ATTACHMENT A-3

THE ESTIMATION OF WHOLE-BODY DOSES FROM THE INTAKE OF RADIOCAESIUM FOLLOWING THE ACCIDENT AT THE FUKUSHIMA DAIICHI NUCLEAR POWER STATION

UNSCEAR 2020/2021 Report, annex B, Levels and effects of radiation exposure due to the accident at the Fukushima Daiichi Nuclear Power Station: implications of information published since the UNSCEAR 2013 Report

Content

This attachment describes the approaches the Committee has used to estimate the intakes of radiocaesium and resulting whole-body doses from internal exposure following the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS). Four different approaches have been used to estimate intakes and doses in the first year after the accident based, respectively, on:

(a) Whole-body measurements of radiocaesium in several thousand people in municipalities mainly within Fukushima Prefecture;

(b) Measurements of concentrations of radiocaesium in food and drinking water, including market-basket and duplicate-diet surveys;

(c) Measurements of radiocaesium concentrations in air; and

(d) Predictions of radiocaesium concentrations in air based on a source term and atmospheric transport, dispersion and deposition model (ATDM).

The estimated intakes and resulting doses in the first year using these four approaches are compared and the approach adopted by the Committee to update its estimates of doses in the UNSCEAR 2013 Report is described. Intakes and doses beyond the first year have been estimated using an empirical model based on measurements over decades of the transfer of radiocaesium deposited from weapons' fallout to food in Japan.

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CONTENTS

I. INTRODUCTION

1. This attachment summarizes the approaches and models used by the Committee to estimate doses to the population of Japan resulting from intakes of radiocaesium following the accident at FDNPS. Data and information that have been published, or made available to the Committee, since the UNSCEAR 2013 Report [UNSCEAR, 2014] are summarized, in particular where these have the potential to improve the validity of the estimated doses in the UNSCEAR 2013 Report, and/or reduce their uncertainty. The Committee has used this new information to adapt the approaches and models it had used in the UNSCEAR 2013 Report to estimate doses, and the more significant changes are described, in particular more realistic estimates are presented of the amount of radiocaesium ingested in the first year and in subsequent years following the accident.

2. The Committee has used four different approaches to estimate doses from the intake of radiocaesium in the first year following the accident. These were based, respectively, on: *(a)* whole-body measurements of radiocaesium in several thousand people in municipalities mainly within Fukushima Prefecture; *(b)* measurements of concentrations of radiocaesium in food and drinking water, including market-basket and duplicate-diet surveys; *(c)* measurements of radiocaesium concentrations in air; and *(d)* predictions of radiocaesium concentrations in air based on a source term and atmospheric transport, dispersion and deposition modelling (ATDM). The estimated intakes and resulting doses in the first year using these approaches are compared and the approach adopted by the Committee to update its estimates of doses in the UNSCEAR 2013 Report [UNSCEAR, 2014] is described. Intakes and doses beyond the first year have been estimated using an empirical model based on measurements over decades of the transfer of radiocaesium deposited from weapons' fallout to food in Japan.

3. The Committee has focused on estimating doses for four groups of geographical areas of Japan: Group 1 included municipalities in Fukushima Prefecture from which some or all of the population was evacuated in the days to months after the accident; Group 2 included municipalities and parts of municipalities of Fukushima Prefecture that were not evacuated; Group 3 included selected prefectures in eastern Japan that were neighbouring Fukushima Prefecture (Ibaraki, Miyagi, Tochigi and Yamagata prefectures); and Group 4 included all the remaining prefectures of Japan. Within these groups, the Committee has assessed doses for the three age groups: 1-year-old infants, 10-year-old children and adults.

II. DOSE ASSESSMENT IN THE UNSCEAR 2013 REPORT

4. Assessment of doses from the intake of radiocaesium (and other radionuclides) into the body in the UNSCEAR 2013 Report [UNSCEAR, 2014] took account of intakes via inhalation and ingestion of food and drinking water. The former was based on the source term assumed in the UNSCEAR 2013 Report and an ATDM of released radiocaesium; and the latter was based on numerous measurements of the concentrations of radionuclides in food products in a database compiled by the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA) in collaboration with the Ministry of Agriculture, Forestry and Fisheries (MAFF) and the Ministry of Health, Labour and Welfare (MHLW) of Japan [UNSCEAR, 2014] in March–May 2011.

5. Two methods were used to estimate doses from the intake of radiocaesium by inhalation. The first was based on ATDM of the time-dependent concentrations in air of ^{134}Cs, ^{136}Cs and ^{137}Cs on a 5 × 5 km uniform grid covering Japan. While these concentrations were derived using

the then best available source term and ATDM, there were significant uncertainties in their values at specific locations and times. This approach was used to estimate doses received by people from evacuated municipalities of Fukushima Prefecture.

6. The second was based on the estimated time-integrated concentrations of radiocaesium in air derived from measured ground deposition levels scaled by the ratio of time-integrated air concentration to deposition density derived from ATDM. This approach was used to estimate doses received by people living in non-evacuated municipalities of Fukushima Prefecture and the rest of Japan.

7. The Committee used standard values of the age-dependent breathing rates and dose coefficients for organ doses and for effective dose [ICRP, 1995] for the purposes of estimating doses from the time-integrated air concentrations. These dose coefficients were based on a default particle size of 1 µm. No allowance was made for any possible reduction in concentrations of radiocaesium in air indoors compared with those outdoors.

8. Doses from ingestion in the first year were based on measurements of concentrations of radiocaesium in food compiled under the guidance of FAO and IAEA in collaboration with MAFF and MHLW. The measured concentrations were combined with information on the quantity and types of foods people ate to obtain estimated doses.

9. Within Japan, extensive measurements were made of the concentrations of radionuclides in different foods (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. The measurement data were for foods as marketed, not as consumed (e.g., after culinary preparation, etc.). Many of the measurements were at or below the minimum detection level (MDL) of 10 Bq/kg and, in these cases, in estimating doses, it was assumed that the concentrations of ^{134}Cs and ^{137}Cs were each at MDL in each type of food.

10. There were insufficient data in the first months after 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 obtained their food from supermarkets where food is sourced from the whole of the country, and the average concentrations of radionuclides in foodstuffs over wide areas were used to estimate the average exposures of groups within the population. Mean concentrations measured in groups of foodstuffs in Fukushima Prefecture, five surrounding prefectures (Chiba, Gunma, Ibaraki, Miyagi and Tochigi) and the rest of Japan formed the basis for the main assessment of doses from ingestion.

11. Information on the quantities and types of foodstuffs consumed per capita of the population, based on surveys carried out in Japan, was provided by the Government of Japan for use in the assessment.

12. After the first year, the Committee estimated intakes and doses from ingestion of foods using the FARMLAND model [Brown and Simmonds, 1995] to predict the transfer of radionuclides through terrestrial food chains. Information about the agricultural practices in Japan and Japanese-specific data on the transfer of radionuclides to specific foodstuffs were used. Account was taken of the restrictions in place on food supplies.

13. The Committee compared its dose estimates with results emerging from whole-body monitoring campaigns that had been and were being carried out, in particular, the studies of Momose et al. [Momose et al., 2012] and Hayano et al. [Hayano et al., 2013]. The Committee

judged that the available measurements (i.e., those of which it was aware and/or had access to) of radiocaesium in people from these whole-body monitoring campaigns were insufficient to estimate directly the internal exposure of the population of Fukushima Prefecture or the rest of Japan. It noted, however, that dose estimates based on whole-body monitoring were substantially lower than those estimated on the basis of the data base compiled by FAO and IAEA on radionuclide concentrations in food.

III. ESTIMATING DOSES FROM INTERNAL EXPOSURE DUE TO INTAKES OF RADIOCAESIUM IN THE FIRST YEAR

14. Four approaches have been used by the Committee to estimate updated doses from intakes of radiocaesium in the first year. These were based on: *(a)* whole-body measurements of radiocaesium in several thousand people in municipalities mainly within Fukushima Prefecture; *(b)* measurements of concentrations of radiocaesium in food and drinking water, including market-basket and duplicate-diet surveys; *(c)* measurements of radiocaesium concentrations in air; and *(d)* predictions of radiocaesium concentrations in air based on a source term and ATDM. Each is considered in the following subsections.

A. Estimates of intakes of radiocaesium and doses from whole-body monitoring data

15. The Committee has revisited the information available from whole-body monitoring campaigns and evaluated the extent to which plausible estimates of internal doses can be made from them, not least as there has been a modest increase in the amount of monitoring data now available.

16. Whole-body monitoring was carried out after the accident at FDNPS by national institutes, such as the Japan Atomic Energy Agency (JAEA) and the National Institute of Radiological Sciences (NIRS), and by universities, hospitals and local authorities. The measurements provide direct information, subject to measurement uncertainties, about the amount of radiocaesium in the body at the time the measurements were made. If there is further information available about how and when the intake or intakes of radiocaesium occurred, the measurements can be used with a model of radiocaesium metabolism in the body to estimate the dose from internal exposure.

17. Monitoring was generally carried out using large NaI(Tl) detectors scanning the body for a few minutes, with the recorded spectrum enabled, either to measure the radiocaesium body content through proper calibration, or to put an upper limit on the content in the case of measurements below MDL. The focus of many of these studies was on estimating maximum doses to provide reassurance to those monitored rather than on making realistic assessment of the distributions of doses among the exposed population. The published results of these campaigns are summarized in table A-3.1.

18. The study of Sugimoto et al. [Sugimoto et al., 2014] provided further analysis of essentially the same measurement data included in the earlier study of Tsubokura et al. [Tsubokura et al., 2012]. The second study by Tsubokura et al. [Tsubokura et al., 2014] covered later measurements made at Minamisoma Municipal General Hospital and Hirata Central Hospital, with lower proportions of measurements above MDL, and less useful results for the Committee’s purposes, than the earlier studies. Neither the Sugimoto et al. [Sugimoto et al., 2014] or the Tsubokura et al. [Tsubokura et al., 2014] studies have therefore been considered further in this attachment.

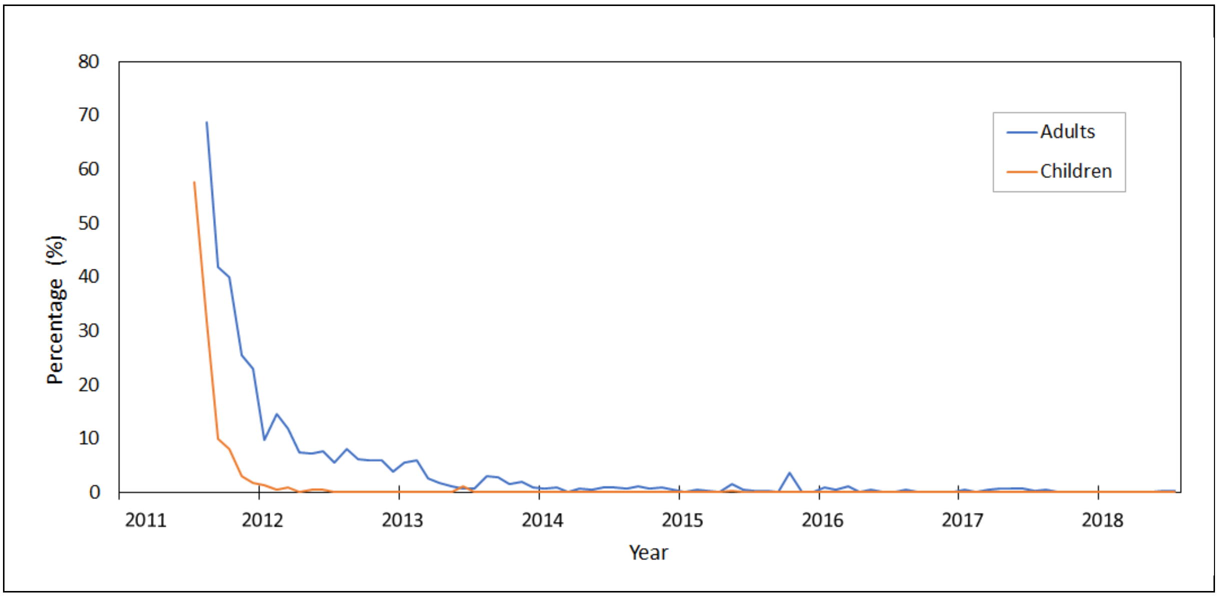
Table A-3.1. Summary of whole-body monitoring campaigns carried out following the Fukushima Daiichi Nuclear Power Station accident (ordered by the date measurements began)

Reference	*Measurement dates*	*Target population*	*Measurement programme*	*Age group*	*Number of people monitored*	*Summary of results*
[Matsuda et al., 2013; Morita et al., 2013]	March–April 2011	Adult evacuees and first responders	Whole-body counter	Adults	173	39% of measurements of ^{134}Cs above MDL (33 Bq) 32% of measurements of ^{137}Cs above MDL (33 Bq) Acute intake by inhalation assumed
[Kim et al., 2016]	27 June–28 July 2011	Evacuees from various municipalities of Fukushima Prefecture	NIRS fixed installation	Adults Children (<15 years)	125 49	47% of measurements of ^{134}Cs above MDL 26% of measurements of ^{137}Cs above MDL ^{137}Cs/^{134}Cs = 1.1 Acute intake by inhalation assumed on 12 March 2011 Data compare well with JAEA estimates [Momose et al., 2012] ^{134}Cs body burden adult: ~550 Bq/body (mean), 300 Bq/body (median), 7 kBq/body (max) No significant difference in doses estimated for adults and children
[Hayano et al., 2014]	11 July–29 July 2011	Evacuees from Minamisoma City who had subsequently returned	Anzai chair-type whole-body counter	Adults (≥16 years)	566	Complex and indirect corrections had to be applied to the measurements for shielding by the body Average body burden of ^{134}Cs in July 2011 was 825 ± 360 ± 110 Bq (see text below) Acute intake by inhalation assumed
[Momose et al., 2012]	11 July 2011–31 January 2012	Evacuees from 11 municipalities of Fukushima Prefecture	JAEA fixed whole-body counter in Tokai Village JAEA mobile units in Fukushima Prefecture	Adults Children (<17 years)	3 128 6 799	20% of measurements above MDL of 300 to 370 Bq ^{137}Cs/^{134}Cs ratio is between 1.12 and 1.26 No correlation between committed effective dose of children and parents Maximum body burden: 2.7 kBq (<8 years old), 14 kBq (adults) Acute intake by inhalation assumed Measurement results up to end of December 2011 may have been affected by contamination on clothes

Reference	*Measurement dates*	*Target population*	*Measurement programme*	*Age group*	*Number of people monitored*	*Summary of results*
[Hayano et al., 2013]	October 2011–February 2012	Residents of Fukushima Prefecture (73%), Ibaraki Prefecture (23%)	Hirata Central Hospital	Adults Children (<15 years)	4 716 6 310	Some measurements up to end of February 2012 might have been affected by external contamination on clothes Maximum of 15% of measurements of ^{137}Cs above MDL (in November–December 2011); less than 5% of measurements above MDL after February 2012 (but see above) ^{137}Cs body burden, whole population: ~12 Bq/kg (mean), ~9.5 Bq/kg (median), 77 kBq/kg (max)
[Tsubokura et al., 2012]	October 2011–March 2012	Residents of Minamisoma City	Minamisoma Municipal General Hospital	Adults Children (<15 years)	8 066 1 432	16.4% of measurements on children above MDL; median body content = 590 Bq (for positive measurements) 38% of measurements on adults above MDL; median body content = 744 Bq (for positive measurements) Difference in exposure between adults and children is statistically significant
[Sugimoto et al., 2014]	October 2011–March 2012	Residents of Minamisoma City	Minamisoma Municipal General Hospital	Adults Children (<15 years)	7 214 1 067	40% of measurements on adults and 9% of measurements on children above MDL For positive measurements, median body burden was 11 Bq/kg for adults and 8.5 Bq/kg for children Contains an analysis of risk factors (food consumption and habits) related to radiocaesium detection, not detailed here
[Tsubokura et al., 2014]	April 2012–March 2013	Residents of Minamisoma City	Minamisoma Municipal General Hospital and Hirata Central Hospital	Median age 14 years Age range 2–97 years	30 622	Measurements of ^{137}Cs above MDL: 612 participants (6.1%) from Minamisoma Hospital and 144 participants (0.7%) from Hirata Hospital >50 Bq/kg ^{137}Cs measured in 9 participants Median ^{137}Cs content in body of these 9 participants: 4 830 Bq (69.6 Bq/kg); range 2 130–15 918 Bq (50.7–216.3 Bq/kg) All 9 participants consumed homegrown produce and wild mushrooms

19. As well as the published studies, Minamisoma City municipal administration has made the results of whole-body monitoring carried out at Minamisoma Municipal General Hospital available on its web portal [Minamisoma, WEB]. Monitoring started on 11 July 2011 and more than 10,000 measurements had been carried out by the end of January 2012. The percentages of those measured with levels of radiocaesium in the body above the MDL was about 40% among adults in the first three months but declined rapidly (see figure A-3.I). Among the results available are those of repeated measurements made on the same subjects that generally show a gradual decrease in the levels of radiocaesium in the body.

Figure A-3.I. Reduction over time of the percentage of whole-body measurements made on adults and children at hospitals and schools in Minamisoma City that were above the minimum detection level (4 Bq/kg body mass of ^{137}Cs or ^{134}Cs) [Minamisoma, WEB]



20. In addition, Fukushima Prefecture has carried out screenings of more than 100,000 residents with whole-body counters. Hayano et al. [Hayano et al., 2013] reported that, in this monitoring campaign, different assumptions were made to assess doses: *(a)* for measurements made before February 2012, an acute intake by inhalation in March 2011 was assumed; and *(b)* for measurements made from February 2012 onwards a constant daily intake of radiocaesium was assumed. Hayano et al. [Hayano et al., 2013] reported that only 52 individuals in the study were assessed as receiving doses of more than 1 mSv. A detailed breakdown of the results has not been made available to the Committee.

1. Summary of results of whole-body measurements studies

21. Most of the whole-body monitoring campaigns began in June and July 2011, three to four months after the accident. One earlier study, published since the UNSCEAR 2013 Report, is worthy of note [Matsuda et al., 2013], as the measurements enable a reasonable assessment of the dose due to intake in the short-term [UNSCEAR, 2015]. Matsuda et al. [Matsuda et al., 2013], reported on measurements made at Nagasaki University in March and April 2011 on 173 adult evacuees and first responders who were in Fukushima Prefecture at the time of the accident. The overall detection rates (per cent of subjects above MDL) of ^{134}Cs and ^{137}Cs were, respectively, 39% and 32%, although subjects measured in the first week after the accident had detection rates of about 50%. The mean measured amounts of ^{134}Cs and ^{137}Cs in the body were 450 and 540 Bq, respectively, and ranged from 160 to 16,000 Bq of each radionuclide, for subjects measured in the first week, to 130–1,900 Bq for ^{134}Cs and 130–1,100 Bq for ^{137}Cs, for those measured later.

Committed effective doses[1] from internal exposure due to the radionuclides in the body were estimated assuming an acute intake via inhalation of particulate aerosol (activity median aerodynamic diameter (AMAD) = 1 µm) with absorption Type F on either the first day or the last day of the stay of the subject in Fukushima Prefecture, to give a range spanning the true dose. Committed effective doses from radiocaesium intakes were estimated to be between about 2 and 300 µSv for those measured in the first week and between about 2 and 20 µSv for those measured later.

22. Kim et al. [Kim et al., 2016] reported on measurements made on 174 residents of Fukushima Prefecture between 27 June and 28 July 2011: 12 from Futaba Town, 6 from Okuma Town, 5 from Tomioka Town, 6 from Naraha Town, 5 from Hirono Town, 90 from Namie Town, 8 from Kawauchi Village, 5 from Katsurao Village, 5 from Tamura Town, 20 from Iitate Village and 12 from Kawamata Town. Although this study was published some years after the UNSCEAR 2013 Report, the measurements were carried out as a pilot study for the larger measurement campaign reported by Momose et al. [Momose et al., 2012], which was available before publication of the UNSCEAR 2013 Report [UNSCEAR, 2014]. The focus of the campaign was initially on the residents (before the accident) of Iitate Village, Namie Town and of Yamakiya municipality in Kawamata Town, who were chosen by the Fukushima prefectural government. The other subjects were chosen by each municipality and were added to the study at the request of the municipalities. The percentage of measurements with a positive detection (above MDL of 320 Bq for ^{134}Cs and 570 Bq for ^{137}Cs, before correction for body size) was: 26% (43 adults and 2 children) for ^{137}Cs; 47% (66 adults and 15 children) for ^{134}Cs; and 22% (36 adults and 2 children) for both radionuclides. Detection rates were highest in the residents from Futaba Town and from Iitate Village and were about 50% in the residents from Namie Town (where the majority of those measured were from).

23. The whole-body contents of ^{134}Cs ranged from MDL up to 2,600 Bq for adults and from MDL up to 1,400 Bq in children. Doses were estimated assuming an acute intake of radiocaesium by inhalation on 12 March 2011, as this scenario was considered reasonable for conservative internal dose estimations. The measurements of ^{134}Cs were used because the detection rate of ^{137}Cs was much lower. The maximum committed dose was 0.63 mSv (630 µSv) in an elderly male subject; the highest dose in children was 0.20 mSv (200 µSv). Median doses were only estimated for adult residents of Namie Town (26 µSv), Iitate Village (27 µSv) and Futaba Town (68 µSv), where there were sufficient measurements above MDL. The 95th percentiles of doses ranged from 85 to 370 µSv for adults and from 110 to 130 µSv for children. The authors considered the influence of different scenarios on the total intakes corresponding to a given measured body content of ^{137}Cs on the 120th day of exposure. Compared with an acute intake on the first day, assuming a chronic intake over 100 days reduced the total intake by around 30% in adults and by about a factor of four for children.

24. The study by Hayano et al. [Hayano et al., 2014] was reviewed by the Committee in its 2015 White Paper [UNSCEAR, 2015] and was considered to provide one of the most reliable retrospective assessments of dose from internal exposure due to intakes of radiocaesium. The authors reported on whole-body counting measurements made at Minamisoma Municipal General Hospital between 11 and 29 July 2011. The measurements were made using an Anzai chair-type whole-body counter, where interpretation of the measurements was complicated because of shielding of the environmental background by the human body. The authors developed a method to correct for this shielding which they tested and validated, but the resulting estimates of body burdens and doses were associated with considerable uncertainty. Measurements were made on 566 adults (≥16 years) from Minamisoma City, about 85% of

[1] Committed effective dose from intake up to the time of measurement.

whom were evacuated during March 2011 but had subsequently returned. Of the subjects, 256 were males and 310 were females; 240 subjects lived in Kashima Ward (outside the 30-km zone) before the accident, 322 in Haramachi Area (inside the 30-km zone) and 4 in Iitate Village. The average body burden of these subjects was estimated at 825 Bq of ^{134}Cs, with statistical uncertainty of ±360 Bq, derived by measuring 287 subjects twice on the same day, and systematic uncertainty of ±110 Bq, derived by comparing measurements made with the chair-type counter and by a better shielded whole-body counter a short time later. The initial body burden of ^{134}Cs was estimated assuming acute inhalation of radiocaesium in March 2011 and no further radiocaesium intake before the day of measurement. Using a ratio of 1:1 for ^{134}Cs:^{137}Cs in the early phase of the accident, committed effective doses from radiocaesium intakes were estimated. The distribution of committed effective doses for males and females was reproduced in the Committee's 2015 White Paper [UNSCEAR, 2015]. The average committed effective doses for males and for females were both around 80 µSv.

25. Momose et al. [Momose et al., 2012] examined 9,927 evacuees from Futaba Town, Hirono Town, Iitate Village, Katsurao Village, Kawamata Town, Kawauchi Village, Minamisoma City, Namie Town, Naraha Town, Okuma Town and Tomioka Town. Measurements were made on evacuees from Iitate Village, Kawamata Town and Namie Town (all in the deliberate evacuation area, where evacuation took place between April and June 2011) from 11 July 2011 to the end of August 2011. For evacuees from the other municipalities (some of whom were evacuated in March 2011), measurements started on 1 September 2011. The subjects were selected by the relevant municipality, and priority was given to pregnant women, followed, in order, by mothers of children less than 4 years old, children aged 4–12 years of age, children aged 13–17 years of age and adults.

26. Approximately 20% of those monitored had levels of radiocaesium in the body above MDL, which varied with the equipment used from 160 to 340 Bq of ^{134}Cs and from 210 to 370 Bq of ^{137}Cs. Whole-body contents ranged from MDL up to 2,700 Bq, of ^{134}Cs and ^{137}Cs in total, for children up to 8 years of age, and up to 14,000 Bq for adults. Doses were conservatively estimated based on the assumption of a single intake via inhalation on 12 March 2011. Dose distributions suggested that committed effective doses corresponding to whole-body content close to MDL were overestimated. The results showed that 99.8% of those monitored had committed effective doses less than 1 mSv. Twenty-two individuals received doses that exceeded 1 mSv, all but one being children, and the maximum dose was 3 mSv. By fitting a log-normal distribution to the measurements (and resulting estimated doses) and extrapolating below MDL, median doses of 25 µSv for adults and 20 µSv for 13 to 17-year-old children were estimated. Doses estimated for different municipalities varied within a range of about a factor of four, with the highest doses generally in Iitate Village and lowest in Naraha Town.

27. The authors acknowledged that the higher doses estimated for children than adults were not consistent with the assumption of a single acute intake via inhalation. There was also no correlation between the effective doses of children with a significant body content greater than MDL and the effective doses of their parents.

28. Changing into contamination-free gowns before measurement decreased the number of measurements above MDL significantly, and the authors concluded that a small amount of contamination on clothes may have affected the measurement results up to the end of December 2011. The authors also concluded that the dose estimates were associated with a large uncertainty because of the lack of information on how and when radionuclides were taken into the bodies of those measured.

29. Tsubokura et al. [Tsubokura et al., 2012] reported on voluntary screening carried out on residents of Minamisoma City, aged 6 years and older, between 26 September 2011 and 31 March 2012. The authors noted that many residents had been evacuated but approximately half had returned by August 2011. A total of 9,498 residents enrolled in the study (24% of the registered population on 15 August 2011). A total of 3,286 individuals (35% of those measured) had detectable levels of radiocaesium, 235 children and 3,051 adults. In adults, the detected radiocaesium levels ranged from 210 to 12,771 Bq with a median of 744 Bq; in children, the levels ranged from 210 to 2,953 Bq with a median of 590 Bq. The measured levels were reported to have been converted to committed effective dose based on the assumption of acute inhalation immediately after the accident in adults, and of chronic ingestion after the accident in children. However, the authors only reported that committed effective doses were less than 1 mSv in all but one resident. The authors commented that it was uncertain whether the measured body contents were due to continuing chronic intakes or from acute intakes still present in the body, since there was no information available about individual intake scenarios.

30. Hayano et al. [Hayano et al., 2013] reported on measurements made on residents of Fukushima Prefecture and surrounding prefectures at Hirata Central Hospital. A total of 32,811 subjects were measured, 73% from Fukushima Prefecture, 23% from Ibaraki Prefecture and smaller numbers from Tochigi and Miyagi prefectures. Measurements were made between 17 October 2011 and 30 November 2012. Of those measured, 1,340 out of 11,026 adults (12%) and 487 out of 6,310 children (8%) measured between October 2011 and the end of February 2012 exceeded the detection limit of 300 Bq for both ^{134}Cs and ^{137}Cs. These detection rates fell significantly in the period March to November 2012, to less than 1% (212 out of 21,785) for adults and less than 0.1% (12 out of 13,220) for children, following the introduction of a policy of having every subject change into a hospital gown before measurement. The authors noted that surface (clothes) contamination may have affected the measurements made in the first five months. The authors, therefore, restricted their analysis to measurements made after March 2012 and made no estimates of the distribution of committed effective doses in the population studied. For children, based on MDL and assuming a constant daily intake, the authors indicated that committed effective doses would have been less than 21 µSv (for children around the age of 10 years) and less than 13 µSv (for children around the age of 15 years). The authors also acknowledged that the results were not conclusive for Fukushima Prefecture as a whole but were consistent with results obtained from other municipalities and with prefectural data. The highest radiocaesium concentrations (maximum concentrations of 184 Bq/kg of ^{137}Cs and 108 Bq/kg of ^{134}Cs, corresponding to a committed dose of about 1 mSv) were found in a small number of senior residents that were linked with their regular consumption of foods, such as wild mushrooms, wild boar, fresh-water fish, for which contamination advisories had been issued. The individuals' body burdens decreased at rates consistent with the biological half-life of radiocaesium after the subjects were advised to avoid such foodstuffs.

2. Inferring intakes and doses from whole-body measurements

31. These whole-body monitoring campaigns provide direct measurements made on people of the contents of radiocaesium in their bodies, from which intakes of radiocaesium and committed effective doses can be estimated, subject to knowledge or assumptions of when and how the intakes occurred. The total intake, I_a in Bq, can be deduced from a whole-body measurement, $M_a(t)$ in Bq of particular radionuclide, a, at a particular time, t, by taking into account the whole-body retention function of the radionuclide, $R_a(t)$ in relative units, that

corresponds to the fraction of the intake that is retained in the body at a given time after an intake at time t = 0 (see equation A-3.1):

$$I_a = \frac{M_a(t)}{R_a(t)}, \text{ Bq} \qquad \text{(A-3.1)}$$

32. The retention function $R_a(t)$ depends on the intake pathway, the chemical form of the radionuclide, and the age and sex of the subject [ICRP, 1993; ICRP, 1995]. Estimating an intake, and the resulting committed effective dose, from a whole-body measurement thus requires information about the age and sex of the person measured and modelling to describe the temporal pattern of intake.

33. In all of the studies reviewed, there was a general lack of information about when and how the intakes of radiocaesium occurred and estimates of intakes and doses have been made using assumptions about the timing and mode of intake. In the study of Matsuda et al. [Matsuda et al., 2013], although the period during which the intakes of radionuclides could have occurred was short (the average length of stay in Fukushima Prefecture was 4.8 days), there was no information available as to where the subjects were before they were evacuated, and the ranges of estimated intakes and doses varied widely (by up to two orders of magnitude or more) according to whether it was assumed that the intake occurred on the first or the last day of the individual’s stay in Fukushima Prefecture. No dose distributions were presented, only the ranges of doses for different groups.

34. Kim et al. [Kim et al., 2016] and Momose et al. [Momose et al., 2012] made estimates of the median and various percentiles of the distributions of committed effective doses from the whole-body measurements assuming an acute intake of radiocaesium by inhalation on 12 March 2011. In both cases, this acknowledged assumption was made because it would result in conservative estimates of the doses. Hayano et al. [Hayano et al., 2014] presented the distribution of committed effective doses subject to the same assumption of an acute intake of radiocaesium by inhalation. In the absence of estimates of the dose distributions by the authors of two of the studies [Hayano et al., 2013; Tsubokura et al., 2012], the Committee has made its own assessments assuming that the intakes were short-term from either inhalation or ingestion of radiocaesium. The Committee has further assumed that measurements that were below MDL in each study could be assigned a whole-body content equal to half of MDL.

35. The results for the five studies from which meaningful distributions of doses (including estimates of means and/or medians and percentiles of the distribution) can be derived are summarized in table A-3.2. The Committee considers these to be the best estimates of committed effective doses from radiocaesium intakes that can be made from the whole-body measurement information that was available to it. For most of the studies, the number of measurements above MDL in children was much lower than in adults, and dose estimates could generally only be made for adults.

Table A-3.2. Characteristics of distributions of committed effective doses from intakes of radiocaesium estimated from whole-body monitoring studies

Study	*Number of people measured*	*Number above MDL*	*Time of measurements*	*Estimated committed effective dose from intakes up to the time of measurement (μSv)*		
				Mean	*Median*	*95th percentile*
[Kim et al., 2016][a] (Evacuees from various municipalities)	174	81 (^{134}Cs)	June–July 2011		26 (adults from Namie Town) 27 (adults from Iitate Village) 68 (adults from Futaba Town)	Adults 180 (Namie Town) 140 (Iitate Village) 370 (Futaba Town) 85 (remaining municipalities) Children 130 (Namie Town) 110 (remaining municipalities)
[Hayano et al., 2014][b] (Minamisoma City – mainly evacuees)	566		July 2011	80		170
[Momose et al., 2012][c] (Evacuees from various municipalities)	9 927	1 900	July 2011–January 2012		25 (adults: >17 years) 20 (children: 13–17 years)	150 (adults) 100 (children)
[Tsubokura et al., 2012][d] (Minamisoma City – including evacuees)	9 498	3 286	September 2011–March 2012	50		180 (adults)
[Hayano et al., 2013][e] Measured at Hirata Central Hospital	32 811	1 552	October 2011–November 2012	50		150 (adults and children)

[a] Median and 95th percentile committed effective doses estimated by the authors for subjects from the named municipalities assuming intake was by inhalation on 12 March 2011; there were too few subjects and too few children with detectable amounts of radiocaesium to make estimates of median values for other municipalities.
[b] Mean value and standard deviation estimated by the authors assuming intake was by acute inhalation in March 2011; 95th percentile derived by the Committee distribution of doses.
[c] Median and 95th percentile committed effective doses estimated by the authors assuming intake was by inhalation on 12 March 2011; median committed effective doses for adults and children were estimated by extrapolation below MDL assuming a log-normal distribution.
[d] Mean and 95th percentile committed effective doses estimated by the Committee from the distributions of measured radiocaesium concentrations in the body by setting all measurements below MDL to half of MDL (125 Bq for ^{137}Cs and 105 Bq for ^{134}Cs) and assuming a short-term intake of radiocaesium.
[e] Mean and 95th percentile committed effective doses estimated by the Committee from the distributions of measured radiocaesium concentrations in the body by setting all measurements below MDL to half of MDL (150 Bq for both ^{137}Cs and ^{134}Cs) and assuming a short-term intake of radiocaesium. The Committee used all of the measurement data from October 2011 for its estimates; the authors restricted their analysis to measurement data taken after March 2012 because of possible surface contamination on clothing before that date; the doses may, therefore, be overestimates. Of those measured, 73% were from Fukushima Prefecture, 23% from Ibaraki Prefecture and smaller numbers from Tochigi and Miyagi prefectures.

36. Subject to the uncertainties associated with the assumptions made in estimating the doses, the dose estimates summarized in table A-3.2 are representative of the people who were monitored. It is less clear how representative those monitored were, either of the populations from which they were selected, or of wider population groups affected by the FDNPS accident. In the study of Kim et al. [Kim et al., 2016], the subjects were chosen either by the prefectural government or by the relevant municipality, but the basis of the selection of the subjects is not stated; more than half of the subjects were from Namie Town, with 11% from Iitate Village and 7% from Kawamata Town. Hayano et al. [Hayano et al., 2014] provided information on the subjects measured in their study: about 85% were evacuated at different times in March 2011; and 42% were from Kashima Area of Minamisoma City and 57% from Haramachi Area. The results of this study could therefore be considered representative of evacuees from these locations, but their wider applicability to other evacuees is less clear. No detailed information was provided about the selection of subjects in the study of Momose et al. [Momose et al., 2012], only the municipalities covered and the priority order in which the measurements were conducted. The only information provided in the study of Hayano et al. [Hayano et al., 2013] was that 73% of subjects were residents of Fukushima Prefecture, 23% of Ibaraki Prefecture, and small numbers were from Tochigi and Miyagi prefectures. The study of Tsubokura et al. [Tsubokura et al., 2012], on the other hand, could be considered representative of the population of Minamisoma City as this campaign was reported to have comprised voluntary screening of all residents aged six years and over, and covered 24% of the registered population.

37. Irrespective of how representative those measured were of the population studied in each case, there is also the question of the extent to which the doses estimated from the whole-body measurements made in each of these studies can be used to infer or estimate the doses from intakes of radiocaesium in other groups of the population. In the studies of Kim et al. and Momose et al. those measured were all described as evacuees, although the measurements by Kim et al. and Momose et al. were initially focused on those from the deliberate evacuation area who were not evacuated until April to June 2011 [Kim et al., 2016; Momose et al., 2012], with evacuees from the 20-km precautionary evacuation zone monitored either in smaller numbers or later. Those measured by Tsubokura et al. and Hayano et al. were all residents of Minamisoma City, many of whom were reported to have been evacuated, but approximately half of whom were reported to have returned [Hayano et al., 2014; Tsubokura et al., 2012]. Furthermore, those measured by Hayano et al. [Hayano et al., 2013] were described only as residents of Fukushima and surrounding prefectures. The application of the results of these whole-body monitoring studies to the estimation of doses to groups of the population other than those measured is, therefore, not straightforward and will bring added uncertainty. Most of the estimated doses were also for adults, with only sparse information from which to estimate doses to children. In general, therefore, doses to children need to be estimated from the adult doses.

B. Estimates of intakes by ingestion and doses from measurements of radiocaesium in food and drinking water

38. The second approach to the estimation of intakes of radiocaesium and doses from internal exposure is based on measurements of the radiocaesium content of food and drinking water as consumed. This approach is less direct than measurements of the radiocaesium in the body, but enables intakes from one of the pathways (ingestion) to be estimated from measurements with the minimum of further assumptions. Intakes from ingestion can be derived from measurements of the radiocaesium content in the whole daily diet (or ration) sampled by the market-basket or duplicate-diet surveys. Alternatively, and less directly again, intakes from ingestion can be derived from measurements of radiocaesium concentrations in food and drinking water, with

additional assumptions about how much of each type of food is consumed and how each food type is sourced and distributed to consumers.

1. Intakes from ingestion based on market-basket and/or duplicate-diet studies

39. The dose from intake of radiocaesium by ingestion can be derived from measurements of the radiocaesium content in the whole daily diet (or ration) sampled by the market-basket or duplicate-diet methods. In the available literature, six publications were found with data of this type collected in the period 2011–2013 in Fukushima Prefecture, four neighbouring prefectures (Ibaraki, Iwate, Miyagi and Tochigi) and eight distant prefectures (Hokkaido, Kanagawa, Kochi, Nagasaki, Niigata, Osaka, Saitama and Tokyo) of Japan.

40. Koizumi et al. [Koizumi et al., 2012] collected 10–25 pre-packed daily food sets purchased in grocery stores in each of the Fukushima, Iwaki, Nihonmatsu and Soma cities at the beginning of July 2011. The average daily intake of both ^{134}Cs and ^{137}Cs varied from 0.4 Bq/d in Fukushima City to 3 Bq/d in Soma City, and, for the 55 samples from Fukushima Prefecture, the average was estimated as 1.1 ± 1.5 Bq/d. Tsutsumi et al. [Tsutsumi et al., 2013] purchased total diet samples in 14 food categories in September 2011 at local food markets in Fukushima Prefecture, Miyagi Prefecture and Tokyo. Following regular culinary processing, food samples were measured with a gamma spectrometer. The daily intake rate for adults was assessed to be equal to 0.4, 3 and 3.3 Bq/d in Tokyo, Miyagi Prefecture and Fukushima Prefecture, respectively. Co-op Fukushima (a regional retail consumer cooperative) conducted a broad survey of ^{134}Cs and ^{137}Cs content in daily meals in Fukushima Prefecture [Sato et al., 2013] from November 2011 to March 2012 and from June 2012 to September 2012, each covering 100 families throughout the prefecture. Mean concentration of ^{134}Cs in food was 0.27 ± 0.45 Bq/kg (range 0.05–5.0 Bq/kg) and that of ^{137}Cs was 0.37 ± 0.61 Bq/kg (range 0.07–6.7 Bq/kg).

41. Harada et al. [Harada et al., 2013] collected 53 sets of 24-hour food-duplicate samples on 4 December 2011 from families in Fukushima Prefecture and neighbouring areas and analysed them for their content of ^{134}Cs and ^{137}Cs. In Fukushima Prefecture, the mean dietary intake rate of ^{134}Cs and ^{137}Cs was 4.5 ± 2.6 Bq/d (range <0.26−17 Bq/d). The estimated intake was significantly lower in the Tokyo region and especially in western Japan. In a comprehensive paper, Harada et al. [Harada et al., 2014] evaluated the main routes of exposure to Fukushima Prefecture residents. In August 2012, duplicate-diet samples were collected from 125 residents of three municipalities. The average intake of ^{134}Cs and ^{137}Cs with diet was from 1.1 Bq/d in Kawauchi Village to 3.5 Bq/d in the Tamano Area of Soma City. In the same municipalities, aerosol samples were taken and the annual inhalation of ^{134}Cs and ^{137}Cs (from resuspension of deposited material) was estimated to be 1–2 orders of magnitude lower than the annual intake from foods.

42. Uekusa et al. [Uekusa et al., 2014] conducted a comprehensive study of radionuclide food intake with both market-basket and duplicate-diet sampling in Fukushima Prefecture (three municipalities), four neighbouring prefectures (Ibaraki, Iwate, Miyagi and Tochigi) and eight distant prefectures (Hokkaido, Kanagawa, Kochi, Nagasaki, Niigata, Osaka, Saitama and Tokyo). The total number of samples was 939. The intake rate of radiocaesium (^{134}Cs and ^{137}Cs) was estimated with the market-basket method to be 0.17–1.7 Bq/d, 0.15–0.68 Bq/d and 0.15–1.3 Bq/d in March 2012, September 2012 and March 2013, respectively. The intake was higher in Fukushima Prefecture and its neighbouring prefectures than in distant areas in all the considered periods. The intake rate was observed to decrease over time in most areas.

43. These market-basket and duplicate-diet studies provide direct information about intakes of radiocaesium in food. The results are summarized in table A-3.3. The estimated intakes of radiocaesium from ingestion are generally low (a few Bq/d). Estimated intakes in Fukushima Prefecture were generally higher than those in neighbouring prefectures, which were in turn generally higher than those in more distant prefectures. The range of estimated intakes of radiocaesium from ingestion for locations within Fukushima Prefecture was generally less than an order of magnitude. Estimated annual committed effective doses from these intakes of radiocaesium, assuming the daily intakes remained the same over a year, ranged from about 1 µSv to some tens of microsievert. However, these studies provide an estimate based on measured intakes at particular points in time, so estimates of annual doses from the intakes must be considered uncertain. In addition, the studies did not start until July 2011 and can provide no information about intakes at earlier times, without the use of further assumptions and models.

Table A-3.3. Summary of results of market-basket and duplicate-diet studies

Study	*Number of samples*	*Time of measurements*	*Estimated intake rate of ^{137}Cs and ^{134}Cs (Bq/d)*	*Estimated annual committed effective dose (µSv)[a]*
[Koizumi et al., 2012]	10–25 food sets from each of the Fukushima, Iwaki, Nihonmatsu and Soma cities	July 2011	1.1 ± 1.5 (mean) 0.4 (Fukushima City) – 3 (Soma City)	6.4 ± 13 (mean) 2.6 (Fukushima City) – 17 (Soma City)
[Tsutsumi et al., 2013]	14 sample groups in Fukushima Prefecture, Miyagi Prefecture and Tokyo	September 2011	0.4 (Tokyo) – 3.3 (Fukushima Prefecture)	2 (Tokyo) – 19 (Fukushima Prefecture)
[Sato et al., 2013]	200 samples in total over two seasons prepared by families from across Fukushima Prefecture	November 2011–March 2012 (winter 2011–2012), June 2012–September 2012 (summer 2012)	3.0–24 (winter 2011–2012; 10 samples >1 Bq/kg) 6.5–7.0 (summer 2012; 2 samples >1 Bq/kg)	17–130 (winter 2011–2012; 10 samples >1 Bq/kg; assuming intake over whole year) 37–40 (summer 2012; 2 samples >1 Bq/kg; assuming intake over whole year)
[Harada et al., 2013]	53 samples from families in Fukushima Prefecture, Tokyo region and western Japan	4 December 2011	4.5 ± 2.6 (mean)	27 ± 16
[Harada et al., 2014]	125 samples from families in Kawauchi Village, Tamano Area of Soma City and Haramachi Area of Minamisoma City	August 2012	1.0 ± 0.99 (Kawauchi Village) 3.5 ± 3.9 (Tamano Area) 1.6 ± 1.4 (Haramachi Area)	5.8 ± 7.4 (Kawauchi Village) 19 ± 30 (Tamano Area) 8.8 ± 10.7 (Haramachi Area)
[Uekusa et al., 2014]	939 samples over three periods from Fukushima Prefecture, four neighbouring prefectures and eight more distant prefectures	March 2012, September 2012, March 2013	<MDL–1.7 (March 2012) 0.15–0.68 (September 2012) 0.15–1.3 (March 2013)	0–9.4 (March 2012) 0.88–3.8 (September 2012) 0.85–7.1 (March 2013)

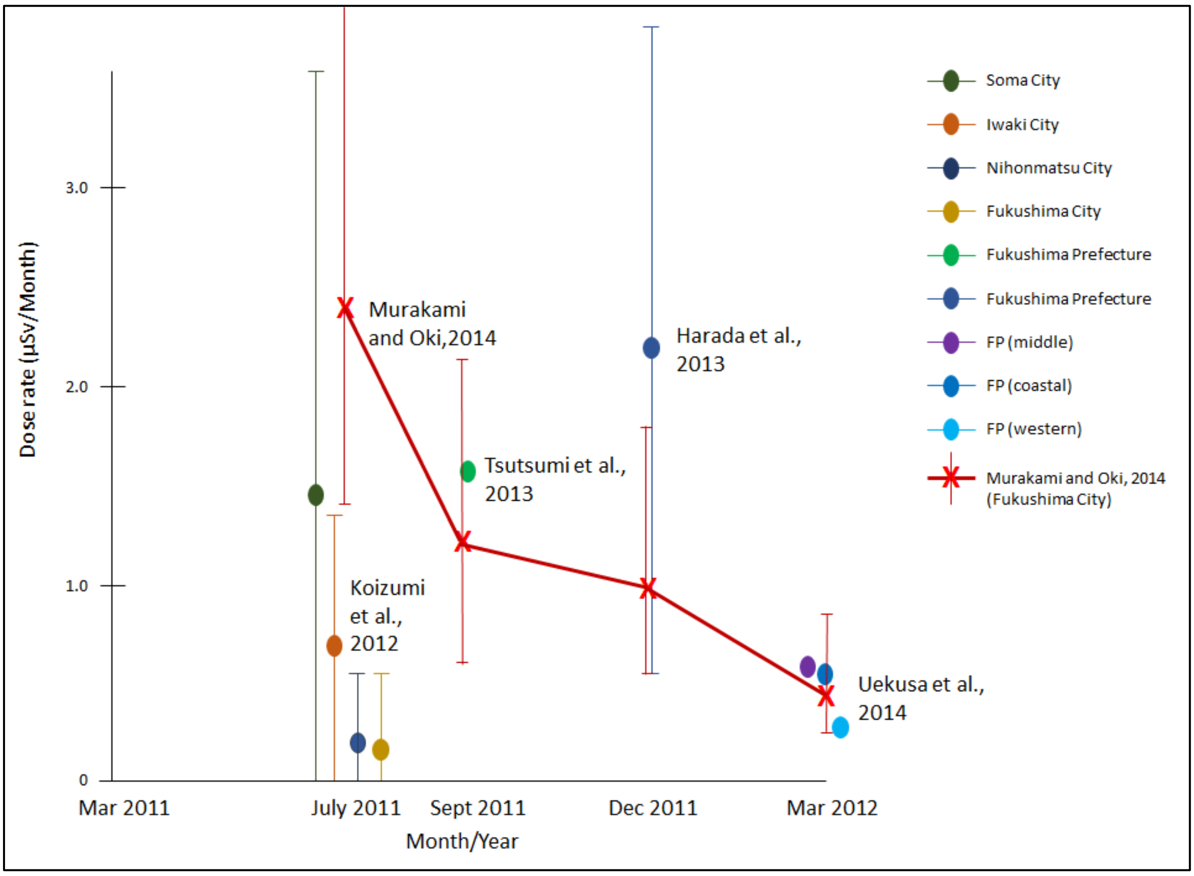
[a] Estimated by those who conducted the studies, assuming the same daily intake from food for the whole year.

2. Intakes from ingestion based on food monitoring data

44. Making realistic estimates of radionuclide intake from measured levels of radionuclides in food and drinking water (and the resulting doses) requires the collection of data in a systematic and random manner and use of a model or models to account properly for the daily food ration, the food delivery and distribution system, culinary losses, etc. Following the natural catastrophe of an earthquake and tsunami and the subsequent accident at FDNPS, the acquisition of such data will have been challenging and, potentially, associated with much uncertainty. The database of concentrations of radionuclides in foodstuffs used in the UNSCEAR 2013 Report to estimate doses in the first year from ingestion provides an example of the potential pitfalls. While this database was extensive and the only one available at the time of the UNSCEAR 2013 Report, it was not suitable for making realistic estimates of doses from intakes by ingestion. In particular, the focus was on identifying food with radionuclide concentrations above the standard limits at which food restrictions were applied. In addition, the Committee assumed that food with a measured concentration less than MDL had a concentration equal to MDL. Taken together, these two factors resulted in the doses from ingestion estimated in the UNSCEAR 2013 Report for the first year after the accident being about an order of magnitude too high; this was confirmed by the results of whole-body monitoring campaigns reported just prior to the publication of the UNSCEAR 2013 Report [UNSCEAR, 2014]. Doses estimated on the basis of measured levels in food and drinking water require validation either by means of estimates from market-basket or duplicate-diet studies or from whole-body monitoring of people.

45. Murakami and Oki [Murakami and Oki, 2014] estimated doses from ingestion in the first year after the accident based on measured concentrations of radionuclides in food and drinking water. But they used data from a wider range of sources than was available to the Committee when preparing the UNSCEAR 2013 Report, and also took account of the regional trade in foods (specifically, of the relative contribution of foods from different parts of Japan arriving at food markets, where most Japanese people purchase food). The authors carefully studied and took into account the stochastic nature of food contamination, countermeasures, culinary losses, etc. They have provided estimates, with uncertainties, by age and sex, of equivalent dose to the thyroid and effective dose from ^{131}I intakes and of effective dose from ^{134}Cs and ^{137}Cs intakes for residents of Fukushima City, Osaka and Tokyo. They estimated average doses in these three locations, as well as doses to agricultural workers (about 4% of the population) in Fukushima City, who may have preferentially consumed locally produced vegetables, and evaluated the effect of countermeasures (e.g., restricting the distribution of food, voluntarily withholding rice, and providing bottled water instead of tap water for infants). They compared their estimates of the effective dose from ingestion of ^{134}Cs and ^{137}Cs in food and drinking water with the estimates of Koizumi et al. [Koizumi et al., 2012] and Harada et al. [Harada et al., 2013], that were based on market-basket and food-duplicate surveys in five periods from July 2011 to March 2012. A similar comparison including some of the other studies in table A-3.3 is presented in figure A-3.II.

Figure A-3.II. Comparison of estimates of effective dose to adults from intakes of radiocaesium by ingestion within Fukushima Prefecture[a]



[a] The ranges of uncertainty shown correspond to plus or minus one standard deviation.

46. Given the large uncertainties in the estimated dose rates, there is broad agreement (within one or two standard deviations) between the estimates based on the market-basket and duplicate-diet studies and those based on the modelling approach of Murakami and Oki [Murakami and Oki, 2014]. The Committee has assumed that Murakami and Oki's estimate for Fukushima City is applicable to the whole of Fukushima Prefecture while recognizing that there will be some variation with location. The results of the market-basket and duplicate-diet studies in Fukushima Prefecture and other prefectures indicate that the spatial variation in ingestion doses is not large and the Committee has judged that the variation between municipalities within Fukushima Prefecture is unlikely to be more than a factor of a few.

47. Murakami and Oki estimated the average committed effective dose from ingestion of radiocaesium for residents of Fukushima City to be 19 µSv in the first year after the accident (with a median of 8.2 µSv and 95th percentile of 43 µSv) [Murakami and Oki, 2014].

C. Intakes from inhalation based on measurements of radiocaesium concentrations in air

48. The third approach makes use of measurements of concentrations of radiocaesium in the air at various locations in Fukushima Prefecture and elsewhere, derived from re-analysis of filter tapes for measuring suspended particulate matter at air pollution monitoring stations [Ebihara et al., 2019; Oura et al., 2015; Tsuruta et al., 2014; Tsuruta et al., 2018]. Attachment A-9 provides further details of these measurements. Twenty-two such monitoring stations are located in, or close to, Fukushima Prefecture (see figure A-9.II of the annex and figure A-9.XI of attachment A-9). The time-integrated concentrations of ^{137}Cs in air as measured at these monitoring stations, as well

as the average for 11 monitoring stations in Tokyo Metropolitan Area, are given in table A-3.4; in addition, estimated intakes of ^{137}Cs by inhalation (during the period when the plumes containing the measured concentrations of ^{137}Cs passed by each monitoring station) are given together with the estimated committed effective doses for an adult from the intake by inhalation of both ^{134}Cs and ^{137}Cs. The uncertainties associated with these measured air concentrations are relatively small (standard deviation typically less than 10%) and they provide, therefore, a more reliable basis for estimating the contribution of inhalation to the total intake of radiocaesium than those based on air concentrations derived from ATDM (see section III.E and table A-3.7).

Table A-3.4. Measured time-integrated concentrations of ^{137}Cs in air and estimates of its intake by inhalation and resulting committed effective doses

Site of monitoring station	*Measured time-integrated concentration of ^{137}Cs in air outdoors (Bq s/m^3)*	*Intake of ^{137}Cs by inhalation for adults (Bq)*[a]	*Committed effective dose to adults from intake of ^{134}Cs and ^{137}Cs (μSv)*[b]
Fukushima Prefecture			
Aizuwakamatsu	1×10^5	14	0.16
Asahi	2×10^6	280	3.2
Daishin	2×10^6	280	3.2
Furukawa	1.5×10^6	220	2.4
Futaba [c]	2×10^8	28 000	320
Haramachi [c]	1.8×10^7	2 600	29
Kitakata	1×10^5	14	0.16
Minami-aizu	4×10^5	57	0.63
Minamimachi	2.0×10^6	280	3.1
Moriai	1.9×10^6	260	2.9
Naraha [c]	7×10^7	9 900	110
Nihonmatsu	3×10^6	420	4.7
Shibata	3×10^5	42	0.47
Shinchi	3×10^6	420	4.7
Shirakawa	2×10^6	280	3.2
Shiroishi	1×10^6	140	1.6
Soma	1×10^7	1 400	16
Sugitsumacho	1.8×10^6	250	2.8
Sukagawa	3×10^6	420	4.7
Tanakura	1×10^6	140	1.6
Yabuki	2×10^6	280	3.2
Yonezawa-kanaike	5×10^5	71	0.79
Tokyo Metropolitan Area			
Average of 11 monitoring stations	7.4×10^5	110	1.2

[a] Intake assuming 90% occupancy indoors and the ratio of indoor to outdoor concentration of radiocaesium in air of 0.5. Intake of ^{134}Cs assumed to be the same as that of ^{137}Cs.
[b] Committed effective dose assuming 90% occupancy indoors and the ratio of indoor to outdoor concentration of radiocaesium in air of 0.5.
[c] Monitoring station located within the 20-km precautionary evacuation zone; people living in the vicinity of the station were evacuated on 12 March 2011 and would not have been exposed to the measured air concentrations.

49. The parameters used to derive the intakes and committed effective doses are given in table A-3.5 and it has been assumed that the concentration of ^{134}Cs in air was the same as that of ^{137}Cs.

Table A-3.5. Ingestion and inhalation effective dose coefficients and daily breathing rates [ICRP, 1993; ICRP, 1995]

	Radionuclide	*1-year-old*	*10-year-old*	*Adult*
Ingestion dose coefficient e_{50} (mSv/Bq)	^{134}Cs	1.6×10^{-5}	1.4×10^{-5}	1.9×10^{-5}
	^{137}Cs	1.2×10^{-5}	1.0×10^{-5}	1.3×10^{-5}
Inhalation dose coefficient e_{50} (mSv/Bq)[a]	^{134}Cs	7.3×10^{-6}	5.3×10^{-6}	6.6×10^{-6}
	^{137}Cs	5.4×10^{-6}	3.7×10^{-6}	4.6×10^{-6}
Daily breathing rate, V (m^3/d)		5.2	15.3	22.2

[a] For aerosols, Type F, AMAD = 1 µm.

50. It should be noted that the monitoring stations with the highest measured concentrations of ^{137}Cs in air (Futaba, Naraha, and Haramachi) are within the 20-km precautionary evacuation zone and that people living in these municipalities (Futaba Town, Naraha Town, and the Haramachi Area of Minamisoma City) were evacuated on 12 March 2011 and would not have been exposed to the measured air concentrations. Committed effective doses from intakes by inhalation have been estimated using the assumptions set out in detail in attachment A-10 (i.e., people assumed to spend 90% of their time indoors with the time integral of the radiocaesium concentration indoors being about one half of that outdoors). Subject to these assumptions and excluding the locations from which people were evacuated, intakes of ^{137}Cs from inhalation range from about 14 Bq in Aizuwakamatsu City in the west of Fukushima Prefecture to about 1,400 Bq in Soma City to the north of FDNPS. The corresponding committed effective doses from intakes of radiocaesium by inhalation range from about 0.16 to about 16 µSv.

51. While these measurements provide a fairly direct and reliable estimate of intakes by inhalation and resulting doses from internal exposure at the monitoring stations where the measurements were made, they provide no information about the intakes and doses at other locations in Fukushima Prefecture or elsewhere in Japan. In order to estimate doses from intakes by inhalation to the wider population, some interpolation between the measurements or a more general modelling approach would be needed.

D. Intakes from inhalation based on predicted radiocaesium concentrations in air

52. The fourth approach makes use of estimates of concentrations of radiocaesium in the air derived using an assumed source term and ATDM. This approach is the least direct but still has its origins in measurements (i.e., the totality of measurements in the environment, in particular, of dose rates and radionuclide concentrations in air and on the ground).

53. Doses from inhalation of radiocaesium (and other radionuclides) have been estimated based on an assumed source term for releases to the atmosphere and models to describe how released material is dispersed in, and deposited from, the atmosphere. Further details are set out in attachment A-10. Time-integrated concentrations of radiocaesium in the air, either over the complete period of the release for residents, or over the relevant shorter periods for those evacuated, can be used with the breathing rates and dose coefficients set out in table A-3.5 to estimate intakes of radiocaesium by inhalation and the corresponding committed effective doses.

54. The committed effective dose from inhalation of radiocaesium in each municipality of Fukushima Prefecture has been estimated using the methods described in attachment A-10. For adults who were not evacuated, the committed effective dose from inhalation of radiocaesium in

each municipality varied over several orders of magnitude from less than 0.001 µSv to more than 100 µSv depending on the temporal pattern of the releases from FDNPS and their dispersion in the atmosphere. The population-weighted average committed effective dose from inhalation of radiocaesium to those who were not evacuated in Fukushima Prefecture was about 4 µSv. The intakes that resulted in these doses would have occurred within the first few days of the accident during the passage of the plumes of released material. The committed effective dose from inhalation of radiocaesium to adults who were evacuated also varied, from about 0.2 µSv to more than 100 µSv, depending on the evacuation scenario (i.e., the start, duration, route and final destination of the evacuation). The population-weighted average over all of the scenarios was about 12 µSv.

55. A comparison has been made in attachment A-9 of the time-integrated concentrations of ^{137}Cs in air predicted using the source term and ATDM and the time-integrated concentrations measured at the monitoring stations (see figure A-9.XII and table A-9.4). At higher concentrations, the predictions are in good agreement with the measurements (within a factor of two to three); and at lower concentrations the agreement is less good, with the predictions being lower than the measurements by up to an order of magnitude or more.

E. Comparison of doses estimated from whole-body measurements with estimates made using a combination of the other approaches

56. A comparison is made in table A-3.6 between the committed effective doses to adults from radiocaesium intakes by inhalation and ingestion, as measured in the whole-body monitoring studies, with the committed effective doses estimated using a combination of the other approaches (specifically, intakes by inhalation based on measured air concentrations and/or estimated using a source term and ATDM and those by ingestion based on Murakami and Oki's analysis of measured concentrations of radiocaesium in food and drinking water). Uncertainties, in terms of the 5th and 95th percentiles about the estimated doses, are also presented in table A-3.6 and have been derived as follows: *(a)* uncertainties were estimated by the respective authors for doses estimated from whole-body counting measurements made by Momose et al. [Momose et al., 2012], Hayano et al. [Hayano et al., 2014] and Kim et al. [Kim et al., 2016], and by the Committee for measurements made by Tsubokura et al. [Tsubokura et al., 2012] and Hayano et al. [Hayano et al., 2013]; *(b)* uncertainties in doses from intakes by ingestion were those estimated by Murakami and Oki [Murakami and Oki, 2014] for Fukushima City and have been assumed to be equally applicable to other locations throughout Fukushima Prefecture, albeit recognizing that this will introduce additional uncertainty;[2] and *(c)* uncertainties in doses from intakes by inhalation, and in doses from inhalation and ingestion combined, were estimated by the Committee using the methods described in attachment A-12.

57. Making direct and meaningful comparisons of doses estimated using the different approaches is not straightforward for two main reasons:

(a) Firstly, the dose quantities estimated are often not the same: some estimates are averages while others are median values; and doses estimated from whole-body measurements generally represent committed doses from intakes up to the time of the measurement, whereas doses estimated on the basis of measured levels of radiocaesium in food or air represent committed doses from annual intakes;

[2] The results of the market-basket and duplicate-diet studies for Fukushima Prefecture and other prefectures indicate that the spatial variation in ingestion doses is not large and the Committee has judged that the variation between municipalities within Fukushima Prefecture is unlikely to be more than a factor of a few.

(b) Secondly, there is generally insufficient information available (in published material) about where those measured by whole-body monitoring were at the time of the accident and subsequently, how they were selected for measurement, to determine how representative their estimated doses are of the exposures of the wider population groups from which they were drawn (e.g., of a municipality, a prefecture, an evacuated area, etc.); this hinders meaningful comparisons with doses estimated using other approaches which are generally for well-defined populations. Caution therefore needs to be exercised in comparing the doses in table A-3.6, in particular careful note should be taken of the relevant footnotes that include qualifications to the entries in the table, in particular their comparability.

58. Some comments are also warranted about the representativeness of the results of whole-body monitoring included in the table:

– **Minamisoma City**: Hayano et al. [Hayano et al., 2014] and Tsubokura et al. [Tsubokura et al., 2012] both present results for Minamisoma City. Hayano et al. reported on measurements made on people who lived in the "most contaminated zone", about 85% of whom had been evacuated at various times during March but had since returned. These measurements cannot therefore be considered representative of residents of Minamisoma City as a whole. Tsubokura et al. reported on measurements made on 24% of the population of Minamisoma City many of whom had been evacuated but approximately half had returned by the time the measurement campaign began. They also stated that the results may not be representative of the entire population of Minamisoma City because those measured were volunteers. Disaggregation of the measurements made by both Hayano et al. and Tsubokura et al. (i.e., distinguishing between those who were, and those who were not, evacuated) would, in principle, enable more reliable estimates to be made of doses to evacuees and non-evacuees in Minamisoma City; in addition, it would better inform judgments on how the measurements could be used to infer doses in other population groups;

– **Evacuated municipalities**: Both Kim et al. [Kim et al., 2016] and Momose et al. [Momose et al., 2012] reported on measurements made on people from several of the municipalities that were evacuated, either in March or later. Momose et al. [Momose et al., 2012] presented distributions of dose for six of the municipalities and for all of the 11 municipalities taken together. Subject to any potential bias in the selection of people measured (with priority given to younger adult females), the estimated doses can be considered broadly representative of the evacuated municipalities. The number of people measured from each of the municipalities included in the study of Kim et al. was not proportional to the population of each municipality (ranging from 1/200 to 1/3,000), and in most of the municipalities was too small (generally less than 10 people) to provide dose estimates that were either statistically meaningful or that could be considered representative of a municipality. Even for Namie Town, where the largest number of people measured (90) were from, there is no information about whether those measured were evacuated before or after the passage of the plumes of released radioactive material; in these circumstances, the estimated doses cannot be considered representative of all of those evacuated;

– **Hirata Central Hospital**: Hayano et al. [Hayano et al., 2013] reported on measurements made on residents of a number of prefectures (73% from Fukushima Prefecture, 23% from Ibaraki Prefecture and the remainder from Miyagi and Tochigi Prefectures). No further information was provided about where, within these prefectures, those measured were at the time of the accident or subsequently. The authors acknowledge that their results are not conclusive for the prefecture as a whole and, therefore, the distributions of doses derived from these measurements cannot be considered representative of Fukushima Prefecture as a whole or of any other subset of the population measured. Disaggregation of the measured intakes and related doses by municipality would be helpful in judging the representativeness of the measurements for particular population groups.

59. Within the uncertainty bounds, and given the inherent differences in the quantities being compared, the sums of the doses from inhalation and ingestion intakes estimated using the other approaches are broadly in agreement with the committed effective doses estimated from the whole-body counting measurements (see table A-3.6). This indicates that the other approaches are able to provide estimates of doses comparable with the measurements made in people and therefore are more realistic than the doses presented in the UNSCEAR 2013 Report [UNSCEAR, 2014].

60. Irrespective of the approach used, the average effective doses from intakes of radiocaesium are low (both in absolute terms and relative to the total doses from all radionuclides and all exposure pathways), ranging from a few tens of µSv to about 100 µSv for those population groups for which whole-body measurements were made.

Table A-3.6. Comparison of effective doses from intakes of radiocaesium estimated from whole-body measurements with those estimated using a combination of other approaches

Population measured using whole-body counting	*Whole-body counting (all intakes)*		*Other approaches (based on measured and predicted concentrations of radiocaesium in air, food and drinking water)*		
	Committed effective dose up to time of measurement (µSv) (5th to 95th percentile)		*Average committed effective dose from intakes within first year (µSv) (5th to 95th percentile)*		
	Average	*Median*	*Inhalation*	*Ingestion*	*All intakes*
Minamisoma City [a] [Tsubokura et al., 2012]	~50[b] (18–180)		~42[c]/29[d] (2.6–160[e]/ 18–39[f])	~19[g] (8–43[h])	~61/48
Minamisoma City [i] [Hayano et al., 2014]	~80[j] (7–160)		13[k] (4.1–30[l])	~19[g] (8–43[h])	~32
Hirata Central Hospital [m] [Hayano et al., 2013]	~50[n] (15–150)		~5.1[o] (0.0040–20[p])	~19[g] (8–43[h])	~24
Evacuated municipalities [q] [Momose et al., 2012]		~25[r] (4–150)	~7.8[s] (3.8–14[t])	~19[g] (8–43[h])	~27
Evacuated municipalities [u] [Kim et al., 2016]		~30–70[v] (large)[w]	~4.8[x] (2.4–8.4[y])	~19[g] (8–43[h])	~24

[a] Adult residents of Minamisoma City. According to Tsubokura et al. [Tsubokura et al., 2012], those measured were volunteers and may not be representative of the whole population; many had been evacuated and approximately half of them had returned by August 2011.

[b] Estimated by the Committee assuming short-term intake with all measurements less than MDL assumed to be equal to half MDL. Committed dose for intakes up to September 2011 to March 2012 (i.e., 6 to 12 months after the accident) and are not directly comparable with those estimated by other approaches for intakes within the first year. The assumption of a short-term intake may have resulted in a small overestimate (up to a few tens of per cent) of the dose up to the time of measurement, and including intakes after the time of measurement to derive a dose in the first year may add a few tens of per cent to the dose estimated from the whole-body measurement (i.e., the two factors will have partially compensated each other). Alternative, plausible, assumptions about how to treat measurements less MDL would be unlikely to alter the estimated dose by more than several tens of per cent.

[c] Estimated by the Committee as the average dose for residents of Minamisoma City from air concentrations predicted by scaling measured deposition densities by ratios derived from ATDM. Not directly comparable with the dose estimated on the basis of whole-body counting as it is not known what proportion of those measured were evacuees or residents.

[d] Estimated by the Committee from the measured time-integrated air concentration in the Haramachi Area of Minamisoma City. May not be directly comparable with doses estimated on the basis of whole-body counting as it is not known what proportion of those measured had been evacuated before the arrival of the plumes nor how representative the measured concentration was for Minamisoma City as a whole.

[e] Estimated by the Committee taking account of all significant contributors to uncertainty and variability in the predicted doses of residents of Minamisoma City.

[f] Estimated by the Committee taking account of the uncertainty in the measured air concentrations and in the extent to which air concentrations are reduced inside buildings.

[g] Estimated by Murakami and Oki [Murakami and Oki, 2014] from measured concentrations in food and drinking water in Fukushima City. The Committee has assumed this estimate to be applicable to the whole of Fukushima Prefecture while recognizing that there will be some variation with location. The results of the market-basket and duplicate-diet studies for Fukushima Prefecture and other prefectures indicate that the spatial variation in ingestion doses is not large and the Committee has judged that the variation between municipalities within Fukushima Prefecture is unlikely to be more than a factor of a few.

[h] The quoted percentiles are those estimated by Murakami and Oki for their estimates of doses from ingestion in Fukushima City. The Committee's assumption that the estimates for Fukushima City are applicable to Fukushima Prefecture as a whole will increase the quoted uncertainties.

[i] Hayano et al. [Hayano et al., 2014] reported only on measurements made of those who lived in "the most contaminated zone", about 85% of whom had been evacuated at different times during March 2011, but had returned in July 2011.

[j] Estimated by the authors assuming acute inhalation of radiocaesium in March 2011 and no further intake of radiocaesium up to the time of measurement (July 2011) and are not directly comparable with those estimated by other approaches for intakes within the first year. The assumption of an acute intake by inhalation on 12 March may have resulted in a small overestimate (up to a few tens of per cent) of the committed dose from intakes up to the time of measurement. The estimated doses are not representative for Minamisoma City as a whole as the authors only reported the results of measurements for those living in the "most contaminated zone", about 85% of whom were evacuated at various times in March 2011.

[k] Estimated by the Committee as the average dose for evacuees from Haramachi and Kashima Areas of Minamisoma City (who comprised 82% of those measured).

[l] Estimated by the Committee taking account of all significant contributors to uncertainty and variability in the predicted doses of evacuees from Haramachi and Kashima Areas of Minamisoma City.

[m] Seventy-three per cent from Fukushima Prefecture, 23% from Ibaraki Prefecture with the remainder from Miyagi and Tochigi prefectures. No information available on where, within the prefectures, those measured were at the time of the accident or where they lived subsequently within the respective prefectures.

[n] Estimated by the Committee assuming short-term intake with all measurements less than MDL assumed to be equal to half MDL. Committed dose for intakes up to October 2011 to March 2012 (i.e., 7 to 12 months after the accident) and are not directly comparable with those estimated by other approaches for intakes within the first year. The Committee has used the measurement data in the first year after the accident at FDNPS, although the authors restricted their analyses to measurements made after March 2012 because of possible surface contamination of clothes before this date. The assumption of a short-term intake may have resulted in a small overestimate (up to a few tens of per cent) of the dose up to the time of measurement. Alternative, plausible, assumptions about how to treat measurements less MDL would be unlikely to alter the estimated dose by more than several tens of per cent. The quoted dose is the average of those measured but, without knowing where the people were, within the respective prefectures, at the time of the accident and subsequently, it is difficult to attribute this dose to one or other specific population group. The authors acknowledge that their results are not conclusive for Fukushima Prefecture as a whole.

[o] Estimated by the Committee as the average dose to residents in Fukushima Prefecture based on predicted air concentrations derived by scaling measured deposition densities by ratios derived using source term and ATDM. It may not be directly comparable with the dose estimated from whole-body counting as it is not known whether those measured were representative of the population of Fukushima Prefecture as a whole.

[p] Estimated by the Committee taking account of all significant contributors to uncertainty and variability in the predicted doses of residents of Fukushima Prefecture.

[q] Adult evacuees from Futaba Town, Hirono Town, Iitate Village, Katsurao Village, Kawamata Town, Kawauchi Village, Minamisoma City, Namie Town, Naraha Town, Okuma Town and Tomioka Town. Measurements initially made (from 11 July 2011) on evacuees from Iitate Village, Kawamata Town and Namie Town, and from 1 September 2011 on those from elsewhere. No information is available on the numbers of those measured in each municipality.

[r] Estimated by the authors by extrapolating to the 50th percentile assuming a log-normal distribution. Committed dose for intakes up to July 2011 to January 2012 (i.e., 3 to 10 months after the accident) and are not directly comparable with those estimated by other approaches for intakes within the first year. The assumption of an acute intake by inhalation on 12 March may have resulted in a small overestimate (up to a few tens of per cent) of the committed dose from intakes up to the time of measurement. The median dose and percentiles take no account of potential bias consequent upon a fraction of the measurements being affected by contamination on clothes (see section III.A.1). The quoted value is the median dose of those measured which is not necessarily the median dose of the population of the evacuated municipalities and, therefore, not directly comparable with the doses estimated using other approaches which are the averages for the population of all of the evacuated municipalities. The authors also presented dose distributions for each of the six evacuated municipalities, with the doses varying from about a factor of two lower, to a few tens of per cent higher, than those for all municipalities.

[s] Estimated by the Committee as the average dose for all evacuees from Fukushima Prefecture based on predicted air concentrations using source term and ATDM. It may not be directly comparable with the dose estimated from whole-body counting as it is not known whether those measured were representative of evacuees as a whole.

[t] Estimated by the Committee taking account of all significant contributors to uncertainty and variability in the predicted doses of evacuees as a whole.

[u] Adult evacuees from the same municipalities as in footnote q apart from Minamisoma City and inclusion of Tamura Town. More than half of those measured were from Namie Town, about 11% from Iitate Village and about 7% from each of Kawamata Town and Futaba Town. Median doses only estimated for Namie Town, Iitate Village and Futaba Town.

[v] Estimated by the authors assuming a log-normal distribution. Committed dose for intakes up to June 2011 to July 2011 (i.e., 3 to 4 months after the accident) and are not directly comparable with those estimated by other approaches for intakes within the first year. The assumption of an acute intake by inhalation on 12 March may have resulted in a small overestimate (up to a few tens of per cent) of the committed dose from intakes up to the time of measurement. The quoted values are the range of median doses of those measured in Futaba Town (68 μSv), Iitate Village (27 μSv) and Namie Town (26 μSv), which are not necessarily the median dose in the whole population of the evacuated municipalities and, therefore, not directly comparable with the average doses for the whole population of the 11 evacuated municipalities estimated using the other approaches.

[w] Uncertainties are large because of the small numbers of people measured (90, 20 and 12 in Namie Town, Iitate Village and Futaba Town, respectively). 5th percentiles not determined (less than MDL) and the 95th percentiles are a factor of about 5 to 6 times greater than the median values.

[x] Estimated by the Committee as the average dose for evacuees, with account taken of where those measured were evacuated from, based on predicted air concentrations using source term and ATDM; the estimated dose is directly comparable with that estimated based on whole-body counting but is not representative of the dose for all evacuees, rather just those measured.

[y] Estimated by the Committee taking account of all significant contributors to uncertainty and variability in the predicted doses of evacuees taking account of where those measured were evacuated from.

61. The comparison between doses estimated from whole-body counting and the other approaches can also provide some insights into the relative contribution of inhalation and ingestion to the intake of radiocaesium; caution should however be exercised in drawing too definitive conclusions given the various qualifications on the estimated doses and their comparability (see footnotes to table A-3.6). For Minamisoma City, where those measured were combinations of evacuees and residents, the contribution of inhalation is of the order of 60 to 80%, based on measured and predicted air concentrations, respectively. In evacuated municipalities, the contribution of inhalation is about 20–40%, albeit associated with large uncertainty owing to significant uncertainties in the intakes, in particular, the predicted air concentrations. For those measured by Hayano et al. [Hayano et al., 2013] at Hirata Central Hospital (about three-quarters and one-quarter, respectively, from Fukushima and Ibaraki prefectures), the contribution of inhalation is about 15–20%, albeit associated with significant uncertainty owing to lack of information on where those measured were within the respective prefectures (i.e., whether they were distributed pro rata with the prevailing population density) at the time of the accident and subsequently.

62. More meaningful estimates of the contribution of inhalation can be obtained from measured air concentrations [Oura et al., 2015] of radiocaesium at numerous locations in Fukushima Prefecture and elsewhere in Japan, in particular as they are associated with much smaller uncertainties than those predicted on the basis of an assumed source term and ATDM. The relative contributions of inhalation and ingestion to the average committed effective dose in the first year for Fukushima City and the Tokyo Metropolitan Area are given in table A-3.7. The doses from inhalation are based on the average measured air concentrations at four monitoring stations in Fukushima City and 11 stations in the Tokyo Metropolitan Area; the doses from ingestion are those estimated by Murakami and Oki [Murakami and Oki, 2014]. The contribution of inhalation to the total dose is about 13% at Fukushima City and about 16% for the Tokyo Metropolitan Area. These may be more indicative of the contribution from inhalation across larger (non-evacuated) areas of Fukushima Prefecture than those that can be derived from table A-3.6.

Table A-3.7. Relative contributions of inhalation and ingestion to committed effective dose from the intake of radiocaesium

Location	*Average committed effective dose from intakes of radiocaesium within the first year (μSv)* (*5th to 95th* percentile)		
	Inhalation	*Ingestion*	*All intakes*
Fukushima City	~2.8[a] (1.7–4.0)	~19[b] (8–43)	~22 (4–39)
Tokyo Metropolitan Area	~1.2[c] (0.11–2.4)	~6.1[b] (3.0–12)	~7.3 (2.7–12)

[a] Average of measured time-integrated air concentrations of ^{137}Cs at four monitoring stations in Fukushima City (Furukawa, Minamimachi, Moriai and Sugitsumacho) [Oura et al., 2015]; average time-integrated air concentration 1.8 10^{6} Bq s/m^{3}.
[b] Average ingestion doses estimated by Murakami and Oki [Murakami and Oki, 2014].
[c] Average of measured time-integrated air concentrations of ^{137}Cs at 11 monitoring stations in Tokyo Metropolitan Area (Edogawaku-minamikasai, Hachiojishi-Kawaguchimachi, Hachiojishi-tatemachi, Himonya, Kannanadori-kakinokizaka, Kannanadori-matsubarabashi, Katsushikaku-mizumotokoen, Machidashi-nogaya, Nakaharakaido-minamisenzoku, Omeshi-higashiome and Setagayaku-seijyo) [Oura et al., 2015]; average time-integrated air concentration 7.4 10^{5} Bq s/m^{3}.

F. Approach adopted by the Committee in updating its estimates in the UNSCEAR 2013 Report of doses from the intake of radionuclides in the first year

63. As in its UNSCEAR 2013 Report [UNSCEAR, 2014], the Committee has chosen to use a less direct modelling approach in updating its estimates of doses from the intakes of all radionuclides (including those of radiocaesium) by inhalation and ingestion. Doses from intakes by inhalation have been estimated using an assumed source term and ATDM as described in attachment A-10. Doses from intakes by ingestion in the first year have been based on the estimates of Murakami and Oki [Murakami and Oki, 2014]. This approach was adopted taking account of the following:

(a) While the whole-body counting measurements are informative of intakes of, and doses from, radiocaesium at particular locations or for particular population groups (e.g., Minamisoma City, the evacuated municipalities), they are limited in the extent to which they can provide a basis for estimating doses from intakes of radiocaesium elsewhere (i.e., for the whole of Japan) and/or for the wide spectrum of radionuclides released in a nuclear accident;

(b) In these circumstances, the use of an assumed source term and ATDM was the only way in which the Committee could estimate the spatial variation in doses from intakes of all radionuclides by inhalation across the whole of Fukushima Prefecture and elsewhere in Japan;

(c) The analysis carried out by Murakami and Oki of intakes of, and related doses from, ingestion of radionuclides provides the only method currently available for consistently estimating doses from all relevant radionuclides from ingestion of food and drinking water from the early period after the accident onwards;

(d) Whole-body monitoring measurements are only informative about total intakes of radiocaesium (and not of other radionuclides, or about the relative contribution from inhalation or ingestion) up to the time of measurement; market-basket and duplicate-diet studies are only informative about intakes by ingestion at the time the studies were carried out.

64. For doses from ingestion, the estimates of Murakami and Oki have been used. The authors made estimates of doses (and their associated uncertainties) to males and females and for several age groups: *(a)* the average dose estimates for males and females have been used, *(b)* the doses for those aged 1–6 years have been used for the 1-year-old infant, *(c)* the doses for those aged 7–12 years have been used for the 10-year-old child, and *(d)* the doses for those aged 19 years or more have been used for adults. For the 1-year-old infant, this may have resulted in an overestimate in the dose by a few tens of per cent because of the age dependence of the dose from internal exposure from ingestion of radiocaesium. This approach is consistent with the approach adopted for intakes of radioiodine (see attachment A-2) and results in estimates of doses from ingestion that are broadly comparable with those from the market-basket and duplicate-diet studies and with the whole-body monitoring studies. The Committee has assumed that Murakami and Oki’s dose estimates for Fukushima City are applicable to the whole of Fukushima Prefecture while recognizing that there will be some variation with location. The results of the market-basket and duplicate-diet studies for Fukushima Prefecture and other prefectures indicate that the spatial variation in ingestion doses is not large and the Committee has judged that the variation between municipalities within Fukushima Prefecture is unlikely to be more than a factor of a few.

65. For neighbouring (Group 3) and distant (Group 4) prefectures, doses from ingestion of radiocaesium have been estimated from the doses for Fukushima Prefecture according to the ratios of the average doses from ingestion for these groups of prefectures to the average dose from ingestion for Fukushima Prefecture estimated in the UNSCEAR 2013 Report [UNSCEAR, 2014]. These average doses in the UNSCEAR 2013 Report had been estimated from a large database of measurements of food sampled in 2011 from markets all over the country (see attachment C-8 of the UNSCEAR 2013 Report), and have been used as a surrogate for the averages of the measured concentrations. The resulting ratios for radiocaesium are: Group 3/Group 2 = 0.23 and Group 4/Group 2 = 0.143 (see appendix C and attachment C-15 of the UNSCEAR 2013 Report). The resulting doses for the Group 3 and Group 4 prefectures are broadly consistent with the estimates from Murakami and Oki [Murakami and Oki, 2014] for the Osaka and Tokyo Metropolitan Areas.

66. Since food rations were sampled either from local families or from food markets with subsequent culinary processing, the data on the radiocaesium content of the food and drinks takes into account the effects of remediation and of the monitoring and inspection measures applied in agriculture and forested areas (see chapter IV of the annex B). In the long term, if these measures were to be relaxed there may be some minor increase in corresponding ingestion doses, and then the long-term dose projections may become somewhat underestimated.

67. Absorbed doses to red bone marrow, breast and colon from the ingestion of radiocaesium have been assessed from the effective dose estimates using the respective ratios of the dose coefficients for the absorbed dose in each organ from ingestion of radiocaesium to the effective dose coefficients in each age group [ICRP, 1993; ICRP, 1995].

IV. ESTIMATING DOSES FROM INTERNAL EXPOSURE DUE TO INTAKES OF RADIOCAESIUM BY INGESTION AFTER THE FIRST YEAR

68. To assess doses from ingestion after the first year, the information from the market-basket and duplicate-diet studies has been used. These studies provide a direct estimate of intakes of radiocaesium from ingestion from about July 2011 onwards and an indication of intakes in 2012 and 2013 [Harada et al., 2013; Harada et al., 2014; Koizumi et al., 2012; Sato et al., 2013; Tsutsumi et al., 2013; Uekusa et al., 2014]. The data were collected between July 2011 and March 2013. In order to use the combined results of these studies, the Committee has adjusted the resulting estimates of intakes to the same date, 15 March 2012, taking account of both radioactive decay and the decline in the radiocaesium concentrations in foods predicted by the model of Smith et al. [Smith et al., 2017] following the deposition of the radiocaesium on to the ground (see below).

69. The results are summarized in table A-3.8, which gives the mean, median and other statistical parameters of the distributions of the estimates of the daily intake by ingestion of ^{134}Cs and ^{137}Cs for adult residents of Fukushima Prefecture, four neighbouring prefectures and eight distant prefectures of Japan.

70. The intakes were highest in Fukushima Prefecture, lower by a factor of 1.3 in the neighbouring prefectures, and lower by a factor of three in distant prefectures of Japan. The ratios do not directly reflect the ratios of ^{137}Cs soil deposition densities in corresponding areas because of the system of food supply and distribution in Japan.

71. For comparison, Murakami and Oki [Murakami and Oki, 2014] estimated an effective dose rate for adults from ingestion of ^{134}Cs and ^{137}Cs in Fukushima City in March 2012 of

0.44 µSv per month. Assuming that the ratio of ^{134}Cs to ^{137}Cs at the time of the accidental release of these radionuclides was 1:1, this dose rate would correspond to intake rates of about 0.4 Bq/d of ^{134}Cs and of about 0.5 Bq/d of ^{137}Cs. These intakes are within a factor of two of the mean daily intakes in Fukushima Prefecture estimated for March 2012 from the market-basket and duplicate-diet studies, as presented in table A-3.8.

72. Uekusa et al. [Uekusa et al., 2014] provides information to enable comparisons between the estimated intakes of children of various age groups with the intakes of adults. The authors collected duplicate diets from six children in each of three age groups and from 21 adults (defined as 13 years old and above) in each of the nine prefectures, and analysed the samples for their radiocaesium content. The Committee derived the ratios of the median intakes for children to the median intakes for adults in each prefecture in 2011–2012. The average value of these ratios was 0.57 for both of the age groups 1–6 years and 6–12 years. Although the number of participants in each prefecture was quite limited, the ratios were similar in all the nine studied prefectures.

Table A-3.8. Estimates of the daily intake for adults from ingestion of radiocaesium, derived from the market-basket and duplicate-diet studies, adjusted to 15 March 2012 [Harada et al., 2013; Harada et al., 2014; Koizumi et al., 2012; Sato et al., 2013; Tsutsumi et al., 2013; Uekusa et al., 2014]

Location	*No. of studies* [a]	*Radionuclide*	*Daily intake (Bq/d)*				
			Mean	*Median*	*SD* [b]	*Min.*	*Max.*
Fukushima Prefecture	18	^{134}Cs	0.72	0.44	0.53	0.19	2.1
		^{137}Cs	1.0	0.78	0.75	0.27	3.1
Neighbouring prefectures	11	^{134}Cs	0.43	0.37	0.16	0.28	0.79
		^{137}Cs	0.60	0.49	0.21	0.36	1.1
Distant prefectures	33	^{134}Cs	0.26	0.24	0.16	0.075	0.68
		^{137}Cs	0.32	0.25	0.22	0.090	0.99

[a] The six papers cited included 62 studies in total in different prefectures/municipalities.
[b] Standard deviation.

73. To estimate doses over the longer term from ingestion of food containing radiocaesium, Smith et al. [Smith et al., 2017] have developed a model to predict the time-dependent changes in the concentration of radiocaesium in foods following its deposition. The authors focused on ^{137}Cs as being the radionuclide of most concern over the longer term, given the 2-year half-life of ^{134}Cs. They made use of over 4,000 measurements of the concentration of ^{137}Cs in foods and in the whole diet in Japan carried out over 50 years prior to the FDNPS accident, where the sources of the ^{137}Cs were atmospheric nuclear weapons' testing and the Chernobyl accident. The model included: *(a)* a fast decline in concentrations in foods or the whole diet following deposition, to represent rapid wash-off from plant surfaces and initial sorption to soil; *(b)* a slow decline, to represent soil fixation processes; and *(c)* a very long-term component, to represent declines due to vertical migration, erosion and further slow reductions in bioavailability. Different combinations of the model parameters were used to find the best fit to the long-term measurement data. Measurement data from five regions not used in model development were then used to test the model predictions and good agreement was found. In addition, whole diet measurements made following the FDNPS accident provided a further test of the model and showed consistency with the rapid decline component.

74. The doses from ingestion of radiocaesium after the first year were assessed using the model of Smith et al. [Smith et al., 2017], which used the following generic equation A-3.2:

$$C(t) = \int_{-\infty}^{t} D(\tau) \cdot (A \cdot e^{-(\lambda+k_1)(t-\tau)} + B \cdot e^{-(\lambda+k_2)(t-\tau)} + C \cdot e^{-(\lambda+k_3)(t-\tau)})d\tau \qquad \text{(A-3.2)}$$

where *C(t)* is the activity concentration of the radionuclide in the environmental compartment of interest (wheat, rice, vegetables, in Bq/kg and whole diet, in Bq/d) at time t (y), and *D(τ)* in (Bq/(m^2 y)) is the time-dependent radionuclide ground deposition rate at time, τ (y) preceding time *t*. *A*, *B*, and *C* (m^2/kg for foodstuffs; m^2/d for diet) are coefficients representing, respectively, a fast decline in activity concentrations after fallout (at rate k_1, y^{-1}), a slow decline (at rate k_2, y^{-1}) as a result of soil fixation processes, and the very long-term component (at rate k_3, y^{-1}), which declines due to vertical migration, erosion and further slow reductions in bioavailability; λ is the physical decay constant of ^{137}Cs.

75. Equation A-3.2 was fitted to the monitoring data from 1963–2008 collected in nine prefectures of Japan to derive the following parameter values for the whole diet (with 98% coverage limits in brackets):

- *B* (m^2/d) = 9.6×10^{-4} (6.1×10^{-4} – 1.3×10^{-3})
- k_2 (y^{-1}) = 0.89 (0.52 – 1.3)
- *C* (m^2/d) = 6.4×10^{-5} (4.7×10^{-5} – 8.1×10^{-5})
- k_3 (y^{-1}) = 0.051 (0.042 – 0.060).

76. The short-term parameters *A* and k_1 are not necessary for fitting long-term monitoring data.

77. For a single deposition on the ground *D* (Bq/m^2) at *t* = 0, and for times, *t*, greater than a year after this deposition (when the short-term decline has had effect and can be ignored), this model can be used to predict the intake, i_a, of caesium radionuclide, *a*, in the whole daily diet as a result of this short-term deposition according to the following equation A-3.3:

$$I_a(t) = D\cdot\exp(-(\lambda_a \cdot t)) \cdot (B\cdot\exp(-(k_2 \cdot t)) + C\cdot\exp(-(k_3 \cdot t))), \text{ Bq/d}, \qquad \text{(A-3.3)}$$

where the parameter values and their uncertainty are presented above.

78. The declines over time given by this equation have been used with the estimated intakes adjusted to 15 March 2012 (*t = θ*) from the market-basket and duplicate-diet studies described above, and set out in table A-3.8, according to the following equation A-3.4:

$$I_a(t) = I_a(\theta)\cdot\exp(-(\lambda_a \cdot (t-\theta)))\cdot(2.1 \exp(-0.89\cdot t) + 0.14 \exp(-0.051\cdot t)), \text{ Bq d}^{-1} \qquad \text{(A-3.4)}$$

where λ_{137} = 0.023 y^{-1} and λ_{134} = 0.336 y^{-1} are the physical (radioactive) decay constants for ^{137}Cs and ^{134}Cs, respectively, and the factors of 2.1 and 0.14 (unitless) have been derived from equation A-3.3 for time *θ* = 1 y, as follows:

$$D = I_a(\theta)/(\exp(-(\lambda_a \cdot \theta))\cdot(B\cdot\exp(-(k_2 \cdot \theta)) + C\cdot\exp(-(k_3 \cdot \theta))))$$

Therefore,

$$I_a(t) = I_a(\theta)\cdot\exp(-(\lambda_a \cdot (t-\theta)))\cdot(B^* \exp(-k_2 \cdot t) + C^* \exp(-k_3 \cdot t))$$

where *(for θ = 1 y):*

$$B^* = B/(B\cdot\exp{-k_2} + C\cdot\exp{-k_3}) = 2.1$$

$$C^* = C/(B\cdot\exp{-k_2} + C\cdot\exp{-k_3}) = 0.14$$

79. The committed effective dose, E_a, in mSv can then be calculated from the intake in Bq using the dose coefficients for ingestion for each radionuclide given in table A-3.5. Doses projected for the long-term periods of 1–10 years and 11–60 years (i.e., up to age 80 for adults) after deposition have been calculated using the formulae A-3.5a and 5b:

$$E_a(1\text{–}10) = \int_1^{10} E_a(t) \cdot dt, \text{ mSv} \quad \text{(A-3.5a) or}$$

$$E_a(11\text{–}60) = \int_{11}^{60} E_a(t) \cdot dt, \text{ mSv} \quad \text{(A-3.5b)}$$

V. UPDATED ESTIMATES OF COMMITTED EFFECTIVE DOSES FROM INTAKE OF RADIOCAESIUM

80. Updated estimates of committed effective doses from inhalation of radiocaesium (along with all other radionuclides), using a source term and ATDM, are presented in attachment A-10 and are not addressed further here.

81. The updated estimate of the committed effective doses from ingestion of radiocaesium for adults in Fukushima Prefecture is 19 μSv in the first year. This value was estimated by Murakami and Oki [Murakami and Oki, 2014] for Fukushima City and has been assumed to apply to the whole of Fukushima Prefecture. The corresponding committed effective doses for 10-year-old children and 1-year-old infants are given in table A-3.9, as are the committed effective doses in neighbouring prefectures and other prefectures in Japan estimated as described in section III.F above.

Table A-3.9. Updated estimates of the prefecture average committed effective doses to adults, children and infants, in different population groups, from the ingestion of ^{134}Cs and ^{137}Cs from food and drinking water in the first year

Population group	*Location*	*Prefecture average committed effective dose from ingestion of ^{134}Cs and ^{137}Cs (μSv)*		
		1-year-old	*10-year-old*	*Adult*
2	Fukushima Prefecture	8.0	12	19
3	Neighbouring prefectures	1.8	2.8	4.4
4	Distant prefectures	1.1	1.7	2.7

82. The 5th and 95th percentiles on these estimates are about a factor of two below and a factor of five above the average committed effective dose for Fukushima Prefecture [Murakami and Oki, 2014]; for other prefectures, expert judgment has been used by the Committee to derive 5th and 95th percentiles of factors of 0.3 to 3 times the average dose.

83. For those evacuated, surveys have indicated that intakes of radionuclides in food would have been very low in the period before and during evacuation, because most of the food that evacuees consumed immediately after the accident was sourced from either stockpiles prepared before the accident or relief supplies from outside the affected areas [Hirakawa et al., 2017]. So, only committed effective doses from ingestion of food once the evacuees reached their destination have been included in their estimated first year doses.

84. Intakes of radiocaesium from ingestion in the first year would have continued over the whole of the year at a generally declining rate, albeit with shorter term deviations from this trend depending on the foods consumed (e.g., consumption of wild produce with enhanced levels of radiocaesium).

85. Committed effective doses from intakes of radiocaesium by ingestion after the first year have been estimated using intakes of radiocaesium from ingestion derived from the market-basket and duplicate-diet studies and the model of Smith et al. [Smith et al., 2017] (see section IV). The average doses up to 10 years after the accident and for lifetimes are shown in table A-3.10 for adults for Fukushima Prefecture, four neighbouring prefectures and for the rest of Japan. The 5–95% range of doses was estimated by the Committee using the Monte-Carlo simulation.

86. The data in table A-3.10 show that projected doses to adults from ingestion of radiocaesium are very low, ranging from 5 to 14 µSv over 1–10 years and from 1 to 4 µSv over 11–60 years over all prefectures. The new ingestion dose estimates for doses after the first year based on whole ration measurements in 2011–2013 and the model of Smith et al. [Smith et al., 2017] are about a factor of five to six times lower than similar internal doses presented in the UNSCEAR 2013 Report [UNSCEAR, 2014].

Table A-3.10. Updated estimates of prefecture average and percentiles of committed effective doses to adults from ingestion of radiocaesium in food and drinking water after the first year

Time period (years)	*Quantity*	*Committed effective dose to adults (µSv)*		
		Group 2 Fukushima Prefecture	*Group 3 Neighbouring prefectures*	*Group 4 Distant prefectures*
1–10	Average	14	8.3	4.6
	5–95%	6–31	4–18	2.1–10
11–60	Average	3.8	2.3	1.2
	5–95%	1.0–15	0.4–15	0.3–5

87. Mean committed effective doses to other age groups from ingestion of ^{134}Cs and ^{137}Cs were estimated taking account of the age dependence of the intakes by ingestion derived from [Uekusa et al., 2014]. Resulting average committed effective doses in the first year, in the first 10 years and up to age 80 years for all three age groups are given in table A-3.11.

Table A-3.11. Updated estimates of prefecture average committed effective doses (µSv) to 1-year-old infants, 10-year-old children and adults from ingestion of radiocaesium in food and drinking water over different time periods

Age (in 2011)	*Exposure duration (years)*	*Group 2 Fukushima Prefecture*	*Group 3 Neighbouring prefectures*	*Group 4 Distant prefectures*
1-year-old infants	1	8.0	1.8	1.1
	10	16	6.5	3.7
	Up to age 80	20	8.8	4.9
10-year-old children	1	12	2.8	1.7
	10	23	8.3	5.3
	Up to age 80	27	11	6.5
Adults	1	19	4.4	2.7
	10	33	13	7.3
	Up to age 80	37	15	8.5

88. Based on Murakami and Oki [Murakami and Oki, 2014], a Monte-Carlo simulation of long-term processes (see table A-3.10) and expert judgment, the Committee has assessed the coverage interval (5–95%) for the prefecture-averaged doses in table A-3.11 as being between 0.3 and 3.0 times the respective doses.

VI. MICROPARTICLES

89. Several studies have identified radiocaesium in the environment associated with water-insoluble “glassy spherules”. The fraction of the radiocaesium deposited on to the ground in the form of such microparticles varies from a few per cent at distances of up to 30 km from FDNPS to up to about 80% at large distances (more than 200 km) [Ikehara et al., 2020; Utsunomiya et al., 2019].

90. The solubility of these microparticles in water, sea water and a pulmonary fluid simulator has been studied in several experiments [Okumura et al., 2019; Suetake et al., 2019; Utsunomiya et al., 2019]. Dissolution of microparticles was found to occur much faster in seawater ($T_{1/2}$ = 1.7 years) than in pure water ($T_{1/2}$ = 17 years excluding decay) [Okumura et al., 2019]. In another series of experiments with larger particles, Suetake et al. [Suetake et al., 2019] showed that the dissolution of microparticles in a pulmonary fluid simulator occurs more rapidly than in pure water or seawater, however, the dissolution time in this case was of the order of a few decades.

91. Due to the low solubility of radiocaesium associated with microparticles, one can assume their slower migration deep into the soil and, accordingly, a slower decrease in dose rate from exposure to deposited material. On the other hand, these particles are not fixed in clay, like caesium cations, and can be transported faster from the soil by precipitation, including into water bodies. The overall effect of these processes on the external exposure of a person has not yet been studied. However, the updated model used in this report to assess external exposures to deposited material has taken account of the observed slower decrease in the dose rate over soils in Japan than observed after the Chernobyl accident in Ukraine [Likhtarev et al., 2002] and the Russian Federation [Golikov et al., 2002] (see attachment A-1); however, it is not apparent what influence microparticles play in this process.

92. With regard to inhalation of radiocaesium from the plume of released radionuclides, the slow dissolution of the microparticles would class them according to type S (slow) biokinetics in the respiratory tract. For this category, dose coefficients [ICRP, 1995] are an order of magnitude higher than for more highly soluble forms (type F). The respiratory tract, in particular the lungs, would be predominantly exposed. It would follow that, in the presence of a significant fraction of microparticles (10% or more) in the mixture of caesium radionuclides inhaled from the plume, these particles could increase the estimated dose from inhalation.

93. In the case of surface contamination of vegetables with caesium-bearing microparticles, the ingestion dose would be lower compared with soluble forms of radiocaesium because of their much lower solubility in the gastro-intestinal tract (i.e., by about an order of magnitude). In addition, the reduced solubility of the microparticles would reduce the uptake of radiocaesium from soil into the food chain.

94. The effect of such microparticles on estimated doses is therefore complex, resulting in higher doses from one exposure pathway and lower doses from another, than as assumed in the models used in this report. While the presence and behaviour of radiocaesium in the environment in the form of microparticles is worthy of further scientific investigation, the Committee judges that it will have no material impact on the overall levels of dose to the public estimated in its update of its UNSCEAR 2013 Report [UNSCEAR, 2014].

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