ATTACHMENT A-12

APPROACH FOR ASSESSING UNCERTAINTIES AND VARIABILITY IN ESTIMATED DOSES

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 general approach adopted for evaluating and propagating uncertainties in estimating doses to the public from the accident at the Fukushima Daiichi Nuclear Power Station (FDNPS);
- How the general approach has been applied in estimating uncertainties and variability in doses for each of the significant pathways of exposure; and
- How the approach has been applied in estimating the distribution of doses in particular groups of the population (municipalities, prefectures, evacuated areas, etc.) from all pathways of exposure and in estimating the uncertainty in the average doses for the same groups.

Notes

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CONTENTS

I. GENERAL APPROACH FOR EVALUATING UNCERTAINTIES

1. The approach adopted by the Committee and described in this attachment is in accordance with the Joint Committee for Guides in Metrology [JCBM, web], in particular with the ISO/IEC Guide 98-3 Supplement 1 [JCGM, 2008a].

2. The uncertainties of doses *D* have been evaluated by probability density functions (PDF), which take into account the uncertainties and variabilities of the input quantities on which the doses depend, including any model parameters unless otherwise noted.

3. The PDFs quantify the probabilities for the unknown and unknowable true values $\widetilde{D}$ of the doses given the information about the input quantities. Note that the superscripted ~ is used to indicate a true value of a quantity [ISO, 2019] (see [JCGM, 2012] for the terminology). The PDFs represent Bayesian probabilities. They cannot be handled by frequentistic statistics because these cannot handle Type B uncertainties, which dominate the uncertainties of the doses.

4. The uncertainties take into account the observed variability of input quantities, for example the deposition densities of radionuclides, as well as the uncertainties of other input quantities, the values of which are unknown (e.g., consumption rates, occupation factors etc.). While the former are taken into account as Type A uncertainties, the latter are Type B uncertainties for which PDFs are assigned from other sources, for example from the literature, general knowledge, and expert judgement. Both types of uncertainty are equally relevant and have been taken into account in estimating the overall uncertainties. Mathematically, there is no difference between variability and uncertainty.

5. For any model of evaluation of a dose *D*:

$$D = G(X_1, \ \ldots, \ X_m) = G(\boldsymbol{X}) \qquad \text{(A-12.1)}$$

with a model function *G*, the uncertainties could be evaluated according to ISO/IEC Guide 98-3 [JCGM, 2008b] or ISO/IEC Guide 98-3 Supplement 1 [JCGM, 2008a]. The ISO/IEC Guide 98-3 [JCGM, 2008b] uses normal (Gaussian) distributions and an approximation based on a Taylor expansion truncated after the first order term. However, given the complexity of the model equations and the non-Gaussian character of many input quantities, the ISO/IEC Guide 98-3 Supplement 1 [JCGM, 2008a] is to be preferred and has been adopted by the Committee in its assessment. It applies to any distribution type and allows the calculation of posterior PDF of the measurand (here the dose) using Monte Carlo methods (see also [ISO, 2019] for details of such procedures).

6. To derive the PDF of a dose, *D*, PDFs of the input quantities relevant to its estimation have to be established; this process is described in section II for the different exposure pathways. Then, a joint probability distribution, $f_X(\tilde{x}|x)$, can be formed, which, for independent input quantities, is given by:

$$f_{\boldsymbol{X}}(\tilde{\boldsymbol{x}}|\boldsymbol{x}) = \prod_1^m f_{X_i}(\tilde{x}_i|x_i) \qquad \text{(A-12.2)}$$

with x being any available and relevant information and x_i being the subset of information available for X_i. A joint probability distribution has to be assigned to those X_i that are not independent and inserted in equation A-12.2 for the respective input quantities (see [JCGM, 2008b] for further details). For the evaluation of the uncertainties of doses, the Committee has

assumed that the different exposure pathways are statistically independent so that no correlations had to be taken into account.

7. The probability distribution $f_D(\tilde{D}|x)$ can then be calculated from the joint probability distribution $f_X(\tilde{x}|x)$ using the model equation $D = G(X)$ and the so-called Markov equation:

$$f_D(\tilde{D}|\boldsymbol{x}) = \int_{-\infty}^{+\infty} f_{\boldsymbol{X}}(\xi|\boldsymbol{x}) \cdot \delta(\tilde{D} - G(\xi))\ d\,\xi \qquad \text{(A-12.3)}$$

8. In practice, the evaluation of the integral of equation A-12.3, is performed by conducting n_M Monte Carlo trials. In each trial, a set of random numbers $x_{1,i}, \ldots, x_{n,i}$ is drawn from each of the PDFs $f_{X_i}(\tilde{x}_i|x_i)$ of the input quantities and the respective doses $D_i = G(x_{1,i}, \ldots, x_{n,i})$ are calculated according to equation A-12.1. The vector $\vec{D}_M = \{D_1, \ldots, D_{n_M}\}$ is ordered ascendingly and then cumulative probabilities i/n_M are assigned to the $D_i$of $\vec{D}_M$. $\vec{D}_M$ is a discrete representation of the distribution function $F_D(\tilde{D}|x) = \int_{-\infty}^{\tilde{y}} f_D(\eta|x)\, d\eta$ of D. From this posterior distribution function all required moments of the PDF can be derived numerically.

9. This process has been used by the Committee to derive PDFs of the doses from each exposure pathway. For the calculation of the total dose, E, summed over the different exposure pathways, $E = E_{\text{ext}} + E_{\text{ing}} + E_{\text{inh}}$, the PDF of the total dose was also calculated by Monte Carlo trials with samples drawn from the PDFs of the doses from each pathway, $f_{E_i}(\tilde{E}_i|\boldsymbol{x})$ ($i =$ ext, ing, inh). The Committee has used the same procedure for the estimation of PDFs of the effective doses and absorbed doses in various organs.

10. For all calculated doses (effective dose and absorbed doses in various organs) and dose rates uncertainties were evaluated and the PDF have been reported as graphs of the PDFs or by suitable moments of the distributions, such as means, medians and specified percentiles. Sensitivity analyses were not performed, but the relevance of the individual sources of uncertainty can be judged from the data given for the individual cases. Detailed descriptions of the calculations and the models of evaluation are given in attachments A-1, A-2, A-3, A-9 and A-10.

11. A similar process, based on Monte Carlo simulations, has been used to derive the PDF of the average dose in the population group (and therefore the mean and 95th percentile upper bound) from the PDFs of the doses from each exposure pathway, in this case by calculating the average dose in the population group summed over the exposure pathways in each Monte Carlo trial. Again, the same procedure has been used for average effective doses and absorbed doses in various organs. The PDFs of the average doses have been used, in particular, for the assessment of the health implications of the estimated doses (see attachment A-23), where the Committee has carried out power calculations using the average dose in a specified population group (e.g., adults living in a municipality) and the 95th percentile upper bound of this dose.

II. APPLICATION OF THE GENERAL APPROACH FOR EVALUATING AND PROPAGATING UNCERTAINTIES

A. Assessment of uncertainties and variability in doses to residents from radionuclides in the air

12. The Committee's aim was to make realistic estimates of doses and, for this purpose, it has used the best models and input data available to it. However, there are uncertainties associated with these estimates because of variability of input quantities, incomplete knowledge or information, imperfect models and the many assumptions that had to be made as a consequence.

13. Figure A-12.I shows the key modelling steps in assessing doses to the public for residents (i.e., those who were not evacuated) in Fukushima Prefecture and neighbouring prefectures from the exposure pathways of inhalation and external exposure from radionuclides in the air. The estimated doses from inhalation and from external exposure from the plume are largely based on measured levels of deposition density of radionuclides on the ground:

(a) As a first step, the concentrations of ^{137}Cs in air were estimated from the measured levels of deposition density of ^{137}Cs on the ground using the ratios of estimates from atmospheric transport, dispersion and deposition modelling (ATDM) of the time-integrated activity concentrations in air to the deposition density (for the reference radionuclide ^{137}Cs) as a function of location (see attachments A-9 and A-10 for further details);

(b) Then, concentrations of ^{131}I (separately for elemental, organic and aerosol-bound forms), ^{132}Te/^{132}I and ^{134}Cs in air were derived from the estimated concentrations of ^{137}Cs in air using the ratios of the concentrations of these radionuclides in air to the concentration of ^{137}Cs in air determined from ATDM. Because the ATDM did not provide estimates of the concentrations in air for the short-lived radionuclide, ^{133}I, its concentrations were derived from ^{131}I concentrations using the ratio of ^{133}I to ^{131}I at 14:46 on 11 March 2011 from Nishihara et al. [Nishihara et al., 2012] and correcting for the different physical half-lives of the two isotopes;

(c) External exposure to radionuclides in the air and exposure from inhalation were then assessed from the radionuclide concentrations in air, using: age-dependent breathing rates (for inhalation dose); reduction factors to take account of the reduction in the concentrations of radionuclides, and shielding, inside buildings; occupancy factors to account for the proportion of time spent indoors for the various age and social groups of the Japanese population; and relevant dose coefficients.

14. The main sources of uncertainty and variability that were judged by the Committee to significantly influence uncertainties in the estimated doses to residents from exposure to radionuclides in the air are:

(a) Spatial variability of the deposition density of deposited radionuclides;

(b) Relationship between the deposition density of ^{137}Cs and its time-integrated concentration in air as a function of location (the bulk deposition velocity);

(c) Ratios of the concentrations of ^{131}I (separately for elemental, organic and aerosol-bound forms), ^{133}I, ^{132}Te/^{132}I and ^{134}Cs in air relative to the concentration of ^{137}Cs in air;

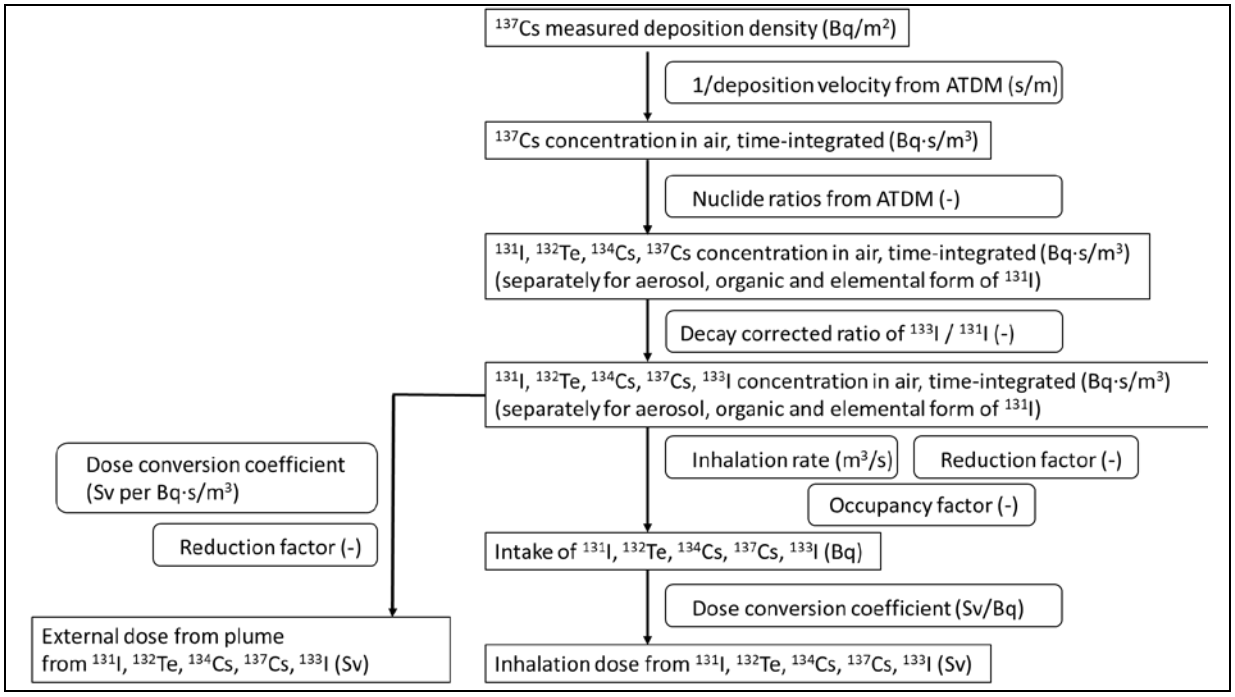
(d) Factor by which the concentration of radionuclides in air inside buildings is reduced compared with the concentration outdoors;

(e) Breathing rate of reference individuals in the exposed population (adult male, adult female, 10-year-old child, and 1-year-old infant); and

(f) Dose coefficients for intakes of radioiodine and radiotellurium by inhalation.

Note that variability as a result of age has been addressed by considering three representative age groups separately to produce dose distributions for each age group. Dose distributions for the population as a whole have then been obtained from the distributions for each age group using the age profile of the population obtained from census data.

Figure A-12.I. Key modelling steps in assessing doses from inhalation and external exposure from the plume for residents



15. The Committee has taken explicit account of each of these uncertainties or variabilities when evaluating uncertainties in its estimates of dose. It recognizes, however, that numerous other sources of uncertainty or variability will also have contributed to uncertainties in its estimated doses (e.g., uncertainties in the measurements of deposition densities of radionuclides, in the assumed occupancy factor, in the dose coefficients for intakes by inhalation of radionuclides other than radioiodine and radiotellurium, and uncertainties due to imperfections in the models used, etc.). However, based on expert judgement and a limited scoping analysis, the Committee has concluded that the exclusion of these additional sources of uncertainty would not materially affect its estimates of uncertainties in doses (e.g., the uncertainties in the measured deposition densities are small compared with their spatial variability and can be neglected when estimating overall uncertainties in doses).

16. Deposition densities of radionuclides on the ground (and, similarly, derived concentrations of radionuclides in air) generally exhibit large spatial variability within a given municipality[1] and have a significant impact on the distribution of individual doses within a given population group. The approach used for uncertainty modelling describes this variability directly by estimating the distribution of deposited activity from all deposition measurements within each municipality. The spatial variability of the deposition densities within a given municipality is, in general, log-normally distributed and far exceeds uncertainties associated with measurements – hence the latter

[1] Or prefecture.

not being explicitly included in the Monte Carlo analysis. Uncertainties associated with the assumption that each measurement at a specific location can be taken to be representative of the average ^{137}Cs deposition density over the area around the measurement location were taken as log-normally distributed with an estimated geometric standard deviation (GSD) = 1.5.

17. The uncertainty of the ratios of time-integrated activity concentrations in air to the deposition density were assessed by estimating the distribution of these values (as derived from the ATDM results) within a circular area of 3 km around the location of each deposition measurement. This distribution of ratios was then applied to the deposition density at each monitoring location, resulting in a distribution of calculated air concentrations for ^{137}Cs. When there is only dry deposition, the uncertainty in the bulk deposition velocity will simply be a reflection of the uncertainty around the dry deposition velocity assumed in the ATDM. The largest fluctuations in the bulk deposition velocity arise when there is rainfall or snowfall (i.e., when there is wet as well as dry deposition) and such fluctuations will be captured by the spatial variability if there is rainfall at one location and no rainfall at a nearby location. A scoping analysis has indicated that the uncertainties in the bulk deposition velocity encompass a wide range where there is some wet deposition, and the Committee therefore considers that its approach has sufficiently captured the modelling uncertainties in the ATDM (for the purpose of estimating doses to residents).

18. Uncertainties in the ratios of the concentrations of ^{131}I (separately for elemental, organic and aerosol-bound forms), ^{132}Te/^{132}I and ^{134}Cs in air relative to the concentration of ^{137}Cs in air were assumed to follow a log-normal distribution with a geometric standard deviation of 1.5 (based on expert judgement). Additionally, the uncertainty of the gaseous and the aerosol-bound fraction was described by a normal distribution with an estimated standard deviation of 0.3. The uncertainty in the ^{133}I/^{131}I ratio at a given location was modelled by a log-normal distribution with a geometric standard deviation of 1.2 (based on expert judgement).

19. For the reduction in exposures from being indoors, the Committee has used new data experimentally derived for Japanese houses [Hirouchi et al., 2018]. The measured reduction factors ranged from less than 0.1 to approximately 1. The Committee has used a reduction factor of 0.5 as a central estimate, with an uncertainty described by a triangular distribution with minimum = 0.1, peak = 0.5 and maximum = 0.95 (as proposed by [Ohba et al., 2020]). The application of the reduction factor takes into account variabilities in the amount of time people spend indoors and outdoors according to the age group (represented by the occupancy factor), and the percentages of the population in different occupation categories (indoor worker, outdoor worker, pensioner), taken from the published literature and based on national statistical data for Japan (see attachment A-1 for further details).

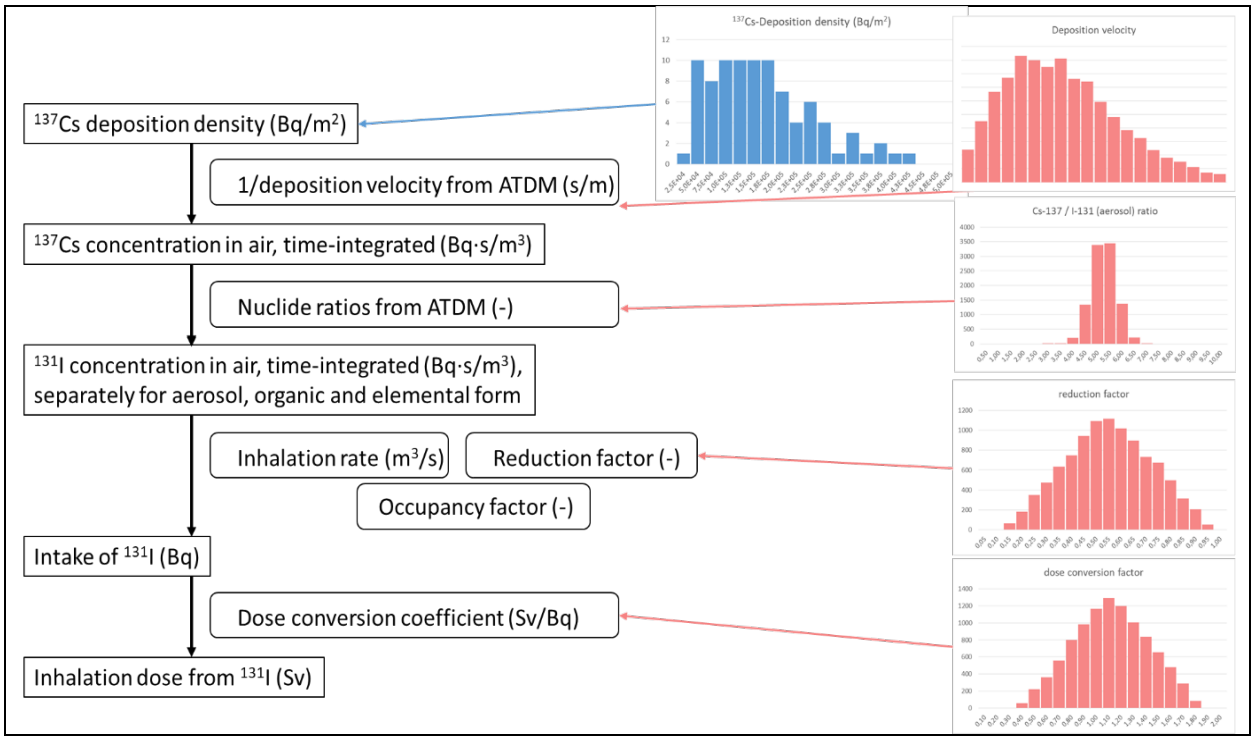
20. To estimate uncertainty in breathing rates, the Committee has assumed the breathing rates to be log-normally distributed about the International Commission on Radiological Protection (ICRP) standard values of the age-dependent breathing rates, with GSD = 1.3, as assigned by the United States National Cancer Institute [NCI, 1997].

21. The uncertainty in the Japan-specific dose conversion coefficients for iodine and tellurium isotopes was explicitly modelled by assuming a triangular distribution with minimum value = dose coefficient for Kelp-rich diet, peak value = dose coefficient for typical Japanese diet, and maximum value = dose coefficient for Western pattern diet.

22. As an example, figure A-12.II indicates how variability and uncertainty were considered with a probabilistic Monte Carlo approach for assessing doses from inhalation of ^{131}I for residents in municipalities in Fukushima Prefecture and neighbouring prefectures. For each

location where a deposition measurement exists a distribution of potential doses was calculated taking into account the uncertainty of the various model parameters as described in paragraphs 16 to 21 above. Finally, all these distributions were numerically combined to give an overall distribution of doses within one municipality by weighting each location-specific dose distribution with the ratio of the population around this location to the total population of the municipality. The resulting overall dose distribution describes the potential distribution of individual doses within one municipality.

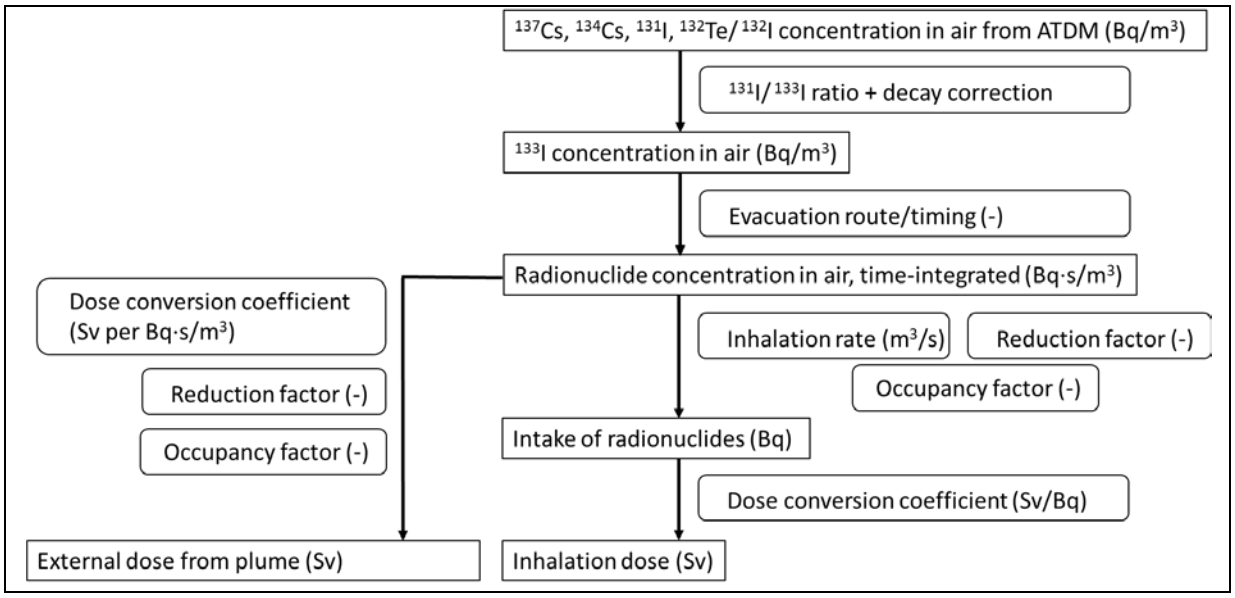
Figure A-12.II. Illustrative example of the modelling of variability (blue distribution) and uncertainty (red distributions) in the assessment of doses from inhalation of ^{131}I for residents



B. Assessment of uncertainties and variability in doses to evacuees from radionuclides in the air

23. Figure A-12.III shows the key modelling steps in assessing doses to evacuees from inhalation and external exposure from the plume. The key difference compared with the assessment of doses to residents is that estimates of exposure were based not on concentrations of radionuclides in air derived from measured deposition densities but on concentrations estimated directly from the source term and ATDM of Terada et al. [Terada et al., 2020]. This was because for evacuees information was needed about the time dependence of the concentrations of radionuclides in the air.

Figure A-12.III. Key modelling steps for the assessment of doses from inhalation and external exposure from the plume for evacuees



24. In this case, the main sources of uncertainty and variability that were judged by the Committee to significantly influence uncertainties in the estimated doses from exposure to radionuclides in the air are:

(a) Uncertainties and spatial variability of the modelled concentrations of radionuclides in air;

(b) Ratio of the concentration of the short-lived ^{133}I in air relative to the concentration of ^{131}I in air;

(c) Uncertainties in evacuation routes;

(d) Factor by which the concentration of radionuclides in air inside buildings is reduced compared with the concentration outdoors;

(e) Breathing rate of reference individuals in the exposed population (adult male, adult female, 10-year-old child, 1-year-old infant); and

(f) Dose coefficients for intakes of radioiodine and radiotellurium by inhalation.

25. As with doses to residents, the Committee judged that not taking explicit account of the uncertainties in the assumed occupancy factor, in the dose coefficients for intakes by inhalation of radionuclides other than radioiodine and radiotellurium, and uncertainties due to imperfections in the models used would not materially affect the estimates of uncertainties in doses. Other, additional, sources of uncertainty were not considered, including, specifically, uncertainties due to incomplete knowledge about the release rates of radionuclides over time and the weather conditions during the releases.

26. The exact timing of evacuation is a further, potentially important, source of uncertainty. In the evacuation scenarios defined by [Ohba et al., 2020], the timing of evacuation is specified with a 6-hour resolution. A limited scoping analysis has been performed which showed that the estimated doses to evacuees for 20 of the 40 evacuation scenarios were insensitive to the exact timing of the evacuation within these 6-hour periods. For the other 20 scenarios, the estimated doses would be significantly higher in most cases (and significantly lower in a few cases) if it were assumed that the evacuation started 6 hours later than indicated in the scenarios specified by [Ohba et al., 2020] – see attachment A-22 for more details. While this scoping analysis

demonstrated the potential importance of uncertainty in the timing of the evacuation, the Committee was unable to include it explicitly in its uncertainty analysis in the absence of further information on the uncertainty associated with this quantity.

27. Each evacuation scenario was modelled as a series of discrete time steps starting at the original location on 11 March 2011, progressing along the evacuation route (simplified as a straight line between the original location and the destination location after evacuation) and ending at the destination location. For each time step the nearest ATDM grid cell was identified and the air concentration at this grid cell at the relevant time was taken to be the air concentration for the time step. The time-integrated air concentration for the entire modelling period was then obtained by summing the air concentrations over all of the time steps.

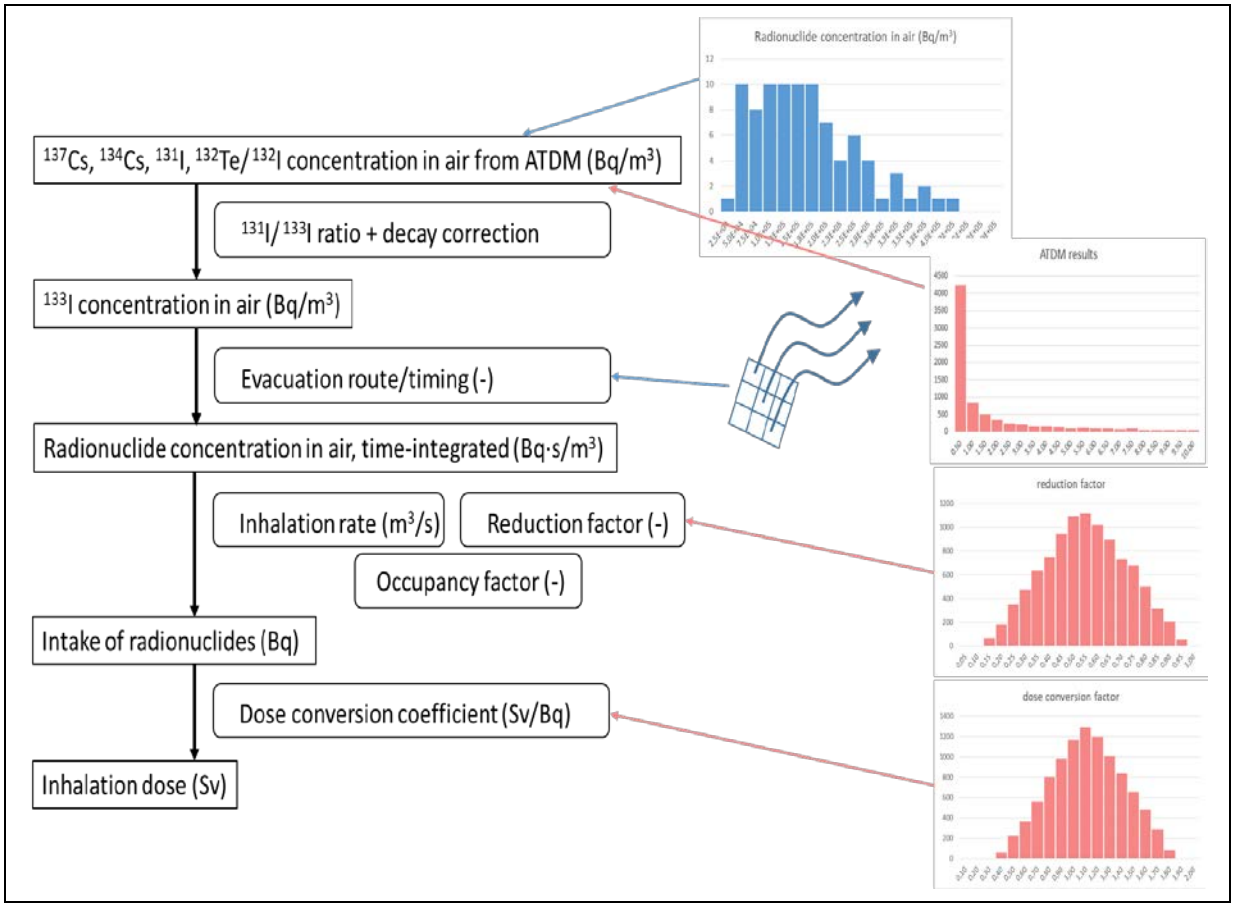
28. An assessment of the uncertainties in the concentrations of released radionuclides in air derived directly from ATDM is not straightforward, particularly given that the source term and ATDM have been derived by optimizing the agreement between the ATDM results and the considerable amount of measurement data, albeit largely of deposition density measurements. The comparison between ATDM estimates and the measurements of ^{137}Cs concentrations in air derived from SPM monitoring stations described in attachment A-9 indicates agreement within a factor of ten for about 70% of the measurements within or close to Fukushima Prefecture. Such a comparison, based on the time integrated concentration over the entire period of the releases from the FDNPS and all of the 23 measurements of air concentrations in or near to Fukushima Prefecture, would indicate a log-normal distribution with a GSD of about 5 for the PDF of air concentrations due to source term and ATDM uncertainties. Focusing on the few air concentration measurements within the evacuated areas and on the time periods when the evacuations were taking place leads to better agreement and could support the use of a lower GSD (see attachment A-9). However, the available measurements of concentrations of ^{137}Cs in air, and particularly those within the areas that were evacuated, are too sparse to provide a robust estimate of the uncertainties in the air concentrations of radiocaesium derived directly from ATDM. Of greater interest for inhalation doses are the air concentrations of radioiodine. These may be associated with greater uncertainty because radioiodine was assumed to be released in three different physico-chemical forms, in defined relative proportions, each with different deposition characteristics; there is even less information available to quantify these uncertainties. The Committee has therefore used expert judgement to quantify the uncertainties in the concentrations of all radionuclides in air estimated directly from ATDM. The uncertainty of air concentration estimates from ATDM at a given location have been assumed to be represented by a combination of*: (a)* the spatial variation of the air concentration derived from ATDM within a circular area with a radius of 3 km; and *(b)* a log-normal uncertainty distribution with a GSD of 3. A scoping calculation has shown that the 95th percentile of the distribution of doses to evacuees is relatively insensitive to the choice of GSD in the range of 3 to 5.

29. The uncertainty in evacuation routes was considered by assessing doses for a number of parallel evacuation routes (within a 3-km radius around the straight line connecting the start point and the destination of the evacuation as provided by Ohba et al. [Ohba et al., 2020]) and deriving the distribution of doses from the doses for these different routes.

30. Uncertainties in the reduction factor for the concentration of radionuclides in the air inside buildings, in the breathing rate, in the ratio of the gaseous and the aerosol-bound fraction of iodine, in the ^{133}I/^{131}I ratio and in the dose conversion factor for radioisotopes of iodine and tellurium were taken into account in the same manner as for residents (see section II.A). A sample size of 10,000 was used for the Monte Carlo simulations.

31. Figure A-12.IV indicates, as an example, how variability and uncertainty was considered with a Monte Carlo approach for assessing doses to evacuees from inhalation of ^{131}I.

Figure A-12.IV. Illustrative example of the modelling of variability (blue distributions, left) and uncertainty (red distributions, right) in the assessment of doses from inhalation of ^{131}I for evacuees



C. Assessment of uncertainties and variability in external doses from deposited radionuclides

32. Doses to members of public from exposure to radioactive material deposited in the terrestrial environment following the accident at FDNPS were calculated as summarized below (also described in more detail in attachment A-1).

33. The integrated doses for various age and social population groups, for evacuees and those returning subsequently to their homes were estimated using the following equation:

$$D(t_1, t_2|a_0) = c \int_{t_1}^{t_2} \dot{D}(x|a_0)\mathrm{d}x \qquad \text{(A-12.4)}$$

where $\dot{D}(t|a_0)$ is the rate of the dose quantity of interest, effective or organ equivalent dose; a_0 is the age when accidental radiation exposure started for the considered population group; times t_1 and t_2 bound the exposure period; and the unit conversion coefficient c depends on the selected dimensions of the quantities used (time, deposition density, dose rate coefficients, decay data, and half-lives).

34. The dose rate was evaluated as:

$$\dot{D}(t|a_0) = r(t) q_{\text{Cs-137}} \sum_m \rho_m \; e^{-\lambda_m t} \dot{d}_m(a+t) \sum_j f_j(t) p_j(a+t) \qquad \text{(A-12.5)}$$

where $q_{\text{Cs-137}}$ is the deposition density of ^{137}Cs (Bq/m^2) on 15 March 2011 (the assumed time of the deposition); $r(t)$ is the empirical two-exponential function describing dose reduction due to natural processes of redistribution (downward migration, weathering, run-off); ρ_m is the ratio of the deposition density of radionuclide *m* to that of ^{137}Cs on 15 March 2011 (unitless); λ_m is its radioactive decay rate (s^{-1}); $\dot{d}_m(a+t)$ is the corresponding age-dependent dose rate coefficient for radionuclide *m* including also the effect of its radioactive progeny; $f_j(t)$ is the time-dependent location factor, i.e. a ratio of the ambient dose rate in air in a specific location, *j*, to that above open ground undisturbed from the moment of deposition (unitless); and $p_j(a+t)$ is the fraction of time spent by the individual of age $a+t$ in the location *j*.

35. The sources of uncertainty and variability that the Committee has included in assessing the uncertainties in the estimated doses from external exposure to deposited radionuclides are:

(a) Spatial variability of the deposition density of ^{137}Cs ($q_{\text{Cs-137}}$);

(b) Dose rate reduction factor ($r(t)$);

(c) Ratio of the deposition density of radionuclide *m* to that of ^{137}Cs (ρ_m);

(d) Dose rate coefficient for radionuclide *m* ($\dot{d}_m(a+t)$);

(e) Location factor ($f_j(t)$); and

(f) Occupancy factor ($p_j(a+t)$).

36. The Committee has taken explicit account of each of these uncertainties or variabilities when evaluating uncertainties in its estimates of dose. Other sources of uncertainty or variability (e.g., uncertainties in the measurements of deposition densities of radionuclides, and uncertainties due to imperfections in the models used) have again been judged not to materially affect its estimates of uncertainties in doses.

37. The spatial variability of the deposition density was based on the spatial variability of the measurement data. The uncertainty associated with assuming that the ^{137}Cs deposition density measured at a particular location is representative of the area averaged value has been taken to be log-normally distributed with an estimated GSD of 1.5. The dose rate coefficients [ICRP, 2020] were assumed to follow normal distributions with the 95% confidence interval specified by a relative uncertainty of 20%. The empirical dose rate reduction function was assumed to be log-normally distributed with a GSD of 1.2, for integration periods of 1 and 10 years after the accident, and with a GSD of 1.3 for longer integration periods, to address higher uncertainty due to extrapolation of the fitted function beyond the data-supported domain. Isotopic ratios ρ_m were also assumed to be log-normally distributed with a GSD of 1.1 for all radionuclides except for ^{131}I, for which the uncertainty in the mean value was expressed by a GSD of 1.5 to reflect the higher variability observed in the measured data. Uncertainty specific to location and occupancy factors was evaluated as corresponding to log-normally distributed quantities with a GSD of 1.2; correspondingly, the uncertainty of the combined factor was taken as represented by a GSD of 1.3, assuming statistical independence of both factors. Sample size in the stochastic simulations was chosen equal to 10,000.

38. This Monte Carlo technique was applied to generate PDFs for different ages, types of occupancy and periods of exposure. The main statistical properties of the generated PDFs for the cumulative external doses from deposited radionuclides are summarized in table A-12.1. Specifically, the ratios of the estimated geometric mean (GM) and 5th and 95th percentiles to the corresponding arithmetic mean (AM) of a generated distribution were calculated. These ratios for different population groups were found to be very similar, so only the group-averaged values are shown in table A-12.1.

Table A-12.1. Statistical characteristics of the uncertainty PDFs, expressed as a ratio to the corresponding arithmetic mean, associated with estimates of cumulative external doses from deposited radionuclides

Exposure period	*5th percentile*	*GM*	*AM*	*95th percentile*
1 year	0.54	0.94	1	1.66
10 years	0.54	0.94	1	1.66
Lifetime	0.49	0.93	1	1.76

D. Assessment of uncertainties and variability in dose from ingestion

39. The assessment of uncertainties and variability in doses from ingestion is based to a large extent on Murakami and Oki [Murakami and Oki, 2014]. In this study variations in individual ingestion doses to adults in the first year were estimated by Monte Carlo simulations, which took account of:

(a) Variability in radionuclide concentrations in drinking water;

(b) Uncertainty in the daily consumption of drinking water;

(c) Variability in radionuclide concentrations in foods; and

(d) Uncertainty in the daily consumption of each foodstuff.

40. Other sources of uncertainty considered, but not explicitly assessed, by Murakami and Oki included the treatment of measurements that were below the minimum detection limits and differences in individual behaviours. They compared their results with the results of market-basket and duplicate diet studies to validate their approaches, and also estimated doses for a more conservative scenario regarding the source of some foods, but estimated doses for this scenario were not included in the percentile intervals adopted by the Committee.

41. Murakami and Oki [Murakami and Oki, 2014] assumed the uncertainties in the daily consumption of drinking water and in the daily consumption of each foodstuff were log-normally distributed, based on the results of surveys and other research; variabilities in radionuclide concentrations were based on measurement data. The Committee has used the uncertainties estimated by Murakami and Oki (table 2 in [Murakami and Oki, 2014],) together with expert judgement to derive percentile intervals (5–95%) for doses from ingestion (of ^{131}I, ^{134}Cs and ^{137}Cs). These were conservatively estimated to be 0.3 and 3.0 times the average doses. This is equivalent to a geometric standard deviation of about 1.9. For doses from ingestion of drinking water to evacuees prior to their evacuation, smaller uncertainty ranges were assumed (a ratio of 1.7 between 95% and average values), equivalent to a geometric standard deviation of about 1.4. Given the relatively small contribution of ingestion doses to the total doses, the Committee considers that applying these assumptions to all doses from foodstuffs is justified.

E. Combination of doses from different exposure pathways

42. As indicated in section I, the doses to members of the public from each of the exposure pathways described above have been combined to estimate total doses in the population groups considered (groups of evacuees according to each evacuation scenario, residents of municipalities in Fukushima Prefecture and four neighbouring prefectures, residents of prefectures in all other prefectures) by applying a Monte Carlo approach to generate samples of individual doses from each pathway separately and then adding up the sampled doses to give a sample of total dose (assuming statistical independence between the various pathways). The main statistical properties (e.g., mean, median, 95% coverage interval) were then derived from the resulting distributions of total doses. These statistical properties are presented in detail for each population group in attachments A-13 to A-19.

43. A Monte Carlo approach has similarly been applied to estimate the distribution (and statistical properties) of the average dose in each population group. These distributions of the average doses have been used, inter alia, for the purposes of the power calculations used to assess the health implications of the exposures (see attachment A-23 for further details).

REFERENCES

Hirouchi, J., S. Takahara, H. Komagamine et al. Investigation of reduction factor of internal exposure for sheltering in Japan. ASRAM2018. Asian Symposium on Risk Assessment and Management, Xiamen, China, 2018.

ICRP. Dose coefficients for external exposures to environmental sources. ICRP Publication 144. Annals of the ICRP 49(2). International Commission on Radiological Protection, Elsevier Ltd., 2020.

ISO. Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation – Fundamentals and application – Part 2: Advanced applications. International Organization for Standardization. ISO 11929-2:2019 (2019).

JCGM. Guides in metrology. GUM: Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology. [Internet] Available from (https://www.bipm.org/en/publications/guides/).

JCGM. Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). Supplement 1: Propagation of distributions using a Monte Carlo method. Joint Committee for Guides in Metrology (JCGM 101:2008). ISO/IEC Guide 98-3/Suppl.1:2008 (2008a).

JCGM. Uncertainty of measurement. Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). Joint Committee for Guides in Metrology (JCGM 100:2008). ISO/IEC Guide 98-3:2008 (2008b).

JCGM. International vocabulary of metrology – Basic and general concepts and associated terms (VIM), 3rd edition. Joint Committee for Guides in Metrology (JCGM 200:2012). ISO/IEC Guide 99 (2012).

Murakami, M. and T. Oki. Estimated dietary intake of radionuclides and health risks for the citizens of Fukushima City, Tokyo, and Osaka after the 2011 nuclear accident. PLOS ONE 9(11): e112791 (2014).

NCI. Estimated exposures and thyroid doses received by the American people from iodine-131 in fallout following the Nevada atmospheric nuclear bomb tests. DHHS/NIH/NCI, National Cancer Institute, Bethesda, 1997.

Nishihara, K., H. Iwamoto and K. Suyama. Estimation of fuel compositions in Fukushima-Daiichi Nuclear Power Plant. JAEA-Data/Code 2012-018. Japan Atomic Energy Agency, Tokaimura, 2012.

Ohba, T., T. Ishikawa, H. Nagai et al. Reconstruction of residents' thyroid equivalent doses from internal radionuclides after the Fukushima Daiichi nuclear power station accident. Sci Rep 10(1): 3639 (2020).

Terada, H., H. Nagai, K. Tsuduki et al. Refinement of source term and atmospheric dispersion simulations of radionuclides during the Fukushima Daiichi Nuclear Power Station accident. J Environ Radioact 213: 106104 (2020).

UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. Volume I: Report to the General Assembly and Scientific Annex A. UNSCEAR 2013 Report. United Nations Scientific Committee on the Effects of Atomic Radiation. United Nations sales publication E.14.IX.1. United Nations, New York, 2014.