United Nations Scientific Committee on the Effects of Atomic Radiation

ATTACHMENT A-10

METHODOLOGY FOR ESTIMATING EXTERNAL DOSES FROM THE PLUME AND INTERNAL DOSES FROM INHALATION OF RADIONUCLIDES IN THE PLUME

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 methodology used for assessing doses to the public from inhalation of, and external radiation from, radioactive material released to the atmosphere during the accident at Fukushima Daiichi Nuclear Power Station (FDNPS).

Notes

This publication has not been formally edited.

CONTENTS

I. INTRODUCTION

1. This attachment describes the methodology used for assessing doses to the public from inhalation of, and external radiation from, radioactive material released to the atmosphere during the accident at FDNPS. The estimates of effective, thyroid, red bone marrow, colon and breast doses have been based on environmental measurements and realistic models and assumptions.

2. The Committee focused on four groups of geographical areas of Japan:

- Group 1 included municipalities in Fukushima Prefecture where members of the public were evacuated in the days to months after the accident;
- Group 2 included all non-evacuated municipalities of Fukushima Prefecture;
- Group 3 included selected prefectures in eastern Japan that were neighbouring Fukushima Prefecture (Ibaraki, Miyagi, Tochigi and Yamagata prefectures);
- Group 4 included all of the remaining 42 prefectures of Japan.

3. The age groups considered were the three standard age groups (1-year-old infant, 10-year-old child and adult) defined by the International Commission of Radiological Protection (ICRP). Account has been taken of uncertainty in the estimated doses and variability between individuals depending on their location, lifestyle and habits etc. (see attachment A-12).

II. METHODOLOGY FOR ESTIMATION OF EXTERNAL DOSE FROM RADIOACTIVE PLUMES

4. Insufficient measurements of dose rates and concentrations of radionuclides in air were available for the estimation of dose received over the first few days after the start of the release. The concentrations in air were therefore obtained from the results of atmospheric transport, dispersion and deposition models (ATDM). These modelling results were used either directly (for doses to evacuees) or in combination with the measurement data on the deposition density of radionuclides (for doses to permanent residents) to estimate concentrations in air for the purposes of assessing doses to the public (see attachment A-9 for further details). A semi-infinite cloud model was used to estimate the doses from external exposure from the time-integrated concentrations in the air.

5. Terada et al. [Terada et al., 2020] did not provide estimates of the concentrations of ^{133}Xe in air, and the contribution of ^{133}Xe has not been included in the Committee's updated dose estimates. The Committee has, however, carried out some scoping calculations to assess its possible contribution to the estimated doses. Moriguchi et al. [Moriguchi et al., 2019] derived a ratio of the air concentration of ^{133}Xe to that of ^{137}Cs of 800 from Nishihara et al. [Nishihara et al., 2012], and this ratio is broadly consistent with the ratio of the air concentration of ^{133}Xe to that of ^{131}I derived from the few available measurements of ^{133}Xe in air reported by Terasaka et al. [Terasaka et al., 2016]. If a ratio of 800 is assumed, then including ^{133}Xe would increase the effective dose to adults from external exposure to the plume of airborne radioactive material by about 30%. If account is also taken of the contribution of ^{133}Xe to the effective dose from inhalation (to reflect its tissue solubility), then the effective dose from inhalation would increase by less than 0.1%. As the effective dose from external exposure to radioactive material in the

plume is generally only 1–3% or less of the effective dose from inhalation of radioactive material in the plume, including the contribution of ^{133}Xe would have increased the total effective dose from exposure to the plume by less than 1%. This contribution is small in comparison with the uncertainties in the dose estimates.

A. Computational model

1. Doses to evacuees

6. The dose E_i^{cl} from external exposure to radionuclides in the radioactive plume was estimated from the modelled radionuclide concentrations in the surface air (as provided by the ATDM model from [Terada et al., 2020] – see attachment A-9) using the following equation:

$$E_i^{cl} = 10^{-6} \cdot RF_i^{cl} \cdot \sum_m e_{m,i}^{cl} \cdot \int_0^{T_{cl}} C_m^{air}(t) \cdot dt \text{ (mSv)} \qquad \text{(A-10.1)}$$

where:

- $e_{m,i}^{cl}$ is the dose-rate conversion coefficient for a semi-infinite volume source in air equal to the ratio of the dose rate for the representative person of population group, i, to uniform activity concentration of radionuclide, m, in air (nSv/h per Bq/m^3 or nGy/h per Bq/m^3) (see table A-10.3);
- RF_i^{cl} is the aggregated dose reduction factor for external exposure from radionuclides in air (dimensionless); this aggregated reduction factor is calculated from sum of the products of f_j and p_{ij}, where f_j is the ratio of dose rate from external exposure from the plume at location, j (e.g., outdoors, or inside houses or at workplaces) to the dose rate at an undisturbed open field under an semi-infinite radioactive plume; p_{ij} is the fraction of time spent by the representative of population group, i, in the typical location, j;
- T_{cl} is the time duration of human exposure from the passage of a radioactive plume over a site of interest (h);
- C_m^{air} is the time-dependent concentration of radionuclide, m, in surface air (Bq/m^3).

7. This approach was applied to evacuees, where the time duration of exposure depended on the evacuation scenario. Further details about the evacuation scenarios considered by the Committee are presented in attachment A-11.

2. Doses to residents

8. For all other population groups, the time-integrated concentration in air was estimated from measurements of the deposition density of radionuclides by scaling by the ratio of the deposition density to the time-integrated air concentration estimated using ATDM (the “bulk deposition velocity” see attachment A-9). The external dose E_i^{cl} from radionuclides in the radioactive plume was calculated from measurements of the deposition density of radionuclides as follows:

$$E_i^{cl} = 2.8 \cdot 10^{-10} \cdot RF_i^{cl} \cdot \sum_m \frac{A_m}{V_m} \cdot e_{m,i}^{cl} \text{ (mSv)} \qquad \text{(A-10.2)}$$

where A_m is the measured deposition density of radionuclide, *m*, on the ground (Bq/m^2); V_m is the "bulk deposition velocity" of radionuclide, *m*, estimated from ATDM (m/s), which is location dependent; and the other symbols are the same as above.

B. Model parameters

9. The Committee used the latest ICRP Publication 144 [ICRP, 2020] to provide the dose coefficients for air kerma, ambient dose equivalent and effective dose, as well as for equivalent organ doses for six age groups and both sexes (only adults). Values of dose-rate conversion coefficients for photon exposure from submersion in a radioactive plume and for the full list of radionuclides considered in the Committee's dose assessment are shown in table A-10.1.

Table A-10.1. Effective dose-rate conversion coefficients and absorbed dose-rate conversion coefficients for the thyroid for photon exposure from submersion in a radioactive plume [ICRP, 2020]

Radionuclide	*Effective dose coefficient ((nSv/h) per (Bq/m^3))*			*Thyroid dose coefficient ((nGy/h) per (Bq/m^3))*		
	1 year	*10 years*	*Adult*	*1 year*	*10 years*	*Adult (male)*
^{131}I	0.066	0.061	0.056	0.071	0.073	0.068
^{133}I	0.109	0.100	0.094	0.111	0.114	0.108
^{132}Te (+^{132}I)	0.449	0.413	0.390	0.453	0.466	0.435
^{134}Cs	0.279	0.256	0.242	0.283	0.289	0.272
^{137}Cs (+^{137m}Ba)	0.105	0.092	0.087	0.101	0.104	0.098

10. The durations of the passage of the main radioactive plumes were relatively short (a few hours) and the contribution to dose from external exposure from the plumes was small compared with that from deposited radionuclides. As little information was available to the Committee about the shielding effects of Japanese house types for external exposure from the plume, the same dose reduction factor was assumed as for external exposure from the ground (see attachments A-1 and A-4).

11. Implicit in this approach is the simplifying assumption that the concentrations of radionuclides in air were uniform over the volume of a plume from which photons can reach the point at which the dose was delivered. The Committee considered this assumption to be reasonable because the nearest population groups to the release point resided at least a few kilometres away.

III. METHODOLOGY FOR ESTIMATION OF INTERNAL DOSE FROM INHALATION OF RADIONUCLIDES

12. The assessment of dose from the inhalation of radionuclides in air was based on the concentrations of radionuclides in air estimated using ATDM (see attachment A-9), either directly or in combination with the measurement data on the deposition density of radionuclides, the age-dependent breathing rates and the appropriate dose conversion coefficients (i.e., the radiation dose that results from breathing in a unit amount of a radionuclide) specific to a Japanese population (see attachments A-2 and A-4).

A. Computational model

1. Doses to evacuees

13. The dose E_i^{inh} from the inhalation of airborne radionuclides was estimated on the basis of modelled radionuclide concentrations in the surface air (as provided by the ATDM model from [Terada et al., 2020]):

$$E_i^{inh} = 10^3 \cdot \nu_i \cdot RF_i^{inh} \cdot \sum_m e_{m,i}^{inh} \cdot k_m \cdot \int_0^{T_{cl}} C_m^{air}(t) \cdot dt \text{ (mSv)} \qquad \text{(A-10.3)}$$

where:

- ν_i is the age-dependent breathing rate (m^3/s);
- RF_i^{inh} is the aggregated dose reduction factor for inhalation of radionuclides in the air (dimensionless); this aggregated reduction factor was calculated from the sum of the products of f_j and p_{ij}, where f_j is the ratio of dose rate from internal exposure from inhalation of radionuclides from the plume at location *j* to the dose rate at an undisturbed open field in the radioactive plume; p_{ij} is the fraction of time spent by the representative of population group, *i*, in the typical location, *j*;
- $e_{m,i}^{inh}$ is the dose conversion coefficient for the committed dose to the representative person of population group, *i*, from the inhalation of unit amount (1 Bq) of radionuclide, *m*, under reference conditions (a default particle size of 1 µm and typical absorption type) (Sv/Bq);
- k_m is the factor accounting for particle size and absorption type for radionuclide, *m*, that are different from those assumed under reference conditions (dimensionless);
- T_{cl} is the time duration of inhalation from a radioactive plume passing over the site of interest (*h*);
- C_m^{air} is the time-dependent concentration of radionuclide, *m*, in surface air (Bq/m^3) as provided by the ATDM model from Terada et al. [Terada et al., 2020]; for iodine isotopes three different chemical forms were considered separately in the ATDM model as well as in the dose assessment.

2. Doses to residents

14. The dose from the inhalation of radionuclides in the air was calculated from measurements of the deposition density of radionuclides as follows:

$$E_i^{inh} = 10^3 \cdot \nu_i \cdot RF_i^{inh} \cdot \sum_m \frac{A_m}{V_m} \cdot e_{m,i}^{inh} \cdot k_m \text{ (mSv)} \qquad \text{(A-10.4)}$$

where A_m is the measured deposition density of radionuclide, *m*, on the ground (Bq/m^2); V_m is the “bulk deposition velocity” of radionuclide, *m*, estimated from ATDM (m/s), which is location dependent; and the other symbols are the same as above.

B. Model parameters

15. The Committee has used a new model to derive dose coefficients specific to the Japanese population reflecting differences in their intakes of stable iodine and fractional thyroid uptake U (see attachment A-2). Dose coefficients were calculated for inhalation of various physico-chemical forms of ^{131}I, ^{132}I, ^{133}I and ^{132}Te and three types of the diet: a typical Japanese diet (U=15%), a kelp-rich diet (U=5%), and a Western pattern diet (with the reference value of U of about 30%) that is popular among some groups of the Japanese population. Dose coefficients were derived for absorbed dose in the thyroid, red bone marrow, female breast and colon as well as for effective dose, from inhalation of aerosols of Type F, activity median aerodynamic diameter (AMAD)=1 µm, and for methyl iodide and elemental iodine. The population-specific dose coefficients used by the Committee can be found in attachment A-4 and are for people with a typical Japanese diet; values for effective dose and absorbed dose in the thyroid for inhalation of ^{131}I, ^{132}I, ^{133}I and ^{132}Te are listed in table A-10.2.

Table A-10.2. Japan-specific dose coefficients for inhalation of ^{131}I, ^{132}I, ^{133}I in three chemical forms and of ^{132}Te in aerosol form by members of the public with a dietary intake of stable iodine typical for Japan (U=15%), i.e., effective dose per exposure and thyroid absorbed dose per exposure

Radio-nuclide	*Radionuclide form*	*Effective dose per exposure (Sv per (Bq·s/m^3))*			*Thyroid absorbed dose per exposure (Gy per (Bq·s/m^3))*		
		1-year-old	*10-year-old*	*Adult*	*1-year-old*	*10-year-old*	*Adult (male)*
^{131}I	Aerosol[a]	2.0×10^{-12}	1.6×10^{-12}	9.6×10^{-13}	4.8×10^{-11}	3.7×10^{-11}	2.1×10^{-11}
	Methyl iodide	2.7×10^{-12}	2.4×10^{-12}	1.6×10^{-12}	6.7×10^{-11}	5.8×10^{-11}	3.6×10^{-11}
	Elemental iodine	4.1×10^{-12}	3.7×10^{-12}	2.3×10^{-12}	9.5×10^{-11}	8.3×10^{-11}	5.1×10^{-11}
^{132}I	Aerosol[a]	7.2×10^{-14}	7.2×10^{-14}	1.5×10^{-14}	3.4×10^{-13}	2.3×10^{-13}	1.3×10^{-13}
	Methyl iodide	4.6×10^{-14}	4.0×10^{-14}	2.9×10^{-14}	7.9×10^{-13}	5.9×10^{-13}	3.5×10^{-13}
	Elemental iodine	4.7×10^{-13}	6.8×10^{-13}	6.4×10^{-14}	1.0×10^{-12}	7.4×10^{-13}	4.4×10^{-13}
^{133}I	Aerosol[a]	5.0×10^{-13}	3.7×10^{-13}	1.7×10^{-13}	9.8×10^{-12}	6.3×10^{-12}	3.5×10^{-12}
	Methyl iodide	6.4×10^{-13}	4.9×10^{-13}	3.2×10^{-13}	1.5×10^{-11}	1.1×10^{-11}	6.5×10^{-12}
	Elemental iodine	1.3×10^{-12}	1.2×10^{-12}	4.7×10^{-13}	2.1×10^{-11}	1.6×10^{-11}	9.2×10^{-12}
^{132}Te	Aerosol[a]	4.9×10^{-13}	4.2×10^{-13}	2.2×10^{-13}	5.4×10^{-12}	3.6×10^{-12}	2.1×10^{-12}

[a] Type F, AMAD=1 µm.

16. The values of the dose conversion coefficients for inhalation of ^{134}Cs and ^{137}Cs were taken from ICRP Publication 71 [ICRP, 1995], see table A-10.3. These were based on generic anatomical and physiological human data for a reference person, as defined by ICRP, and as such are not intended to be specific to inhabitants of any specific region.

Table A-10.3. Committed dose coefficients for inhalation of ^{134}Cs and ^{137}Cs by members of the public [ICRP, 1995]

Radionuclide	*Radionuclide form[a]*	*Effective dose per exposure (Sv per (Bq·s/m^3))*			*Thyroid absorbed dose per exposure (Gy per (Bq·s/m^3))*		
		1-year-old	*10-year-old*	*Adult*	*1-year-old*	*10-year-old*	*Adult (male)*
^{134}Cs	Aerosol	4.4×10^{-13}	9.4×10^{-13}	1.7×10^{-12}	3.8×10^{-13}	9.0×10^{-13}	1.6×10^{-12}
^{137}Cs	Aerosol	3.3×10^{-13}	6.5×10^{-13}	1.2×10^{-12}	2.6×10^{-13}	6.2×10^{-13}	1.1×10^{-12}

[a] Type F, AMAD=1 µm.

17. Values of the age-dependent breathing rates, v_i, on which the dose coefficients per unit exposure in tables A-10.2 and A-10.3 were based are shown in table A-10.4, and were taken from ICRP Publication 66 [ICRP, 1994]. The inhalation rates applied are the average rates over a day from the ICRP model of the respiratory tract and include time spent sleeping, at home and at work, and hence they are suitable for someone exposed for 24 hours a day.

Table A-10.4. Age-dependent breathing rates, v_i, from ICRP [ICRP, 1994]

Age group	*Inhalation rate (m^3/s)*
Adult (outdoor worker)	2.92×10^{-4}
Adult (indoor worker or pensioner)	2.57×10^{-4}
10-year-old	1.77×10^{-4}
1-year-old	6.02×10^{-5}

18. In the absence of any more specific information, the default particle size and absorption types specified by ICRP [ICRP, 1995] were assumed, that is, k_m was taken as one.

19. Hirouchi et al. [Hirouchi et al., 2018] have presented new data for the reduction factor (f_j) of internal exposure to take account of the filtering of air inside buildings (i.e., the ratio of the indoor to the outdoor cumulative radionuclide concentrations or doses), which has been experimentally derived for Japanese houses. The reduction factors ranged from less than 0.1 to approximately 1. In the UNSCEAR 2013 Report [UNSCEAR, 2014] no reduction to account for such filtering effect was assumed (i.e., reduction factor of 1 was assumed). The study of Hirouchi et al. indicates that lower reduction factors are more realistic for Japanese houses (especially for post-1992 buildings). The Committee has therefore used a reduction factor of 0.5 (with an uncertainty range of 0.1 to 0.95) in its updated assessment of internal doses from inhalation of radionuclides when staying indoors, which allows for a more realistic estimation of doses from inhalation.

20. The same values for p_{ij}, the fraction of time spent by the representative of population group, i, in the typical location, j, have been used as in the methodology for assessing external dose from deposited radionuclides (see attachments A-1 and A-4). These are listed in table A-10.5.

Table A-10.5. Fraction of time (occupancy factors) spent in various locations by the reference representative of the considered population groups

Type of location	*Occupancy factors for a population group*			
	Children		*Adult worker*	
	1-year-old	*10-year-old*	*Outdoor*	*Indoor*
Indoors, including:	0.9	0.9	0.7	0.9
At home and others	0.7	0.7	0.7	0.6
At work, school, kindergarten, etc.	0.2	0.2		0.3
Outdoors, including:	0.1	0.1	0.3	0.1
Residential areas	0.1	0.1	0.2	0.1
Unpaved surfaces			0.1	

21. The values of “bulk deposition velocity”, V_m, for radionuclide, m, were derived from the ATDM calculations as the ratios of the modelled estimates of the deposition density to the modelled estimates of the time-integrated concentration in air (see attachment A-9).

IV. CONTRIBUTION OF SHORT-LIVED RADIONUCLIDES TO THE INHALATION DOSE

22. This section presents an analysis of the contribution of short-lived radionuclides to the thyroid dose from inhalation of radioactive material released from FDNPS. The short-lived radionuclides considered here include only ^{132}Te (together with its daughter ^{132}I, which is typically in secular equilibrium due to the much shorter half-life of ^{132}I of 2.3 hours compared to the half-life of ^{132}Te of 3.2 days) and ^{133}I; the contribution of all other shorter lived radionuclides (e.g., ^{129}Te, ^{129m}Te, ^{131m}Te, ^{135}I, ^{136}Cs) to the total dose from inhalation is small by comparison (see e.g., [Ohba et al., 2017]).

23. Table A-10.6 shows the estimated contribution of short-lived radionuclides to the thyroid dose from inhalation for some locations in Fukushima Prefecture and Miyagi Prefecture. Median values, 5th and 95th percentiles are presented, which have been derived from the results of all cells of the ATDM grid within a radius of about 6 km around the centre of each location (i.e., these statistical values have been derived from all ATDM results within an area of about 110 km^2, corresponding to about 110 grid cells in the ATDM local model and about 13 in the ATDM regional model).

24. The results show that areas with relatively high contributions of short-lived radionuclides to the inhalation doses are located mainly north-west of FDNPS (up to a distance of about 10 km, e.g., in the municipality of Futaba). In this area the contribution of ^{132}Te/^{132}I and ^{133}I together can reach up to about 50% of the contribution of the dose from ^{131}I.

25. Another area with relatively high contributions of short-lived radionuclides is located in the north-eastern part of Miyagi Prefecture (see location Tome in table A-10.6), where the contribution of ^{132}Te/^{132}I and ^{133}I together can reach up to about 40% of the dose from ^{131}I (although the total doses in this area are relatively low, especially if compared to doses in the eastern parts of the Fukushima Prefecture).

26. In most other areas the contributions of short-lived radionuclides to the inhalation doses are significantly lower, typically being between 0% and 20% of that from ^{131}I, with most of the values in the lower part of this range. In Fukushima City for example, the median value of the contribution of short-lived radionuclides is about 3%, and it is about 8% for Iwaki City.

27. The differences in the contribution of short-lived radionuclides to the inhalation doses can be explained by the contribution of different plumes to the time-integral of the concentration of radionuclides in air: those areas with relatively high contributions of short-lived radionuclides were mainly affected by the first plume emitted from FDNPS on the afternoon of 12 March 2011. All later plumes – and thus in all areas which were mainly affected by these later plumes – had significantly lower contributions from short-lived radionuclides relative to the first plume (i.e., the later plumes were emitted 2.5 to 10 days later than the first plume).

28. The estimated contributions of short-lived radionuclides to inhalation doses are broadly consistent with the findings of others. Ohba et al. [Ohba et al., 2020] estimated the contribution to be 59% (relative to that of ^{131}I) for the plume released on 12–13 March 2011, and 8% for the plumes released on 15–16 March 2011; Shinkarev et al. [Shinkarev et al., 2015] estimated the contribution to be as great as 30–40% for the plume released on 12 March 2011.

Table A-10.6. Contribution of short-lived radionuclides to the thyroid dose from inhalation (relative to the contribution of ^{131}I)

Location	*Contribution of short-lived radionuclides to thyroid dose to 1-year-old infants relative to that from ^{131}I*								
	(^{132}Te + ^{132}I)/^{131}I			*^{133}I/^{131}I*			*(^{132}Te + ^{132}I + ^{133}I)/^{131}I*		
	Median	*5th %ile*	*95th %ile*	*Median*	*5th %ile*	*95th %ile*	*Median*	*5th %ile*	*95th %ile*
Fukushima City	0.01	0.01	0.02	0.01	0.01	0.02	0.03	0.02	0.04
Futaba	0.05	0.04	0.12	0.06	0.02	0.28	0.14	0.06	0.36
Iwaki City	0.06	0.05	0.10	0.02	0.01	0.07	0.08	0.07	0.16
Sendai	0.02	0.01	0.04	0.04	0.02	0.21	0.06	0.03	0.24
Tome	0.04	0.03	0.06	0.31	0.23	0.36	0.35	0.26	0.42

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