *Group 3: Members of the public living in the prefectures of Miyagi, Gunma, Tochigi, Ibaraki, Chiba and Iwate. The prefectures of Chiba, Gunma, Ibaraki, Miyagi and Tochigi were grouped together to calculate the dose from ingestion in these prefectures. For Iwate Prefecture, the dose from ingestion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

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

2. Contribution of external exposure to the total effective dose

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

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

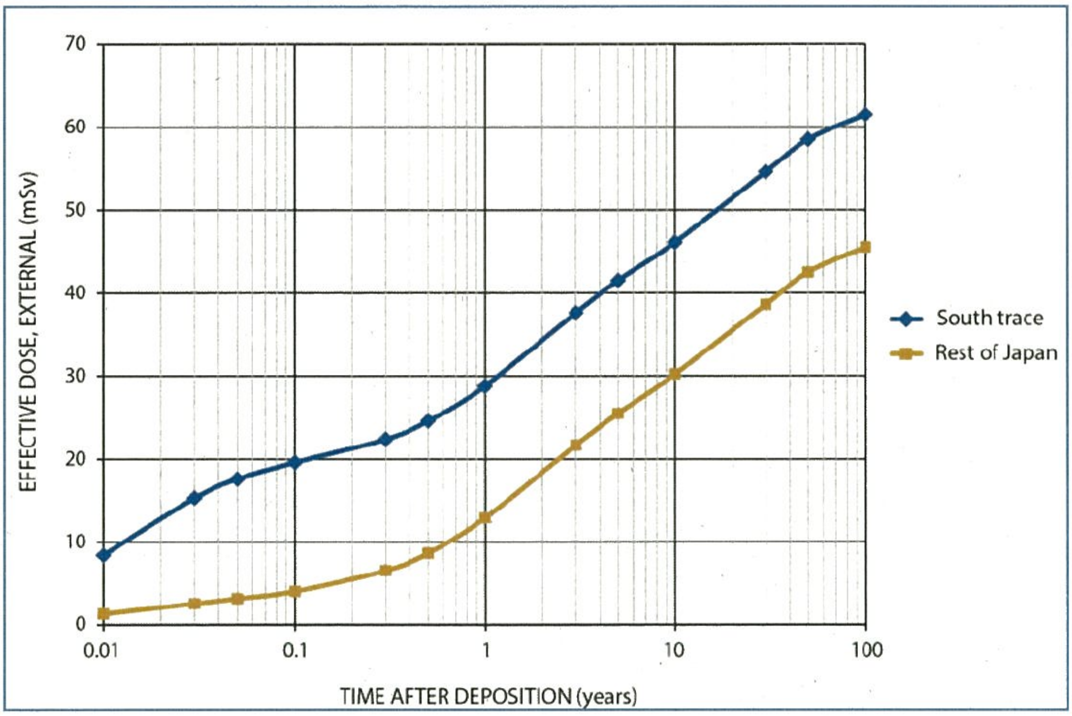


C83. The deposition of radionuclides on the ground at locations within the south trace (the towns of Tomioka, Naraha and Hirono and Iwaki City of Fukushima Prefecture) was significantly enhanced in ^{132}Te, ^{131}I and ^{132}I compared with the rest of Japan. As a consequence, for the assessment for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

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

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

The doses are normalized to the deposition density on the ground of 1 MBq/m² of ^{137}Cs. A typical adult is defined as an adult living in a wooden house and working indoors in a concrete multi-storey building



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

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

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

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

3. Contribution of internal exposure from ingestion to total dose

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

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

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

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

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

4. Estimates of doses from drinking water

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

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

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

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

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

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

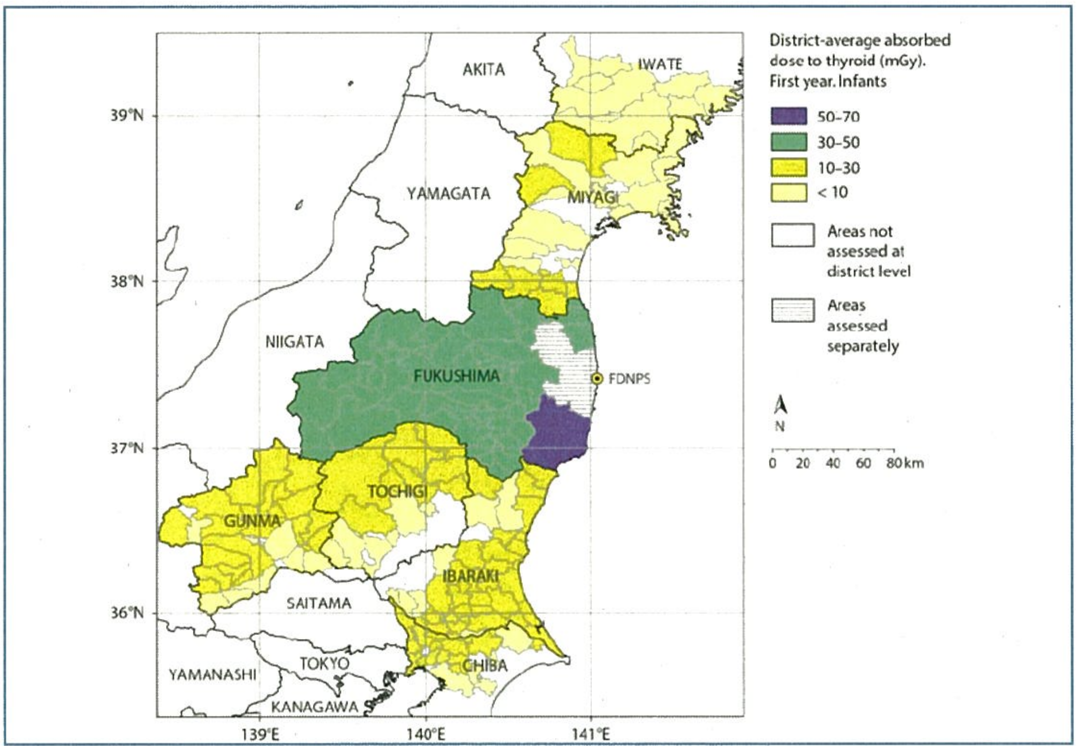
C90. Two papers have reported estimates of average doses from drinking water to Japanese citizens. Murakami and Oki [M26] estimated absorbed doses to the thyroid from a number of pathways including ingestion of drinking water for citizens of Tokyo for the first year following the accident. Amano et al.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

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

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

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

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



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

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

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

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

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

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

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

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

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

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

6. Estimates of doses to residents of evacuated communities

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

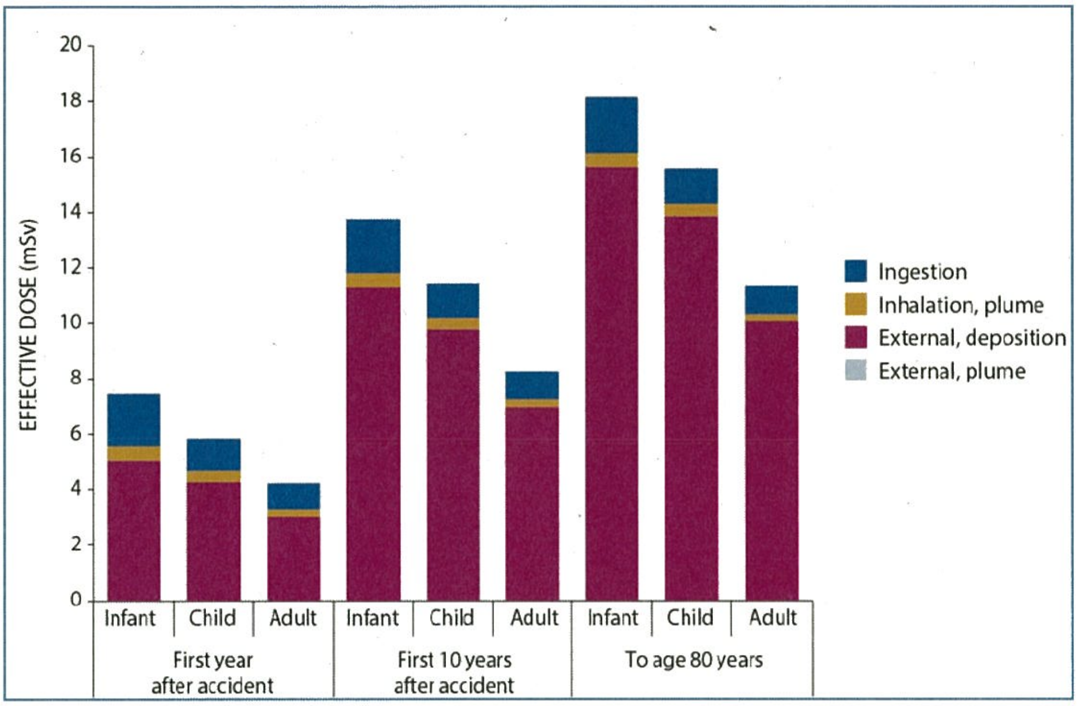
[b] *Group 2: Members of the public living in the non-evacuated districts of Fukushima Prefecture.*

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

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

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

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



C104. The estimated average effective doses incurred over the 10-year-exposure period and the effective doses up to age 80 years are larger by factors of up to two and three, respectively, than those received in the first year. The greatest increases in dose were in the areas with the highest deposition densities.

C105. Most of the absorbed dose to the thyroid of the residents of Japan was received during the first year from inhalation of ^{131}I and ingestion of food containing this radionuclide. Continued exposure from the longer-lived radioisotopes of caesium is estimated to result in an absorbed dose to the thyroid up to age 80 years less than 50% higher than that received in the first year.

C. Radiation exposure outside of Japan

1. Countries neighbouring Japan

C106. When WHO undertook its preliminary dose estimation in 2011 [W11], very few measurement data were available for countries outside of Japan. In the absence of measured data, WHO applied a modelling approach to estimate doses received by people in these countries. The countries and regions considered were the far-eastern part of the Russian Federation, Indonesia, the Philippines, the Republic of Korea and South-East Asia. The effective doses and the equivalent doses to the thyroid for these places were all less than 0.01 mSv in the first year following the accident and the key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway.

C107. Following the FDNPS accident, Keum et al. also estimated the radiation doses to people in the Republic of Korea [K10]. These were based on measured levels of activity concentration and deposition density of radionuclides. Estimates of effective doses and equivalent doses to the thyroid in five age groups (infants, 5-year olds, 10-year olds, 15-year olds and adults) were made. The doses estimated for the Republic of Korea and in the WHO report are summarized in table C15.

2. Rest of the world

C108. The assessment of doses for countries outside of Japan was based on a review of estimates published in the literature, including the results of the WHO preliminary dose estimation [W11], supported by the extensive measurements, and dose assessments carried out by Member States of the United Nations. These dose estimates are summarized in table C15. Based on an analysis of this body of information, the Committee concluded that the total effective doses to individuals living outside of Japan were less than 0.01 mSv in the first year following the accident.

Table C15. Estimated doses in the first year following the accident reported for regions outside of Japan

Geographic location	*Estimated effective dose (mSv)*			*Comments*
	Adults	*10-year old*	*1-year old*	
Neighbouring countries				
The Republic of Korea, Indonesia, the Philippines, far-eastern part of the Russian Federation and South-East Asia [W11]	<0.01	<0.01	<0.01	WHO applied a modelling approach to doses received by people outside of Japan. The key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway. An estimate of equivalent doses to the thyroid was also made and these were also less than 0.01 mSv
The Republic of Korea [K10]	1.4×10^{-4}	1.9×10^{-4}	5.7×10^{-5}	Estimated the effective doses and equivalent doses to the thyroid for five age groups (infants, 5-year olds, 10-year olds, 15-year olds and adults) for the first year and up to age 70 years. Equivalent doses to the thyroid ranged from 5.0×10^{-4} for infants to 1.2×10^{-3} mSv for adults in the first year. Estimates were made using measured levels of airborne activity concentration and deposition density
Rest of the world				
Rest of the world [W11]	<0.01	<0.01	<0.01	WHO applied a modelling approach to doses received by people outside of Japan. The key exposure pathways were ingestion of radionuclides in food and external irradiation by deposited radionuclides. In all cases, most of the estimated dose was from the ingestion pathway. Estimates of equivalent dose to the thyroid were made and these were also less than 0.01 mSv
Belarus [K6]				Estimated the equivalent doses to the thyroid of children aged 1 to 2 years from inhalation of radioiodine. These ranged from 5×10^{-7} to 7×10^{-5} mSv. The maximum values were registered 24 days after the accident
Cuba [A8]	2×10^{-3}			Estimated the effective doses from the inhalation of ^{131}I and ^{137}Cs using measured concentrations in aerosols
France [I32]	2×10^{-4}			Estimated the maximum potential exposures (effective doses in adults and equivalent doses to the thyroid of 1-year-old infants) by inhalation and ingestion of ^{131}I. Based on measurements from mid-March 2011 to May 2011. The reported equivalent dose to the thyroid of 1-year olds in France was 4.5×10^{-2} mSv
Germany [B9]	3×10^{-5}		5×10^{-5}	Estimated the effective doses for the first year after the accident from inhalation and external exposure for ^{131}I, ^{134}Cs and ^{137}Cs from measurements of air samples and deposition density from late March to end of April 2011 in the south-west of Germany
Greece [K21]	1.1×10^{-6}	1.9×10^{-6}		Estimated the effective doses from the inhalation of ^{131}I using measured concentrations in aerosols; no doses from ingestion were calculated
Italy [I30]	3.5×10^{-2}		1.8×10^{-1}	Estimated the effective doses from external exposure, inhalation and ingestion of ^{131}I, ^{134}Cs, ^{137}Cs in milk and water. Ingestion of radionuclides in water was the major contributor of dose. Very conservative assumptions were applied as the highest concentration values measured for each radionuclide in rainwater were used to calculate the dose from ingested water

Geographic location	*Estimated effective dose (mSv)*			*Comments*
	Adults	*10-year old*	*1-year old*	
Netherlands [K17]	$<1 \times 10^{-5}$			Estimated the total effective doses from inhalation pathway using the measured airborne concentration of ^{131}I
Portugal [C1]	4.6×10^{-5}			Estimated the total effective doses from inhalation and ingestion pathways for ^{132}Te, ^{131}I, ^{134}Cs and ^{137}Cs from measured concentrations in aerosol samples and deposition densities from late March to mid-April 2011
Romania [C8]	8.5×10^{-5}			Estimated the total monthly effective doses from ingestion of ^{131}I in sheep milk and meat in Romania for the first year after the accident
Serbia [B11]	7.2×10^{-3}			Estimated the effective doses from ^{131}I concentrations in food, milk, air and rainwater. Doses were from inhalation and ingestion of food during one month. Ingestion of radionuclides in milk was the major pathway

D. Estimates of collective doses

C109. The collective effective doses and the collective absorbed doses to the thyroid from the major exposure pathways (external exposure, inhalation and ingestion) were estimated for the first year, 10 years and to age 80 years following the accident for Fukushima Prefecture, neighbouring prefectures and the rest of Japan, and are summarized in table C16.

Table C16. Collective effective doses and absorbed doses to the thyroid for the population of Japan (128 million in 2010)

Exposure pathway	*Exposure duration*		
	First year	*10 years*	*Up to age 80 years*
Collective effective dose (thousand man-sieverts)			
Inhalation	1.2	1.2	1.2
External	10	25	36
Ingestion	6.5	10	11
Total	18	36	48
Collective absorbed doses to thyroid (thousand man-grays)			
Inhalation	22	22	22
External	10	25	36
Ingestion	50	53	54
Total	82	100	110

C110. The main contributor to the collective effective dose in the first year was external exposure from deposited radionuclides; the ingestion of radionuclides in food was the next most important contributor. The collective effective dose will increase over the first 10 years owing to the continued external exposure and the ingestion of residual radionuclides in foods. After the first 10 years, the increase in the collective effective dose will continue predominantly due to external exposure.

C111. Most of the collective absorbed dose to the thyroid in the first year was caused by ingestion and inhalation of ^{131}I in the spring of 2011, with a smaller contribution from external exposure over the whole year. The collective absorbed dose to the thyroid will slowly increase over the first 10 years owing to the continued external exposure and the ingestion of radionuclides in foods. After the first 10 years, the slow increase will continue because of external exposure.

C112. These collective doses to the population of Japan due to the FDNPS accident can be compared to those to the populations of European countries exposed to radiation following the Chernobyl accident in the former Soviet Union in 1986. The collective effective dose and collective absorbed dose to the thyroid from the Chernobyl accident determined for the 20-year period (1986–2005) by the Committee from the results of both environmental and human measurements were about 360,000[36] man Sv and 2,300,000 man Gy, respectively. The lifetime doses would be about 400,000 man Sv and

[36] About 260,000 man Sv without the contribution of the dose to the thyroid (see annex D [U12]).

2,400,000 man Gy, respectively. The estimated collective effective dose to the population of Japan due to a lifetime exposure following the FDNPS accident is approximately 10–15% of the corresponding value for European populations exposed to radiation following the Chernobyl accident. The estimated collective absorbed dose to the thyroid for the Japanese population is approximately 5% of that for European populations due to the Chernobyl accident.

IV. UNCERTAINTIES

C113. The doses presented are settlement-, district- or prefecture-averages for representative members of the public. The estimated doses were based on the best available models and input data at the time of the study. However, there are uncertainties associated with the results of any assessment of this type because of incomplete knowledge or information, and the assumptions that were made. The main sources of uncertainty are discussed here.

A. Assessment of dose from external irradiation and inhalation

C114. The estimated doses for external exposure in the non-evacuated areas were largely based on measured levels of deposition density of radionuclides on the ground. The uncertainties associated with individual measurements of ^{134}Cs and ^{137}Cs are relatively small but those for ^{131}I are larger because of the significant amount of radioactive decay that occurred before the measurements were made.

C115. There are also uncertainties in how well the measurements represented the spatial distribution of the radionuclides for each district or prefecture when estimating district- or prefecture-average doses. For Fukushima Prefecture, there are extensive measurements with adequate spatial information. Comparisons were made between the measurements of deposition density from the MEXT ground surveys, the USDOE airborne radiometric survey and the NOAA–GDAS ATDM results for total ground deposition. These data were analysed over the grid cells of approximately 1-km squares, with all data corrected for radioactive decay to 1 April 2011. The resultant spreadsheets and maps are provided in attachments C-20 and C-21. The analysis shows good agreement between the measured deposition densities of ^{137}Cs on the ground from the MEXT and USDOE surveys. The marked spatial variability is consistent with the spatial variability seen in other datasets. Based on a comparison of the measured values, uncertainties associated with spatial variability in deposition density contribute an uncertainty of about a factor of two to the uncertainties in the estimated district-average doses. For the Group 4 prefectures, comparatively fewer measurements were made and the uncertainties in prefecture-average doses are likely to be larger.

C116. For external irradiation from deposited radionuclides, a further source of uncertainty is from the reduction in exposures from being indoors and the shielding effects of the building materials. The doses presented in previous sections are for the wooden houses which are the most common type of houses in Fukushima Prefecture. For people who live in wooden fireproof houses or concrete multi-storey apartments, the doses were estimated to be about factors of two and four lower, respectively, than those presented in the tables above. However, these factors were based mostly on European data obtained following the Chernobyl accident and not on measurements conducted in Japan. A further factor directly influencing the estimation of dose from external exposure is the indoor occupancy for the various age and social groups of the Japanese population.

C117. The estimates of exposure of the communities evacuated in March were based on the source term and NOAA–GDAS ATDM results directly. The agreement between the NOAA–GDAS ATDM results and the measured data for the deposition density of ^{137}Cs is good for many areas but for some locations, the ATDM results under- or overestimated the levels by up to a factor of ten. On average, the district-average deposition densities of ^{137}Cs obtained from NOAA–GDAS ATDM are about a factor of two higher than the values from the MEXT surveys. For ^{131}I, the district-average values obtained from NOAA–GDAS ATDM range from overestimates by up to a factor of two, to underestimates by up to a factor of 10, with an average of about one.

C118. A source of uncertainty in the estimation of doses to evacuees from inhalation derives from incomplete knowledge about the release rates of radionuclides over time and the weather conditions during the releases. The ATDM results have large uncertainties when used to estimate doses at specific locations. These uncertainties are discussed in section III.E in appendix B where the NOAA–GDAS ATDM results are compared with the ATDM results obtained by the French Institute for Radiation and Nuclear Safety (IRSN) [S3]. The ratios of the IRSN ATDM estimates for air concentrations of ^{131}I to those of the NOAA–GDAS ATDM results varied from about 0.5 and 12. These ratios reflect the uncertainty in the settlement-average doses from inhalation for these populations for specific locations and times. For deposition density, the ratio of the IRSN ATDM estimates to those of the NOAA–GDAS ATDM results varied between about 0.2 and 8. Again, these ratios reflect the uncertainty in the settlement-average doses from external exposure. The uncertainties in the total doses in the first year across all exposure pathways for the evacuated settlements are smaller than these ranges because of the contributions to the total doses from the other pathways and at other locations.

C119. Similar uncertainties with the NOAA–GDAS ATDM results are relevant to the assessment of doses from external exposure and inhalation of radionuclides from the passing plume outside of the evacuated areas. For this assessment, the impact of these uncertainties were partially reduced by the application of a scaling method based on the measured deposition densities of radionuclides on the ground and the ratio of air concentration to deposition density derived from NOAA–GDAS ATDM. As detailed in section III of appendix B, the ratio of the bulk deposition velocities for ^{131}I estimated by IRSN ATDM to those estimated by NOAA–GDAS ATDM ranged from a factor of about 4 higher to a factor of about 30% lower, depending on the location. These factors imply concentrations in air (and consequently doses from inhalation for the non-evacuated population) ranging from a factor of about 30% higher to a factor of about 4 lower, depending on the location. In addition, the doses from external exposure and inhalation from the passing plume usually contributed less than half of the total dose and the uncertainties introduced by the uncertainties in the NOAA–GDAS ATDM results are less important than for the evacuated population.

C120. The weather conditions during the passage of the plumes following the accident and the nature of the deposition (such as dry or wet deposition, amount of precipitation) significantly influenced the radionuclide distribution in the urban and forest environments. Lack of detailed information on these factors can cause significant uncertainty in the estimation of the dose from external exposure. Future work to provide a more detailed reconstruction of the dispersion and deposition conditions in March 2011 may allow for better estimates of early doses from external exposure and inhalation, particularly in the evacuated areas.

C121. An additional factor that affects the estimation of absorbed dose to the thyroid from inhalation is the ratio of particulate to gaseous forms of ^{131}I in the air. Measurement data were limited and available mostly at substantial distances from the release site. For Fukushima Prefecture, where absorbed doses to the thyroid could be more significant, there were no measurement data for the relative amounts of particulate and gaseous forms of ^{131}I in air; this ratio was therefore estimated from the modelling of the reactor releases and the ATDM results. The estimated value for this ratio has an uncertainty of up to a factor of two.

B. Assessment of dose from ingestion

C122. Using the FAO/IAEA food database of concentrations of radionuclides in foodstuffs, the Committee estimated doses from ingestion as a function of time in the first year following the releases for a range of organs and age groups. The full results are given in attachment C-15 and were all based on the food marketed at the location of interest, thereby allowing for the proportion of each food type that was imported into Japan. Some uncertainties in these dose estimates can be expected, reflecting the uncertainties in the measurement data and the types of foods that were available at different times. The doses in the first year were based on measurements made on food that was not randomly sampled, because priority was given to the identification of foods with the highest radionuclide concentrations. It is therefore, likely that the mean concentrations used in the Committee's assessment are overestimates of the true means, particularly in the first months after the accident when relatively few measurements were made.

C123. As discussed in section III.A of this appendix, if it is assumed that only 25% of food was from the local prefecture then the estimated doses would have been about a factor of three lower than those presented in this study. For doses beyond the first year, the uncertainties in the modelled values of radionuclide concentrations in foods would be reflected in uncertainties in the estimated doses. It was difficult to quantify the uncertainties in these modelled values as there was insufficient information on the transfer of radionuclides to food as a function of time for foods produced in Japan.

C124. The use of a constant activity concentration of 10 Bq/kg for foods when the measurements results were below the limits of detection also contributed to the uncertainty in the doses from intakes in the first year. This value was used for ^{131}I, ^{134}Cs and ^{137}Cs for the first four months following the accident, but only for ^{134}Cs and ^{137}Cs after four months. This is the reason for an apparent marked reduction in estimated doses from intakes in the fifth and subsequent months, particularly for the thyroid. The results also reflect the impact of the restrictions on food supplies, because products from the areas more affected by the accident were excluded from the market. Further information on the possible impact of this assumption is given in the compilation of information on doses from ingestion provided in attachment C-15. Sato et al. [S2] have shown the cautious nature of this assumption, particularly after the first few months. A duplicate-diet study conducted with a large number of volunteers in Fukushima Prefecture showed that many people were likely to have had lower doses from radiocaesium than those estimated by the Committee. However, the study could not consider the first few months after the accident when levels in food were higher and it did not consider intakes of ^{131}I, which contribute most to the doses in the first year. They also noted that the study group was not a random sample and that participants had a high degree of concern about their exposures, so they may not have been representative of the population as a whole.

C125. There were significant differences in the levels of radionuclides in different foodstuffs depending on where they were grown, reflecting differences in the deposition densities of radionuclides on the ground as well as local factors, such as the time of planting of the crop and the soil type. A key factor is where people obtain their food. In Japan, the majority of people use supermarkets to obtain their food and that food could have come from anywhere in the country, with a fraction being imported.

However, some people may grow their own vegetables and also provide these to neighbours, and farmers may consume their own produce. If individuals living in the areas of higher deposition density had eaten locally produced food even though restrictions had been introduced following the accident, then they could have received exposures significantly higher than those presented here. The impact of this can only be quantified using the modelled results, based on deposition data. Further information is provided in the compilation of doses from ingestion given in attachment C-15. This shows that the impact of the restrictions was to reduce doses by up to two orders of magnitude in Fukushima Prefecture, depending on age group and location.

C126. The Committee's estimates of doses beyond the first year from ingestion were obtained using the modelling approach based on deposition data. It was assumed that 25% of food was from the prefecture where the individual lived and 75% from elsewhere in Japan, with allowance made for foods being imported into Japan. In order to assess the uncertainties associated with these assumptions, estimates were made for Fukushima Prefecture assuming that 100% of the local food consumed was from the prefecture, both with and without allowing for imported food. The effect of this is seen in table C17.

Table C17. Influence on effective doses to adults in Fukushima Prefecture of assuming that 100% of local food consumed was from the prefecture

Time (years)	*Effective dose (mSv) with food restrictions; values without restrictions shown in parentheses*		
	25% local, standard result	*100% local, but allowing for imports*	*100% local, no allowance for imports*
1	0.06 (2.0)	0.20 (7.9)	0.27
10	0.14 (2.1)	0.50 (8.3)	1.4
up to age 80	0.17 (2.1)	0.62 (8.4)	1.5

C127. The effect of assuming that 100% of local food consumed were from the prefecture is particularly marked when restrictions on food supplies were taken into account. Because the vast majority of people in Japan eat food from supermarkets, the above dose estimates do not apply to many individuals. It is very unlikely that anyone would have eaten only locally produced food and so the doses presented above should be viewed as the upper bound of possible doses from ingestion. Conversely, it should be recognized that following the accident, many people avoided produce from Fukushima Prefecture or even from Japan, and the settlement-average doses from ingestion would have been lower than those given above.

C128. It took some days for the food restrictions to be introduced in Japan and it is possible that some people ate food with activity concentrations of radionuclides above the restriction levels during this time. For most communities, this was unlikely to have resulted in a significant exposure relative to the exposure received over a full year. However, in the case of Iitate Village, there was a period of a number of weeks when the residents were living in the area and potentially eating local produce and drinking the locally sourced water. The estimates of dose from ingestion for Iitate Village are included in the evacuation scenarios using the standard parameters for ingestion, but an adult living in Iitate Village and eating only locally produced vegetables could have received an additional effective dose of about 10 mSv in the first week following the accident. This assumption is unlikely given the time of year and the limited availability of green vegetables growing in the open, but cannot be excluded as a possibility.

C129. Standard models have been used to determine the radiation doses following intakes of radionuclides into the body. These are based on a standard-sized person with particular metabolic characteristics. It has not been possible to generally consider the effect of the variability between people on the doses from intakes or the uncertainty in the models and data used. However, one aspect that has been briefly considered is that the Japanese diet is relatively high in stable iodine and this could have led to less transfer of radioiodine to the thyroid than in the standard model. There are indications that the transfer of iodine from blood to the thyroid is 20% [Y8] rather than the value of 30% used in the standard ICRP model [I25]. This could lead to slightly lower doses from intakes of ^{131}I, but the effect overall would be small (less than a 30% reduction in dose), compared with the other uncertainties associated with the dose assessment.

C130. The doses in the first year from ingestion of radionuclides in seafood were based on the measurement data contained in the database. Information on the contribution of ingestion of seafood to the total dose from ingestion was only available for individual radionuclides and for each month separately; these show that their contribution to the total dose was not greater than 10% overall. This reflects the restrictions put in place on the consumption of seafood from Fukushima Prefecture.

C131. Table C18 shows the estimates of future radiation doses from the ingestion of seafood. These estimates were based on the calculated levels of ^{137}Cs in seawater over the next 10 years from modelling the marine environment, based on work carried out by [N3]. The modelling of the changes in concentrations of radionuclides in seawater with time beyond 10 years is based on results from measurements of fallout from the testing of nuclear weapons in the atmosphere. These estimated effective doses are all very low and are less than those from the ingestion of terrestrial foods, even two years after the accident. This is because of the significant dilution of radiocaesium in the water and therefore the very low concentrations in seafood away from the FDNPS site. It is assumed that monitoring and restrictions on seafood will continue so that any products above the levels specified by the Japanese authorities will not be consumed.

Table C18. Estimated effective doses to different age groups from the consumption of radionuclides in seafood at various times after the accident

Time after the accident (years)	*Annual effective dose to different age groups (mSv in a year)*		
	Adults	*10-year old*	*1-year old*
2	3.9×10^{-5}	2.1×10^{-5}	1.4×10^{-5}
5	8.2×10^{-6}	4.3×10^{-6}	3.1×10^{-6}
10	3.2×10^{-6}	1.7×10^{-6}	1.2×10^{-6}
20	2.3×10^{-6}	1.2×10^{-6}	8.6×10^{-7}
50	8.1×10^{-7}	4.3×10^{-7}	3.1×10^{-7}

C132. There are two published papers that used a probabilistic approach for estimating doses from ingestion [K19, Y2]. The paper by Yamaguchi estimated a range of doses from ingestion that are consistent with those given here and which do not show a significant variation. The range of doses estimated by Koizumi et al. were lower than those given here but were based on a very limited set of measurements.

C. Future remediation and protective measures

C133. Since mid-2011, extensive remediation work has been underway or is being planned in the regions of Japan with the higher deposition densities, to reduce the dose rate and concentrations of radionuclides in areas where people live or grow food [S6]. This work includes the use of technologies for decontamination of inhabited areas, and of countermeasures in agriculture (such as phytoremediation) and in forestry. The experimental studies and tests in Fukushima Prefecture were planned to be completed by the first half of 2012. At that time, a large-scale environmental remediation programme was planned to be launched in the affected areas of Fukushima Prefecture. In some affected areas beyond the restricted area, local authorities initiated decontamination activities, mostly focused on public areas and especially on children's facilities (kindergartens, schools, hospitals and so on). Similar work, although in the temperate European environment, was intensively conducted in the Chernobyl-affected areas two decades ago, and the conclusions and recommendations from this work were summarized by the Chernobyl Forum [I1] and UNSCEAR [U12].

C134. It was not possible to include consideration of remediation in the dose assessment at this stage, because the effectiveness of the different measures to be applied in Japan was not known. Estimates of the effective doses from external irradiation that would be received by those who were evacuated if they were to return to their homes and regular lifestyles without any environmental remediation having been implemented are however shown in table C19. These estimates provide an upper bound to the doses that might be received in the future.

Table C19. Effective doses from external exposure of adults who were evacuated from localities of Fukushima Prefecture, if they were to return to their homes

Municipality	*Effective dose from external exposure (mSv in period indicated)*[a]		
	11 March 2012–11 March 2013	*11 March 2013–11 March 2014*	*11 March 2014–11 March 2015*
Futaba Town	11	6.7	4.5
Hirono Town	0.42	0.25	0.17
Iitate Village	4.1	2.5	1.7
Katsurao Village	2.0	1.2	0.83
Kawamata Town	0.50	0.30	0.20
Kawauchi Village	0.37	0.22	0.15
Minamisoma City	0.61	0.37	0.25
Namie Machi	9.8	6.0	4.0
Naraha Town	0.66	0.40	0.27
Okuma Town	12	7.3	4.9
Tamura City	0.19	0.12	0.08
Tomioka Town	5.3	3.2	2.2

[a] *External exposure from deposited radionuclides.*

C135. Although remediation may result in reduction in the activity concentrations of radionuclides in crops and animal products, if it is assumed that the restriction criteria for foodstuffs given above would continue to apply, the estimated doses from ingestion would not be affected. In future, more detailed studies could be carried out to investigate the impact of remediation on ingestion doses but this is beyond the scope of this assessment.

C136. The annual external doses to adults are already substantially below the Japanese criteria for evacuation (20 mSv). Decontamination of settlements with techniques that from past experience reduce the doses by about 1.5 would further reduce external doses for all the population groups [I1, U3]. The results in table C19 indicate that, after March 2014, the settlement-average effective doses to adults from external exposure were estimated to be less than 1 mSv in a year in seven of the evacuated localities.

V. COMPARISON WITH OTHER ASSESSMENTS

A. Direct measurements of radionuclides in people

C137. Measurements of radionuclides in people provide a direct source of information on their exposure. Two main sets of data were available to the Committee, the first from in vivo measurements of ^{131}I in the thyroid, particularly of children, and the second from in vivo whole-body monitoring for ^{134}Cs and ^{137}Cs. Such measurements can only indicate the levels of these radionuclides that are in individuals at the time that they were monitored. Assumptions have to be made to estimate total radiation exposures (such as when the intakes took place and how much was by inhalation or ingestion).

C138. Only a limited number of in vivo measurements of ^{131}I activity in the thyroid were reported for the weeks following the accident. Thyroid monitoring was carried out by local authorities on 1,080 children aged between 1 and 15 years in Iwaki City, Kawamata Town and Iitate Village over the period from 26 to 30 March 2011 using hand-held dose-rate instruments [K13]. The absorbed doses to the thyroid from internal exposure were calculated assuming exposure was continuous over the period from 12 to 24 March 2011. The results of the Committee's analysis of the measurement data for infants and children were consistent with the assessment by the Japanese authorities. In its analysis, the Committee assumed a single exposure on 15 March 2011. The Committee's estimates of settlement-average absorbed doses to the thyroid from internal exposure were two to five times higher than the corresponding values derived from the direct monitoring of these children.

C139. Tokonami et al. [T20] reported the results of measurements made on the thyroid from 12 to 16 April 2011 on 62 evacuees from Tsushima District of Namie Town and the coastal area of Minamisoma City. They detected ^{131}I in 46 people and, for the adults in this group, estimated that the absorbed doses to the thyroid were in the range of 2 to 35 mGy. While three quarters of their estimates of absorbed dose to the thyroid were below 10 mGy, a quarter of the estimates were in the range 15 to 35 mGy. The estimates in this higher range are consistent with the estimates of absorbed doses to the thyroid for adults made by the Committee, but the lower range is lower by a factor of up to four. There is likely some overestimation introduced by the overall chain of models (i.e. in the assumed magnitude and pattern of the releases, the assumed protective measures, and the dosimetric and other factors) adopted by the Committee to estimate absorbed doses to the thyroid for the evacuees.

C140. As part of the Health Examination for Citizens in Fukushima Prefecture programme, whole-body counting of more than 106,000 residents of Fukushima Prefecture and neighbouring prefectures was conducted by the end of January 2013 [H5, M24].

C141. The paper of Momose et al. [M24] details a series of whole-body measurements on about 10,000 evacuees made from July 2011 to January 2012. The presence of ^{134}Cs and ^{137}Cs could be detected in the body in only 20% of the evacuees (minimum detectable activity was about 300 Bq). The Committee estimated the average effective dose from the intake of ^{134}Cs and ^{137}Cs since March 2011 from these measurements to be about 0.05 mSv to adults and about 0.03 mSv to adolescents. For almost all of the evacuees, the effective dose was estimated to have been below 1 mSv; an effective dose to just one person in about 5,000 adults and adolescents was estimated to have been about 1 mSv.

C142. According to Hayano et al. [H5], 33,000 residents of Fukushima Prefecture and neighbouring prefectures were examined by whole-body monitoring at Hirata Central Hospital located south-west of FDNPS in Fukushima Prefecture between October 2011 and February 2012. Only 12% of those monitored had an activity of ^{134}Cs and ^{137}Cs in the body above the minimum detectable level of about 300 Bq. Between March and November 2012, this proportion fell to 1%. This confirms that most of the radionuclide intake occurred soon after the accident. Based on the whole-body measurements conducted on adults between October 2011 and February 2012, the Committee estimated the average effective doses from the intake of ^{134}Cs and ^{137}Cs since March 2011 to be in the range of about 0.02 to 0.07 mSv, respectively.

C143. Both estimates, based on the large number of measurements [H5, M24], are substantially lower than the doses estimated in this study from the inhalation and ingestion of ^{134}Cs and ^{137}Cs. Although the aim of this study was to provide as realistic as possible an assessment of the doses to the Japanese population, these results would indicate that some of the assumptions made were still cautious, an inevitable consequence of the incompleteness of the information available to the Committee.

B. WHO study

C144. The preliminary exposure assessment by WHO [W11] and the related health risk assessment [W12] used data available up to September 2011. Although the assessments were intended to be realistic, given the limited information available at the time, some of the assumptions made by WHO were likely to lead to overestimation of doses.

C145. In table C20, the WHO results for the effective dose to adults and the absorbed doses to the thyroid of 1-year-old infants are compared with the results obtained in this study. This assessment used more comprehensive data than were available for the WHO study and it was therefore possible to make more realistic assumptions in parts of the assessment. In general, the estimates from this study of the effective doses in the first year in districts of Fukushima Prefecture are within the dose ranges in the WHO preliminary dose estimation. There is also good agreement in the estimates of the absorbed doses to the thyroid. Table C20 shows that in some cases, the estimated doses for specific locations were lower in this assessment than in the WHO study. This reflects the additional information available, in particular, for the evacuated areas, where more detailed information on the patterns of movement of the evacuees was available than for the WHO preliminary dose estimation [W11]. However, there are also locations where the estimated doses in this study were higher than those in the WHO study.

Table C20. Comparison of estimates of the effective dose to adults and of the absorbed dose to the thyroid of 1-year-old infants

Location	*WHO assessment [W12]*		*Committee's assessment*	
	First year	*Lifetime*	*First year*	*Up to age 80 years*
	EFFECTIVE DOSE TO ADULTS (mSv)			
Namie Town	22	24	5.0[a]	[d]
Naraha Town	4	8	3.7[a]	[d]
Iitate Village	12	14	8.0[b]	[d]
Katsurao Village	5	6	6.0[b]	[d]
Minamisoma City	5	8	5.7	[d]
Iwaki City	1	2	2.2	4.2
Rest of Fukushima Prefecture	1–5	2–10	1.0–4.3	1.2–12
Neighbouring prefectures	~1	~1	0.2–1.4	0.2–4.1
	ABSORBED DOSE TO THYROID OF 1-YEAR-OLD (mGy)			
Namie Town	122	123	81[c]	[d]
Naraha Town	39	42	82[c]	[d]
Iitate Village	73	74	56[c]	[d]
Katsurao Village	48	48	73	[d]
Minamisoma City	43	46	53[c]	[d]
Iwaki City	31	32	52	[d]
Rest of Fukushima Prefecture	31–39 (or 30–40)	32–42	33–52	[d]
Neighbouring prefectures	≤9	≤10	3–15	[d]

[a] *Within restricted zone.*

[b] *Within deliberate evacuation zone.*

[c] *Assessed NIRS evacuation scenario.*

[d] *Not assessed by Committee.*

VI. CONCLUSIONS

C146. For the great majority of people in Japan, the additional radiation doses received in the first year following the radioactive releases from the accident at FDNPS were less than the background doses received each year from natural sources of radiation (about 2.1 mSv [N23]). This is particularly the case for people living in prefectures remote from Fukushima Prefecture where doses of 0.2 mSv or less were estimated to have been received.

C147. For those residents who were evacuated in the first days after 11 March 2011, the estimated settlement-average total effective doses to adults in the first year were on average less than 6 mSv. For those who were evacuated at later times, the estimated settlement-average total effective doses to adults in the first year were on average less than 10 mSv. These doses include those received before and during evacuation and for the remainder of the year at the evacuation destination. The estimated settlement-average absorbed doses to the thyroid of one-year-old infants in the first year ranged from about 15 up to about 80 mGy. This is significantly higher than absorbed doses to the thyroid from natural background radiation; the average annual absorbed dose to the thyroid from naturally occurring sources of radiation is typically of the order of 1 mGy. For a small number of hospital and nursing-home patients, residents and other individuals who may have remained in the 20-km zone for longer periods, higher exposures may have occurred.

C148. For those people who were not evacuated, the highest district-average doses were received by those living in Fukushima City, where the district-average total effective doses in the first year were 4.3 mSv for adults and 7.5 mSv for 1-year-old infants. If no remediation were undertaken, people who were infants at the time of the accident could receive effective doses up to about 20 mSv, in addition to those received from natural sources of radiation, over their lifetimes. People living in a number of settlements within the districts of Koori Town, Otama Village, and the cities of Date, Iwaki, Koriyama, Nihonmatsu and Minamisoma were estimated to have received average effective doses in the first year in the range of 2 to 4 mSv for adults and 5 to 7 mSv for infants. For the remaining districts within Fukushima Prefecture the district-average effective doses were in the range of 1 to 2 mSv for adults and 2 to 5 mSv for infants. To provide context, 80-year cumulative effective doses from background exposure to natural sources of radiation in Japan are on average about 170 mSv (i.e. 2.1 mSv annually for 80 years). The variability of the deposition density of radionuclides in the environment and variations in human behaviour and food habits are such that the estimates of the effective dose to an individual could be up to about two to three times higher or lower in some locations than the average effective dose for the district.

C149. The highest estimated absorbed doses to the thyroid of individuals in non-evacuated districts in the first year were in the cities of Iwaki and Fukushima, with the district-average absorbed dose to the thyroid of 1-year-old infants in the first year being about 50 mGy. The estimated doses to 10-year-old children and adults were lower than those of 1-year-old infants by factors of about two and about three to four, respectively. For the Group 3 prefectures (Chiba, Gunma, Ibaraki, Iwate, Miyagi and Tochigi), the district-average absorbed doses to the thyroid of infants in the first year were assessed to be in the range of about 3 to 15 mGy. In the remainder of the 40 prefectures of Japan, the prefecture-average absorbed doses to the thyroid of infants in the first year were assessed to be about 3 mGy.

C150. There were only a limited number of direct in vivo measurements of ^{131}I in the thyroid reported for the weeks immediately following the accident. The estimates of absorbed dose to the thyroid from these measurements were up to two to five times lower than the settlement-average absorbed doses to the thyroid estimated in this study. There is likely some overestimation introduced by the overall chain of models (i.e. in the assumed magnitude and pattern of the releases, the assumed protective measures, and the dosimetric and other factors) adopted by the Committee to estimate absorbed doses to the thyroid for the evacuees. The estimates of dose from internal exposure by gamma-emitting radionuclides derived from whole-body monitoring are substantially lower than the doses estimated in this study and therefore reflect some caution in the assumptions used in assessing the doses from internal exposure in this study.

C151. The estimated doses to evacuees have the largest associated uncertainties for all of the estimates made by the Committee during this study, and in view of the absence of measurements of concentrations of radionuclides in air at the time of exposure, are likely to remain so. Doses had to be estimated from the ATDM results, and assumptions about the temporal pattern of the releases, the time-varying location of people during the evacuation and any protective measures that were applied, all of which have associated uncertainties. Further information will, in time, become available on the pattern and magnitude of the releases and this may lead to some reduction in the overall uncertainty in the estimation of doses to evacuees.

C152. For the locations with the highest estimated doses, the most important exposure pathway was external exposure from deposited material, although there may also have been a significant contribution from inhalation and ingestion of radionuclides. For the locations with lowest estimated doses, ingestion of radionuclides in food gave the most significant contribution.

C153. The estimated doses depend on the radionuclide concentrations in the environment and on the age/social group of the population. Infants aged 1 year at the time of the accident had the highest estimated doses, followed by 10-year-old children and then by those adults who spent more time outdoors. Adults who spent more time indoors had the lowest estimated doses. However, the differences in the estimated effective doses among the considered groups were not large, being less than a factor of two.

C154. Generally, the total effective doses that will be incurred over the 10-year period following the accident were estimated to be a factor of up to two larger than those received in the first year. Lifetime doses were estimated to be up to a factor of three greater than the doses received in the first year, with the greatest increases in dose being in the areas with the highest levels of deposition density of radionuclides. Most of the absorbed doses to the thyroid were received by the residents of Japan during the first year by the pathways of inhalation of ^{131}I in air and ingestion of food containing ^{131}I. The doses to the thyroid over a lifetime were estimated to be less than 50% higher than those received in the first year. Children born over the next decades will not receive any dose to the thyroid from ^{131}I since it will have totally decayed, but will receive some exposure from ^{134}Cs and ^{137}Cs.

C155. The doses presented here are considered to be typical of the average exposures for each group of people. Doses would be significantly lower for some people, particularly those living in concrete multi-storey apartments and who had avoided locally produced fresh food after the accident. Doses would be higher for those who spent a significant proportion of each day outdoors and who ate locally produced food.

C156. The actions taken to protect the public significantly reduced the radiation exposures that could have been received. This was particularly the case for settlements within the 20-km evacuation zone and the deliberate evacuation zones, where the protective measures reduced the potential exposures in the first year by up to a factor of 10. The Committee estimated that effective doses thus averted ranged up to 50 mSv for adults; the absorbed doses to the thyroid of 1-year-old infants averted by evacuation ranged up to about 750 mGy.

C157. Collective doses to the Japanese population were also estimated for comparative purposes. The estimated lifetime collective effective dose to the population of Japan following the FDNPS accident is approximately a factor of eight lower than the corresponding value for European populations exposed to radiation following the Chernobyl accident, while the collective absorbed dose to the thyroid is a factor of about 20 lower.

C158. Based on an analysis of doses reported for countries neighbouring Japan and for the rest of the world, the Committee concluded that the total effective doses to individuals in populations living outside of Japan were less than 0.01 mSv in the first year following the accident.

C159. While the Committee has aimed to make realistic estimate of dose to public based on the available information, it is likely that some overestimation has been introduced generally by the overall chain of models used by the Committee and the lack of information on individual protective measures.