SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCEAR 2016
Report to the General Assembly, with Scientific Annexes

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NOTE

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ANNEX A

METHODOLOGY FOR ESTIMATING PUBLIC EXPOSURES DUE TO RADIOACTIVE DISCHARGES

15 December 2020

Sources, Effects and Risks of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation 2016 Report to the General Assembly, with Scientific Annexes

Corrigendum

1. Annex A (Methodology for estimating public exposures due to radioactive discharges), page 81, table 25

Column headed "Asia and Pacific"

In the entry for radionuclide ^{54}Mn, *for* 5.3×10^{-9} *read* 2.7×10^{-9}

In the entry for radionuclide ^{58}Co, *for* 8.6×10^{-10} *read* 4.6×10^{-10}

In the entry for radionuclide ^{60}Co, *for* 2.6×10^{-9} *read* 1.5×10^{-9}

In the entry for radionuclide ^{65}Zn, *for* 3.7×10^{-9} *read* 3.6×10^{-9}

In the entry for radionuclide ^{106}Ru[a], *for* 6.0×10^{-11} *read* 3.7×10^{-11}

In the entry for radionuclide ^{131}I, *for* 8.8×10^{-14} *read* 7.1×10^{-14}

In the entry for radionuclide ^{134}Cs, *for* 3.1×10^{-11} *read* 2.1×10^{-11}

In the entry for radionuclide ^{137}Cs[a], *for* 1.5×10^{-11} *read* 1.2×10^{-11}

In the entry for radionuclide ^{232}Th[a], *for* 1.6×10^{-8} *read* 1.1×10^{-8}

In the entry for radionuclide ^{238}U[a], *for* 3.3×10^{-11} *read* 3.2×10^{-11}

In the entry for radionuclide ^{241}Am, *for* 1.2×10^{-9} *read* 1.1×10^{-9}

Column headed "Europe"

In the entry for radionuclide ^{54}Mn, *for* 5.2×10^{-9} *read* 2.6×10^{-9}

In the entry for radionuclide ^{58}Co, *for* 8.3×10^{-10} *read* 4.3×10^{-10}

In the entry for radionuclide ^{60}Co, *for* 2.5×10^{-9} *read* 1.3×10^{-9}

In the entry for radionuclide ^{65}Zn, *for* 2.1×10^{-9} *read* 2.0×10^{-9}

In the entry for radionuclide ^{106}Ru[a], *for* 5.2×10^{-11} *read* 2.9×10^{-11}

In the entry for radionuclide ^{131}I, *for* 8.5×10^{-14} *read* 6.8×10^{-14}

In the entry for radionuclide ^{134}Cs, *for* 3.2×10^{-11} *read* 2.3×10^{-11}

In the entry for radionuclide ^{137}Cs[a], *for* 1.6×10^{-11} *read* 1.3×10^{-11}

V.20-07528 (E)

In the entry for radionuclide ^{232}Th[a], *for* 1.5×10^{-8} *read* 9.1×10^{-9}

In the entry for radionuclide ^{241}Am, *for* 6.8×10^{-10} *read* 6.0×10^{-10}

Column headed “Latin America”

In the entry for radionuclide ^{54}Mn, *for* 5.2×10^{-9} *read* 2.6×10^{-9}

In the entry for radionuclide ^{58}Co, *for* 8.1×10^{-10} *read* 4.1×10^{-10}

In the entry for radionuclide ^{60}Co, *for* 2.4×10^{-9} *read* 1.2×10^{-9}

In the entry for radionuclide ^{65}Zn, *for* 1.4×10^{-9} *read* 1.3×10^{-9}

In the entry for radionuclide ^{90}Sr[a], *for* 5.1×10^{-13} *read* 5.0×10^{-13}

In the entry for radionuclide ^{106}Ru[a], *for* 4.8×10^{-11} *read* 2.5×10^{-11}

In the entry for radionuclide ^{131}I, *for* 5.7×10^{-14} *read* 4.0×10^{-14}

In the entry for radionuclide ^{134}Cs, *for* 2.6×10^{-11} *read* 1.6×10^{-11}

In the entry for radionuclide ^{137}Cs[a], *for* 1.2×10^{-11} *read* 7.9×10^{-12}

In the entry for radionuclide ^{232}Th[a], *for* 1.3×10^{-8} *read* 7.4×10^{-9}

In the entry for radionuclide ^{241}Am, *for* 4.0×10^{-10} *read* 3.3×10^{-10}

Column headed “North America”

In the entry for radionuclide ^{54}Mn, *for* 5.3×10^{-9} *read* 2.7×10^{-9}

In the entry for radionuclide ^{58}Co, *for* 8.5×10^{-10} *read* 4.5×10^{-10}

In the entry for radionuclide ^{60}Co, *for* 2.6×10^{-9} *read* 1.4×10^{-9}

In the entry for radionuclide ^{65}Zn, *for* 5.6×10^{-9} *read* 5.5×10^{-9}

In the entry for radionuclide ^{106}Ru[a], *for* 5.6×10^{-11} *read* 3.3×10^{-11}

In the entry for radionuclide ^{131}I, *for* 8.3×10^{-14} *read* 6.6×10^{-14}

In the entry for radionuclide ^{134}Cs, *for* 3.2×10^{-11} *read* 2.2×10^{-11}

In the entry for radionuclide ^{137}Cs[a], *for* 1.6×10^{-11} *read* 1.2×10^{-11}

In the entry for radionuclide ^{232}Th[a], *for* 1.7×10^{-8} *read* 1.2×10^{-8}

In the entry for radionuclide ^{241}Am, *for* 1.0×10^{-9} *read* 9.2×10^{-10}

Column headed “West Asia”

In the entry for radionuclide ^{54}Mn, *for* 5.2×10^{-9} *read* 2.6×10^{-9}

In the entry for radionuclide ^{58}Co, *for* 8.0×10^{-10} *read* 4.0×10^{-10}

In the entry for radionuclide ^{60}Co, *for* 2.3×10^{-9} *read* 1.2×10^{-9}

In the entry for radionuclide ^{65}Zn, *for* 5.9×10^{-10} *read* 5.3×10^{-10}

In the entry for radionuclide ^{90}Sr[a], *for* 2.2×10^{-13} *read* 2.1×10^{-13}

In the entry for radionuclide ^{106}Ru[a], *for* 4.6×10^{-11} *read* 2.3×10^{-11}

In the entry for radionuclide ^{131}I, *for* 4.7×10^{-14} *read* 3.0×10^{-14}

In the entry for radionuclide ^{134}Cs, *for* 2.4×10^{-11} *read* 1.4×10^{-11}

In the entry for radionuclide ^{137}Cs[a], *for* 1.0×10^{-11} *read* 6.3×10^{-12}

In the entry for radionuclide ^{232}Th[a], *for* 1.2×10^{-8} *read* 6.3×10^{-9}

In the entry for radionuclide ^{238}U[a], *for* 5.8×10^{-12} *read* 5.6×10^{-12}

In the entry for radionuclide ^{241}Am, *for* 2.3×10^{-10} *read* 1.5×10^{-10}

2. Annex A (Methodology for estimating public exposures due to radioactive discharges), page 99, table A2

For the existing equation T2 *substitute*

$$C_{air,progeny}(x) = C_{air,parent}(x)\frac{\lambda_{\text{progeny}}}{\lambda_{\text{progeny}}-\lambda_{\text{parent}}}\left(1 - e^{-(\lambda_{\text{progeny}}-\lambda_{\text{parent}})\left(\frac{x}{u_a}\right)}\right) \quad \text{(T2)}$$

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Electronic attachments (http://www.unscear.org/unscear/en/publications/2016.html)

1. Comparison of the Committee's earlier and current methodologies
2. Summary of the Committee's pre-2010 methodologies and their development
3. Population densities around uranium mines and nuclear power sites
4. Sensitivity studies in support of the methodology development
5. Electronic workbooks that implement the current methodology

I. INTRODUCTION

1. For many years the Committee has had a methodology for assessing the radiation exposures of the general public from discharges of radionuclides to the environment, where the term discharge refers to authorized releases from normal operations. The methodology does not apply for accidental releases. Every few years, the Committee has updated its estimates of the global radiological impact of the various types of nuclear installation, using this methodology and the latest available information on the level and nature of discharges. The most recent versions of the methodology, which in turn were built on earlier versions, were published in annex A of the UNSCEAR 2000 Report [U6] and annex B of the UNSCEAR 2008 Report [U10]. Although used successfully for many years, the Committee decided at its fifty-sixth session in 2008 to review and, where appropriate, update its methodology [U10] as part of its strategic plan for 2009–2013, with a view to subsequently updating its assessments of the levels of radiation exposure from energy production.

2. The global impact of energy production was one of the Committee's thematic priorities identified in its strategic plan for 2014−2019 (see [U12]). The Committee decided to specifically assess the global radiological impact of discharges from both nuclear and non-nuclear sources of electrical energy production, and thus to review its methodology so that it could be used to:

(a) Evaluate the radiation levels worldwide to which people are usually exposed as a consequence of electricity generation;

(b) Assess the typical variations in exposure worldwide to different sources of radioactive discharges;

(c) Identify sources of possible concern for public exposure;

(d) Allow users to derive benchmarks for comparison purposes and to derive relationships for their investigative work;

(e) Analyse temporal trends in the contributions of different sources to overall public exposure.

3. The Committee recognizes that it is impractical to carry out a full site-specific assessment for each site of electricity generation in the world that discharges radionuclides to the environment. However, it decided that, where possible, its approach should be able to take into account differences among regions of the world. It also decided that the methodology should be robust, transparent and applicable to the different electrical energy sources, and that it should build on the experience gained in applying the previous methodology. One change agreed was that for ease of application to different electrical energy sources and to all parts of the nuclear fuel cycle, the methodology should provide estimates of the doses[1] per unit discharge of key radionuclides to different environments. With information on the discharges from the various facilities, these factors could then be used to estimate doses per unit electrical energy produced (see annex B).

[1] Where the word "dose" is used in this annex without qualification, it should be taken to mean effective dose to an individual or collective effective dose to a population, according to context, unless otherwise stated.

4. The methodology is thus designed to assess individual and collective doses from unit discharge of each of the key radionuclides to atmosphere, lakes, rivers and seas. The individuals considered are those living in the area local to the point of discharge with behaviour indicative of most people living in that area; the doses to these characteristic individuals are referred to here as "characteristic individual doses" and are not to be confused with those to the so-called "representative person" (previously termed by the International Commission on Radiological Protection, ICRP, as the "critical group") used for radiation protection purposes [I13]. The Committee agreed that, where possible, estimates should be available for collective doses as a function of distance from the point of discharge and of the levels of individual dose that make up these collective doses. The Committee also agreed to take account of some differences among geographical regions, notably on population densities. For ease of application and transparency, the methodology has been implemented through a series of Excel® workbooks, which should also facilitate any future updates of the Committee's assessments.

5. The Committee intends to use the methodology to conduct its worldwide assessments of the radiological impact of discharges of radionuclides. The methodology aims to provide best estimates of radiation doses, in contrast to other established methodologies (e.g. [I2]) which aim to ensure that doses are not underestimated and thus adopt cautious parameter values and assumptions. The Committee's methodology only applies to continuous routine releases to the environment and is not intended to be comprehensive, covering all situations and other uses (such as for estimating the risks of radiation-induced health effects).

6. This scientific annex describes the methodology to assess doses from discharges to atmosphere, freshwater bodies and sea, together with the approach adopted for globally dispersed radionuclides. The limitations of the models and data used are also discussed. An appendix provides detailed information on the implementation of the methodology, including the end points considered, the relevant mathematical equations and model parameters, a specification of the series of Excel® workbooks that implement the methodology, information on how the workbooks can be used to assess exposures from different types of discharge, and a description of how progeny of radionuclides were treated and quality assurance conducted. In addition more detailed supporting information and the workbooks themselves are provided in electronic attachments, which can be downloaded only from the UNSCEAR website (http://www.unscear.org/unscear/en/publications/2016.html).

II. GENERAL CONSIDERATIONS

A. Dosimetric quantities

7. Although for strict scientific purposes other quantities are appropriate, the Committee has for many years used two protection quantities, namely effective dose and collective effective dose for its evaluations of levels and trends of exposures. These have the advantage of simplifying comparison of doses from different types of radiation and different distributions of dose within the body, and of averaging over age and sex; moreover, many regulatory authorities keep records in terms of these quantities. The quantity effective dose is based on another underlying radiation protection quantity, the equivalent dose, which takes into account the inferred differences in biological effectiveness of different types of radiation by applying defined radiation weighting factors to the absorbed dose to an

organ or tissue. Equivalent doses to different organs and tissues are then combined using defined tissue weighting factors, which take into account the inferred differences in detriment from irradiation of the particular organ or tissue, averaged over the sex and age distributions of typical populations. This enables external and internal exposures from a source of radiation to be added to produce an overall effective dose[2] from that source, which can then be compared with effective doses from other sources. In this annex, the definition of effective dose used to express both individual and collective doses is generally that of Publication 60 of the ICRP [I10]. Although ICRP made some modifications to the weighting factors in the definition of effective doses in its 2007 recommendations [I13], it has not yet published a full set of dose coefficients for external and internal exposure and so the Committee has used the previous values, unless otherwise stated.

8. It is important to note that there are differences between the quantities of individual and collective dose, although they are calculated in similar ways. In this methodology and any related studies, the collective (effective) dose is always estimated for a defined population over a specified period of time. The collective dose used here is the product of the mean effective dose to a specified population from a particular source, and the number of people in that population, integrated over a defined period of time. In other words, a collective dose is the dose received by all members of a particular population combined, over a defined period of time. When evaluating collective doses, the population and time period should always be specified and any underlying assumptions—such as the population remaining the same over the time period—should be acknowledged. The Committee has used the quantity, collective dose, for many years to compare the radiation exposures of populations from different sources of ionizing radiation, or following different protection measures. In particular, the quantity provides a convenient basis for comparing the impacts of radioactive discharges from nuclear and other sources of electrical energy, and for incorporation by analysts into measures of economic utility for decision-aiding. However, collective dose should only be used for comparative purposes; it is inappropriate to use it for quantifying exposure in epidemiological studies or for making risk projections. Specifically, the Committee has stated that it does not recommend the aggregation of very low doses over extended time periods to large numbers of individuals to estimate absolute numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than normal natural background levels [U13].

9. The Committee decided to retain its previous approach where collective dose was estimated for local, regional and global components. The spatial variation in collective dose can be estimated for discharges to atmosphere because *(a)* dispersion can be expressed as a function of distance from the discharge point and *(b)* data on the distribution of population density are also available as a function of distance. However, for aquatic discharges, when using a simple generic approach, it is not possible to determine collective doses as a function of distance. Because people over a wide area may all obtain their drinking water and fish from the same water body, there is not a simple relationship between distance from the discharge point and dose. A simplified approach is therefore used based on a discharge to a single water body so that, for aquatic discharges, less spatial resolution in collective doses is possible than for discharges to atmosphere.

10. The Committee considered that the assessment of characteristic individual doses is also useful in addressing the thematic priority in its strategic plan mentioned above. As noted previously, as far as possible, the dose estimates are based on best estimates of parameter values. For example, for discharges to atmosphere, the characteristic individual dose estimated is the dose to someone living

[2] For both individual and collective doses, the effective doses estimated here are the sum of the effective doses from external exposure received during the period of interest and the committed effective doses from intakes by inhalation and ingestion during the same period.

5 km from the discharge point who is assumed to obtain a proportion of their food from this location, rather than a more cautious assumption of living 1 km or less from the discharge point. For aquatic discharges, the characteristic individual dose estimated is the dose to someone assumed to be living in the area near to the discharge location and to obtain part of their food—and in the case of discharges to freshwater bodies, their drinking water—from the receiving water body.

11. In this regard, for estimating characteristic individual doses, the Committee considered it to be more realistic to assume that only a proportion of their food consumed was locally produced (locally produced food is that grown by the individual or bought fresh from local markets) rather than an approach often used for regulatory purposes of assuming all their food consumed was 100% locally produced. There is little information on how much locally produced food people consume. In France, a comprehensive investigation was carried out to determine the amount of locally produced food that people ate [B3]. This showed that rural populations in France consumed more locally produced food than urban populations, as would be expected, and that there was a significant variation for different foods. For example, for milk consumption in France as a whole, only 3% was found to be locally produced but in rural areas, the figure was 30%, on average. For leafy vegetable consumption in France as a whole, just over 25% was found to be locally produced but in rural areas the figure was 70%. For cereal consumption in France, the percentage locally produced was very low, at 0.1% both for the country as a whole and for rural areas. While recognizing that there are likely to be wide variations in practice across the world, the Committee agreed that a simple assumption of 25% of the food consumed being locally produced was reasonable for its generic methodology and that this value be used for both terrestrial and aquatic foods. This value is consistent with the value used in the Committee's recent assessment of doses in Japan following the nuclear accident at the Fukushima-Daiichi nuclear power station [U12].

12. The methodology employs published dose coefficients to estimate doses from external and internal exposure. The dose coefficients used for internal exposure are those for adult members of the public and are the committed effective doses to 70 years of age per unit intake of radionuclide given by ICRP [I14]. The dose coefficients for external exposure from radionuclides in the air or deposited on the ground following discharges to air or water bodies were selected from literature sources relevant to the situation being considered. The main dose coefficients used for internal and external exposure are summarized in table 1 both for radionuclides that are discharged and for their key progeny, where appropriate (see also the appendix). It should be noted that for dose coefficients for internal exposure the contribution of short-lived progeny is included in the dose coefficient assigned to the parent. However, for the dose coefficients for external exposure the dose coefficients are for the parent alone and any contribution from short-lived progeny has to be added separately using the values given in table 1(b). Except for isotopes of argon (e.g. ^{41}Ar), krypton (e.g. ^{85}Kr), xenon (e.g. ^{133}Xe, ^{135}Xe and ^{138}Xe) and radon (e.g. ^{222}Rn), which are all gases, the discharges are assumed to be particulate with a default size of 1 μm AMAD. The dose coefficients for tritium in the form of tritiated water (HTO) and of organically bound tritium (OBT) are provided for use with the "specific activity" model for tritium in the environment described in chapter III. The chemical form assumed for each element is generally the default type for public exposure given in ICRP Publication 72 [I12].

Table 1. Radionuclide-specific dose coefficients for internal exposure from inhalation and ingestion and for external exposure from the plume and deposition

Values are given to one decimal place only as this is considered sufficient for this purpose

(a) Radionuclides discharged

Radio-nuclide	*Progeny*[a]	*Lung absorption type*[b] *[I12]*	*Committed effective dose coefficients for adults to age 70 years for internal exposure*[c]		*Effective dose coefficients for external exposure*[d]	
			Inhalation D_{inh} *(Sv/Bq) [I14]*	*Ingestion* D_{ing} *(Sv/Bq) [I14]*	*Plume* $D_{ex,cloud}$ *(Sv/(Bq s/m³)) [E2, P2]*	*Deposition* $D_{ex,deposit}$ *(Sv/(Bq /m²))*[e] *[P2]*
^{3}H	—	M	4.5×10^{-11}	0	0	0
^{14}C	—	M	2.0×10^{-9}	5.8×10^{-10}	2.6×10^{-18}	0
^{35}S[f]		M	1.4×10^{-9}	7.7×10^{-10}	3.1×10^{-18}	0
^{41}Ar[f]	—	n/a	0	0	6.2×10^{-14}	0
^{54}Mn	—	M	1.5×10^{-9}	7.1×10^{-10}	3.9×10^{-14}	5.2×10^{-14}
^{58}Co	—	M	1.6×10^{-9}	7.4×10^{-10}	4.5×10^{-14}	5.0×10^{-9}
^{60}Co	—	M	1.0×10^{-8}	3.4×10^{-9}	1.2×10^{-13}	2.0×10^{-7}
^{65}Zn	—	M	1.6×10^{-9}	3.9×10^{-9}	2.8×10^{-14}	9.0×10^{-9}
^{85}Kr[f]	—	n/a	0	0	9.9×10^{-17}	0
^{90}Sr[c]	^{90}Y	M	3.6×10^{-8}	2.8×10^{-8}	9.8×10^{-17}	0
^{106}Ru[c]	^{106}Rh	M	2.8×10^{-8}	7.0×10^{-9}	0	0
^{129}I	—	F	3.6×10^{-8}	1.1×10^{-7}	2.8×10^{-16}	3.1×10^{-9}
^{131}I[d]	—	F	7.4×10^{-9}	2.2×10^{-8}	1.7×10^{-14}	2.4×10^{-10}
^{133}Xe[f]	—	n/a	0	0	1.2×10^{-15}	0
^{135}Xe[f]	^{135}Cs	n/a	0	0	1.0×10^{-14}	0
^{138}Xe[f]	^{138}Cs	n/a	0	0	5.4×10^{-14}	0
^{134}Cs	—	F	6.6×10^{-9}	1.9×10^{-8}	7.1×10^{-14}	6.2×10^{-8}
^{137}Cs[c]	^{137m}Ba	F	4.6×10^{-9}	1.3×10^{-8}	9.3×10^{-17}	4.6×10^{-13}
^{210}Pb		M	1.1×10^{-6}	6.9×10^{-7}	4.5×10^{-17}	2.5×10^{-10}
^{210}Po	—	M	3.3×10^{-6}	1.2×10^{-6}	3.9×10^{-19}	1.2×10^{-13}
^{222}Rn[f,g]	^{218}Po ^{214}Pb, ^{214}Bi, ^{214}Po	n/a	4.8×10^{-9}	n/a	n/a	n/a
^{226}Ra	—	M	3.5×10^{-6}	2.8×10^{-7}	2.8×10^{-16}	3.8×10^{-9}
^{230}Th	—	S	1.4×10^{-5}	2.1×10^{-7}	1.5×10^{-17}	0
^{232}Th	^{228}Ra, ^{228}Ac, ^{228}Th, ^{212}Pb	S	2.5×10^{-5}	2.3×10^{-7}	7.2×10^{-18}	8.7×10^{-11}
^{234}U	—	M	3.5×10^{-6}	4.9×10^{-8}	6.1×10^{-18}	5.5×10^{-11}
^{238}U	^{234}Th, ^{234m}Pa	M	2.9×10^{-6}	4.5×10^{-8}	2.5×10^{-18}	1.9×10^{-11}
^{239}Pu	—	M	5.0×10^{-5}	2.5×10^{-7}	3.5×10^{-18}	3.5×10^{-11}
^{240}Pu	—	M	5.0×10^{-5}	2.5×10^{-7}	3.4×10^{-18}	1.5×10^{-11}
^{241}Am	—	M	4.2×10^{-5}	2.0×10^{-7}	6.7×10^{-16}	7.9×10^{-9}

(b) Radionuclides considered to have different chemical forms in the environment or as progeny of others

Radio-nuclide	*Lung absorption type[b] [I12]*	*Committed effective dose coefficients for adults to age 70 years for internal exposure[c]*		*Effective dose coefficients for external exposure[d]*	
		Inhalation D_{inh} *(Sv/Bq) [I14]*	*Ingestion* D_{ing} *(Sv/Bq) [I14]*	*Plume* $D_{ex,cloud}$ *(Sv/(Bq s/m³)) [E2, P2]*	*Deposition* $D_{ex,deposit}$ *(Sv/(Bq /m²))[e] [P2]*
HTO	n/a	1.8×10^{-11}	1.8×10^{-11}	0	0
OBT	n/a	4.1×10^{-11}	4.2×10^{-11}	0	0
^{90}Y	—	—	—	7.9×10^{-16}	0
^{106}Rh	—	—	—	9.4×10^{-15}	5.5×10^{-15}
^{135}Cs[f]	F	6.9×10^{-10}	2.0×10^{-9}	9.5×10^{-18}	2.4×10^{-11}
^{138}Cs[f]	F	2.4×10^{-11}	9.2×10^{-11}	1.2×10^{-13}	3.9×10^{-12}
^{137m}Ba	—	—	—	2.7×10^{-14}	1.7×10^{-7}
^{212}Pb	—	—	—	5.7×10^{-15}	4.7×10^{-12}
^{214}Pb	M	1.4×10^{-8}	1.4×10^{-10}	1.1×10^{-14}	5.6×10^{-13}
^{210}Bi	—	—	—	2.6×10^{-16}	2.2×10^{-11}
^{214}Bi	—	1.4×10^{-8}	1.1×10^{-10}	7.1×10^{-14}	2.5×10^{-12}
^{214}Po	n/a	0	0	3.8×10^{-18}	1.9×10^{-23}
^{218}Po	n/a	0	0	4.2×10^{-19}	2.3×10^{-18}
^{228}Ra	M	2.6×10^{-6}	6.9×10^{-7}	0	0
^{228}Ac	F	2.5×10^{-8}	4.3×10^{-10}	4.0×10^{-14}	1.7×10^{-11}
^{228}Th	S	4.0×10^{-5}	7.2×10^{-8}	8.1×10^{-17}	6.9×10^{-11}
^{234}Th	S	7.7×10^{-9}	3.4×10^{-9}	2.9×10^{-16}	1.3×10^{-11}
^{234m}Pa	n/a	0	0	1.2×10^{-15}	1.1×10^{-14}

[a] The progeny considered in the methodology are listed. For further details see the appendix; The symbol "—" means either that the progeny are not considered or that the progeny are stable isotopes.

[b] This refers to the rate of absorption from the lung. The symbols relate to fast (F), medium (M) or slow (S) absorption.

[c] For these radionuclides with short-lived progeny, the dose coefficients for internal exposure for the parent include the contribution from the progeny and coefficients are not given separately for the progeny.

[d] In all cases the dose coefficients for external exposure are for the parent only and the contribution from progeny has to be considered separately.

[e] Integrated effective dose to 100 years following a continuous deposition rate of 1 Bq/(m^2 s) for one year. The Petoussi-Henss et al. values are not used directly but are modified to allow for changes in external dose with time [G2].

[f] Considered for discharges to atmosphere only.

[g] See section III.A.3 for more information on the treatment of radon inhalation.

B. Integration times

13. The methodology is applicable to discharges that can be assumed to be continuous and takes into account *(a)* the build-up of long-lived radionuclides in the environment and *(b)* the continued exposure to long-lived radionuclides after discharges have ceased. This is done by considering a year's discharge of a radionuclide, its dispersion in the environment and the subsequent exposures of people over many years; the resulting dose rates are then integrated to various times. Using these integrals, it is also possible to consider that the discharges may continue for many years from the same site. This is because the integrated dose to say 100 years from one year's discharge is numerically equal to the dose in the 100th year from a continuous discharge at a constant rate. The Committee agreed that 100 years was generally a reasonable assumption for the length of continuous discharge for estimating characteristic individual doses as it covers the lifetime of individual power plants and also the possibility that additional power plants may be constructed on the same site. Separate considerations apply for the disposal of waste residues (mill tailings) from uranium and coal mining operations as discussed below.

14. Collective dose rates can be integrated to infinity (referred to as the collective dose commitment) to take account of all possible future doses from a discharge. However collective dose rates are generally integrated to shorter times; values ranging from 80 to 10,000 years have been used in the Committee's past reports, see electronic attachments 1 and 2 (collective doses integrated to various times are sometimes referred to as truncated collective doses). For most radionuclides, integrating collective dose rates to 100 years gives a significant proportion of the collective dose commitment [S9]. However, some relatively long-lived, environmentally mobile radionuclides (^{3}H, ^{14}C, ^{85}Kr and ^{129}I) become globally dispersed and can continue to contribute to the integrated collective doses for many years. For both ^{3}H and ^{85}Kr (half-lives 12.6 years and 10.7 years, respectively), the integrated collective dose does not increase beyond 100 years. However, for ^{14}C (half-life 5,730 years), the integrated collective dose increases by a factor of more than five between 1,000 and 10,000 years; however the additional collective dose is then negligible if the integration is continued to 1,000,000 years. For the very long-lived ^{129}I (half-life 15.7 million years), the integrated collective dose increases by about a factor of six between 1,000 and 10,000 years and by a factor of over 150 between 10,000 and 1,000,000 years (based on table 70 of [U5]). However, for discharges from nuclear sites, the integrated collective dose from ^{14}C rather than that from ^{129}I dominates the total integrated collective dose and so most of the collective dose will be received in the first 10,000 years [S9, U5]. Also, when comparing options explicit consideration of collective doses at long times is often not necessary because the collective doses at these times are all similar and moreover comprise extremely low levels of individual dose [S9, U5].

15. In general, the uncertainties associated with estimating collective doses increase with integration time, for example, because of possible major changes in environmental conditions and population dynamics. The integrated collective dose to 500 years from a continuous discharge over one year has often been used to provide an upper estimate of the highest future annual collective dose rate if the practice, and hence discharge, were to continue at a constant rate for that number of years [L1]. Five hundred years is used because it is assumed to be the maximum duration of the generation of electrical energy by nuclear power. An integration time of 10,000 years was used in the Committee's assessments conducted before the year 2000. Ten thousand years is consistent with the duration of the warm period between glacial periods [L1] and therefore the maximum number of years over which any reasonable assumptions about the nature of the global environment can be made.

16. When comparing the radiological impact of different sources, it is important not to introduce any bias when choosing integration times for collective dose. For example, choosing a short time (e.g. of a few hundred years) for nuclear power generation would mean that a significant portion of the integrated

collective dose is not included. For non-nuclear energy production, notably that using fossil fuels, the major radionuclides discharged are from the ^{238}U decay chain, particularly ^{226}Ra and its progeny including ^{222}Rn. These radionuclides do not become dispersed globally and so once discharged to the environment need to be considered only for relatively short timescales; a few hundred years is sufficient to allow for the ingrowth of the radiologically significant radionuclide, ^{210}Po.

17. The conventional mining and milling of uranium ore gives rise to various waste residues, which are referred to as mill tailings. These contain enhanced levels of naturally occurring radionuclides and the radon is emitted from the mill tailings for many years following disposal because of the long radioactive half-life of the parent ^{238}U. In assessing the radiological impact of mill tailings, it is necessary to allow for the number of years over which the emissions will continue. Previously, the Committee estimated collective doses from mill tailings assuming that the emissions of radon continued for 10,000 years [U6]. Since the year 2000, improvements have been made to the treatment of mill tailings and the rehabilitation of areas where mill tailings had been disposed of. As discussed in the companion report on radiation exposures from electricity generation (see annex B), enhanced levels of radon emissions may continue for periods of less than 100 years. The Committee therefore agreed that the best estimate of the period of radon emissions from mill tailings should be reduced to 100 years, but that the effect of considering periods of 500 years and 10,000 years should also be evaluated. The same considerations also apply to the disposal of mine spoil or ash from coal used for electricity generation.

C. End points considered

18. Taking account of the considerations discussed in sections A and B above, the Committee has developed its methodology to estimate the following characteristic individual doses (expressed as effective doses, in sieverts, Sv) from each radionuclide discharged continuously at a rate of 1 Bq/s:

(a) For discharges to atmosphere, the characteristic individual dose in the 100th year (as noted above, the dose in the 100th year of continuous discharge is equal to the integrated dose to 100 years from 1 year's discharge) at 5 km from the discharge point (annual individual doses are also calculated at 50, 300, 750 and 1,250 km from the discharge point for use in estimating collective doses);

(b) For discharges to freshwater bodies, the characteristic individual dose in the 100th year;

(c) For discharges to a marine environment, the characteristic individual dose in the 100th year.

19. In addition, integrated collective doses (man Sv) from each radionuclide discharged continuously at a rate of 1 Bq/s for a year are calculated as follows:

(a) For discharges to atmosphere, collective doses are integrated to 100 years (this is equivalent to the collective dose in the 100th year of continuous discharge) in the following distance bands: 0−100 km (local), 100–500 km, 500–1,000 km and 1,000–1,500 km. The results for 100–1,500 km are summed to constitute regional components of collective dose;

(b) For discharges to freshwater bodies, the collective dose is integrated to 100 years. It should be noted that for freshwater bodies, instantaneous mixing in a single water volume is assumed and, with this assumption, it is not possible to distinguish between local and regional components of collective dose;

(c) For discharges to a marine environment, local and regional components of collective dose are integrated to 100 years;

(d) For globally circulating radionuclides only (^{3}H, ^{14}C, ^{85}Kr and ^{129}I), the global collective dose is integrated to 100, 500 and 10,000 years.

20. The results can be scaled to obtain the characteristic individual and collective doses for specific discharges and sources. In chapter III, results are calculated for discharges from different geographical regions of the world, considering different population distributions (generic, nuclear coastal and nuclear inland). Results are also calculated for a generic discharge location situated in a region of very low population density, which may apply to sites of uranium mines and mill tailings.

D. Discharges considered

1. Electrical energy production

21. One of the aims of the methodology is to allow exposures from discharges of radionuclides to atmosphere and water bodies to be assessed for a range of facilities associated with electricity generation, covering both nuclear and non-nuclear power production. The methodology could also be broadly used to assess routine discharges from other sources, but—as noted earlier—it is not intended for site-specific or regulatory purposes. The assessment of exposures due to electricity generation requires adequate and representative discharge data from the various facilities for input into the models that implement the methodology. For example, discharges from the nuclear facilities involved in power production and the fuel cycle listed in table 2 could be considered.

Table 2. Types of nuclear facility for which the methodology may be relevant

Life-cycle stage	*Facility types*
Front end	Uranium mine with mill Enrichment and fabrication
Nuclear reactor operation	Nuclear power reactors (e.g. pressurized water reactors, boiling water reactors, fast breeder reactors, gas cooled reactors, heavy water cooled reactors, and light-water-cooled, graphite-moderated reactors) Research reactors
Back end	Reprocessing Decommissioning Waste management

22. There are also a number of non-nuclear means of electrical energy production that may have associated discharges of naturally occurring radionuclides because of the materials used in construction or at some point in their production cycle. The Committee decided that these should also be covered by the methodology and they are considered in annex B. These could include the use of: *(a)* fossil fuels (coal, gas and oil); *(b)* geothermal sources; and *(c)* solar power, wind and biomass.

2. Radionuclides discharged

23. The radionuclides covered by the methodology are listed in table 1 and are considered by the Committee to give rise to most of the doses from radioactive discharges from different energy sources. This list of radionuclides includes those that have been demonstrated to give rise to the highest integrated collective doses in previous assessments [C3, U6]. Naturally occurring radionuclides are also covered by the methodology in order to assess the radiological impact of discharges from mining and milling of primary materials, fuel production, and non-nuclear forms of electrical energy production [N4].

24. Although the methodology is designed to use data on discharges of individual radionuclides, in many cases discharge data are provided only for groups of radionuclides as a whole. For example, discharges may be given for "total alpha" and then this value will need to be apportioned among the relevant radionuclides included in the methodology (e.g. ^{239,240}Pu, ^{241}Am). For discharges specified as total beta/gamma or particulate there may be many radionuclides that could be discharged, with the most important for nuclear power plants generally being ^{60}Co, ^{90}Sr, ^{134}Cs and ^{137}Cs but with significant contributions from others such as ^{54}Mn or for United Kingdom gas cooled reactors only ^{35}S. In using the methodology, it will be necessary to specify a fraction of the discharge for each relevant radionuclide and also which representative radionuclides to consider as defaults for the sum of discharges from any radionuclides not included in table 1.

25. The methodology is designed to allow different assumptions to be made about the state of equilibrium between components of the decay chains of the naturally occurring radionuclides. Account is taken of the time necessary for ingrowth to occur and differences between the importance of ingrowth of progeny for different types of discharge and for different exposure pathways. Where appropriate, the contribution of progeny is taken into account according to the following assumptions:

(a) Where the progeny are short-lived compared to the parent, their contribution is not considered explicitly but is generally included with the parent, for example, contributions from ^{90}Y and ^{137m}Ba are included in the dose coefficients for intakes by inhalation and ingestion for ^{90}Sr and ^{137}Cs, respectively;

(b) Where the progeny are long-lived compared to the parent, their contribution is not considered further if, over a period of 100 years, there is unlikely to be sufficient ingrowth of the progeny. Examples where this is the case are ^{239}Pu/^{235}U, ^{240}Pu/^{236}U, and ^{241}Am/^{237}Np;

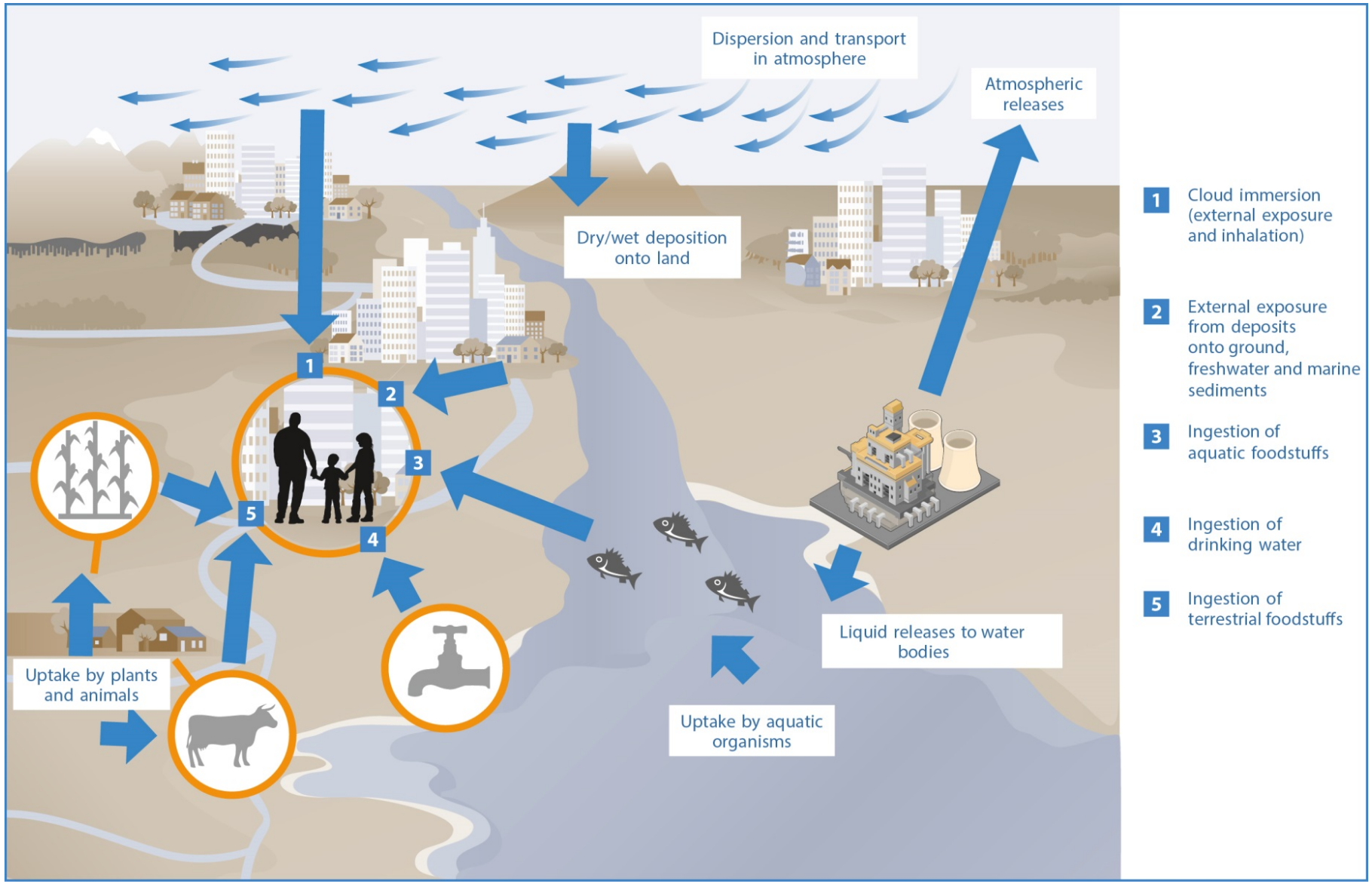
(c) The key radionuclides in the decay chains of the naturally occurring radionuclides are considered separately and other progeny are only considered if they make a significant contribution to exposures or if it is reasonable to assume that they would be discharged in secular equilibrium with the parent.

Further information for specific radionuclides and exposure pathways and details of how this is applied in practice are given in the appendix.

III. DESCRIPTION OF THE METHODOLOGY

26. When radionuclides are discharged to the environment there are various ways in which people can be exposed to radiation. Figure I illustrates the more important exposure pathways.

Figure I. Exposure pathways following discharge of radioactive material to the environment



A. Assessment of doses from discharges to atmosphere

27. This section describes the methodology for estimating characteristic individual and local and regional components of collective dose to the public from a discharge of radionuclides to atmosphere. The appendix gives full details of all of the equations used. The exposure pathways included in the methodology for discharges to atmosphere are:

(a) Internal exposure from inhalation of radionuclides in the plume;

(b) External exposure (beta and gamma emitters) from radionuclides in the plume;

(c) External exposure from deposited radionuclides;

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

28. Other exposure pathways such as internal exposure from inhalation of resuspended radionuclides deposited on the ground and from inadvertent ingestion of soil are also possible. However a review of the literature indicated that the doses from these exposure pathways are negligible compared with those from the exposure pathways listed above for continuous discharges of radionuclides to atmosphere [J5].

29. Characteristic individual doses are calculated for a member of the public assumed to be living at a distance of 5 km from the point of discharge. Local and regional components of collective dose from discharges to atmosphere are derived directly by multiplying individual doses calculated at the midpoints of distance bands or annuli (of 0–100, 100–500, 500–1,000 and 1,000–1,500 km) around the point of discharge by data specific to each geographical region on the number of people within each annulus. Region-specific or generic values are used for parameters in the dose calculation as discussed in the following sections.

1. Population distribution

30. The Committee's previous approach was based on simplified assumptions regarding population density around nuclear sites representative of the situation in the 1980s. Given the importance of population information in determining the overall magnitude of collective doses, and that there have been significant changes in population patterns throughout the world, the Committee decided to update the information on population density. For comparison purposes and to examine the effect of different population densities, four different sets of population data are considered in the methodology. As a default case for comparison purposes, the calculation of collective dose from discharges to atmosphere is based on information on population densities for 2010 weighted by the population in each geographical region [F1]. The population distribution used for the default case is given in table 3 where the same population density is used for each annulus (the population is the assumed density multiplied by the area of the annulus). In addition to values by region, a world-average population distribution has been obtained as an average of the values for each region weighted by the populations in each region. The regions considered in the methodology are those used by the United Nations Environment Programme (UNEP), illustrated in figure II below.

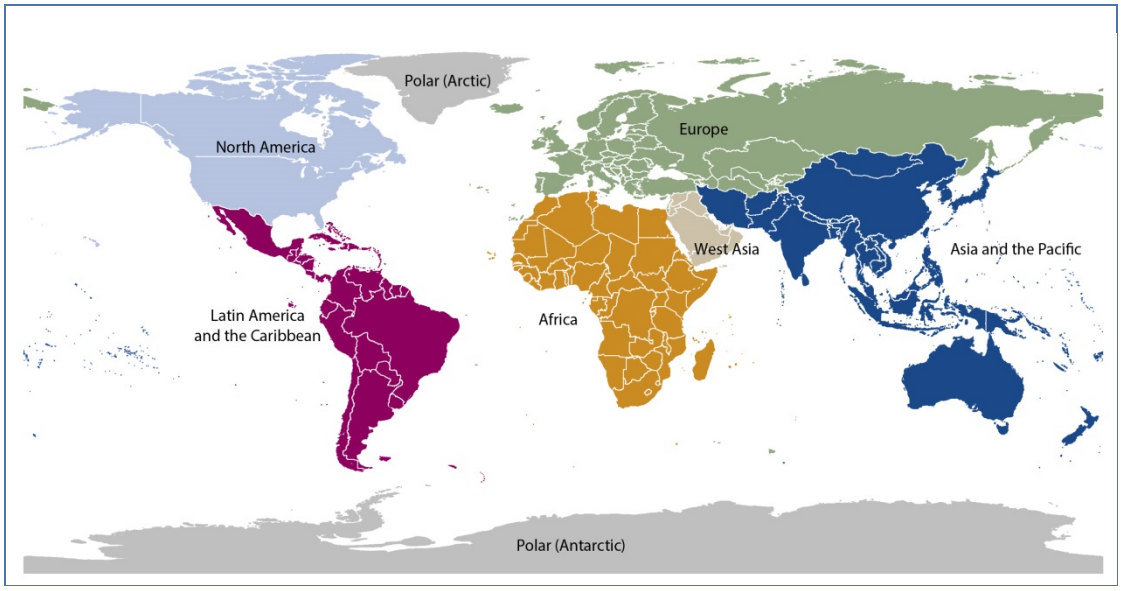
Table 3. Default population distributions for different geographical regions

UNEP region	*Population density, weighted[a] (km^{-2})*	*Population within each annulus*			
		0–100 km	*100–500 km*	*500–1,000 km*	*1,000–1,500 km*
Africa	7.9×10^{1}	2.5×10^{6}	5.9×10^{7}	1.9×10^{8}	3.1×10^{8}
Asia and Pacific	2.8×10^{2}	8.8×10^{6}	2.1×10^{8}	6.6×10^{8}	1.1×10^{9}
Europe	1.3×10^{2}	4.0×10^{6}	9.7×10^{7}	3.0×10^{8}	5.0×10^{8}
Latin America and Caribbean	1.4×10^{2}	4.3×10^{6}	1.0×10^{8}	3.2×10^{8}	5.3×10^{8}
North America	3.2×10^{1}	1.0×10^{6}	2.4×10^{7}	7.6×10^{7}	1.3×10^{8}
West Asia	1.0×10^{2}	3.2×10^{6}	7.7×10^{7}	2.4×10^{8}	4.0×10^{8}
World average[b]	1.6×10^{2}	5.0×10^{6}	1.2×10^{8}	3.8×10^{8}	6.3×10^{8}

[a] The population densities are taken from FAO [F1] and are values for each region weighted as described in this reference.

[b] The world-average value is the average of the values for each region weighted by the population in each region.

Figure II. The geographical regions used in the methodology (taken from UNEP [U3])



31. For nuclear power stations, a more specific analysis of population data is possible. In collaboration with the Metadata and Socio-Economics Unit of UNEP/DEWA/GRID-Geneva,[3] a geographic information system has been used to express the number of people living within specified distance bands around each station. Details of the approach and data used are given in electronic attachment 3; in essence, the numbers of people living within different distances (100, 500, 1,000 and 1,500 km) around the site of each operating nuclear power station have been analysed. These data have been used to derive simplified averages by UNEP region for the population in each annulus. The averages have been estimated separately for inland sites and for sites located on the coast, where the population distribution is likely to be affected by the presence of a large body of water (see table 4). Again a world-average value has also been calculated using all the available data. Because there were, at the time of analysis, no significant operating nuclear power stations in West Asia and only a coastal

[3] United Nations Environment Programme (UNEP) Division of Early Warning and Assessment (DEWA) Global Resource Information Database network (GRID) http://www.grid.unep.ch/.

site for Africa, no population densities are given for these in table 4. The results for the default population distribution in table 3 could be used to consider nuclear sites in these regions if needed.

Table 4. Population distribution around operating nuclear power stations as a function of UNEP region and location

Based on information provided by UNEP for the year 2008

UNEP region[a]	*Population within each annulus*[b]			
	0–100 km	*100–500 km*	*500–1,000 km*	*1,000–1,500 km*
COASTAL				
Africa	3.9×10^6	1.1×10^6	8.7×10^6	3.4×10^7
Asia and Pacific	8.3×10^6	8.8×10^7	2.0×10^8	3.5×10^8
Europe	3.3×10^6	6.4×10^7	1.3×10^8	1.5×10^8
Latin America and Caribbean	3.6×10^6	6.2×10^7	4.8×10^7	4.3×10^7
North America	4.7×10^6	4.0×10^7	7.0×10^7	6.7×10^7
West Asia	n/a	n/a	n/a	n/a
World average[c]	5.6×10^6	6.6×10^7	1.4×10^8	2.0×10^8
INLAND				
Africa	n/a	n/a	n/a	n/a
Asia and Pacific	1.9×10^7	2.0×10^8	4.6×10^8	5.0×10^8
Europe	4.6×10^6	8.9×10^7	1.8×10^8	1.8×10^8
Latin America and Caribbean	4.6×10^6	1.5×10^7	3.7×10^7	3.4×10^7
North America	3.0×10^6	3.9×10^7	7.7×10^7	8.5×10^7
West Asia	n/a	n/a	n/a	n/a
World average[c]	4.6×10^6	7.2×10^7	1.5×10^8	1.5×10^8

[a] Note that at the time of analysis there were no significant operating nuclear power stations in West Asia or inland in Africa (see figure II for definition of UNEP regions) and hence population data are not presented for these regions.

[b] Data are presented to one decimal place, which is considered sufficient for this purpose.

[c] The world-average is the average of the population in each annulus for all nuclear sites for which data are available.

32. The other case considered in the methodology is for uranium mines and mill tailings sites. Most of these facilities are situated in areas of very low population densities, as illustrated in electronic attachment 3. Therefore, the methodology also considers a population distribution with a density of 5 km^{-2} to gain insight into the effect on collective doses. Using this low population density out to 1,500 km results in estimated collective doses from atmospheric discharges that are about two orders of magnitude lower than those estimated using the population distributions in tables 3 and 4. The low value for population density should therefore only be used where appropriate and where it can be assumed to apply over the integration period for the collective dose.

33. There are two main approaches to assessing collective doses from ingestion of terrestrial foods. The first uses information on the distribution of agricultural production to obtain an overall collective dose from the production but with no indication of the individual doses that make up the collective dose. The second approach, which the Committee adopted here, assumes that people obtain their food

from the area where they live. This enables both individual and collective doses to be estimated. However, as discussed earlier, in many parts of the world it is not realistic to assume that people derive all their food from local produce. This is particularly so within a small area that has a high population density, and therefore low agricultural production. The Committee therefore decided that collective doses from ingestion (where it is assumed that 100% of the food is obtained from the area considered) should only be calculated for distances of at least 100 km. For the characteristic individual dose, based on an individual living at a distance of 5 km from the site, 25% of their food is assumed to be locally produced as discussed earlier (paragraph 11).

2. Dispersion in the atmosphere

34. In previous assessments, the Committee adopted a simple generic atmospheric dispersion model. It considered the uncertainties associated with this approach in some detail in its 2000 Report [U6]. Given the generic nature of its assessment objectives, the Committee concluded that the long-term sector-averaged Gaussian model was likely to provide an appropriate level of accuracy. Crawford et al. [C5] acknowledge that simple Gaussian models continue to be used because they produce results that often agree fairly well with measured data and because their results are relatively easy to obtain. The Committee has decided to retain this approach.

35. The variation in activity concentration in air, $C_a(x)$, with downwind distance beyond 1 km is approximately given by the following equation:

$$C_a(x) = D_1 \cdot Q \cdot x^{-n} \quad (1)$$

where D_1 is the annual average dilution factor at 1 km (s/m^3), Q is the discharge rate (Bq/s), x is the downwind distance (km) and n is an empirically-determined index. The Committee agreed to retain the parameter values used in the UNSCEAR 2000 Report, in which a value of 5.3×10^{-7} s/m^3 was found to be the best approximation for D_1 with a value for n of 1.42 for all radionuclides except noble gases, tritium and carbon-14 [U6]. The dilution factor, D_1, was found to be relatively insensitive to changes in the values of parameters, except for wind speed and release height. The value of n was, however, found to be dependent upon deposition velocity and inversion height. For noble gases, which do not deposit, a value of n equal to 1.2 is retained. This value is also retained for tritium because, although tritium rapidly exchanges with water in the soil and vegetation, it is quickly re-emitted to the atmosphere. Carbon-14 also exchanges with carbon in soil and vegetation and partially returns to atmosphere through plant and soil respiration. A value for n of 1.4 is therefore used for this radionuclide.

36. As part of the development of the current methodology, the activity concentrations estimated using this simple relationship were compared with the results obtained using a more complex Gaussian model, for a uniform wind rose (for which activity concentrations were averaged over 12 sectors) that allowed for depletion of the plume but not radioactive decay. The results were found to be very similar (less than a factor of two difference).

37. A reduction factor is now included in the methodology to allow for the radioactive decay of short-lived radionuclides, notably radon, during dispersion over distances of hundreds of kilometres. This factor is based on a mean wind speed, u_a, of 2 m/s [I2].

38. The deposition rate of radionuclides at a specified distance (in Bq/(m^2 s) is determined by the application of a simple “effective deposition velocity” that allows for both wet and dry deposition on vegetation, soil and other surfaces. An annual-average deposition rate of 0.002 m/s [U6] is used for all

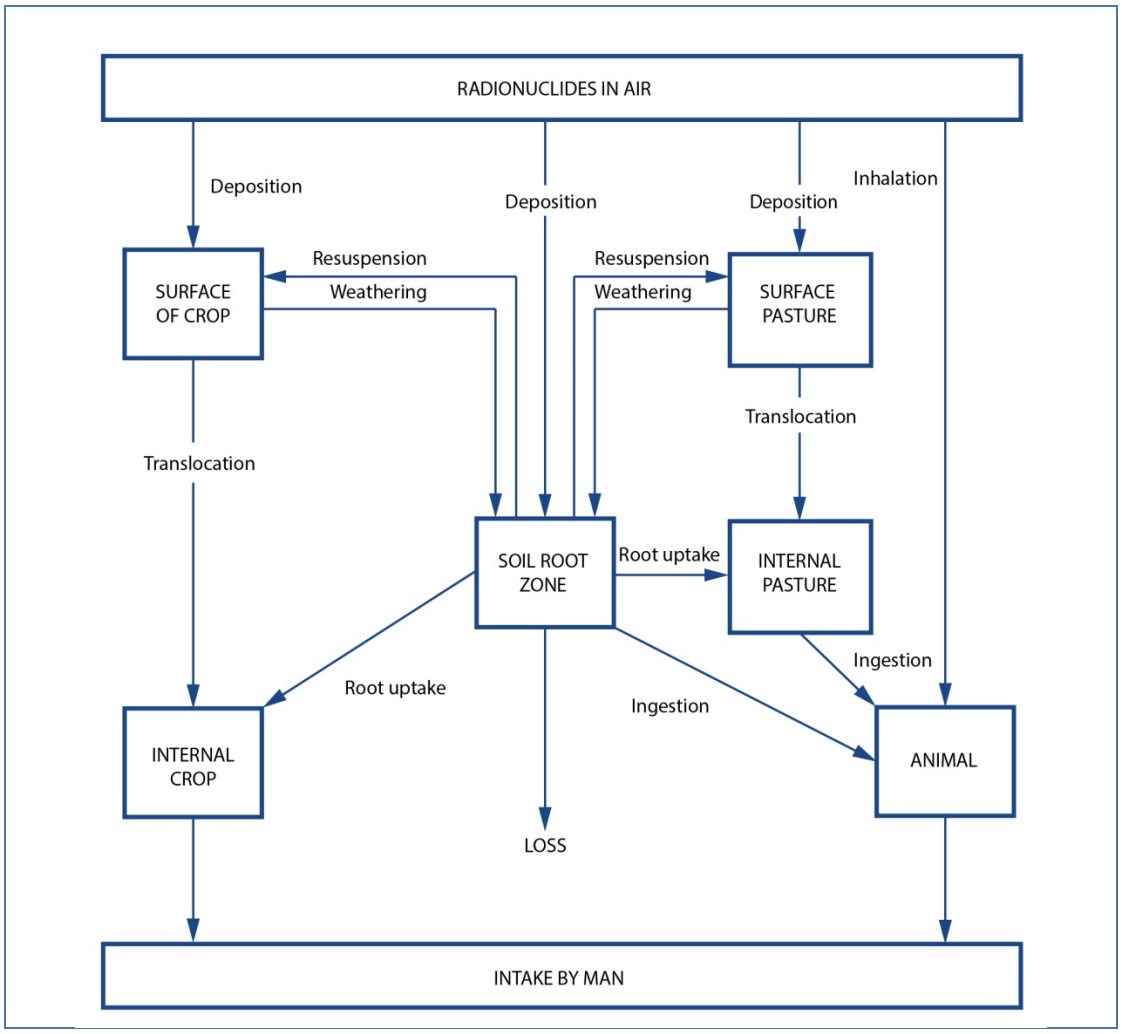
radionuclides, with the exception of the noble gases, tritium and ^{14}C for which a value of zero is applied. As noted above, tritium and ^{14}C exchange with the soil and vegetation; however, this is modelled using a specific activity approach (as discussed below). Because these radionuclides are returned to atmosphere, the deposition rate is not used and the effective deposition velocity is taken to be zero, even for ^{14}C which is partly retained on the ground. This is consistent with the use of the generic approach to the modelling of dispersion applied in the UNSCEAR 2000 Report [U6] and, with the application of a value of *n* of 1.42, 1.4 or 1.2 in equation 1. The use of these parameters ensures that there is a balance between the activity discharged and the activity deposited within a distance of around 2,000 km, thereby ensuring that the relevant exposures are included in the estimation of collective dose.

39. The calculated activity concentrations in air at ground level depend to some extent on the height from which the discharge takes place and whether the discharge is from a point source or a wide area. The heights of stacks from which discharges take place (i.e. point sources) vary considerably. The discharges from uranium mine and mill tailings, on the other hand, take place at ground level over a wide area. Electronic attachment 4 discusses the variation in estimated activity concentrations in air with stack height and the differences for point and area sources. The differences in the concentration profiles with stack height lessen with distance from the stack. For the case illustrated in electronic attachment 4, where a uniform wind rose is assumed together with Pasquill Category D conditions for 65% of the time and all other categories for the rest of the time, the estimated concentration in air for a ground-level discharge is about a factor of three higher than that from a 100 m stack at a distance of 5 km, and less than a factor of two higher than from a 30 m stack. Larger and smaller differences would be seen for the individual Pasquill categories but this comparison applies to the annual average that is needed for assessing routine continuous discharges. At a downwind distance of 100 km, the difference in concentrations for a ground-level discharge and one from a 100 m stack is about a factor of two. For point and area sources, the differences in estimated activity concentrations at these distances are small. The ratio of the time-integrated activity concentrations in air for an area source to that for a point source is 0.9 at 5 km and is 1 beyond 10 to 20 km (see electronic attachment 4). Given these findings, the Committee agreed that, for its generic methodology, it was reasonable to adopt a single stack height of 30 m and to consider all discharges to atmosphere as point sources.

3. Behaviour of radionuclides in a terrestrial environment

40. Radionuclides discharged to atmosphere may be transferred to plants by a number of processes, primarily direct deposition onto the surface of plants and uptake by their roots from material deposited on the soil. The most important processes for the transfer of radionuclides through the terrestrial environment are illustrated in figure III.

Figure III. The important processes for transfer of radionuclides through the terrestrial environment



41. There have been significant developments in the modelling of the transfer of radionuclides through the terrestrial environment in recent years, partly as a result of studies following the Chernobyl accident, see for example [C1]. The standard compilations of the concentration factors, linking different parts of the environment, e.g. soil and plants, and other relevant parameters have been reviewed and updated as part of international coordinated research activities [C1, I5].

42. For the purposes of this methodology, the Committee used the dynamic food-chain model FARMLAND [B6], as implemented in PC-CREAM [S8], to derive integrated activity concentrations in food (fresh weight) per unit deposition rate; these are the activity concentrations integrated to 100 years for continuous deposition at a rate of 1 Bq/(m^2 s) for one year. These estimated concentrations take account of the various environmental transfer, migration and loss processes illustrated in figure III and radioactive decay. Values of radionuclide transfer parameters for terrestrial environments were selected from international compilations of data [I1, I5], supplemented by additional data [S8]. Expert judgement was used to select values appropriate for the Committee's purposes which are not overly cautious. The values selected are intended to be appropriate for a range of environments and climates. The FARMLAND model uses a standard approach to estimate the transfer of radionuclides through terrestrial food chains and has been found to be in good agreement with measured data [S8]. In a comparison exercise carried out as part of the IAEA EMRAS II (Environmental Modelling for

Radiation Safety) programme [I6], the results obtained from FARMLAND were found to be in good agreement with those results from other models. The derived activity concentrations applied in the Committee's methodology are summarized in table 5 and full details of the model and parameter values can be found in Brown and Simmonds [B6] and Smith and Simmonds [S8].

Table 5. Activity concentrations in foodstuffs integrated to 100 years for continuous deposition at a rate of 1 Bq/(m^2 s) for one year [S8]

Radionuclide	*Integrated activity concentration in food (fresh weight) (Bq/kg per Bq/(m^2 s))*			
	Cereals ($C_{cereal,unit}$)	*Vegetables & fruits* ($C_{veg,unit}$)	*Milk & dairy products* ($C_{milk,unit}$)	*Meat & offal* ($C_{meat,unit}$)
^{35}S	3.7×10^{5}	1.2×10^{5}	1.4×10^{6}	6.0×10^{6}
^{54}Mn	8.6×10^{4}	1.3×10^{5}	9.0×10^{4}	1.9×10^{5}
^{58}Co	5.3×10^{4}	9.3×10^{4}	3.9×10^{5}	7.4×10^{5}
^{60}Co	1.1×10^{5}	1.5×10^{5}	2.3×10^{6}	1.3×10^{7}
^{65}Zn	1.8×10^{5}	2.2×10^{5}	7.0×10^{5}	5.8×10^{6}
^{90}Sr	7.1×10^{5}	7.3×10^{5}	1.5×10^{6}	3.3×10^{5}
^{106}Ru	9.8×10^{3}	1.0×10^{5}	1.1×10^{3}	9.7×10^{5}
^{129}I	6.0×10^{5}	2.3×10^{5}	3.1×10^{5}	2.1×10^{5}
^{131}I	4.2×10^{4}	4.1×10^{4}	5.8×10^{4}	2.5×10^{4}
^{134}Cs	4.9×10^{5}	1.4×10^{5}	2.5×10^{5}	1.2×10^{6}
^{135}Cs[a]	7.0×10^{5}	3.3×10^{5}	3.0×10^{5}	1.6×10^{6}
^{137}Cs	5.9×10^{5}	2.2×10^{5}	3.0×10^{5}	1.5×10^{6}
^{138}Cs[a]	8.5×10^{0}	1.7×10^{2}	1.3×10^{-2}	1.3×10^{-3}
^{210}Pb	4.1×10^{4}	1.4×10^{5}	1.2×10^{4}	2.4×10^{4}
^{212}Pb[a]	1.6×10^{2}	3.2×10^{3}	2.1×10^{2}	8.5×10^{-1}
^{214}Pb[a]	7.0×10^{0}	1.4×10^{2}	6.6×10^{-1}	1.1×10^{-4}
^{214}Bi[a]	5.4×10^{0}	1.0×10^{2}	1.4×10^{0}	1.7×10^{-2}
^{210}Po	4.9×10^{3}	9.5×10^{4}	8.2×10^{4}	1.1×10^{5}
^{226}Ra	2.6×10^{5}	3.0×10^{5}	1.7×10^{5}	3.3×10^{4}
^{228}Ra[a]	8.8×10^{4}	1.3×10^{5}	7.4×10^{4}	1.4×10^{4}
^{228}Th[a]	5.4×10^{3}	1.0×10^{5}	1.5×10^{2}	1.2×10^{3}
^{230}Th	7.9×10^{3}	1.1×10^{5}	1.7×10^{2}	2.2×10^{3}
^{232}Th	7.9×10^{3}	1.1×10^{5}	1.7×10^{2}	2.2×10^{3}
^{234}Th[a]	3.4×10^{3}	6.6×10^{4}	1.1×10^{2}	6.6×10^{1}
^{234}U	5.6×10^{4}	1.5×10^{5}	5.7×10^{4}	2.8×10^{5}
^{238}U	5.6×10^{4}	1.5×10^{5}	5.7×10^{4}	2.8×10^{5}
^{239}Pu	1.0×10^{4}	1.1×10^{5}	1.6×10^{2}	8.8×10^{3}
^{240}Pu	1.0×10^{4}	1.1×10^{5}	1.6×10^{2}	8.8×10^{3}
^{241}Am	1.5×10^{4}	1.1×10^{5}	8.5×10^{1}	4.7×10^{3}

[a] Included as progeny only.

43. The dispersion of ^{3}H and ^{14}C in the environment is more complex than that of other radionuclides owing to the role of hydrogen and carbon in biological systems. These radionuclides therefore need to be treated differently from other radionuclides. As previously, the Committee has assumed these radionuclides reach equilibrium rapidly with their corresponding stable element, and used an approach based on their specific activity.

44. The specific-activity model for tritium is based on the assumption that tritium behaves as hydrogen in the environment so that tritium discharged to atmosphere exchanges with the hydrogen in water in air, soil, plants and animals. The concentration of tritiated water (HTO) and organically bound tritium (OBT) in plants is determined on the basis of the water content in plants and a partition factor that takes account of the presence of exchangeable hydrogen in the dry weight of the plant [I5]. Full details of the approach are given in the appendix. The concentrations of HTO and OBT in animal products are determined using concentration factors that relate the concentrations in these products to those in feed, drinking water and inhaled air.

45. The specific activity (or activity concentration) of ^{14}C in elemental or stable carbon is determined from the discharge by taking account of dispersion in the atmosphere and the concentration of stable carbon in the atmosphere. The concentration of ^{14}C, expressed in Bq/kg of stable carbon, is assumed to be the same in plants as in air. The following equation is used to calculate the concentration of ^{14}C in terrestrial foods, $C_{f,C\text{-}14}(x)$, at distance x from the discharge point:

$$C_{f,^{14}\mathrm{C}}(x) = C_{\mathrm{air},^{14}\mathrm{C}}(x) \cdot \frac{S_p}{S_{\mathrm{air}}} \tag{2}$$

where $C_{\mathrm{air,C\text{-}14}}(x)$ is the activity concentration of ^{14}C in air at distance x (Bq/m^3), S_{p} is the concentration of stable carbon in the crop of interest (grams of carbon per kg fresh weight of crop) and S_{air} is the concentration of stable carbon in air (grams of carbon per cubic metre of air).

Similarly the concentration of ^{14}C in animal products, $C_{\mathrm{f,C\text{-}14}}$ at distance x from the discharge point is given by:

$$C_{f,^{14}\mathrm{C}}(x) = \frac{f_C \cdot C_{\mathrm{pasture},^{14}\mathrm{C}}(x) \cdot S_a}{S_p} \tag{3}$$

where f_c is the fraction of feed containing ^{14}C (assumed to be 1 in the methodology), $C_{\mathrm{pasture,C\text{-}14}}(x)$ is the concentration of ^{14}C in pasture at distance x from the discharge point (derived as for crops using equation (2)), S_a is the concentration of stable carbon in the animal product (grams of carbon per kilogram fresh weight) and S_p is the concentration of stable carbon in the pasture (grams of carbon per kilogram fresh weight of pasture).

46. The values of the model parameters forming part of the specific-activity model for ^{3}H and ^{14}C are summarized in table 6 (see the appendix for more information). The symbols used here and in the workbooks are those used in the IAEA publication describing this model for ease of reference.

Table 6. Parameters and their values associated with the specific-activity model for ^{3}H and ^{14}C (taken from [I5])

Parameter	*Symbol*	*Value*	*Unit*
Stable carbon concentration in air	S_{air}	0.2	g of C/m^3
Stable carbon concentration in cereals (fresh weight)	S_p	390	g of C /kg
Stable carbon concentration in vegetables (fresh weight)	S_p	30	g of C /kg
Stable carbon concentration in pasture (fresh weight)	S_p	100	g of C /kg
Stable carbon concentration in cow meat (fresh weight)	S_a	200	g of C /kg
Stable carbon concentration in cow milk (fresh weight)	S_a	65	g of C /kg
Fraction of feed containing ^{14}C	f_c	1	—
Fractional water content of cereals (fresh weight)	WC_p	0.12	L/kg
Fractional water content of vegetables (fresh weight)	WC_p	0.92	L/kg
Fractional water content of pasture (fresh weight)	WC_p	0.76	L/kg
HTO:H_2O water vapour pressures	γ	0.909	—
Absolute humidity	H_a	6×10^{-3}	L/m^3
Relative humidity	RH	0.7	—
Empirical constant	$CR_{s\text{-}a}$	0.3	—
Concentration ratio for HTO intake through milk	$CR_{a,HTO}$	0.87	(Bq/kg fresh weight) per (Bq/L)
Concentration ratio for HTO intake through meat	$CR_{a,HTO}$	0.66	(Bq/kg fresh weight) per (Bq/L)
Water equivalent factor[a], cereals	WEQ_p	0.56	L/kg
Water equivalent factor, vegetables	WEQ_p	0.51	L/kg
Water equivalent factor, pasture	WEQ_p	0.56	L/kg
Partition factor[b]	R_p	0.54	—
Concentration ratio for OBT intake, milk	$CR_{a,OBT}$	0.24	(Bq/kg fresh weight) per (Bq/kg dry weight)
Concentration ratio for OBT intake, meat	$CR_{a,OBT}$	0.4	(Bq/kg fresh weight) per (Bq/kg dry weight)

[a] The water equivalent factor is the mass (kg) of water produced per unit mass (kg) of dry matter combusted.

[b] The ratio of the concentration of non-exchangeable organically-bound tritium in combustion water to that in tissues (e.g. leaves).

4. External and internal exposure

(a) *External exposure*

47. The Committee considers that its previous methodology [U6] for estimating the dose from external exposure due to immersion by assuming a semi-infinite cloud of radionuclides is still appropriate. It acknowledges some limitations with this approach, most notably where activity concentrations in air are likely to be non-uniform over a distance of a few hundred metres to one kilometre from the point of discharge. However, given the distances over which the Committee's assessments are made, the application of dose coefficients for external exposure used previously, which were based on [E2], is unlikely to be a source of significant error. The dose coefficients applied in the Committee's methodology are presented in table 1.

48. The annual characteristic individual dose from immersion in the plume, $H_{E(\text{ex,cloud}),i}$ for radionuclide, i (Sv/a) is estimated at a series of distances, x (m), from the discharge point by assuming 100% occupancy (the fraction of the time that is spent at a particular location) at locations at those distances (O_{ann} (s/a)) and applying the relevant dose coefficients for external exposure due to immersion in the plume, $D_{\text{ex, cloud},i}$ from table 1 (Sv per (Bq s/m^3)). Account is then taken of the fraction of time spent outdoors, O_{out} (dimensionless) and the shielding effect of buildings, L_{cloud} (dimensionless) as shown in equation (4) and discussed below.

$$H_{E(\text{ex,cloud}),i}(x) = C_{\text{air},i}(x) \cdot D_{\text{ex,cloud},i} \cdot O_{\text{ann}} \cdot \left(O_{\text{out}} + (1 - O_{\text{out}}) \cdot L_{\text{cloud}}\right) \quad (4)$$

Where $C_{\text{air},i}$ (x) is the activity concentration of radionuclide i in air (Bq/m^3) at location x. The annual individual dose from external exposure due to deposited material, $H_{E(\text{ex,deposit}),i}$ (x) (Sv/a) at a distance x (m) from the discharge point is calculated from the time-integrated activity concentration (to 100 years) of the radionuclide i on soil at the location of interest, $\dot{d}_i(x)$ (Bq s/m^2), the length of the discharge, $t_{\text{discharge}}$ (s/a) the relevant dose coefficient for external exposure due to deposition, $D_{\text{ex,deposit},i}$ (Sv/ Bq s/m^2), the fraction of time spent outdoors, O_{out} (dimensionless) and the dimensionless location factor that takes account of the shielding effect of buildings, as shown in equation (5) and discussed below.

$$H_{E(\text{ex,deposit}),i}(x) = \dot{d}_i(x) \cdot t_{\text{discharge}} \cdot D_{\text{ex,deposit},i} \cdot \left(O_{\text{out}} + (1 - O_{\text{out}}) \cdot L_{\text{deposit}}\right) \quad (5)$$

49. The Committee's previous methodology applied the dose coefficients for external exposure from radionuclides deposited on soil provided by Beck [B1]. An alternative approach was used for the Committee's 2013 Report of the levels of radiation exposure due to the nuclear accident at the Fukushima-Daiichi nuclear power station [U12] based on the model published by Petoussi-Henss et al. [P2]. The effective dose coefficients calculated using this more recent model [P2] were similar to or within a factor of two of those used previously. For the sake of simplicity and consistency with its 2013 Report [U12], the Committee decided to apply dose rate coefficients for external exposure, $\dot{e}_{\text{dep}}$ (nSv/h per kBq/m^2) from Petoussi-Henss et al. These values are based on calculations using a voxel phantom and the latest definition of effective dose [I13] (the use of the previous definition of effective dose in the methodology would make little difference to the calculated effective doses for external exposure). Where data for particular radionuclides were not available, the data set was supplemented by factors derived from the United States Federal Guidance Report No. 12 [E2].

50. Petoussi-Henss et al. [P2] modelled the geometry as an infinite mono-energetic plane source shielded by a soil layer of depth 0.5 g/cm^2. Such an assumption gives a good description of the radiation field after wet deposition on the ground and after dry deposition following the first rainfall [I15, J1]. With this geometry, the air kerma from a ^{137}Cs (^{137m}Ba) source is reduced by a factor of 0.67 compared to a plane source on the ground–air interface. The effective dose coefficients were derived assuming a constant density of air of 1.2×10^{-3} g/cm^3 and a soil density of 1 g/cm^3, which is considered to be representative of the upper 2 cm of soil [P2].

51. In order to model the reduction of gamma dose rates because of migration into the soil, the Committee adopted an attenuation function *r(t)* derived empirically from data on the migration of ^{137}Cs [G2]:

$$r(t) = p_1 \cdot \exp\left(-\frac{\ln 2}{T_1}t\right) + p_2 \cdot \exp\left(-\frac{\ln 2}{T_2}t\right) \quad (6)$$

where p_1, and p_2 are dimensionless parameters with values derived empirically, T_1 and T_2 are the initial and final times, respectively, following deposition and t is the time after the deposition of interest. The parameter values in this function were determined from gamma-spectrometric analyses of over 400 soil samples taken during 1986–2003 in the areas of Germany (specifically Bavaria), the Russian Federation, Sweden and Ukraine affected by deposition from the accident at the Chernobyl nuclear power plant in 1986 (e.g. [G2, J3, L2, S2]). For the purposes of the Committee's methodology, parameter values derived for areas distant from the Chernobyl plant were applied, namely p_1 was taken to be 0.5 and p_2 to be 0.5; T_1 was assumed to be 1.5 years while T_2 was assumed to be 50 years. Thus the relationship below with T = 100 years was applied to the value of the dose coefficient from deposition ($\dot{e}_{\text{dep}}$) given in [P2]:

$$e_{\text{dep}} = \dot{e}_{\text{dep}} \cdot \int_0^t \mathrm{e}^{(-\lambda_i t)} r(t)\,dt = \dot{e}_{\text{dep}} \cdot \int_0^t \left(p_1 \mathrm{e}^{-\left(\lambda_i + \frac{\ln 2}{T_1}\right)t} + p_2\, \mathrm{e}^{-\left(\lambda_i + \frac{\ln 2}{T_2}\right)t} \right) dt \quad (7)$$

Substituting for p_1, p_2, T_1, T_2 in the above equations and changing from a decay constant to a half-life, the effective dose (Sv) from external exposure in year 100, e_{dep}, is given by:

$$e_{\text{dep}} = \dot{e}_{\text{dep}} \cdot \left[\frac{0.5}{\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{1.5}} \left(1 - \mathrm{e}^{-\left(\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{1.5}\right)T} \right) + \frac{0.5}{\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{50}} \left(1 - \mathrm{e}^{-\left(\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{50}\right)T} \right) \right] \quad (8)$$

This can be simplified to

$$e_{\text{dep}} = \dot{e}_{\text{dep}} \cdot \left[\frac{0.75 t_{1/2}}{(t_{1/2} + 1.5)\ln 2} \left(1 - \mathrm{e}^{-\left(\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{1.5}\right)T} \right) + \frac{25 t_{1/2}}{(t_{1/2} + 50)\ln 2} \left(1 - \mathrm{e}^{-\left(\frac{\ln 2}{t_{1/2}} + \frac{\ln 2}{50}\right)T} \right) \right] \quad (9)$$

As an example, for caesium-137 and caesium-134 the following values can be calculated:

$$e_{\text{dep}}\left({}^{137}\text{Cs}+{}^{137\text{m}}\text{Ba}\right) = 1.55\cdot\times\ 10^{-7}\ \text{Sv/(Bq/m}^2\text{)} \quad (10)$$

$$e_{\text{dep}}\left({}^{134}\text{Cs}\right) = 6.23\cdot\times\ 10^{-8}\ \text{Sv/(Bq/m}^2\text{)} \quad (11)$$

52. Despite differences in climate, little variation in indoor occupancies has been found between countries and there is no evidence of a significant difference due to climate [A1]. Studies show that indoor occupancies range from around 84 to 91% [G1, O2]. The Committee considered that values of between 70% (for an outdoor worker) and 90% (for pensioners and indoor workers) were appropriate for a Japanese population [U12]. In accordance with its previous methodology, the Committee assumed an indoor occupancy factor of 80% [U6]. In equations (4) and (5) above the outdoor occupancy O_{out} is used; this is simply a fractional value and is 1 − 0.8 = 0.2.

53. People indoors receive some protection from external exposure due to gamma-emitting radionuclides in the plume as it passes overhead. The reduction in ambient dose equivalent rate depends on the nature and structure of the building as well as on the energy of the radiation. A number of studies of the shielding effect of various types of buildings have been published, particularly following the Chernobyl accident [E2]. For example, the work of Le Grand [L1] and Jacob and Meckbach [J1, J2] indicated that shielding factors (i.e. the ratio of the ambient dose equivalent rate indoors to that outdoors) for radiation from airborne radionuclides ranged from 0.01 to 0.7 for single-family houses in various European countries. For multi-storey buildings the shielding factor varies with storey, with the lowest values in the basement and first storey and the highest value for the top storey. Le Grand [L1] estimated that shielding factors appropriate for an airborne plume with photon energy of 0.68 MeV ranged from 0.01 to 0.1 for the ground floor and from 0.09 to 0.4 for the upper floors of buildings. For its methodology, the Committee has selected a shielding factor of 0.2 for radionuclides in the plume, being within the range applicable to single and multi-storey buildings.

54. The UNSCEAR 1982 Report [U4] provided an overview of shielding factors appropriate for deposited radionuclides, with values ranging from 0.05 in office buildings, 0.2 in masonry homes, and 0.4 in wooden buildings. This information was based on work by Burson and Profio, which showed a range of shielding factors depending on the nature of the building, with the lowest factors being for basements of large multi-storey buildings [B8]. The United States Nuclear Regulatory Commission [N6] and others have suggested a generic shielding factor of 0.5 for regulatory purposes, which it considers appropriate for photon energies above a few hundred kiloelectronvolts [E2]; for photons of lower energy, use of such a value may considerably overestimate the dose equivalent [K6]. In their assessment of the radiation exposure of the population of the United States of America [N3, S1], the National Council on Radiation Protection and Measurements (NCRP) applied a shielding factor of 0.59 (±6%) for terrestrial gamma radiation, which it considered to be appropriate for photon energies of greater than a few hundred kiloelectronvolts.

55. Location factors are used to express the ratio of external exposures in terms of ambient dose equivalent rate at a specific location to the ambient dose equivalent at the location for which calculated or measured ambient dose equivalent was obtained (for example, this might be between the exposures outdoors in an urban and a rural environment). This is a broader term than shielding factor which just allows for the reduction of ambient dose equivalent from being indoors. For the purposes of this methodology, the two terms can be considered to be equivalent, because it is the reduction in external exposures from being indoors that is relevant. Golikov et al. evaluated the location factors for gamma radiation in air in rural and urban environments in the Russian Federation five years after the Chernobyl accident [G2]. In urban areas, they derived location factors for living areas that varied from 0.01 for a multi-storey house to 0.09 for a wooden house, while they estimated the factor for buildings where

people work to be around 0.02. In rural areas, location factors for living areas ranged from 0.02 (for a multi-storey house) to 0.13 (for a single-storey wooden building). This work formed the basis for the time-dependent location factors used in the Committee's 2013 Report on the levels and effects of radiation exposure due to the nuclear accident at the Fukushima-Daiichi nuclear power station [U12]. Three different time-dependent location factors were used for that assessment: *(a)* for paved external surfaces, *(b)* for non-paved external surfaces, and *(c)* for inside buildings. This time dependence is important when assessing exposures due to an accident. However, for routine releases it is the dose in the 100th year of continuous discharge that is of interest and the effect of using a time-dependent location factor is small compared to differences in location factors for different building types. These results also show a greater degree of shielding from deposited radionuclides than from radionuclides in the plume, and this is reflected in the Committee's choice of values for its methodology. In accordance with its previous methodology [U6], the Committee has used a shielding (location) factor of 0.1 to allow for the reduction in ambient dose equivalent from external exposure due to deposited material while indoors. This value was chosen as representative of occupancy in a single-storey building and was considered to be reasonably consistent with the result that would be obtained if an approach based on time-dependent location factors had been used.

(b) *Internal exposure from inhalation*

56. As previously, the Committee uses a standard approach to assess the internal exposure from inhalation of radionuclides in the air following discharges to atmosphere. This approach uses the estimated activity concentration of a radionuclide in air (section III.A.2 above), an appropriate breathing rate and the relevant dose coefficient for intake by inhalation (table 1).

57. The Committee continues to use a nominal adult breathing rate of 20 m^3/d [U7] in its methodology to maintain consistency with previous assessments, recognizing differences between this value and that used by ICRP to derive dose coefficients. As discussed earlier, the Committee considers that the dose coefficients for inhalation given in ICRP Publication 119 [I14] using the ICRP model of the respiratory tract [I11] continue to be appropriate (table 1). No account is taken of any reduction in activity concentrations in air when people are indoors because the Committee considers this to be a second-order effect that will not have a significant effect on the estimated doses.

58. A different approach is needed for the inhalation of isotopes of radon. In the UNSCEAR 2006 Report, the Committee considered a number of issues related to the assessment of doses from the inhalation of radon and its short-lived progeny [U9]. It concluded that it should continue to use a value for the radon dose coefficient of 9 nSv per (Bq h)/m^3 for this methodology, with equilibrium factors (the ratio between the activity of the short-lived radon progeny and the activity that would be at equilibrium with the radon parent) of 0.6 for radon outdoors and 0.4 for radon indoors (indoor occupancy being 80% as discussed earlier) to calculate annual effective doses from inhalation of radon and its short-lived progeny (see the appendix for more details).

(c) *Internal exposure from ingestion*

59. Members of the public may be exposed through ingestion of food that contains radionuclides resulting from discharges to atmosphere. As indicated in section III.A.3, radionuclides discharged to atmosphere may be transferred to human food by a number of routes. The annual effective dose from the ingestion of food, *f*, containing radionuclide, *i*, at distance *x* (m) from the discharge point in region *r*, $(H_{E(\mathrm{ing}),f,r,i}(x))$ (Sv/a) is given by equation (12):

$$H_{E(\text{ing}),f,r,i}(x) = C_{f,i}(x) \cdot D_{\text{ing},i} \cdot F_{\text{local}} \cdot I_{f,r} \quad (12)$$

where $D_{\text{ing},i}$ (Sv/Bq) is the effective dose coefficient for ingestion of radionuclide i as given in table 1; F_{local} is the fraction of food that is locally produced (dimensionless); $I_{f,r}$ is the average consumption rate of food f in region r (kg or L per year) as discussed below; $C_{f,i}$ is the activity concentration of radionuclide i in terrestrial food f at distance x from the discharge point (Bq/kg) given by:

$$C_{f,i}(x) = C_{f,\text{unit},i} \cdot \dot{d}_i(x) \quad (13)$$

where $C_{f,\text{unit},i}$ is the activity concentrations in foodstuffs integrated to 100 years for continuous deposition at a rate of 1 Bq/(m^2 s) for one year (Bq/kg per Bq/(m^2 s)) given in table 5 and $\dot{d}_i(x)$ is the deposition rate at distance x of radionuclide i (Bq /(m^2 s)). The food contamination monitoring and assessment programme (GEMS/Food) database for 2012 — part of the WHO Global Environment Monitoring System — formed the basis for the population-weighted consumption rates used by the Committee to calculate doses from ingestion for each UNEP region [W2]. For the Committee's methodology, the World Health Organization (WHO) combined the data for specified food groups and reconfigured them for the UNEP regions and subregions (figure II). The resulting values of $I_{f,r}$ for terrestrial foods are presented in table 7. World-average values have also been derived; these are the averages of the values for each region weighted by the population densities given in table 3. As discussed in paragraph 11, for the estimation of characteristic individual doses, it is assumed that only 25% of foods consumed are produced locally (F_{local} is 0.25). However in estimating collective doses, people are assumed to obtain 100% of their food from the area where they live (F_{local} is 1.0), this assumption is considered reasonable because collective doses are estimated for areas of 30,000 km^2 or more.

Table 7. Annual average per caput consumption rates of terrestrial foods by UNEP region

UNEP region	*Annual average per caput consumption rate[a] (kg) for each food type*			
	Cereals	*Vegetables and fruit*	*Milk and dairy products*	*Meat and offal*
Africa	130	220	31	17
Asia and Pacific	140	240	45	30
Europe	110	280	120	65
Latin America and Caribbean	110	210	77	63
North America	88	260	120	100
West Asia	140	180	43	34
World average[b]	130	230	65	44

[a] Values are rounded to two significant figures in order not to imply great precision.

[b] World-average values are the averages of the values for each region weighted by the population densities given in table 3.

60. The Committee considered that the inclusion of all food groups and all 13 regions in the WHO GEMS/Food [W2] would imply a level of accuracy that was inconsistent with other aspects of the revised methodology. Although the dietary data in GEMS/Food were based on clusters of countries with similar dietary habits, this clustering would not have been consistent with other information for UNEP regions used to calculate doses (e.g. population distribution and energy production). Therefore, a simplified approach was used based on the UNEP regions shown in figure II; any differences in intakes and hence doses because of this simplification were deemed commensurate with those due to other simplifying assumptions made in the methodology.

61. As discussed in section III.A.3, activity concentrations in foods integrated to 100 years for continuous deposition at a rate of 1 Bq/(m^2 s) for one year have been determined using combined food- and radionuclide-specific transfer parameters. These estimated concentrations take account of a range of physical processes that do not depend on the chemical element (such as interception by plant surfaces) and biochemical factors that do depend on the chemical element, such as root uptake and transfers from animal feed to meat and milk. For tritium and carbon-14, combined transfer parameters are defined per unit activity concentration in air based on a specific-activity approach. The intake of radionuclides is then determined using the population-weighted food consumption rates for the different geographical regions. This is a slightly different approach from that used previously by the Committee, where simple global average intakes were used, (see electronic attachments 1 and 2); however, the overall difference in the resulting dose estimates is not significant.

62. A limited sensitivity analysis was carried out to determine the applicability of the generic food-chain model for different regions of the world and whether the foods and related consumption rates were appropriate. This analysis is outlined in electronic attachment 4 and the Committee concluded that it was reasonable to use the food-chain model and the consumption data by geographical region for the purposes of assessing worldwide exposures.

B. Assessment of doses from discharges to a freshwater environment

63. The extent of dispersion of radionuclides in freshwater bodies varies significantly depending on characteristics of the water body, particularly the volume of the body into which the discharge occurs and the water flows. However, the Committee decided that there would be value in developing generic dose-calculation factors that provide an estimate of the integrated activity concentrations in water from a discharge of each radionuclide for a year, allowing for dispersion within different types of water body. An approach for estimating individual doses and for calculating regional components of collective dose was developed on this basis. (As discussed previously, for discharges to rivers using the simple, generic approach adopted in the methodology, it is not possible to distinguish between local and regional components of collective dose).

64. The following exposure pathways are considered for discharges to freshwater bodies (see figure I):

(a) Internal exposure from ingestion of radionuclides in drinking water;

(b) External exposure (beta and gamma emitters) from radionuclides in sediments deposited on the riverbank;

(c) Internal exposure from ingestion of radionuclides incorporated into freshwater fish;

(d) Internal exposure from ingestion of radionuclides incorporated into terrestrial foods because of irrigation.

65. Other exposure pathways such as internal exposure from inadvertent ingestion of water and sediment, external exposure when swimming or boating, and external exposure from radionuclides deposited on irrigated land, are also possible. However, the exposure pathways above have been found to be the largest contributors to individual and collective doses following continuous discharges to water bodies [J5]. The external exposure pathway, *(b)* above, is included only in the calculation of characteristic individual dose. This pathway is unlikely to be a significant contributor to collective doses from aquatic discharges from nuclear power stations and reprocessing plants, as demonstrated by

past assessments (e.g. [J6]). Individual doses are estimated from individual consumption rates and occupancy data, while collective doses from ingestion are calculated using region-specific data on total fish catches, water abstraction and agricultural production. Thus, the resulting individual and collective dose estimates are not directly linked in the way that they are for discharges to atmosphere. In effect, collective doses from discharges to a freshwater body are based on the total usage of water or total amount of produce from the generic water body, irrespective of the location of people.

66. The Committee's methodology initially considered three types of environment for assessing doses arising from aquatic discharges to freshwater bodies: *(a)* lakes, *(b)* small rivers and *(c)* large rivers. However, the Committee agreed that the dispersion of aquatic discharges from facilities on the shores of a large lake can be assessed using the same approach as for large rivers. Given the differences in characteristics and hence dispersion in different rivers and lakes throughout the world, the Committee agreed that the distinction between lakes and large rivers was a second-order effect and did not need to be considered further for its purposes. It should be noted that the Committee's methodology does not apply to closed lake systems, i.e. those without rivers feeding into or out of the lake.

67. Two types of river are defined to allow for the range of discharge conditions that may occur. For example, inland nuclear facilities (with the exception of mines and mills) are assumed to discharge into large rivers, and non-nuclear facilities and mines into small rivers. The dimensions and flow rates associated with a range of rivers into which nuclear and other facilities discharge were reviewed in order to select appropriate parameter values for the Committee's methodology.

1. Dispersion of radionuclides in freshwater bodies

68. The Committee's methodology for deriving activity concentrations of radionuclides following their discharge into freshwater bodies assumes that complete mixing occurs immediately. This is a simplification because for rivers complete dilution would occur over some tens of kilometres downstream, the actual distance depending on the width of the river, which is in turn related to the volumetric flow rate. Nevertheless, significant mixing does occur over relatively short distances. As an illustration of this, table 8 shows results from using the NCRP screening model, which is designed for the purpose of demonstrating compliance with environmental standards for discharges of radionuclides [N2]. The table indicates that the activity concentration in unfiltered water assuming complete mixing of the radionuclide across the total width of the river essentially equals the actual activity concentration in unfiltered water in the plume (i.e. the value of the partial mixing correction factor approaches one) for rivers up to a width of around 100 m at a downstream distance of around 5 km. For wider rivers, the value of the correction factor would be of the order of one to five at this distance; complete mixing would, however, occur over a distance of around 100 km for such rivers. Specific information is available for the Techa–Iset–Tobol–Irtysh–Ob river system in the Russian Federation [N5]. This is a complex river system and complete mixing does not occur until some distance downstream. (At 27 km downstream there was not complete mixing with nearly a factor of 5 variation in measured concentrations at different locations across the river.) However, the abstraction point for drinking water is likely to be at some distance downstream from the discharge point and fish will be caught over large sections of the river. Given this and the generic nature of the revised methodology, the distances over which collective doses are calculated, and other uncertainties associated with the approach, the Committee considered it unlikely that assuming complete mixing would significantly affect the collective dose estimate. Although the dose to an individual obtaining their drinking water from the immediate vicinity of a source would depend on the location of the abstraction point relative to the point of discharge, because of the generic nature of the approach, assuming complete mixing is also appropriate for individual dose estimation.

Table 8. Correction factors to complete mixing in a river plume as a function of downstream distance from the point of discharge for different river widths [N2]

The correction factor for partial mixing represents the ratio of the activity concentration in water in the plume to the activity concentration in water if, at the same point, complete mixing in the total width of the river were assumed. Complete mixing would give a value of 1

Distance downstream (km)	*Partial mixing correction factor at various river widths*[a]				
	10 m	*50 m*	*100m*	*200 m*	*400 m*
0.1	3.2	6	8	10	12
1	1	2.4	3.2	5	8
5	1	1	1.6	2.6	3.6
10	1	1	1	1.9	3
50	1	1	1	1	1.4
100	1	1	1	1	1

[a] Values are rounded to one decimal place.

69. For the purposes of the Committee's methodology, the activity concentrations of radionuclides in river water are therefore derived assuming that the discharged radionuclides are dispersed uniformly across the river. Under these conditions, the activity concentrations in water depend upon the volumetric flow rate of the river alone, which, in turn, is primarily determined by the width of the river. Thus, it is assumed that, for all freshwater pathways, the activity concentration in unfiltered freshwater is given by:

$$C_{\mathrm{uw},i} = Q_i / F \qquad (14)$$

where $C_{\mathrm{uw},i}$ is the activity concentration of radionuclide, i, in unfiltered water at the discharge point (Bq/m^3); Q_i is the discharge rate of radionuclide, i, (Bq/s) and F is the volumetric flow rate of the river at the point of discharge (m^3/s). The activity concentrations of radionuclides in filtered water are determined from the suspended sediment load and the radionuclide-specific partition factors for freshwater environments. These activity concentrations are then used, for example, to derive activity concentrations of radionuclides in freshwater fish. To derive activity concentrations of radionuclides in drinking water, a water treatment factor is applied.

70. For the large river (and as noted earlier, for lakes), a width of 240 m and flow rate of 1,000 m^3/s are assumed for the purposes of the methodology. Table 9 gives some illustrative flow rates and other dimensions for a range of rivers of different sizes throughout the world. The values assumed for a large river are consistent with the data for major sections of the Rhône, Loire, Danube and Rhine; these are rivers into which a number of nuclear installations discharge radionuclides. They are also similar to other major rivers throughout the world, as shown in table 9, although some rivers have greater flows, notably the Amazon.

Table 9. Flow rates and dimensions of some typical rivers and those assumed in the methodology

River	*Country*	*Flow rate (m^3/s)*	*Length in specified country (km)*	*Width (m)*	*Depth (m)*
Amazon[a]	Peru, Columbia, Brazil	2.0×10^5	6.9×10^3		
Danube[b]	Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Romania, Moldova, Ukraine	3×10^3	3×10^3	5×10^2	6
Ganges[a]	India, Bangladesh	1.6×10^4	2.5×10^3		
Kennet (tributary of Thames)	United Kingdom	1×10^1	3.3×10^1	17	1
Loire[c]	France	7.8×10^2	5.6×10^2	2.6×10^2	3
Mississippi[a]	United States of America	1.6×10^4	3.7×10^3		
Nile[d,e]	Egypt	1.8×10^3	1.5×10^3		
Paraná [f]	Brazil, Paraguay, Argentina	1.7×10^4	4.8×10^3	1.8×10^4	
Pearl	China[g]	2.2×10^3	2.2×10^3		
Rhône[c]	France	1.2×10^3	4.0×10^2	2×10^2	7
Thames[h]	United Kingdom	5×10^1	2.3×10^2	50	2
Yangtze	China[g]	3.2×10^4	6.3×10^3		
Yellow	China[g]	2.1×10^3	5.5×10^3		
ASSUMED VALUES IN THE METHODOLOGY					
Methodology—small river[i]		1×10^1	1×10^2	30	1
Methodology—large river[i]		1×10^3	5×10^2	240	4

[a] Milliman and Farnsworth (2011) [M2].

[b] Maringer (2000) [M1].

[c] Smith and Simmonds (2009) [S8].

[d] Wahaab and Badawy (2004) [W1].

[e] Hamza (2014) [H1].

[f] Encyclopaedia Britannica (Parana-River) [E3].

[g] Information provided by the Chinese delegation.

[h] Hilton et al. (2003) [H4].

[i] The dimensions of the small river are similar to those of the River Kennet in the United Kingdom; those of the large river are similar to those of major sections of the Rhône and Loire in France and other rivers.

71. For the small river, a flow rate of 10 m^3/s (width of 30 m and depth of 1 m) is assumed in the methodology. This is similar to that of the River Kennet in the United Kingdom.

72. The measured suspended sediment loads of the Colorado and Mississippi Rivers have been shown to vary by three or more orders of magnitude [H2, S10]. However, a value of 5×10^{-4} t/m^3 is considered to be appropriately representative within this range and is assumed for large rivers; this also agrees with other data presented for the Colorado River [V1].

73. The suspended sediment loads of small rivers also vary by several orders of magnitude, depending on flow rate. For low flow rates, values in the range 2 to 5×10^{-5} t/m^3 may be considered to be typical (see, for example, Hejduk and Banasik [H3]). A value of 2×10^{-5} t/m^3 was adopted for the purposes of this methodology.

2. Behaviour of radionuclides in a freshwater environment

(a) *Transfers in freshwater environments*

74. The key element-specific parameters that account for the transfer of radionuclides in an aquatic environment are concentration factors that relate the concentrations of elements in fish to their concentrations in water, and partition coefficients that relate the distribution of elements between sediment and water. Standard compilations of these data [I3, I5] have also been updated since the Committee's assessments were issued in the UNSCEAR 2000 and 2008 Reports [U6, U10, U11].

75. The activity concentration of a radionuclide in an aquatic food is derived by applying an equilibrium concentration factor, defined as the ratio of the concentration of the radionuclide in the aquatic food (fresh weight) at equilibrium to its concentration in water (Bq/kg per Bq/L) (note in some compilations of data the term "bioaccumulation factor" is used for these values). The most recent international compilation of concentration factors for freshwater environments [I5] provides transfer parameter values appropriate for equilibrium conditions. Where the available data permit, ranges of observed values are presented together with mean values. Those mean values have been used for the purposes of this methodology supplemented by data from other sources, where necessary; the values adopted by the Committee for this methodology are given in table 10.

76. The transfer of radionuclides between the water column and suspended and bottom sediments depends on both the characteristics of the water body and the chemical and physical characteristics of the radionuclides themselves. The partition coefficient, K_d, relates to the partitioning of radionuclides between the solid and aqueous phases and is expressed as the ratio of the activity of a radionuclide per unit dry weight of sediment at equilibrium to the activity of that radionuclide per unit volume of water (Bq/kg per Bq/L) (this can also be referred to as a distribution coefficient). The most recent international compilation of K_d values for freshwater environments is presented in [I5], although the Committee also used values from other sources, where data were not available in [I5]. The data used are given in table 10 and are intended to represent generic best estimates, recognizing that K_d values vary depending on the characteristics of the water body.

Table 10. Values of radionuclide-specific parameters used in the model for freshwater environments

Radionuclide	*Concentration factor for freshwater fish, B_{fish} (L/kg) (fresh weight)*	*Activity concentrations in sediment (dry weight) in the 100th year of continuous discharge at 1 Bq/s (Bq/kg)*		*Water treatment factor F_{WT} [B7][a]*	*Partition coefficient, K_d (m^3/t)*
		Small river [S8]	*Large river [S8]*		
^{3}H (HTO and OBT)	1.0×10^{0} [N2]	0	0	1.0×10^{0}	0 [I2]
^{14}C	4.0×10^{5} [I5]	5.0×10^{-4}	5.0×10^{-6}	1.0×10^{0}	5.0×10^{0} [I2]
^{35}S	8.0×10^{2} [N2]	2.0×10^{-2}	1.8×10^{-4}	5.4×10^{-1}	2.0×10^{2} [B4]
^{54}Mn	2.4×10^{2} [I5]	3.1×10^{0}	2.0×10^{-3}	3.6×10^{-1}	7.9×10^{4} [I5]
^{58}Co	7.6×10^{1} [I5]	2.3×10^{0}	1.9×10^{-3}	5.4×10^{-1}	4.4×10^{4} [I5]
^{60}Co	7.6×10^{1} [I5]	2.3×10^{0}	1.9×10^{-3}	5.4×10^{-1}	4.4×10^{4} [I5]
^{65}Zn	3.4×10^{3} [I5]	4.9×10^{-2}	4.0×10^{-4}	5.4×10^{-1}	5.0×10^{2} [I2]
^{90}Sr	2.9×10^{0} [I5]	1.2×10^{-1}	7.5×10^{-4}	8.1×10^{-1}	1.2×10^{3} [I5]
^{106}Ru	5.5×10^{1} [I5]	2.0×10^{0}	1.9×10^{-3}	5.4×10^{-1}	3.2×10^{4} [I5]
^{129}I	3.0×10^{1} [I5]	4.0×10^{-1}	1.4×10^{-3}	8.1×10^{-1}	4.4×10^{3} [I5]
^{131}I	3.0×10^{1} [I5]	4.0×10^{-1}	1.4×10^{-3}	8.1×10^{-1}	4.4×10^{3} [I5]
^{134}Cs	2.5×10^{3} [I5]	1.8×10^{0}	1.9×10^{-3}	8.1×10^{-1}	2.9×10^{4} [I5]
^{137}Cs	2.5×10^{3} [I5]	1.8×10^{0}	1.9×10^{-3}	8.1×10^{-1}	2.9×10^{4} [I5]
^{210}Pb	2.5×10^{1} [I5]	8.3×10^{-1}	1.7×10^{-3}	5.4×10^{-1}	1.0×10^{4} [K1]
^{212}Pb	2.5×10^{1} [I5]	6.3×10^{-1}	1.5×10^{-3}	5.4×10^{-1}	1.0×10^{4} [K1]
^{214}Pb	2.5×10^{1} [I5]	1.3×10^{-3}	2.1×10^{-4}	5.4×10^{-1}	1.0×10^{4} [K1]
^{210}Po	3.6×10^{1} [I5]	2.2×10^{0}	1.9×10^{-3}	5.4×10^{-1}	4.0×10^{4} [S3]
^{226}Ra	4.0×10^{0} [I5]	6.4×10^{-1}	1.6×10^{-3}	5.4×10^{-1}	7.4×10^{3} [I5]
^{228}Th	6.0×10^{0} [I5]	4.0×10^{0}	2.0×10^{-3}	3.0×10^{-1}	1.9×10^{5} [I5]
^{230}Th	6.0×10^{0} [I5]	4.0×10^{0}	2.0×10^{-3}	3.0×10^{-1}	1.9×10^{5} [I5]
^{232}Th	6.0×10^{0} [I5]	4.0×10^{0}	2.0×10^{-3}	3.0×10^{-1}	1.9×10^{5} [I5]
^{234}Th	6.0×10^{0} [I5]	3.9×10^{0}	2.0×10^{-3}	3.0×10^{-1}	1.9×10^{5} [I5]
^{234}U	9.6×10^{-1} [I5]	5.0×10^{-3}	4.9×10^{-5}	3.0×10^{-1}	5.0×10^{1} [I2]
^{238}U	9.6×10^{-1} [I5]	5.0×10^{-3}	4.9×10^{-5}	3.0×10^{-1}	5.0×10^{1} [I2]

Radionuclide	*Concentration factor for freshwater fish, B_{fish} (L/kg) (fresh weight)*	*Activity concentrations in sediment (dry weight) in the 100th year of continuous discharge at 1 Bq/s (Bq/kg)*		*Water treatment factor F_{WT} [B7][a]*	*Partition coefficient, K_d (m^3/t)*
		Small river [S8]	*Large river [S8]*		
^{239}Pu	3.0×10^{1} [I2]	4.1×10^{0}	2.0×10^{-3}	2.7×10^{-1}	2.4×10^{5} [I5]
^{240}Pu	3.0×10^{1} [I2]	4.1×10^{0}	2.0×10^{-3}	2.7×10^{-1}	2.4×10^{5} [I5]
^{241}Am	2.4×10^{2} [I5]	3.5×10^{0}	2.0×10^{-3}	2.7×10^{-1}	1.2×10^{5} [I5]

[a] The water treatment factors used are based on flocculation, coagulation, clarification and rapid sand filtration. Where data were not given for a specific element in Brown et al. [B7], an analogue approach was used.

(b) *Transfers from fresh water to terrestrial environments*

77. The irrigation of crops with fresh water may lead to the transfer of radionuclides from a freshwater to a terrestrial environment. This exposure pathway was not included in the Committee's previous methodology but, given the importance of irrigation of crops throughout the world, the Committee decided that it should be considered. In general terms, the rate at which radionuclides present in fresh water are deposited on crops and soil is estimated from information on the rate of irrigation and the length of the crop-growing season. This information is then used to estimate the resultant activity concentrations of radionuclides in terrestrial crops from their activity concentrations in fresh water and the derived calculation factors for their activity concentrations in food per unit deposition rate.

78. There are many different types of irrigation. The most important for the transfer of radionuclides to crops is sprinkler or spray irrigation because radionuclides in the water will be deposited directly on the surface of the plants. Other types of irrigation where water is deposited on the surface of the soil give rise to lower transfers and so were not included in the Committee's methodology. Although there are obvious differences in the behaviour of radionuclides that are deposited on the surface of plants during sprinkler irrigation and that of radionuclides deposited by wet and dry deposition from the atmosphere, the Committee considered that the differences in the overall transfers to plants are a second-order effect in the context of the objectives of the methodology. Therefore, the values of the transfer factors for deposition from the atmosphere are assumed to apply also to irrigation. These parameters include the transfers from plant surfaces and from uptake from the soil. The Committee recognizes that there may be some overestimation in assuming that the rate of uptake from irrigation water is equivalent to that from deposition from the atmosphere, given that greater losses from plant surfaces may be anticipated for the higher deposition rates characteristic of irrigation.

79. The Food and Agriculture Organization of the United Nations (FAO) publishes statistics on water resources in its AQUASTAT database [F4]. The information indicates that 40% of global food production involves irrigation. Data are available on the overall rates of abstraction of water by source (whether from surface or groundwater). Information is available on the overall rate of water abstracted for irrigation, but not on the fraction of irrigation water that is drawn from each source. In the absence of this information, it is assumed that the fraction of water used for irrigation of the total amount abstracted is the same for both sources. Using data from the AQUASTAT database, the fraction of surface water withdrawn for irrigation and the area irrigated per unit volume of water was obtained for each region as shown in table 11, which also gives world-average values. The appendix describes how these values are used in the methodology.

80. From this table, it is clear that, with the exception of West Asia, there is only limited abstraction of water from surface water.

81. The International Commission on Irrigation and Drainage provides data on the area of land under different types of irrigation for 45 countries [I7]. The Committee has used these data to derive the fraction of land under sprinkler/spray irrigation for each region and an average for the world (see table 12). The values in this table are for various times between 1999 and 2012.

82. The fractions given in table 12 are used in the methodology together with the calculated activity concentrations of radionuclides in water and the abstraction rate for irrigation to derive concentrations of radionuclides in foods and hence to estimate individual and collective doses. The Committee agreed that irrigation should only be considered for vegetables and grain and only for large rivers. For small

rivers with low abstraction rates, it is unlikely that there is significant irrigation. Although other crops are likely to be irrigated, the most important are leafy vegetables and grain [F4]. The irrigation of pasture is important in some parts of the world (such as parts of the United States) but it is rare in other major areas with significant cattle production, such as Brazil and Argentina, and so it is not included in the methodology.

Table 11. The fraction of water for irrigation withdrawn from surface waters and the total area irrigated per unit volume of surface water available

Region	*Parameter*	
	Fraction of water for irrigation withdrawn from surface waters (dimensionless)	*Area irrigated per unit volume of withdrawn water (m^2 a /m^3)*
Africa	2.7×10^{-2}	6.0×10^{-1}
Asia and Pacific	9.4×10^{-2}	7.9×10^{-1}
Europe	1.2×10^{-2}	1.9×10^{0}
Latin America and Caribbean	1.0×10^{-2}	8.2×10^{-1}
North America	2.4×10^{-2}	1.3×10^{0}
West Asia	5.7×10^{-1}	4.7×10^{-1}
World average	3.9×10^{-2}	8.5×10^{-1}

Table 12. Fraction of irrigated land that is spray-irrigated (based on information from [I7]

Region	*Fraction*
Africa	0.2
Asia and Pacific	0.1
Europe	0.4
Latin America	0.2
North America	0.5
West Asia	0.3
World average	0.2

(c) *Specific activity models for tritium and carbon-14 in fresh water*

83. The Committee has adopted a specific-activity approach for assessing the transfer of tritium and carbon-14 in a freshwater environment. This is the same approach as it used previously and as described for a terrestrial environment. The assumption that equilibrium conditions exist, which is implicit in the specific-activity model, is considered to be a good approximation for most aquatic compartments in the model [E1, K5]. The model adopted is that described in [I5] in which activity concentrations of tritium in fish are determined on the basis of the HTO concentration in the water column and the fractional water content of fish. The fractional water content is found to be 0.78 L/kg for most fish that form part of the human diet [I5]. The concentration of organically bound tritium (OBT) is also taken into account. The relevant equations and parameter values used in the methodology are given in the appendix.

84. A specific activity approach is also applied to estimate the total tritium concentration in soil water by taking account of the activity concentration of tritium in irrigation water, the rate of irrigation and the effect of mixing with water reaching the soil from precipitation [C1]. The equations and data applied are presented in the appendix.

85. For discharges to aquatic bodies, the specific activity of dissolved inorganic carbon is assumed to be in equilibrium within the part of the environment of interest. The methodology includes a simplified approach based on a dynamic model developed by Sheppard et al. [S4, S5] with some modification to apply it to irrigation based on the approach outlined in [C1]. The equations and parameter values applied are given in the appendix.

3. External and internal exposure

(a) *External exposure from radionuclides in riverbank sediments*

86. Annual individual doses from external exposure during occupancy of riverbanks are calculated using the time-integrated activity concentrations of radionuclides in sediments, the dose coefficients for external exposure from surface deposits and the amount of time spent on riverbanks. This exposure pathway is only considered for the calculation of the characteristic individual dose.

87. For discharges to fresh water bodies, activity concentrations of radionuclides in sediments at a distance of 5 km downstream from the discharge point are used for the purpose of calculating characteristic individual doses from external exposure due to radionuclides in riverbank sediments. It is assumed that there will be continual cycling of radionuclides from the aquatic environment into riverbank sediments taking account of build-up over the 100 year integration period. Dose coefficients for external radiation exposure from surface deposits (Sv/s per Bq/m^2) from the United States Federal Guidance Report No. 12 [E2] are used in the Committee's revised methodology. However, these dose coefficients apply to an infinite surface (assuming a surface deposit only); for river banks, a geometry factor is applied to allow for the finite size of the source of external exposure. Apostoaei et al. [A2] have discussed appropriate geometry factors (these depend upon the surface area of the sediment on the river bank, as represented by the width of the sediment on the bank, and upon the radionuclide). They recommend that factors for ^{137}Cs are applicable in general. The Committee agreed to apply a geometry factor of 0.2 based on the values given by Apostoaei et al. for riverbank sediments with a width of a few metres. In addition, the Committee agreed that the methodology should use an annual occupancy factor of 50 hours for the calculation of the characteristic individual dose.

(b) *Internal exposure from ingestion*

88. Three sources of internal exposure via ingestion are considered in the methodology: drinking water; freshwater fish and irrigated terrestrial foods. In estimating the characteristic individual doses, it is assumed that only 25% of the food is locally produced (see section II, paragraph 11).

Drinking water

89. As described above, the activity concentrations of radionuclides in unfiltered fresh water are assumed to be a function of the volumetric flow rate of the river, which is, in turn, directly related to the type of river assumed. In order to derive activity concentrations in drinking water, element-specific water treatment factors are applied. These are similar to those presented in the UNSCEAR 2000 Report [U6], updated with information included in the most recent edition of the WHO Drinking Water Guidelines [W3]. The WHO provides indicators of the performance of a number of common water-treatment methods for a range of radionuclides.

90. Different treatment techniques are applied across the world and have different effectiveness. Based on information used for the WHO Drinking Water Guidelines [W3], the Committee assumed that—for most countries with high human development indices—flocculation, coagulation, clarification and rapid sand filtration are used. As there are insufficient data available on the techniques employed in less developed countries, the Committee decided to apply a single set of water-treatment factors based on the data for countries with high human development indices. The fractions of each radionuclide removed by standard water-treatment processes assumed in the methodology are shown in table 10.

91. Previously, the Committee used a value of 500 litres per year (1.4 litres per day) [U6, U7, U9] for the worldwide average individual rate of ingestion of drinking water. The Committee has reconfirmed that this value should be retained because it is appropriate for average individual consumption rather than the somewhat higher values typically used for protection purposes.

Freshwater fish

92. Individual doses from the ingestion of freshwater fish are calculated using the activity concentrations of radionuclides in fish and the per caput consumption rate; collective doses are calculated using the activity concentrations and fish-catch data. Information on fish-catch data for each region in 2007 was obtained from [F3]. The total fish catch for each region was divided by the size of the population for the same region to derive per caput consumption rates, which were used to estimate characteristic individual doses. Table 13 shows the resulting annual per caput consumption rates of freshwater fish for each region and a world-average value.

Table 13. Annual per caput consumption of freshwater fish by region

These values represent the total intakes of freshwater fish; the factor of 25% to account for local consumption of food is applied subsequently when calculating characteristic individual doses

Region	*Annual consumption (kg)*
Africa	2.7
Asia and Pacific	7.8
Europe	3.4
Latin America and Caribbean	1.6
North America	4.5
West Asia	1.3
World average	5.7

93. For the calculation of collective doses, the Committee has derived generalized fish-catch information for a range of rivers using data from FAO [F4]. Aquaculture (e.g. the intensive farming of freshwater fish) is excluded from consideration because a large proportion of fish reared in aquaculture come from lakes and ponds [F4].

94. Typical values for the quantity of freshwater fish caught per unit distance and volume of water for typical small and large rivers have been derived for use in the Committee's methodology for each region separately and as a world average. From the FAO data, information was derived on the catch of freshwater fish including and excluding that obtained from aquaculture, plus the annual fish catch for each river in a country. Using information on the length and volume of the relevant stretch of each river, annual fish catches per unit length and per unit volume were calculated and the results are shown in table 14. Based on this information, generic values for small and large rivers were adopted for use in the methodology. It is therefore assumed that one tonne of freshwater fish is caught annually per kilometre from small rivers (of length less than 500 km) and that ten tonnes are caught annually per kilometre from large rivers (length greater than 500 km). Because of the volumes of water assumed for the two river sizes, which also differ by a factor of 10, the freshwater catch per unit volume is independent of river size.

Table 14. Freshwater fish-catch data for a range of rivers

Data taken from FAO [F1] unless otherwise stated

Country	*Country-wide annual fish catch*		*River*	*Annual fish catch for the river(s)*	*River*		*Annual fish catch*	
	Including aquaculture (t)	*Excluding aquaculture (t)*		*Excluding aquaculture (t)*	*Length in specified country (km)*	*Volume (m^3)*	*Per unit volume, excluding aquaculture (t/m^3)*	*Per unit length, excluding aquaculture (t/km)*
Australia	4.0×10^3	1.2×10^3	All rivers					6.2×10^{-1}
China	1.9×10^7	1.6×10^6	Pearl	2.8×10^4	1.4×10^3	2.3×10^9	1.0×10^{-5}	2.0×10^1
Egypt[a]	9.4×10^5	2.3×10^5	Nile	2.3×10^5	1.5×10^3			1.5×10^2
France	4.4×10^4	2.6×10^3	Loire	1.0×10^3	5.6×10^2	4.3×10^8	2.0×10^{-6}	1.9×10^0
			Rhône	1.5×10^3	4.0×10^2	6.3×10^8	2.0×10^{-6}	3.9×10^0
			All rivers	2.6×10^3				3.0×10^{-1}
Germany	5.6×10^4	2.1×10^4	Danube	7.9×10^3	5.0×10^2	2.1×10^8	4.0×10^{-5}	1.6×10^1
Japan	6.7×10^4	2.5×10^4	All rivers					1.4×10^1
Romania	1.6×10^4	5.7×10^3	Danube	5.7×10^3	4.0×10^2	3.2×10^9	2.0×10^{-6}	1.4×10^1
Sudan[b]	8.1×10^4	7.9×10^4	Nile	5.4×10^4				
			Nile tributaries (incl. Blue and White Nile)	2.5×10^4				
United Kingdom	1.6×10^4	2.5×10^3	Thames	2.3×10^2	2.3×10^2	2.5×10^7	9.0×10^{-6}	9.8×10^{-1}
			Kennet (tributary of Thames)	6.0×10^0	3.3×10^1	6.1×10^5	9.0×10^{-6}	1.7×10^{-1}
			All rivers	2.5×10^3				8.0×10^{-1}
United States	2.5×10^5	1.4×10^4	All rivers					3.4×10^{-1}

[a] Additional data obtained from Hamza [H1].

[b] Data for 2012 from internal report published by the Sudan Ministry of Animal Resources and Fisheries [S11].

Irrigated foods

95. As discussed in section III.B.2(b), the ingestion of irrigated foods is included in the methodology for the estimation of both characteristic individual and collective doses. In the calculation of individual doses from this pathway, it is assumed that cereals and vegetables are irrigated. For the assessment of collective doses, it is assumed that only cereals are irrigated, because these represent the bulk of irrigated crops intended for human consumption [F4].

96. As illustrated in table 15 [C1], there are variations in irrigation rate which are likely to depend to some extent upon factors such as the type of crop and the climate. A single value for a daily irrigation rate was considered to be appropriate for the purposes of this methodology. The United States NCRP in its screening methodology uses a value of 5 L/m^2 for the volume of irrigation water applied per unit area for a period of 150 days annually[N2]. The FAO AQUASTAT database [F4] contains data for a wide range of countries on irrigation water withdrawals and/or requirements, and on the total areas of irrigated crops harvested. These data could then be used to indicate values of daily irrigation rates in L/m^2 assuming a total irrigation period of 150 days in a year. Table 16 illustrates the range of irrigation rates thus obtained from the FAO data. The irrigation rate varies from country to country and although some of the highest values are for arid areas of the world, some countries that are generally arid (e.g. Peru) do not have particularly high estimated irrigation rates. From the data in tables 15 and 16 a single value for the daily irrigation rate of 4 L/m^2 was adopted for the methodology.

Table 15. Irrigation rates averaged over the growing season for various crops and climates [C1]

Country or area	*Crop type*	*Daily irrigation rate (L/m^2)*			*Reference*
		Min	Average	Max	
Canada	Forage		0		[C6]
	Garden vegetables	0		1.8	
France (Loire Valley)	Fruit	2		6	[C4]
	Garden vegetables	2		6	
	Grain	0		2.4	
	Maize	0.8		2.8	
India	Banana		2.6		[P1]
	Gram		1.8		
	Ground nut		6.3		
	Improved jowar		2.0		
	Pigeon pea		1.6		
	Rice		0.9		
	Sugar cane		4.1		
	Turmeric		2.1		
	Wheat		4.3		
Republic of Korea	Rice	5		8	[J4]

Country or area	*Crop type*	*Daily irrigation rate (L/m²)*			*Reference*
		Min	Average	Max	
United States (California)	Alfalfa	4.9		7.1	[U14]
	Barley	2.4		3.2	
	Fruit orchards	3.9		4.9	
	Garden vegetables	4.2		5.2	
	Hay	3.2		5.4	
	Oats, rye	2.0		2.5	
	Pasture	3.7		4.4	
	Grapes		1.7		[B5]

Table 16. Effective irrigation rates obtained from data in the FAO AQUASTAT database [F4]

Country	*Daily irrigation rate (L/m²)*
Algeria	5.2
Argentina	3.5
Australia	3.3
Bangladesh	2.8
Brazil	1.9
Canada	4.1
China	1.8
Egypt	5
France	1.4
Greece	2.8
India	2.8
Indonesia	2.3
Japan	8.6
Kenya	3.2
Peru	3.5
Qatar	7.3
Russian Federation	6.5
Spain	4.5
United States	5.1

97. Collective doses from irrigation are determined by assuming that, on average, the fraction of water abstracted for irrigation from the type of river of interest, in a given geographical region, is the same as the fraction of water abstracted for irrigation purposes from all surface waters (rivers, lakes and so on). The fraction of water abstracted for irrigation and the amount of land irrigated per unit volume of water, was derived from information in the FAO AQUASTAT database [F4]. This information, together with the annual yields of cereals [F1] (given in table 17), the integrated activity concentrations of radionuclides in cereals for unit deposition rate (given in table 5), and the percentage of irrigation

that is sprinkler irrigation (see table 12 and section III.B.2(b)), is used to calculate collective doses from irrigation. Table 17 shows the parameter values used in the methodology for the estimation of collective doses in different regions from the irrigation of cereals; world-average values are also given.

Table 17. Parameter values used in the model for the irrigation of cereals

Region	*Annual cereal yield (kg/m^2)*[a]	*Fraction of surface water used for irrigation*[b] $F_{irr,surface}$	*Area irrigated per unit volume of water withdrawn*[b] $A_{irr,unit}$ *(m^2 a/m^3)*
Africa	2.3×10^{-1}	2.7×10^{-2}	6.0×10^{-1}
Asia and Pacific	2.9×10^{-1}	9.4×10^{-2}	7.9×10^{-1}
Europe	3.6×10^{-1}	1.2×10^{-2}	1.9×10^{0}
Latin America and Caribbean	3.3×10^{-1}	1.0×10^{-2}	8.2×10^{-1}
North America	3.0×10^{-1}	2.4×10^{-2}	1.3×10^{0}
West Asia	2.9×10^{-1}	5.7×10^{-1}	4.7×10^{-1}
World average	3.0×10^{-1}	3.9×10^{-2}	8.5×10^{-1}

[a] From FAO 2010 [F1].

[b] From FAO 2014a [F3].

4. Individual and collective doses

98. Annual characteristic individual doses arising from the ingestion of drinking water and freshwater fish are calculated using the derived activity concentrations of radionuclides in water and fish, the relevant consumption rates, and the dose coefficients for ingestion (see table 1). Because the activity concentrations in unfiltered fresh water are assumed to be a function of the river flow rate alone, these individual dose estimates are directly related to the type of river assumed.

99. Collective doses are calculated using the total abstraction rate of drinking water and the total catch of fish associated with the freshwater body. The abstraction rate of drinking water is assumed to be a fraction of that abstracted for municipal use. The abstraction rate was derived from FAO statistics which indicate that around 1–10% of domestic water is used for drinking [F1]. Since not all municipal water will be for domestic use, the lower end of this range is applied in this methodology. The total amount of water abstracted depends on the size of the water body with smaller amounts removed from small rivers than from large rivers; the water flow is also inversely related to this size. This means that, although for small rivers the activity concentrations per unit discharge are higher than for large rivers, the amount of water abstracted is lower and therefore—using the Committee's methodology—the collective doses from drinking water are estimated to be essentially independent of river size.

100. The irrigation pathway is considered using generic irrigation rates and transfer factors appropriate for a terrestrial environment. Characteristic individual doses from this pathway are determined using region-specific population-weighted consumption rates and the assumption that 25% of the food is locally produced. Collective doses are determined from information on the region-specific proportion of water abstracted from surface waters for irrigation purposes, the area irrigated and the annual yield of cereal products.

101. Collective doses from the consumption of water and freshwater fish are calculated on the basis of the total abstraction of water and fish-catch data, respectively, and are thus related to the river as a whole and cannot be divided into local and regional components.

C. Assessment of doses from discharges to a marine environment

102. As indicated above, the Committee decided to develop generic dose calculation factors that take account of dispersion within different types of water bodies. The approach used for assessing doses from discharges into a marine environment is based on a simple two-box compartment model, the characteristics of which are broadly representative of areas where discharges into a coastal environment occur (see figure IV, which is based on [C2]). The larger compartment (referred to as the regional box) could also be used to assess the dispersion of radionuclides discharged into the deep sea from oil and gas platforms, if required.

103. The following exposure pathways are considered for discharges to a marine environment (see figure I):

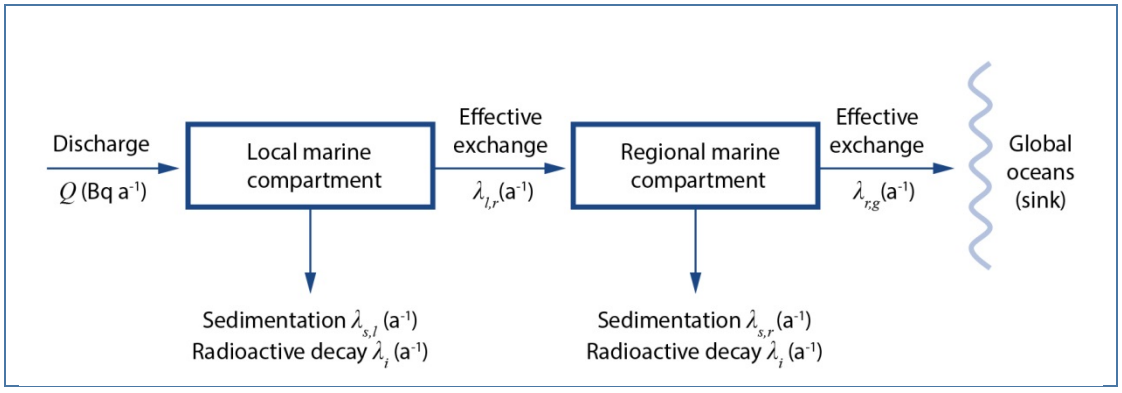
(a) External exposure from radionuclides (beta and gamma emitters) in sediments;

(b) Internal exposure from ingestion of radionuclides incorporated into marine foods.

The first pathway is considered for the calculation of characteristic individual doses only; a review of previous studies assessing collective dose indicated that this pathway provided less than 1% of the collective dose. Similar to discharges to atmosphere and freshwater environments, other exposure pathways (e.g. inadvertent ingestion of water or sediments, and exposures during swimming) are possible; however, the ingestion of marine foods has been found to be the most important exposure pathway in published assessments of collective doses (for example, see [J5]).

Figure IV. Simple two-box compartment model representing a marine environment

Q is the discharge rate (Bq/a); $\lambda_{l,r}$ is the effective rate of transfer between the local and regional compartments (a^{-1}), taking into account exchange between the compartments; $\lambda_{r,g}$ is the effective rate of transfer between the regional and global oceans (a^{-1}), taking into account exchange between the compartments; $\lambda_{s,l}$ and $\lambda_{s,r}$ are the rates of transfer to sediment for the local and regional compartments, respectively (a^{-1}), and λ_i is the radioactive decay constant for radionuclide, i, (a^{-1})



104. Figure IV illustrates the simplified approach used to model the movements of radionuclides between marine compartments. The model considers inputs (such as discharges and incoming transfers of radionuclides) and losses (such as radioactive decay, sedimentation and outgoing transfers of radionuclides). This allows the activity concentrations in the local and regional compartments to be determined. The equations and parameter values associated with this approach are presented in the appendix. The model includes transfer to other marine areas but any contribution to collective doses from the global oceans is only considered for the long-lived radionuclides (^{3}H, ^{14}C and ^{129}I) in a separate global circulation model as discussed below. The size of the regional compartment and the related transfer parameters have been chosen to ensure that the model is a reasonable representation. A comparison with a more complex multi-compartmental marine model [S7, S8], which has been validated against measurement data, has shown that the simple model is adequate for the purpose of this methodology.

105. The dimensions and characteristics applied in the methodology are presented in table 18.

Table 18. Characteristics of the marine compartment model

Characteristic	*Marine compartment*	
	Local	*Regional*
Volume (m^3)	1×10^{9}	1×10^{15}
Effective rate of transfer between compartments (a^{-1}):		
Local to regional, $\lambda_{l,r}$	2×10^{1}	
Regional to global, $\lambda_{r,g}$		1
Depth (m)	10	1 000
Suspended sediment load, SSL (t/m^3)	2×10^{-4}	1×10^{-7}
Sedimentation rate, SR ($t\ m^{-2}\ a^{-1}$)	1×10^{-4}	1×10^{-5}
Length of coastline (km)	10	1 000
OTHER PARAMETERS		
Volume of global oceans, V_g (m^3)	1×10^{18}	
Volumetric exchange between local and regional compartments, $\Delta V_{l,r}$ (m^3/a)	2×10^{10}	
Volumetric exchange between regional compartment and global oceans, $\Delta V_{r,g}$ (m^3/a)	1×10^{15}	

106. The transfer of radionuclides between water and sediments is dependent on a combination of factors that relate to the characteristics of the water body and of individual radionuclides. The key radionuclide-independent parameters are the suspended sediment load and sedimentation rate, which are determined by the nature of the coastal or marine compartment. Values have been chosen from the range of those associated with European waters [S7]. Sedimentation is also dependent upon the radionuclide-dependent partition factor (K_d) for a coastal or marine environment; these values have been derived from [I3].

107. The purpose of the local marine compartment is to allow doses to a characteristic individual living in the area and collective doses to the local population to be calculated. The selected dimensions of the local marine compartment allow tidal, bathymetric and sedimentary conditions to be broadly homogenous throughout the compartment and have been selected so that the compartment is sufficiently large to represent a source of shellfish for the local population. The dimensions of the local

marine compartment are typical of those used in the MARINA II project for European waters [S7]. The dimensions of the regional marine compartment are significantly larger than those generally adopted for site-specific modelling: approximately equivalent to the size of the north-east Atlantic. This again reflects the purpose of the methodology; the regional marine compartment is intended to represent the source of exposure for the regional component of collective dose, which is assumed to extend for a distance of around 1,500 km from the point of discharge.

108. The depth of the sea in the regional marine compartment is assumed to be 1,000 m, which is the depth down to which fish are assumed to be caught.

109. The sensitivity of the calculated activity concentrations of radionuclides in water to changes in the volume of the local compartment and movements between the local and regional compartments was investigated. The calculated activity concentrations in water in the local compartment (assuming constant transfer rates between the local and regional compartments) decrease proportionally as the volume of the local compartment increases. A water transfer rate of 20–40 a^{-1} is typical of those found in European waters based on the volume exchange rates and water volumes given in [S8]. The Committee adopted a volume of 1×10^9 m^3 with a water transfer rate of 20 a^{-1} for the local marine compartment as being reasonably representative of coastal conditions into which nuclear sites are known to discharge.

110. The values of the sedimentation rate and suspended sediment load adopted for the local compartment are typical of values for local compartments around the United Kingdom (e.g. the south-western part of the North Sea) [S7]. The values adopted for the regional compartment correspond to the north-east Atlantic [S7], considered to be typical of large deep oceans.

1. Radionuclide transfers in a marine environment

111. The key element-specific parameters that take account of the transfer of radionuclides from water to other parts of a marine environment are *(a)* concentration factors, which relate concentrations of elements in fish and shellfish to their concentrations in water, and *(b)* partition coefficients, which express the distribution of elements between sediment and water. The most significant international compilation of concentration factors (also referred to as bioaccumulation factors) and partition coefficients, K_d, for coastal and deep-sea environments is presented in [I3]. Following a critical review of the data, these values have been adopted and applied in the present methodology, and are given in table 19.

Table 19. Radionuclide-specific parameters used in the marine model

Radio-nuclide	*Concentration factor (L/kg) (fresh weight)*			*Dose coefficient for external exposure from surface deposit[a], $D_{ex,deposit}$ (Sv/s per Bq/m²) [E2]*	*Partition coefficient (L/kg) (dry weight sediment)*	
	Fish B_{fish} [I3]	*Crustaceans B_{crust} [I3]*	*Molluscs $B_{molluscs}$ [I3]*		*Ocean margin $K_{d,local}$ [I3]*	*Open ocean $K_{d,regional}$ [I3]*
^{3}H	1×10^{0}	1×10^{0}	1×10^{0}	0	1×10^{0}	1×10^{0}
^{14}C	2×10^{4}	2×10^{4}	2×10^{4}	1.3×10^{-20}	1×10^{3}	2×10^{3}
^{35}S	1×10^{0}	1×10^{0}	3×10^{0}	1.3×10^{-20}	5×10^{-1}	1×10^{0}
^{54}Mn	1×10^{3}	5×10^{3}	5×10^{4}	7.9×10^{-16}	2×10^{6}	2×10^{8}
^{58}Co	7×10^{2}	7×10^{3}	2×10^{4}	9.3×10^{-16}	3×10^{5}	5×10^{7}
^{60}Co	7×10^{2}	7×10^{3}	2×10^{4}	2.3×10^{-15}	3×10^{5}	5×10^{7}
^{65}Zn	1×10^{3}	3×10^{5}	8×10^{4}	5.4×10^{-16}	7×10^{4}	2×10^{5}
$^{90}Sr + {}^{90}Y$	3×10^{0}	5×10^{0}	1×10^{1}	1.6×10^{-18}	8×10^{0}	2×10^{2}
$^{106}Ru + {}^{106}Rh$	2×10^{0}	1×10^{2}	5×10^{2}	3.5×10^{-16}	4×10^{4}	1×10^{3}
^{129}I	9×10^{0}	3×10^{0}	1×10^{1}	2.0×10^{-17}	7×10^{1}	2×10^{2}
^{131}I	9×10^{0}	3×10^{0}	1×10^{1}	3.6×10^{-16}	7×10^{1}	2×10^{2}
^{134}Cs	1×10^{2}	5×10^{1}	6×10^{1}	1.5×10^{-15}	4×10^{3}	2×10^{3}
$^{137}Cs + {}^{137m}Ba$	1×10^{2}	5×10^{1}	6×10^{1}	5.8×10^{-16}	4×10^{3}	2×10^{3}
^{210}Pb	2×10^{2}	9×10^{4}	5×10^{4}	2.1×10^{-18}	1×10^{5}	1×10^{7}
^{212}Pb	2×10^{2}	9×10^{4}	5×10^{4}	1.4×10^{-16}	1×10^{5}	1×10^{7}
^{214}Pb	2×10^{2}	9×10^{4}	5×10^{4}	2.4×10^{-16}	1×10^{5}	1×10^{7}
^{210}Po	2×10^{3}	2×10^{4}	2×10^{4}	8.1×10^{-21}	2×10^{7}	2×10^{7}
^{226}Ra	1×10^{2}	1×10^{2}	1×10^{2}	6.1×10^{-18}	2×10^{3}	4×10^{3}
^{228}Ra	1×10^{2}	1×10^{2}	1×10^{2}	0	2×10^{3}	4×10^{3}
^{228}Th	6×10^{2}	1×10^{3}	1×10^{3}	2.1×10^{-18}	3×10^{6}	5×10^{6}
^{230}Th	6×10^{2}	1×10^{3}	1×10^{3}	6.4×10^{-19}	3×10^{6}	5×10^{6}
^{232}Th	6×10^{2}	1×10^{3}	1×10^{3}	4.6×10^{-19}	3×10^{6}	5×10^{6}
^{234}Th	6×10^{2}	1×10^{3}	1×10^{3}	7.5×10^{-18}	3×10^{6}	5×10^{6}
^{234}U	1×10^{0}	1×10^{1}	3×10^{1}	5.9×10^{-19}	1×10^{3}	5×10^{2}
^{238}U	1×10^{0}	1×10^{1}	3×10^{1}	4.2×10^{-19}	1×10^{3}	5×10^{2}
^{239}Pu	1×10^{2}	2×10^{2}	3×10^{3}	2.8×10^{-19}	1×10^{5}	1×10^{5}
^{240}Pu	1×10^{2}	2×10^{2}	3×10^{3}	6.0×10^{-19}	1×10^{5}	1×10^{5}
^{241}Am	1×10^{2}	4×10^{2}	1×10^{3}	2.3×10^{-17}	2×10^{6}	2×10^{6}

[a] These dose coefficients are for the parent only; the contribution from short-lived progeny is added separately (see appendix).

2. External and internal exposure

(a) *External exposure from radionuclides in beach sediments*

112. Annual characteristic individual doses due to external exposure from occupancy of beaches are estimated on the basis of the modelled activity concentrations of each radionuclide in sediments, the relevant dose coefficients for external exposure from surface deposits and the amount of time spent on the beach.

113. The activity concentration of each radionuclide in sediments is estimated using the activity concentration in water, the relevant partition coefficient K_d, an assumed average thickness of sediment of 5 cm and an assumed density of sediment of 1.2 t/m^3 [I2]. The dose coefficients for external exposure from surface deposits are taken from [E2] for each radionuclide. A factor of 0.5 is applied to the dose coefficients to account for the geometry of the radionuclide distribution on a marine shoreline [E2]. The estimates of effective dose include contributions from beta and gamma irradiation of the skin from radionuclides in the sediment. Any additional dose from irradiation of the skin due to direct contact with sediment is not included in the methodology because it is deemed not a major contributor to the overall characteristic individual doses.

114. An average individual beach occupancy rate of around four days per year is assumed, based on data for the Nord-Cotentin area of France [R1]. Because this exposure pathway is unlikely to be a significant contributor to collective doses from nuclear installations [J6], it is not included in the estimation of collective dose.

(b) *Ingestion of marine foods*

115. Annual individual doses from ingestion of radionuclides in marine foods are estimated from the modelled activity concentration of each radionuclide in fish and shellfish (comprising crustaceans and molluscs) harvested from the relevant marine compartment, the region-specific or world-average annual consumption of the food (for adults) and the relevant dose coefficient for ingestion of each radionuclide. Information on the annual consumption of marine fish, crustaceans and molluscs was obtained from WHO [W2] and the values used are given in table 20.

Table 20. Per caput annual consumption of marine foods by region

Based on data provided by WHO [W2]

Region	*Per caput annual consumption of food (kg)*		
	Fish	*Crustaceans*	*Molluscs*
Africa	6.6	0.1	0[a]
Asia and Pacific	6.9	1.4	2.4
Europe	13	0.9	1.0
Latin America and Caribbean	5.9	0.6	0.4
North America	8.2	2.8	1.4
West Asia	4.5	0.3	0[a]
World average	7.5	1.1	1.6

[a] Consumption rate is less than 2×10^{-2} kg/a and treated as 0.

116. Activity concentrations of radionuclides in aquatic foods are estimated from the product of the modelled activity concentrations in water and concentration factors that relate the activity concentrations in sea food to those in water (see table 19). In order to apply this approach, it was necessary to make some assumptions about the origin of the food and therefore the activity concentrations in water that are appropriate to adopt. Thus, it was necessary to make an assumption about the proportions of fish and shellfish that are derived from each compartment in the model.

117. One approach applied to estimate doses to individuals is to assume that a certain proportion of fish and shellfish is derived from the local and regional marine compartments. The proportions assumed would depend upon the purpose of the assessment. In a similar manner to that used for terrestrial and freshwater foods, it is assumed in the Committee's methodology that the characteristic individual obtains 25% of their fish consumption from the local compartment, with the remaining fraction obtained from the regional compartment. All of the crustaceans and molluscs are assumed to be obtained from the local compartment.

118. The respective local and regional components of collective dose from marine discharges are estimated using *(a)* data on the average crustacean-catch and mollusc-catch per unit length of coastline appropriate for the local compartment, and *(b)* data on the average fish-catch per unit volume appropriate for the regional compartment. Catch data for fish, crustaceans and molluscs were derived from the FAO FishStatJ software [F2], which comprises the FAO databases on capture and aquaculture for major fishing areas from 1955 to 2012. The area of sea and length of coastline associated with each of the major fishing areas were determined using a geographical information system (ArcGIS, version 10) and then used to estimate the relevant values for the UNEP geographical regions employed in the methodology; world-average values were also derived. The edible fraction of the catch of fish, crustaceans and molluscs is assumed to be 0.5, 0.35 and 0.15, respectively [S6]. Table 21 shows the catch data for estimating collective doses for the different regions.

Table 21. Annual catch of fish, crustaceans and molluscs used for estimating collective doses from discharges to marine environments [F2]

Region	*Annual catch*		
	Mass of fish per unit area of sea (kg/km^2)	*Mass of crustaceans per unit length of coastline (kg/km)*	*Mass of molluscs per unit length of coastline (kg/km)*
Africa	2×10^2	4×10^3	5×10^3
Asia and Pacific	2×10^2	1×10^4	5×10^4
Europe	2×10^2	1×10^3	5×10^3
Latin America and Caribbean	9×10^1	7×10^3	1×10^4
North America	6×10^1	7×10^3	7×10^3
West Asia	2×10^2	5×10^3	5×10^3
World average	1×10^2	8×10^3	3×10^4

(c) *Individual and collective doses*

119. Annual individual doses arising from the ingestion of marine fish and shellfish are estimated using the modelled activity concentrations of radionuclides in water and fish, the per caput annual consumptions given in table 20 and the dose coefficients for ingestion of the relevant radionuclides given in table 1.

120. To estimate collective doses, region-specific information on the catch of fish and shellfish per unit area of sea or length of coastline are applied from table 21.

IV. GLOBALLY DISPERSED RADIONUCLIDES

121. The Committee has periodically assessed public exposure to long-lived globally dispersed radionuclides discharged from nuclear power and reprocessing plants since 1982. The radionuclides of particular interest are ^{3}H, ^{14}C, ^{85}Kr and ^{129}I. The features of the approaches used and the evolution of the Committee's approach are summarized in electronic attachment 2. The estimated collective doses per unit discharge integrated to various times after discharge are summarized in table 22 at the end of this section.

A. Tritium

122. The Committee's previous approach to estimating the doses from the global circulation of tritium discharged from nuclear installations [U6] was based on a comparison of models developed by Kelly et al. [K2], NCRP [N1], Bergman et al. [B2] and Killough and Kocher [K4]. The relevant concentration of tritium for each compartment of the Committee's model was determined from the total amount of tritium in the compartment divided by the volume of water represented in the compartment. The concentration in humans was then estimated from the modelled concentration of tritium and the relevant fractional intake from each compartment of the model.

123. The global collective dose from discharges to the near-surface atmosphere within the 30°–50° latitude band of the northern hemisphere was estimated by the Committee using the model developed by Killough and Kocher [K4]. This gave a global collective dose per unit discharge of tritium of 2.3 man Sv/PBq [U6]. The global collective dose arising from discharges to the ocean estimated by NCRP [N1] and Bergman et al. [B2] was around one tenth of that arising from discharges to atmosphere. A value of 0.2 man Sv/PBq was therefore adopted in the UNSCEAR 2000 Report [U6] for the collective dose per unit discharge of tritium to the ocean. The Committee still considers these estimates to be appropriate for a world population of 10 billion.

124. The approach used by the Committee to estimate the collective dose commitment is summarized as follows [S8]:

$$S(t) = \sum_c \sum_p I_c(t) \cdot f_{p,c} \cdot R_c \cdot U_p \cdot P \qquad (15)$$

where $S(t)$ is the collective dose commitment truncated at time t (man Sv); $I_c(t)$ is the time-integrated activity concentration in compartment c at time t ((Bq a)/kg); $f_{p,c}$ is the fraction of the individual's intake of water due to pathway p; R_c is the total consumption rate by an individual of water from compartment c (kg/a); U_p is the dose per unit intake from pathway p (Sv/Bq); and P is the number of people in the exposed population. This model was implemented in the PC-CREAM 08 computer system [S8] and has been used to derive values for the global collective doses from unit discharges of tritium for the Committee's methodology. An important factor in the collective dose estimation is the assumed number of people in the world population. The estimate of the United Nations for this for 1 December 2014 was 6.4 billion (6.4×10^9) [U2]. The value for the global population of 10 billion used in the Committee's methodology is equivalent to the United Nations' median estimate of the projected population for 2060 [U1] and is deemed reasonable as a rounded value for collective doses integrated into the future.

B. Carbon-14

125. Carbon-14 is the largest contributor to the collective dose from global dispersion of long-lived radionuclides discharged from reprocessing of nuclear fuel and is a significant contributor to that resulting from operation of nuclear reactors. A 23-compartment model [T1] (see figure VI, annex A of the UNSCEAR 2000 Report [U6]) was applied by the Committee to estimate the activity per unit mass of carbon in each environmental compartment over time. Once mixing had been achieved, a specific-activity approach was used to estimate the collective dose commitments from ^{14}C, assuming that the specific activity of ^{14}C in the carbon ingested by humans was the same as that in the compartments that directly related to the intake of food (i.e. ground vegetation for terrestrial foods and surface water compartments for marine foods). The collective dose commitment per unit discharge to atmosphere, truncated at 10,000 years, was estimated to be 109,000 man Sv/PBq. The model can be used to estimate collective doses for discharges to any compartment; the collective doses from unit discharge to the surface waters of oceans were found to be about the same as those from unit discharges to atmosphere, but doses from unit discharges to deep oceans were around 20% lower [U6]. Killough and Rohwer [K3] found that the estimates from six models differed by a factor of only 1.5, suggesting a remarkable level of agreement (although it has not been possible to fully validate any of the models against global measurements). This has been attributed to the long half-life of ^{14}C relative to its rate of movement in the environment, which makes calculated dose commitments insensitive to the detailed structure of the models [K3].

126. The Committee has therefore not modified its approach to the estimation of collective dose commitment from ^{14}C from that used in 2000. The approach to derive the collective dose commitment is implemented in PC-CREAM 08 and is summarized as follows [S8]:

$$S(t) = \sum_c \sum_p I_c(t) \cdot f_{p,c} \cdot R_c \cdot U_p \cdot P \qquad (16)$$

where $S(t)$ is the collective dose commitment truncated at time t (man Sv); $I_c(t)$ is the time-integrated activity concentration in compartment c at time t (Bq a/kg); $f_{p,c}$ is the fraction of the individual's intake of carbon from pathway p; R_c is the total intake rate of stable carbon (kg/a); U_p is the dose per unit intake from pathway p (Sv/Bq); and P is the size of the exposed population. As before for tritium, the world population is assumed to be 10 billion.

C. Iodine-129

127. The Committee used the global circulation compartment model for ^{129}I developed by Titley et al. [T1] for the assessment it presented in the UNSCEAR 2000 Report (see figure VII, annex A [U6]). The inventories of stable iodine in the compartments of the model and the transfers between the compartments were estimated from environmental measurements and the requirement that the total mass of iodine in the environment was balanced. Iodine intakes by humans from each model compartment were estimated from the average inhalation and food consumption rates combined with the concentrations of stable iodine in the atmosphere and foods respectively, or using a specific-activity approach. Five exposure pathways were considered as follows, with the values of individual intakes of stable iodine used given in brackets: inhalation (0.29 μg/d); deposition from the atmosphere onto crops followed by ingestion by humans or by dairy or beef cattle subsequently ingested by humans (6.6 μg/d); ingestion of surface water (5.3 μg/d); ingestion of marine fish and shellfish (11 μg/d); and root uptake from soils and surface waters followed by ingestion of crops and animal products (200 μg/d).

128. The PC-CREAM computer code [S8] also implements the model by Titley et al. The approach used to estimate the collective dose is similar to that used for tritium and ^{14}C, except that individual intakes were estimated using transfer factors to relate the activity concentrations in food and air to the activity concentrations in the various compartments, rather than to the intake of stable iodine. The Committee still considers this approach to be appropriate.

D. Krypton-85

129. The Committee's approach to estimating the global dispersion of ^{85}Kr is described in detail in the UNSCEAR 1988 Report [U5]. It was based on the approach presented in the UNSCEAR 1982 Report [U4], where a simple two-compartment model was used for the discharge of ^{85}Kr [C2]. The two compartments represent the tropospheres of the northern and southern hemispheres. A transfer coefficient of 0.5 a^{-1} between the compartments was used. The time-integrated activity concentration in air per unit discharge was 10^{-10} (Bq s)/m^3 per Bq [U4]. The dose coefficients to convert from activity concentration in air to absorbed dose rate in air and absorbed dose rate in skin from the emitted beta radiation were derived from [C2].

130. The value of the collective effective dose equivalent per unit discharge used in the UNSCEAR 1982 Report [U4] was 0.17 man Sv/PBq (based on a world population in 1982 of 4 billion). This was scaled to 0.2 man Sv/PBq for an assumed population in 1988 of 4.6 billion [U5]. It was noted that this collective dose commitment would be delivered during the first 50 years after discharge.

131. No changes have been made to the previous approach to modelling the dispersion of ^{85}Kr. Around 50% of the effective dose arises from gamma irradiation of the whole body, and 50% arises from beta irradiation of the skin [I8, Z1]. The value of dose rate for unit activity per mass of air is 8×10^{-9} Sv/a per Bq/kg (the value is given per unit mass of air because this expression is required for the global circulation model and was obtained using a density of air of 1.225 kg/m^3), based on an assumption of immersion in a semi-infinite cloud (with no shielding) [S8]. The collective dose commitment is then estimated as follows:

$$S(t) = I(t) \cdot F \cdot P \qquad (17)$$

where $S(t)$ is the collective dose commitment truncated at time t (man Sv); $I(t)$ is the time-integrated activity concentration in air of the appropriate hemisphere at time t ((Bq a)/kg); F is the dose rate per unit concentration in air (Sv/a per Bq/kg); and P is the number of people in the exposed population. As for the other globally circulating radionuclides, the Committee has taken for its methodology values of collective doses derived by PC-CREAM 08, which implements the model used by the Committee and uses a world population of 10 billion.

Table 22. Collective dose commitments from globally dispersed radionuclides

Radionuclide	*Collective dose commitment truncated after a given time from a radionuclide discharge of 1 Bq/s over a year (man Sv)*					
	To atmosphere			*To a marine environment*		
	100 years	*500 years*	*10 000 years*	*100 years*	*500 years*	*10 000 years*
^{3}H	1.0×10^{-8}	1.0×10^{-8}	1.0×10^{-8}	1.1×10^{-9}	1.1×10^{-9}	1.1×10^{-9}
^{14}C	2.8×10^{-4}	5.6×10^{-4}	2.7×10^{-3}	1.1×10^{-4}	3.5×10^{-4}	2.5×10^{-3}
^{85}Kr	8.0×10^{-9}	8.0×10^{-9}	8.0×10^{-9}	—	—	—
^{129}I	2.7×10^{-3}	3.1×10^{-3}	7.4×10^{-3}	3.3×10^{-6}	6.7×10^{-6}	1.4×10^{-4}

V. LIMITATIONS OF THE MODELS AND DATA USED

132. The methodology is generic and intended for use with discharges of radionuclides from nuclear energy generating technologies, and a number of non-nuclear electrical energy production sources, throughout the world. It builds on previous work that has provided the Committee with robust results that have been suitable for its purposes. In developing the methodology further, no intentional bias has been introduced to either under- or overestimate radiation exposures; the aim has been to be generic and as realistic as possible. It is difficult to quantify the uncertainties, because of the generic nature of the methodology. Nevertheless, this section outlines the limitations and uncertainties associated with the methodology. The Committee notes the following generic limitations:

(a) The input to the models is assumed to be a continuous discharge, and annual average parameter values are used. The models therefore do not apply for short-duration planned or accidental releases of radionuclides to the environment;

(b) Although some parameter values are used that are specific to geographical region (such as for food consumption), most of the models are generic and are not intended for detailed site-specific dose assessments, risk assessments or demonstrating regulatory compliance;

(c) The assumptions and data used for estimating individual doses are intended to apply to a characteristic individual living local to the discharge point with typical habits and behaviour;

(d) In order to be realistic rather than cautious in estimating characteristic individual doses, it is assumed that only 25% of food intake (both terrestrial and aquatic) is locally produced. The resulting ingestion doses are sensitive to this assumption, being directly proportional to the food intake, and the overall dose will be similarly sensitive where ingestion is a major component. However, it should be noted that this assumption is not used in the assessment of collective doses;

(e) The assessed collective doses are directly proportional to the assumed population densities for releases to atmosphere or to the assumed total amount of drinking water or aquatic foods for releases to water bodies. The methodology gives results for releases to atmosphere for four different population distributions with values provided by geographical region for three of them. The effect of using different distributions can be seen in the results presented in the following section but are generally only relatively small. However, the use of a very low population density, suitable for remote sites, leads to collective doses around two orders of magnitude lower than when the default population densities are used. Therefore, the value for the very low population density should be used with caution.

(f) The models and data are thought to be the most appropriate for use currently and are also assumed to apply for representing the future. No account is taken of possible future changes, such as to population distributions in different regions or the effects of climate change. The uncertainties in the results of the methodology increase with time; this is particularly the case for global circulation models of long-lived radionuclides when integrated for 10,000 years or more.

133. Specific limitations and uncertainties relating to the different areas of the methodology are noted in the following sections.

A. Discharges to atmosphere

134. A standard Gaussian-plume model is used to estimate the dispersion of radionuclides following discharges to atmosphere. As discussed in section III.A, the Gaussian model can be implemented generically for assessing exposures from different sources of discharges throughout the world and it produces results that agree reasonably well with measurements [C5]. However, as implemented in the methodology, the model makes no allowance for local topographical features (such as hills, buildings or the site being on the coast) which can strongly influence dispersion, particularly close to the discharge point. The height of the discharge, which is related to both the physical height of the discharge stack and any buoyancy of the discharge caused, for example, by heat (referred to as plume rise), also has a significant effect on the subsequent dispersion of the radionuclides. However, this effect reduces with distance from the discharge point (see electronic attachment 4), and so the Committee agreed to adopt a single value for stack height of 30 m for its generic methodology.

135. A simplified approach has also been retained to account for the deposition of radionuclides in the plume on the ground. An effective deposition velocity of 0.002 m/s is used to represent both dry and wet deposition for all radionuclides (apart from noble gases, tritium and carbon-14, for which, a value of zero is used because noble gases do not deposit, and because deposition is not explicitly modelled for tritium and carbon-14, as they exchange quickly between the atmosphere and ground and a specific activity approach is used instead and). If, for example, a higher deposition velocity were used, it would clearly lead to higher deposition close to the discharge point but lower deposition at greater distances because of depletion of radionuclides in the plume. Thus, overall, for the estimation of collective doses, the effects tend to counteract each other (except for very short-lived radionuclides). However, the estimation of characteristic individual doses is more sensitive to the assumed deposition velocity. Nevertheless, because this methodology is intended for comparative purposes, the Committee considered that the simplified approach was justified.

136. The approach used to estimate the transfer of radionuclides through the terrestrial environment to food is again a standard one. Although the model used, FARMLAND [B6], was developed in the

United Kingdom, it has been validated against measured data [S8] and is in reasonable agreement with models used elsewhere in the world [I6]. Also, to some extent, parameter values that are considered to be widely applicable are used, as discussed in section III. The FARMLAND model was also used in a modified form for the Committee's 2013 assessment of the levels and effects of the nuclear accident following the 2011 great east-Japan earthquake and tsunami [U12]—agricultural practices and parameter values specific to Japan were used. A comparison of the results of the use of two versions of FARMLAND—the one using parameter values that are considered to be widely applicable and the other parameter values that are specific to Japan—are compared in electronic attachment 4. Although there are some differences, these are not significant for the purposes of the methodology.

137. The methodology makes use of consumption rates of terrestrial foods that differ by geographical region (see table 7). This is a compromise between the use of a single diet for the world and more country-specific consumption rates. From table 7, it is clear that there are differences in the total amount of food that is eaten annually, which will have a direct influence on both collective and characteristic individual doses but these are generally less than a factor of two (differences of up to a factor of 5 are seen for individual food types). There are also differences in the composition of the diet, and it is less clear what impact this will have on estimated doses. For discharges from nuclear sites, one of the most important radionuclides in terms of both collective and individual doses is carbon-14 [U8]. A specific-activity model is included in the methodology, so that the intake of carbon-14 is related to the intake of stable carbon in the diet. As carbon is an essential component of the diet and is found in all foods, it is likely that the intake of carbon-14 is insensitive to changes in the dietary composition. This was investigated in a sensitivity study (described in electronic attachment 4) that considered the intakes of carbon for diets typical of Japan and the United Kingdom. This study showed that the total amount of carbon ingested was similar and therefore the dose estimates would be similar even though the foods from which the carbon was derived were different.

138. The estimation of doses due to external exposure from both radionuclides in the plume and those deposited on the ground takes account of the shielding effects of buildings when people are indoors. The methodology uses a single indoor occupancy factor and single shielding/location factors for radionuclides in the plume and those on the ground. The indoor occupancy factor is 0.8 and any variations in this for much of the world are likely to be less than a factor of two and so the effect would be relatively minor. The shielding factors, 0.1 and 0.2 for radionuclides deposited on the ground and in the plume, respectively, are typical of those for standard single-storey buildings. As discussed in section III.A, there are differences between the shielding factors for different building types (shielding factors might be a factor of 5 or 6 higher than used here for wooden buildings and a factor of up to 10 times lower for multi-storey buildings). There is also evidence for location factors changing as a function of time. The empirical models used are based on measurements and there can be good agreement between the results of such models and personal dosimeter measurements where local factors are taken into account. The factors used here are considered to be appropriate for use in the Committee's assessments, recognizing the variations that occur globally

B. Discharges to freshwater and marine environments

139. The methodology includes consideration of two generic freshwater environments for aquatic discharges: *(a)* a small river and *(b)* a large river; the results for a large river are also considered to apply to a large lake. In all cases, instantaneous mixing is assumed within a single body of water, which is obviously a significant simplification. In reality, lakes and rivers are complex environments and rivers have many tributaries and sections with different flow rates, volumes and behaviours. Similarly,

the methodology uses a generic approach for discharges to a marine environment with a simple compartmental model consisting of two compartments representing local and regional marine waters. Again in reality, there are significant differences between marine environments depending on local and regional currents, and the nature of the coastline and local environment. Although there have been validation studies showing good agreement between models and predictions, these are for specific sites and situations and are not necessarily applicable to the simplified generic approach adopted here. However, the Committee considers that its generic approach is adequate for the purpose of assessing worldwide exposures from radioactive discharges and for comparative studies, but notes the limitations of the approach for other purposes.

140. Similar to terrestrial foods, the values for consumption rates of freshwater and marine fish are based on data by geographical region and are suitable for estimating the characteristic individual dose. There are differences in the values of consumption rates for freshwater fish and some marine fish. Table 13 for freshwater fish shows differences of up to a factor of 6 between regions, and table 20 shows differences of a factor of 10 or more for the consumption of crustaceans and even greater differences for consumption rates of molluscs. These differences would be directly reflected in the values of the calculated individual doses.

141. The methodology now considers the transfer of radionuclides from freshwater to terrestrial foods by means of irrigation. There are many different types of irrigation systems and significant variations across the world in their usage, the source of water (surface or groundwater), and the type of crops that are irrigated. The estimation of the transfer of radionuclides to terrestrial foods through irrigation is therefore particularly uncertain. The simplifying assumptions in the methodology however are only intended to be suitable for generic assessments and the Committee considers that its adopted approach is robust enough and suitable for this purpose. Nevertheless, the limitations should be recognized; the importance of these limitations will depend on the relative importance of the irrigation exposure pathway compared to exposures from intakes of drinking water and freshwater fish.

142. The estimation of collective dose from discharges of radionuclides to rivers, lakes and the sea is not based on the sum of individual doses as is the case for discharges to atmosphere. Instead, the collective dose is based on estimates of the total amount of fish caught in the part of the environment of interest, and the amount of water that is abstracted for drinking water and for irrigation. As such, the methodology assumes that the fish, drinking water and irrigated foods are consumed but no account is taken of who consumes them. The Committee considers that this approach is adequate for estimating collective doses for its purposes, but notes that it is not possible with its methodology to break down the collective dose into individual doses or to distinguish between local and regional components of collective dose for any aquatic discharges.

C. Global modelling

143. The approach used to estimate collective doses from the four most important radionuclides that can be globally dispersed (^{3}H, ^{14}C, ^{85}Kr and ^{129}I) is one that is well accepted and has been used by the Committee for a number of years. The globally dispersed radionuclides, particularly ^{14}C, are the biggest contributors to the overall collective doses due to discharges from the nuclear industry when these doses are integrated over 500 years or more. One of the factors that influences the estimated collective doses is the size of the global population that is assumed, because the global collective dose is proportional to the size of the global population. A rounded value of 10 billion people is included in the methodology; the uncertainty associated with this value increases with time. The global models are

based on movements of water, carbon and other natural elements through the environment. Such movements are likely to be affected by changes in the climate, sea level, ocean currents and atmospheric conditions. The model for carbon is a specific activity approach based on the global carbon cycle and the amounts of stable carbon in different parts of the environment. Increases in stable carbon due to the burning of fossil fuels will influence the transfers in the future. These possible future changes are not taken into account in the methodology, which leads to increasing uncertainties in estimation of doses in the longer term. It is also not possible to validate this type of model whose scope covers wide areas and time frames.

D. Comparison of the current and previous methodologies

144. The methodology described in this annex has been developed from that used previously by the Committee [U6, U7, U10]. The main changes that have been made are discussed in electronic attachment 1, with further information given in electronic attachment 2.

145. The main changes that have been introduced are:

(a) The results of the methodology are now given in terms of the dose per unit discharge rather than being normalized to the amount of electricity generated (dose factors normalized to electricity generated can be calculated subsequently as required);

(b) The methodology has been extended for application to the estimation of exposures from discharges of radionuclides from non-nuclear electrical energy production;

(c) The inclusion of factors that depend on geographical region, notably for population distributions, consumption rates and fish-catch data;

(d) The inclusion of a more detailed approach for modelling the transfer of radionuclides from fresh water to irrigated crops;

(e) The results are provided for a range of integration times;

(f) Some updates have been made to the various models included in the methodology.

As noted in electronic attachment 1, many parts of the methodology remain unchanged, because the Committee considered, following review, that they were still appropriate for its purposes.

146. The results of the various workbooks implementing the methodology were compared with data derived from the previous methodology [U6, U7]. The estimates of the annual collective effective doses from the following pathways were compared:

(a) External exposure due to deposited radionuclides from discharges to atmosphere;

(b) Inhalation of radionuclides discharged to atmosphere;

(c) Ingestion of radionuclides discharged to atmosphere;

(d) All pathways from radionuclides discharged to both freshwater and marine environments.

In general, the results are within about an order of magnitude, despite the changes that have been introduced to parts of the methodology (see electronic attachment 1, tables 2–6).

VI. APPLICATION OF THE METHODOLOGY

147. The Committee decided that its calculations should be transparent and that the methodology should be able to be relatively easily applied and updated in the future. It agreed that the methodology be implemented in a series of Excel® workbooks. The appendix describes the end points considered, the workbook design, the mathematical equations to implement the methodology in the workbooks, the treatment of progeny, the quality assurance carried out to ensure that the workbooks were implemented correctly, and details of how the workbooks could be used for assessing the exposures from different source terms.

148. The results of the methodology, as given by the workbooks, are for specific discharges to different environments. The results are in the form of dose calculation factors for individual radionuclides; for radionuclides that are in secular equilibrium with their short-lived progeny, the factors represent the sums of the contributions from the parent and progeny (see appendix). The factors are for characteristic individual doses (in units of sieverts) in the 100th year of a continuous discharge of a radionuclide at a rate of 1 Bq/s, and collective doses (in units of man–sieverts) integrated to 100, 500 and 10,000 years for a continuous discharge of a radionuclide at a rate of 1 Bq/s for 1 year (see section II.C). For most radionuclides the collective doses to 100 years only are provided because this was deemed to be sufficient. However collective doses integrated to other times are given for ^{3}H, ^{14}C, ^{85}Kr and ^{129}I.

149. The resulting characteristic individual and collective dose calculation factors for unit discharge of radionuclides to atmosphere, to the different freshwater environments (the results for a large river also apply to a lake) and to a marine environment—derived using the methodology implemented in the workbooks—are presented in tables 23–31. The doses can then be scaled by the actual rates of discharge of each radionuclide from a particular site and then summed over all relevant radionuclides to give the overall characteristic individual and collective doses. Results are given for sites located in different regions of the world, with additional results for coastal and inland nuclear sites and for sites situated in areas of low population density.

150. For future assessments, where discharges are reported to the Committee for broad groups of radionuclides (e.g. gross alpha, noble gases, radioiodines or particulates), some assumptions would need to be made about the proportion of the different radionuclides constituting the group (see section II.D.2).

Table 23. Estimated characteristic individual doses in the 100th year from a continuous discharge of a radionuclide to atmosphere

The characteristic individual dose is to a person living 5 km from the discharge point obtaining 25% of their food locally. The regions are as shown in figure II

Radionuclide	*Individual effective dose in the 100th year of a continuous discharge at a rate of 1 Bq/s (Sv)*					
	Africa	*Asia & Pacific*	*Europe*	*Latin America*	*North America*	*West Asia*
^{3}H[a]	4.2×10^{-14}	4.4×10^{-14}	4.8×10^{-14}	4.3×10^{-14}	4.7×10^{-14}	4.1×10^{-14}
^{14}C	3.3×10^{-12}	3.7×10^{-12}	3.7×10^{-12}	3.4×10^{-12}	3.6×10^{-12}	3.6×10^{-12}
^{35}S	5.1×10^{-12}	7.2×10^{-12}	1.4×10^{-11}	1.2×10^{-11}	1.8×10^{-11}	7.6×10^{-12}
^{41}Ar	4.2×10^{-14}	4.2×10^{-14}	4.2×10^{-14}	4.2×10^{-14}	4.2×10^{-14}	4.2×10^{-14}
^{54}Mn	1.5×10^{-12}	1.6×10^{-12}	1.9×10^{-12}	1.7×10^{-12}	2.0×10^{-12}	1.5×10^{-12}
^{58}Co	6.4×10^{-12}	6.8×10^{-12}	7.9×10^{-12}	7.4×10^{-12}	8.4×10^{-12}	6.7×10^{-12}
^{60}Co	2.3×10^{-10}	2.5×10^{-10}	3.0×10^{-10}	2.9×10^{-10}	3.5×10^{-10}	2.5×10^{-10}
^{65}Zn	3.0×10^{-11}	3.9×10^{-11}	6.7×10^{-11}	6.1×10^{-11}	8.8×10^{-11}	4.0×10^{-11}
^{85}Kr	8.7×10^{-17}	8.7×10^{-17}	8.7×10^{-17}	8.7×10^{-17}	8.7×10^{-17}	8.7×10^{-17}
^{90}Sr[b]	2.4×10^{-10}	2.8×10^{-10}	3.8×10^{-10}	2.9×10^{-10}	3.7×10^{-10}	2.5×10^{-10}
^{106}Ru[b]	1.9×10^{-11}	2.1×10^{-11}	2.9×10^{-11}	2.7×10^{-11}	3.5×10^{-11}	2.1×10^{-11}
^{129}I	4.3×10^{-10}	4.9×10^{-10}	5.6×10^{-10}	4.6×10^{-10}	5.3×10^{-10}	4.5×10^{-10}
^{131}I	1.3×10^{-11}	1.5×10^{-11}	1.8×10^{-11}	1.4×10^{-11}	1.7×10^{-11}	1.3×10^{-11}
^{133}Xe[b]	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}	1.0×10^{-15}
^{135}Xe	8.6×10^{-15}	8.6×10^{-15}	8.6×10^{-15}	8.6×10^{-15}	8.6×10^{-15}	8.6×10^{-15}
^{138}Xe[b]	3.2×10^{-14}	3.2×10^{-14}	3.2×10^{-14}	3.2×10^{-14}	3.2×10^{-14}	3.2×10^{-14}
^{134}Cs	1.2×10^{-10}	1.4×10^{-10}	1.7×10^{-10}	1.5×10^{-10}	1.8×10^{-10}	1.4×10^{-10}
^{137}Cs[b]	2.1×10^{-10}	2.2×10^{-10}	2.4×10^{-10}	2.3×10^{-10}	2.6×10^{-10}	2.2×10^{-10}
^{210}Pb	1.1×10^{-9}	1.2×10^{-9}	1.3×10^{-9}	1.1×10^{-9}	1.2×10^{-9}	1.0×10^{-9}
^{210}Po	2.1×10^{-9}	2.3×10^{-9}	2.7×10^{-9}	2.4×10^{-9}	2.8×10^{-9}	2.1×10^{-9}
^{222}Rn[b]	2.7×10^{-12}	2.7×10^{-12}	2.7×10^{-12}	2.7×10^{-12}	2.7×10^{-12}	2.7×10^{-12}
^{226}Ra	2.2×10^{-9}	2.3×10^{-9}	2.4×10^{-9}	2.2×10^{-9}	2.3×10^{-9}	2.1×10^{-9}
^{230}Th	5.7×10^{-9}	5.7×10^{-9}	5.7×10^{-9}	5.6×10^{-9}	5.7×10^{-9}	5.6×10^{-9}
^{232}Th[b]	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}	2.8×10^{-8}
^{234}U	1.4×10^{-9}	1.5×10^{-9}	1.5×10^{-9}	1.5×10^{-9}	1.5×10^{-9}	1.4×10^{-9}
^{238}U[b]	1.2×10^{-9}	1.2×10^{-9}	1.2×10^{-9}	1.2×10^{-9}	1.2×10^{-9}	1.2×10^{-9}
^{239}Pu	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}
^{240}Pu	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}	2.0×10^{-8}
^{241}Am	1.7×10^{-8}	1.7×10^{-8}	1.7×10^{-8}	1.7×10^{-8}	1.7×10^{-8}	1.7×10^{-8}

[a] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[b] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 24. Estimated characteristic individual dose in the 100th year of a continuous discharge of a radionuclide to rivers

Characteristic individual doses are to people living 5 km downstream of the discharge point obtaining 25% of their food locally. The regions are as shown in figure II

Radionuclide	*Individual effective dose in the 100th year of a continuous discharge at a rate of 1 Bq/s (Sv)*											
	Africa		*Asia & Pacific*		*Europe*		*Latin America*		*North America*		*West Asia*	
	Small	*Large*[a]	*Small*	*Large*[a]	*Small*	*Large*[a]	*Small*	*Large*[a]	*Small*	*Large*[a]	*Small*	*Large*[a]
^{3}H[b]	3.0×10^{-12}	3.0×10^{-14}	3.0×10^{-12}	3.0×10^{-14}	3.0×10^{-12}	3.0×10^{-14}	3.0×10^{-12}	3.0×10^{-14}	3.0×10^{-12}	3.0×10^{-14}	3.0×10^{-12}	3.0×10^{-14}
^{14}C	1.6×10^{-8}	1.6×10^{-10}	4.5×10^{-8}	4.5×10^{-10}	2.0×10^{-8}	2.0×10^{-10}	9.3×10^{-9}	9.4×10^{-11}	2.6×10^{-8}	2.6×10^{-10}	7.6×10^{-9}	7.8×10^{-11}
^{35}S	6.2×10^{-11}	6.5×10^{-13}	1.4×10^{-10}	1.3×10^{-12}	7.3×10^{-11}	8.0×10^{-13}	4.5×10^{-11}	4.9×10^{-13}	9.0×10^{-11}	9.6×10^{-13}	4.1×10^{-11}	4.7×10^{-13}
^{54}Mn	5.2×10^{-9}	3.5×10^{-12}	5.3×10^{-9}	3.5×10^{-12}	5.2×10^{-9}	3.5×10^{-12}	5.2×10^{-9}	3.5×10^{-12}	5.2×10^{-9}	3.5×10^{-12}	5.2×10^{-9}	3.5×10^{-12}
^{58}Co	4.7×10^{-9}	4.0×10^{-12}	4.7×10^{-9}	4.0×10^{-12}	4.7×10^{-9}	4.1×10^{-12}	4.7×10^{-9}	4.0×10^{-12}	4.7×10^{-9}	4.1×10^{-12}	4.7×10^{-9}	4.0×10^{-12}
^{60}Co	1.2×10^{-8}	1.1×10^{-11}	1.2×10^{-8}	1.1×10^{-11}	1.2×10^{-8}	1.1×10^{-11}	1.2×10^{-8}	1.1×10^{-11}	1.2×10^{-8}	1.1×10^{-11}	1.2×10^{-8}	1.1×10^{-11}
^{65}Zn	1.0×10^{-9}	9.0×10^{-12}	2.7×10^{-9}	2.2×10^{-11}	1.3×10^{-9}	1.1×10^{-11}	6.9×10^{-10}	6.1×10^{-12}	1.6×10^{-9}	1.4×10^{-11}	5.9×10^{-10}	5.3×10^{-12}
^{90}Sr[c]	1.2×10^{-9}	1.9×10^{-11}	1.2×10^{-9}	1.5×10^{-11}	1.2×10^{-9}	2.7×10^{-11}	1.2×10^{-9}	1.9×10^{-11}	1.2×10^{-9}	2.8×10^{-11}	1.2×10^{-9}	2.0×10^{-11}
^{106}Ru[c]	1.7×10^{-9}	3.5×10^{-12}	1.7×10^{-9}	3.4×10^{-12}	1.7×10^{-9}	3.7×10^{-12}	1.7×10^{-9}	3.5×10^{-12}	1.7×10^{-9}	3.8×10^{-12}	1.6×10^{-9}	3.5×10^{-12}
^{129}I	4.7×10^{-9}	6.1×10^{-11}	5.1×10^{-9}	5.3×10^{-11}	4.7×10^{-9}	7.4×10^{-11}	4.6×10^{-9}	5.9×10^{-11}	4.8×10^{-9}	7.6×10^{-11}	4.6×10^{-9}	6.3×10^{-11}
^{131}I	4.0×10^{-10}	1.9×10^{-12}	4.0×10^{-10}	1.9×10^{-12}	4.0×10^{-10}	2.0×10^{-12}	4.0×10^{-10}	1.9×10^{-12}	4.0×10^{-10}	2.0×10^{-12}	4.0×10^{-10}	1.9×10^{-12}
^{134}Cs	8.6×10^{-9}	1.8×10^{-11}	1.2×10^{-8}	2.1×10^{-11}	9.2×10^{-9}	2.0×10^{-11}	7.8×10^{-9}	1.7×10^{-11}	1.0×10^{-8}	2.1×10^{-11}	7.6×10^{-9}	1.7×10^{-11}
^{137}Cs[c]	4.1×10^{-9}	1.1×10^{-11}	6.7×10^{-9}	1.2×10^{-11}	4.5×10^{-9}	1.2×10^{-11}	3.5×10^{-9}	9.9×10^{-12}	5.0×10^{-9}	1.3×10^{-11}	3.4×10^{-9}	1.0×10^{-11}
^{210}Pb	2.0×10^{-8}	2.2×10^{-10}	2.1×10^{-8}	2.0×10^{-10}	2.0×10^{-8}	2.5×10^{-10}	1.9×10^{-8}	2.1×10^{-10}	2.0×10^{-8}	2.6×10^{-10}	1.9×10^{-8}	2.2×10^{-10}
^{210}Po	3.4×10^{-8}	3.5×10^{-10}	3.7×10^{-8}	3.4×10^{-10}	3.4×10^{-8}	3.9×10^{-10}	3.3×10^{-8}	3.5×10^{-10}	3.5×10^{-8}	4.0×10^{-10}	3.3×10^{-8}	3.5×10^{-10}
^{226}Ra	7.6×10^{-9}	1.1×10^{-10}	7.8×10^{-9}	9.0×10^{-11}	7.7×10^{-9}	1.4×10^{-10}	7.6×10^{-9}	1.0×10^{-10}	7.7×10^{-9}	1.4×10^{-10}	7.6×10^{-9}	1.1×10^{-10}
^{230}Th	3.2×10^{-9}	3.7×10^{-11}	3.2×10^{-9}	3.4×10^{-11}	3.2×10^{-9}	4.4×10^{-11}	3.2×10^{-9}	3.7×10^{-11}	3.2×10^{-9}	4.6×10^{-11}	3.2×10^{-9}	3.7×10^{-11}
^{232}Th[c]	3.3×10^{-8}	2.8×10^{-10}	3.3×10^{-8}	2.5×10^{-10}	3.3×10^{-8}	3.2×10^{-10}	3.3×10^{-8}	2.7×10^{-10}	3.3×10^{-8}	3.3×10^{-10}	3.3×10^{-8}	2.8×10^{-10}
^{234}U	7.4×10^{-10}	9.6×10^{-12}	7.4×10^{-10}	8.4×10^{-12}	7.4×10^{-10}	1.2×10^{-11}	7.4×10^{-10}	9.5×10^{-12}	7.4×10^{-10}	1.3×10^{-11}	7.4×10^{-10}	9.7×10^{-12}
^{238}U[c]	7.3×10^{-10}	9.4×10^{-12}	7.4×10^{-10}	8.3×10^{-12}	7.3×10^{-10}	1.2×10^{-11}	7.3×10^{-10}	9.3×10^{-12}	7.3×10^{-10}	1.2×10^{-11}	7.3×10^{-10}	9.5×10^{-12}
^{239}Pu	3.5×10^{-9}	4.1×10^{-11}	3.6×10^{-9}	3.7×10^{-11}	3.5×10^{-9}	4.9×10^{-11}	3.4×10^{-9}	4.1×10^{-11}	3.5×10^{-9}	5.1×10^{-11}	3.4×10^{-9}	4.1×10^{-11}
^{240}Pu	3.5×10^{-9}	4.1×10^{-11}	3.6×10^{-9}	3.7×10^{-11}	3.5×10^{-9}	4.9×10^{-11}	3.4×10^{-9}	4.1×10^{-11}	3.5×10^{-9}	5.1×10^{-11}	3.4×10^{-9}	4.1×10^{-11}
^{241}Am	3.8×10^{-9}	3.4×10^{-11}	5.6×10^{-9}	3.1×10^{-11}	4.1×10^{-9}	4.1×10^{-11}	3.4×10^{-9}	3.3×10^{-11}	4.5×10^{-9}	4.3×10^{-11}	3.3×10^{-9}	3.3×10^{-11}

[a] The dose estimates for large rivers are also assumed to apply to lakes.

[b] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[c] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 25. Estimated characteristic individual dose in the 100th year of a continuous discharge of a radionuclide to a marine environment

The characteristic individual dose is for people ingesting crustaceans and molluscs from the local marine compartment plus 25% of their marine fish consumption from the local compartment and 75% from the regional compartment. The regions are as shown in figure II

Radionuclide	*Individual effective dose in the 100th year of a continuous discharge at a rate of 1 Bq/s (Sv)*					
	Africa	*Asia and Pacific*	*Europe*	*Latin America*	*North America*	*West Asia*
^{3}H	5.0×10^{-17}	1.6×10^{-16}	1.5×10^{-16}	7.0×10^{-17}	1.7×10^{-16}	4.0×10^{-17}
^{14}C	3.2×10^{-11}	1.0×10^{-10}	9.4×10^{-11}	4.5×10^{-11}	1.1×10^{-10}	2.6×10^{-11}
^{35}S	1.9×10^{-15}	1.1×10^{-14}	7.6×10^{-15}	3.5×10^{-15}	9.5×10^{-15}	1.5×10^{-15}
^{54}Mn	2.6×10^{-9}	2.7×10^{-9}	2.6×10^{-9}	2.6×10^{-9}	2.7×10^{-9}	2.6×10^{-9}
^{58}Co	4.0×10^{-10}	4.6×10^{-10}	4.3×10^{-10}	4.1×10^{-10}	4.5×10^{-10}	4.0×10^{-10}
^{60}Co	1.2×10^{-9}	1.5×10^{-9}	1.3×10^{-9}	1.2×10^{-9}	1.4×10^{-9}	1.2×10^{-9}
^{65}Zn	2.8×10^{-10}	3.6×10^{-9}	2.0×10^{-9}	1.3×10^{-9}	5.5×10^{-9}	5.3×10^{-10}
^{90}Sr[a]	2.5×10^{-13}	1.6×10^{-12}	1.1×10^{-12}	5.0×10^{-13}	1.5×10^{-12}	2.1×10^{-13}
^{106}Ru[a]	2.3×10^{-11}	3.7×10^{-11}	2.9×10^{-11}	2.5×10^{-11}	3.3×10^{-11}	2.3×10^{-11}
^{129}I	2.7×10^{-12}	7.6×10^{-12}	7.3×10^{-12}	3.3×10^{-12}	7.0×10^{-12}	1.9×10^{-12}
^{131}I	3.6×10^{-14}	7.1×10^{-14}	6.8×10^{-14}	4.0×10^{-14}	6.6×10^{-14}	3.0×10^{-14}
^{134}Cs	1.5×10^{-11}	2.1×10^{-11}	2.3×10^{-11}	1.6×10^{-11}	2.2×10^{-11}	1.4×10^{-11}
^{137}Cs[a]	7.2×10^{-12}	1.2×10^{-11}	1.3×10^{-11}	7.9×10^{-12}	1.2×10^{-11}	6.3×10^{-12}
^{210}Pb[a]	2.3×10^{-8}	4.2×10^{-7}	2.2×10^{-7}	1.2×10^{-7}	5.1×10^{-7}	4.1×10^{-8}
^{210}Po	1.0×10^{-8}	1.4×10^{-7}	7.5×10^{-8}	4.0×10^{-8}	1.5×10^{-7}	1.3×10^{-8}
^{226}Ra[a]	2.4×10^{-8}	4.2×10^{-7}	2.2×10^{-7}	1.3×10^{-7}	5.1×10^{-7}	4.1×10^{-8}
^{230}Th	3.7×10^{-10}	1.6×10^{-9}	1.3×10^{-9}	6.3×10^{-10}	1.8×10^{-9}	3.2×10^{-10}
^{232}Th[a]	6.3×10^{-9}	1.1×10^{-8}	9.1×10^{-9}	7.4×10^{-9}	1.2×10^{-8}	6.3×10^{-9}
^{234}U	2.5×10^{-13}	6.8×10^{-12}	3.2×10^{-12}	1.5×10^{-12}	5.5×10^{-12}	3.3×10^{-13}
^{238}U[a]	6.4×10^{-12}	3.2×10^{-11}	2.4×10^{-11}	1.2×10^{-11}	3.4×10^{-11}	5.6×10^{-12}
^{239}Pu	9.1×10^{-11}	3.0×10^{-9}	1.4×10^{-9}	5.7×10^{-10}	1.9×10^{-9}	8.5×10^{-11}
^{240}Pu	9.1×10^{-11}	3.0×10^{-9}	1.4×10^{-9}	5.7×10^{-10}	1.9×10^{-9}	8.5×10^{-11}
^{241}Am	1.5×10^{-10}	1.1×10^{-9}	6.0×10^{-10}	3.3×10^{-10}	9.2×10^{-10}	1.5×10^{-10}

[a] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 26. Local and regional components of collective dose for discharges to atmosphere from sites in different regions of the world

The collective doses are out to 1,500 km based on the population distributions given in table 3 for different regions of the world as shown in figure II. They can be used for discharges from any type of source for comparative purposes and are the only values appropriate for non-nuclear sites

Radio-nuclide	*Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (man Sv)*													
	Africa		*Asia and Pacific*		*Europe*		*Latin America*		*North America*		*West Asia*		*World average*[a]	
	Local	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*
^{3}H[b]	1.4×10^{-8}	1.2×10^{-7}	5.6×10^{-8}	4.7×10^{-7}	3.0×10^{-8}	2.5×10^{-7}	2.6×10^{-8}	2.2×10^{-7}	7.3×10^{-9}	6.0×10^{-8}	1.8×10^{-8}	1.5×10^{-7}	3.2×10^{-8}	2.7×10^{-7}
^{14}C	1.1×10^{-6}	5.3×10^{-6}	4.3×10^{-6}	2.2×10^{-5}	2.0×10^{-6}	1.0×10^{-5}	1.9×10^{-6}	9.7×10^{-6}	4.9×10^{-7}	2.5×10^{-6}	1.5×10^{-6}	7.8×10^{-6}	2.4×10^{-6}	1.2×10^{-5}
^{35}S	1.8×10^{-6}	8.2×10^{-6}	9.1×10^{-6}	4.2×10^{-5}	8.2×10^{-6}	3.8×10^{-5}	7.5×10^{-6}	3.5×10^{-5}	2.7×10^{-6}	1.3×10^{-5}	3.5×10^{-6}	1.6×10^{-5}	6.9×10^{-6}	3.2×10^{-5}
^{41}Ar	6.1×10^{-10}	3.2×10^{-15}	2.2×10^{-9}	1.1×10^{-14}	9.8×10^{-10}	5.2×10^{-15}	1.0×10^{-9}	5.5×10^{-15}	2.5×10^{-10}	1.3×10^{-15}	7.9×10^{-10}	4.2×10^{-15}	1.2×10^{-9}	6.5×10^{-15}
^{54}Mn	3.8×10^{-7}	1.8×10^{-6}	1.6×10^{-6}	7.4×10^{-6}	9.0×10^{-7}	4.3×10^{-6}	7.8×10^{-7}	3.7×10^{-6}	2.3×10^{-7}	1.1×10^{-6}	5.0×10^{-7}	2.4×10^{-6}	9.2×10^{-7}	4.4×10^{-6}
^{58}Co	8.9×10^{-7}	4.1×10^{-6}	3.6×10^{-6}	1.7×10^{-5}	2.4×10^{-6}	1.1×10^{-5}	2.2×10^{-6}	1.0×10^{-5}	6.7×10^{-7}	3.1×10^{-6}	1.3×10^{-6}	6.0×10^{-6}	2.3×10^{-6}	1.1×10^{-5}
^{60}Co	3.0×10^{-5}	1.4×10^{-4}	1.3×10^{-4}	6.3×10^{-4}	9.6×10^{-5}	4.6×10^{-4}	9.4×10^{-5}	4.5×10^{-4}	3.1×10^{-5}	1.5×10^{-4}	5.0×10^{-5}	2.4×10^{-4}	9.1×10^{-5}	4.3×10^{-4}
^{65}Zn	8.5×10^{-6}	4.0×10^{-5}	4.3×10^{-5}	2.0×10^{-4}	3.7×10^{-5}	1.7×10^{-4}	3.5×10^{-5}	1.6×10^{-4}	1.2×10^{-5}	5.9×10^{-5}	1.6×10^{-5}	7.6×10^{-5}	3.2×10^{-5}	1.5×10^{-4}
^{85}Kr	1.4×10^{-11}	1.1×10^{-10}	4.8×10^{-11}	4.0×10^{-10}	2.2×10^{-11}	1.8×10^{-10}	2.3×10^{-11}	1.9×10^{-10}	5.5×10^{-12}	4.6×10^{-11}	1.8×10^{-11}	1.5×10^{-10}	2.7×10^{-11}	2.3×10^{-10}
^{90}Sr[c]	8.7×10^{-5}	4.2×10^{-4}	3.6×10^{-4}	1.7×10^{-3}	2.3×10^{-4}	1.1×10^{-3}	1.8×10^{-4}	8.6×10^{-4}	5.5×10^{-5}	2.6×10^{-4}	1.2×10^{-4}	5.5×10^{-4}	2.2×10^{-4}	1.0×10^{-3}
^{106}Ru[c]	3.9×10^{-6}	1.9×10^{-5}	1.8×10^{-5}	8.4×10^{-5}	1.3×10^{-5}	5.9×10^{-5}	1.2×10^{-5}	5.7×10^{-5}	4.1×10^{-6}	1.9×10^{-5}	6.2×10^{-6}	3.0×10^{-5}	1.2×10^{-5}	5.6×10^{-5}
^{129}I	1.6×10^{-4}	7.6×10^{-4}	6.4×10^{-4}	3.1×10^{-3}	3.3×10^{-4}	1.6×10^{-3}	2.9×10^{-4}	1.4×10^{-3}	7.9×10^{-5}	3.8×10^{-4}	2.1×10^{-4}	1.0×10^{-3}	3.6×10^{-4}	1.7×10^{-3}
^{131}I	3.9×10^{-6}	1.4×10^{-5}	1.6×10^{-5}	5.6×10^{-5}	9.3×10^{-6}	3.2×10^{-5}	7.6×10^{-6}	2.7×10^{-5}	2.2×10^{-6}	7.9×10^{-6}	5.1×10^{-6}	1.8×10^{-5}	9.3×10^{-6}	3.2×10^{-5}
^{133}Xe[c]	1.6×10^{-10}	8.0×10^{-10}	5.6×10^{-10}	2.9×10^{-9}	2.6×10^{-10}	1.3×10^{-9}	2.7×10^{-10}	1.4×10^{-9}	6.5×10^{-11}	3.3×10^{-10}	2.1×10^{-10}	1.0×10^{-9}	3.2×10^{-10}	1.6×10^{-9}
^{135}Xe	8.3×10^{-10}	1.7×10^{-10}	3.0×10^{-9}	5.9×10^{-10}	1.4×10^{-9}	2.7×10^{-10}	1.4×10^{-9}	2.9×10^{-10}	3.4×10^{-10}	6.8×10^{-11}	1.1×10^{-9}	2.2×10^{-10}	1.7×10^{-9}	3.4×10^{-10}
^{138}Xe[c]	1.9×10^{-12}	1.7×10^{-31}	6.7×10^{-12}	6.2×10^{-31}	3.0×10^{-12}	2.8×10^{-31}	3.2×10^{-12}	3.0×10^{-31}	7.7×10^{-13}	7.1×10^{-32}	2.4×10^{-12}	2.3×10^{-31}	3.8×10^{-12}	3.5×10^{-31}
^{134}Cs	2.9×10^{-5}	1.4×10^{-4}	1.2×10^{-4}	5.9×10^{-4}	7.3×10^{-5}	3.5×10^{-4}	6.9×10^{-5}	3.3×10^{-4}	2.1×10^{-5}	9.9×10^{-5}	4.4×10^{-5}	2.1×10^{-4}	7.5×10^{-5}	3.6×10^{-4}
^{137}Cs[c]	3.5×10^{-5}	1.7×10^{-4}	1.4×10^{-4}	6.8×10^{-4}	7.9×10^{-5}	3.8×10^{-4}	7.6×10^{-5}	3.6×10^{-4}	2.2×10^{-5}	1.0×10^{-4}	5.0×10^{-5}	2.4×10^{-4}	8.5×10^{-5}	4.1×10^{-4}
^{210}Pb	3.0×10^{-4}	1.4×10^{-3}	1.2×10^{-3}	5.5×10^{-3}	6.0×10^{-4}	2.9×10^{-3}	5.0×10^{-4}	2.4×10^{-3}	1.4×10^{-4}	6.7×10^{-4}	3.5×10^{-4}	1.7×10^{-3}	6.4×10^{-4}	3.1×10^{-3}
^{210}Po	4.4×10^{-4}	2.1×10^{-3}	1.7×10^{-3}	8.2×10^{-3}	1.1×10^{-3}	5.0×10^{-3}	9.0×10^{-4}	4.2×10^{-3}	2.8×10^{-4}	1.3×10^{-3}	5.5×10^{-4}	2.6×10^{-3}	1.0×10^{-3}	4.9×10^{-3}
^{222}Rn[c]	4.0×10^{-7}	1.7×10^{-6}	1.4×10^{-6}	6.0×10^{-6}	6.4×10^{-7}	2.8×10^{-6}	6.8×10^{-7}	2.9×10^{-6}	1.6×10^{-7}	6.9×10^{-7}	5.1×10^{-7}	2.2×10^{-6}	8.0×10^{-7}	3.4×10^{-6}
^{226}Ra	4.3×10^{-4}	2.1×10^{-3}	1.7×10^{-3}	8.0×10^{-3}	8.4×10^{-4}	4.0×10^{-3}	7.4×10^{-4}	3.5×10^{-3}	2.0×10^{-4}	9.5×10^{-4}	5.4×10^{-4}	2.6×10^{-3}	9.3×10^{-4}	4.4×10^{-3}

Radio-nuclide	Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (man Sv)													
	Africa		Asia and Pacific		Europe		Latin America		North America		West Asia		World average[a]	
	Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional
^{230}Th	5.7×10^{-4}	2.7×10^{-3}	2.0×10^{-3}	9.8×10^{-3}	9.5×10^{-4}	4.5×10^{-3}	9.8×10^{-4}	4.7×10^{-3}	2.4×10^{-4}	1.1×10^{-3}	7.3×10^{-4}	3.5×10^{-3}	1.2×10^{-3}	5.5×10^{-3}
^{232}Th[c]	2.9×10^{-3}	1.4×10^{-2}	1.0×10^{-2}	5.0×10^{-2}	4.9×10^{-3}	2.3×10^{-2}	5.0×10^{-3}	2.4×10^{-2}	1.2×10^{-3}	5.8×10^{-3}	3.7×10^{-3}	1.8×10^{-2}	5.9×10^{-3}	2.8×10^{-2}
^{234}U	1.5×10^{-4}	7.3×10^{-4}	5.6×10^{-4}	2.7×10^{-3}	2.7×10^{-4}	1.3×10^{-3}	2.7×10^{-4}	1.3×10^{-3}	6.9×10^{-5}	3.3×10^{-4}	2.0×10^{-4}	9.5×10^{-4}	3.2×10^{-4}	1.5×10^{-3}
^{238}U[c]	1.3×10^{-4}	6.2×10^{-4}	4.8×10^{-4}	2.3×10^{-3}	2.3×10^{-4}	1.1×10^{-3}	2.3×10^{-4}	1.1×10^{-3}	5.9×10^{-5}	2.8×10^{-4}	1.7×10^{-4}	8.1×10^{-4}	2.7×10^{-4}	1.3×10^{-3}
^{239}Pu	1.9×10^{-3}	9.2×10^{-3}	6.8×10^{-3}	3.3×10^{-2}	3.1×10^{-3}	1.5×10^{-2}	3.3×10^{-3}	1.6×10^{-2}	7.9×10^{-4}	3.8×10^{-3}	2.5×10^{-3}	1.2×10^{-2}	3.9×10^{-3}	1.9×10^{-2}
^{240}Pu	1.9×10^{-3}	9.2×10^{-3}	6.8×10^{-3}	3.3×10^{-2}	3.1×10^{-3}	1.5×10^{-2}	3.3×10^{-3}	1.6×10^{-2}	7.9×10^{-4}	3.8×10^{-3}	2.5×10^{-3}	1.2×10^{-2}	3.9×10^{-3}	1.9×10^{-2}
^{241}Am	1.6×10^{-3}	7.7×10^{-3}	5.7×10^{-3}	2.7×10^{-2}	2.6×10^{-3}	1.3×10^{-2}	2.8×10^{-3}	1.3×10^{-2}	6.6×10^{-4}	3.2×10^{-3}	2.1×10^{-3}	1.0×10^{-2}	3.3×10^{-3}	1.6×10^{-2}

[a] The world-average value is based on a world-average population density given in table 3 together with a world-average consumption rate for terrestrial foods (table 7).

[b] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[c] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details of the progeny included).

Table 27. Local and regional components of collective dose for discharges to atmosphere for inland nuclear sites

These collective doses are based on the population distributions out to 1,500 km for inland nuclear sites given in table 4 for the regions shown in figure II. They apply to inland nuclear sites only. Because there were no inland operating nuclear power plants in Africa or West Asia at the time of analysis, results are not given for these regions

Radionuclide	Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (manSv)									
	Asia and Pacific		Europe		Latin America		North America		World average[a]	
	Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional
^{3}H[b]	1.2×10^{-7}	3.3×10^{-7}	3.4×10^{-8}	1.6×10^{-7}	2.8×10^{-8}	2.4×10^{-8}	2.2×10^{-8}	6.7×10^{-8}	2.9×10^{-8}	1.1×10^{-7}
^{14}C	9.2×10^{-6}	1.6×10^{-5}	2.3×10^{-6}	6.7×10^{-6}	2.1×10^{-6}	1.1×10^{-6}	1.5×10^{-6}	2.8×10^{-6}	2.2×10^{-6}	5.2×10^{-6}
^{35}S	2.0×10^{-5}	3.1×10^{-5}	9.4×10^{-6}	2.5×10^{-5}	8.1×10^{-6}	4.0×10^{-6}	8.1×10^{-6}	1.5×10^{-5}	6.3×10^{-6}	1.4×10^{-5}
^{41}Ar	4.6×10^{-9}	1.1×10^{-14}	1.1×10^{-9}	4.8×10^{-15}	1.1×10^{-9}	8.3×10^{-16}	7.4×10^{-10}	2.1×10^{-15}	1.1×10^{-9}	3.9×10^{-15}
^{54}Mn	3.3×10^{-6}	5.4×10^{-6}	1.0×10^{-6}	2.9×10^{-6}	8.4×10^{-7}	4.3×10^{-7}	7.0×10^{-7}	1.3×10^{-6}	8.4×10^{-7}	1.9×10^{-6}
^{58}Co	7.8×10^{-6}	1.2×10^{-5}	2.7×10^{-6}	7.3×10^{-6}	2.3×10^{-6}	1.2×10^{-6}	2.0×10^{-6}	3.6×10^{-6}	2.1×10^{-6}	4.7×10^{-6}
^{60}Co	2.8×10^{-4}	4.6×10^{-4}	1.1×10^{-4}	3.1×10^{-4}	1.0×10^{-4}	5.2×10^{-5}	9.2×10^{-5}	1.7×10^{-4}	8.4×10^{-5}	1.9×10^{-4}
^{65}Zn	9.2×10^{-5}	1.5×10^{-4}	4.2×10^{-5}	1.2×10^{-4}	3.7×10^{-5}	1.9×10^{-5}	3.7×10^{-5}	6.8×10^{-5}	2.9×10^{-5}	6.5×10^{-5}

Radionuclide	Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (manSv)									
	Asia and Pacific		Europe		Latin America		North America		World average[a]	
	Local	Regional	Local	Regional	Local	Regional	Local	Regional	Local	Regional
^{85}Kr	1.0×10^{-10}	2.8×10^{-10}	2.5×10^{-11}	1.2×10^{-10}	2.5×10^{-11}	2.2×10^{-11}	1.7×10^{-11}	5.1×10^{-11}	2.5×10^{-11}	9.4×10^{-11}
^{90}Sr[c]	7.7×10^{-4}	1.3×10^{-3}	2.6×10^{-4}	7.2×10^{-4}	1.9×10^{-4}	9.9×10^{-5}	1.7×10^{-4}	3.0×10^{-4}	2.0×10^{-4}	4.5×10^{-4}
^{106}Ru[c]	3.8×10^{-5}	6.1×10^{-5}	1.4×10^{-5}	4.0×10^{-5}	1.3×10^{-5}	6.6×10^{-6}	1.2×10^{-5}	2.2×10^{-5}	1.1×10^{-5}	2.4×10^{-5}
^{129}I	1.4×10^{-3}	2.2×10^{-3}	3.8×10^{-4}	1.1×10^{-3}	3.1×10^{-4}	1.6×10^{-4}	2.4×10^{-4}	4.3×10^{-4}	3.3×10^{-4}	7.5×10^{-4}
^{131}I	3.4×10^{-5}	4.3×10^{-5}	1.1×10^{-5}	2.3×10^{-5}	8.2×10^{-6}	3.2×10^{-6}	6.7×10^{-6}	9.6×10^{-6}	8.5×10^{-6}	1.5×10^{-5}
^{133}Xe	1.2×10^{-9}	2.2×10^{-9}	3.0×10^{-10}	9.1×10^{-10}	2.9×10^{-10}	1.7×10^{-10}	1.9×10^{-10}	4.0×10^{-10}	2.9×10^{-10}	7.4×10^{-10}
^{135}Xe	6.3×10^{-9}	5.5×10^{-10}	1.6×10^{-9}	2.5×10^{-10}	1.5×10^{-9}	4.3×10^{-11}	1.0×10^{-9}	1.1×10^{-10}	1.5×10^{-9}	2.0×10^{-10}
^{138}Xe[c]	1.4×10^{-11}	5.8×10^{-31}	3.5×10^{-12}	2.6×10^{-31}	3.5×10^{-12}	4.5×10^{-32}	2.3×10^{-12}	1.1×10^{-31}	3.5×10^{-12}	2.1×10^{-31}
^{134}Cs	2.6×10^{-4}	4.3×10^{-4}	8.4×10^{-5}	2.3×10^{-4}	7.4×10^{-5}	3.8×10^{-5}	6.2×10^{-5}	1.1×10^{-4}	6.9×10^{-5}	1.6×10^{-4}
^{137}Cs[c]	3.0×10^{-4}	4.9×10^{-4}	9.1×10^{-5}	2.5×10^{-4}	8.2×10^{-5}	4.2×10^{-5}	6.5×10^{-5}	1.2×10^{-4}	7.8×10^{-5}	1.8×10^{-4}
^{210}Pb	2.5×10^{-3}	4.0×10^{-3}	6.9×10^{-4}	1.9×10^{-3}	5.4×10^{-4}	2.8×10^{-4}	4.2×10^{-4}	7.7×10^{-4}	5.9×10^{-4}	1.3×10^{-3}
^{210}Po	3.7×10^{-3}	6.0×10^{-3}	1.2×10^{-3}	3.3×10^{-3}	9.7×10^{-4}	4.9×10^{-4}	8.2×10^{-4}	1.5×10^{-3}	9.6×10^{-4}	2.1×10^{-3}
^{222}Rn[c]	3.0×10^{-6}	4.7×10^{-6}	7.4×10^{-7}	2.0×10^{-6}	7.3×10^{-7}	3.6×10^{-7}	4.8×10^{-7}	8.7×10^{-7}	7.3×10^{-7}	1.6×10^{-6}
^{226}Ra	3.6×10^{-3}	5.8×10^{-3}	9.7×10^{-4}	2.7×10^{-3}	7.9×10^{-4}	4.1×10^{-4}	5.9×10^{-4}	1.1×10^{-3}	8.5×10^{-4}	1.9×10^{-3}
^{230}Th	4.4×10^{-3}	7.1×10^{-3}	1.1×10^{-3}	3.0×10^{-3}	1.0×10^{-3}	5.4×10^{-4}	7.1×10^{-4}	1.3×10^{-3}	1.1×10^{-3}	2.4×10^{-3}
^{232}Th[c]	2.2×10^{-2}	3.6×10^{-2}	5.6×10^{-3}	1.6×10^{-2}	5.3×10^{-3}	2.7×10^{-3}	3.6×10^{-3}	6.7×10^{-3}	5.4×10^{-3}	1.2×10^{-2}
^{234}U	1.2×10^{-3}	1.9×10^{-3}	3.1×10^{-4}	8.6×10^{-4}	2.9×10^{-4}	1.5×10^{-4}	2.1×10^{-4}	3.8×10^{-4}	3.0×10^{-4}	6.7×10^{-4}
^{238}U[c]	1.0×10^{-3}	1.7×10^{-3}	2.7×10^{-4}	7.4×10^{-4}	2.5×10^{-4}	1.3×10^{-4}	1.8×10^{-4}	3.3×10^{-4}	2.5×10^{-4}	5.7×10^{-4}
^{239}Pu	1.5×10^{-2}	2.4×10^{-2}	3.6×10^{-3}	1.0×10^{-2}	3.5×10^{-3}	1.8×10^{-3}	2.4×10^{-3}	4.3×10^{-3}	3.6×10^{-3}	8.0×10^{-3}
^{240}Pu	1.5×10^{-2}	2.4×10^{-2}	3.6×10^{-3}	1.0×10^{-2}	3.5×10^{-3}	1.8×10^{-3}	2.4×10^{-3}	4.3×10^{-3}	3.6×10^{-3}	8.0×10^{-3}
^{241}Am	1.2×10^{-2}	2.0×10^{-2}	3.0×10^{-3}	8.4×10^{-3}	3.0×10^{-3}	1.5×10^{-3}	2.0×10^{-3}	3.6×10^{-3}	3.0×10^{-3}	6.8×10^{-3}

[a] The world-average value is based on a world average population density given in table 4 together with a world-average consumption rate for terrestrial foods (table 7).

[b] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[c] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 28. Local and regional components of collective dose for discharges to atmosphere for coastal nuclear sites

These collective doses are based on the population distributions out to 1 500 km for coastal nuclear sites given in table 4 for the regions shown in figure II. They apply to coastal nuclear sites only. Because there were no coastal operating nuclear power plants in West Asia at the time of analysis, results are not given for this region

Radionuclide	*Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (manSv)*											
	Africa		*Asia and Pacific*		*Europe*		*Latin America*		*North America*		*World average*[a]	
	Local	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*
^{3}H[b]	2.3×10^{-8}	6.9×10^{-9}	5.3×10^{-8}	1.6×10^{-7}	2.5×10^{-8}	1.2×10^{-7}	2.2×10^{-8}	6.1×10^{-8}	3.4×10^{-8}	6.3×10^{-8}	3.6×10^{-8}	1.1×10^{-7}
^{14}C	1.7×10^{-6}	2.8×10^{-7}	4.1×10^{-6}	7.7×10^{-6}	1.6×10^{-6}	4.8×10^{-6}	1.6×10^{-6}	3.0×10^{-6}	2.3×10^{-6}	2.7×10^{-6}	2.7×10^{-6}	5.0×10^{-6}
^{35}S	2.8×10^{-6}	4.3×10^{-7}	8.6×10^{-6}	1.5×10^{-5}	6.7×10^{-6}	1.8×10^{-5}	6.3×10^{-6}	1.1×10^{-5}	1.3×10^{-5}	1.4×10^{-5}	7.7×10^{-6}	1.4×10^{-5}
^{41}Ar	9.6×10^{-10}	6.1×10^{-17}	2.0×10^{-9}	4.8×10^{-15}	8.1×10^{-10}	3.5×10^{-15}	8.7×10^{-10}	3.4×10^{-15}	1.2×10^{-9}	2.2×10^{-15}	1.4×10^{-9}	3.6×10^{-15}
^{54}Mn	6.1×10^{-7}	9.7×10^{-8}	1.5×10^{-6}	2.6×10^{-6}	7.4×10^{-7}	2.1×10^{-6}	6.6×10^{-7}	1.2×10^{-6}	1.1×10^{-6}	1.2×10^{-6}	1.0×10^{-6}	1.8×10^{-6}
^{58}Co	1.4×10^{-6}	2.2×10^{-7}	3.4×10^{-6}	5.9×10^{-6}	1.9×10^{-6}	5.3×10^{-6}	1.8×10^{-6}	3.2×10^{-6}	3.1×10^{-6}	3.4×10^{-6}	2.6×10^{-6}	4.5×10^{-6}
^{60}Co	4.8×10^{-5}	7.7×10^{-6}	1.2×10^{-4}	2.2×10^{-4}	7.9×10^{-5}	2.2×10^{-4}	7.9×10^{-5}	1.4×10^{-4}	1.4×10^{-4}	1.6×10^{-4}	1.0×10^{-4}	1.8×10^{-4}
^{65}Zn	1.3×10^{-5}	2.1×10^{-6}	4.0×10^{-5}	7.2×10^{-5}	3.0×10^{-5}	8.4×10^{-5}	2.9×10^{-5}	5.1×10^{-5}	5.8×10^{-5}	6.5×10^{-5}	3.6×10^{-5}	6.4×10^{-5}
^{85}Kr	2.1×10^{-11}	6.5×10^{-12}	4.5×10^{-11}	1.4×10^{-10}	1.8×10^{-11}	8.5×10^{-11}	2.0×10^{-11}	5.5×10^{-11}	2.6×10^{-11}	4.8×10^{-11}	3.1×10^{-11}	9.3×10^{-11}
^{90}Sr[c]	1.4×10^{-4}	2.2×10^{-5}	3.4×10^{-4}	6.1×10^{-4}	1.9×10^{-4}	5.2×10^{-4}	1.5×10^{-4}	2.7×10^{-4}	2.6×10^{-4}	2.9×10^{-4}	2.4×10^{-4}	4.4×10^{-4}
^{106}Ru[c]	6.2×10^{-6}	9.9×10^{-7}	1.7×10^{-5}	3.0×10^{-5}	1.0×10^{-5}	2.9×10^{-5}	1.0×10^{-5}	1.8×10^{-5}	1.9×10^{-5}	2.1×10^{-5}	1.3×10^{-5}	2.4×10^{-5}
^{129}I	2.5×10^{-4}	4.0×10^{-5}	6.1×10^{-4}	1.1×10^{-3}	2.7×10^{-4}	7.7×10^{-4}	2.4×10^{-4}	4.3×10^{-4}	3.7×10^{-4}	4.2×10^{-4}	4.0×10^{-4}	7.3×10^{-4}
^{131}I	6.2×10^{-6}	6.4×10^{-7}	1.5×10^{-5}	2.0×10^{-5}	7.6×10^{-6}	1.7×10^{-5}	6.4×10^{-6}	9.4×10^{-6}	1.1×10^{-5}	9.4×10^{-6}	1.0×10^{-5}	1.4×10^{-5}
^{133}Xe[c]	2.5×10^{-10}	3.8×10^{-11}	5.3×10^{-10}	1.0×10^{-9}	2.1×10^{-10}	6.6×10^{-10}	2.3×10^{-10}	4.7×10^{-10}	3.0×10^{-10}	3.8×10^{-10}	3.6×10^{-10}	7.1×10^{-10}
^{135}Xe	1.3×10^{-9}	3.2×10^{-12}	2.8×10^{-9}	2.5×10^{-10}	1.1×10^{-9}	1.8×10^{-10}	1.2×10^{-9}	1.7×10^{-10}	1.6×10^{-9}	1.1×10^{-10}	1.9×10^{-9}	1.8×10^{-10}
^{138}Xe[c]	3.0×10^{-12}	3.3×10^{-33}	6.3×10^{-12}	2.6×10^{-31}	2.5×10^{-12}	1.9×10^{-31}	2.7×10^{-12}	1.8×10^{-31}	3.6×10^{-12}	1.2×10^{-31}	4.2×10^{-12}	1.9×10^{-31}
^{134}Cs	4.6×10^{-5}	7.4×10^{-6}	1.2×10^{-4}	2.1×10^{-4}	6.0×10^{-5}	1.7×10^{-4}	5.8×10^{-5}	1.0×10^{-4}	9.7×10^{-5}	1.1×10^{-4}	8.4×10^{-5}	1.5×10^{-4}
^{137}Cs[c]	5.5×10^{-5}	8.9×10^{-6}	1.3×10^{-4}	2.4×10^{-4}	6.5×10^{-5}	1.8×10^{-4}	6.4×10^{-5}	1.1×10^{-4}	1.0×10^{-4}	1.2×10^{-4}	9.5×10^{-5}	1.7×10^{-4}
^{210}Pb	4.7×10^{-4}	7.6×10^{-5}	1.1×10^{-3}	2.0×10^{-3}	4.9×10^{-4}	1.4×10^{-3}	4.2×10^{-4}	7.5×10^{-4}	6.6×10^{-4}	7.4×10^{-4}	7.2×10^{-4}	1.3×10^{-3}
^{210}Po	6.9×10^{-4}	1.1×10^{-4}	1.6×10^{-3}	2.9×10^{-3}	8.7×10^{-4}	2.4×10^{-3}	7.6×10^{-4}	1.3×10^{-3}	1.3×10^{-3}	1.4×10^{-3}	1.2×10^{-3}	2.1×10^{-3}
^{222}Rn[c]	6.2×10^{-7}	7.5×10^{-8}	1.3×10^{-6}	2.2×10^{-6}	5.3×10^{-7}	1.4×10^{-6}	5.7×10^{-7}	1.1×10^{-6}	7.6×10^{-7}	8.5×10^{-7}	8.9×10^{-7}	1.5×10^{-6}
^{226}Ra	6.8×10^{-4}	1.1×10^{-4}	1.6×10^{-3}	2.8×10^{-3}	6.9×10^{-4}	1.9×10^{-3}	6.2×10^{-4}	1.1×10^{-3}	9.3×10^{-4}	1.0×10^{-3}	1.0×10^{-3}	1.9×10^{-3}

Radionuclide	*Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (manSv)*											
	Africa		*Asia and Pacific*		*Europe*		*Latin America*		*North America*		*World average*[a]	
	Local	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*
^{230}Th	9.0×10^{-4}	1.5×10^{-4}	1.9×10^{-3}	3.5×10^{-3}	7.8×10^{-4}	2.2×10^{-3}	8.2×10^{-4}	1.5×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	2.3×10^{-3}
^{232}Th[c]	4.6×10^{-3}	7.3×10^{-4}	9.8×10^{-3}	1.8×10^{-2}	4.0×10^{-3}	1.1×10^{-2}	4.2×10^{-3}	7.4×10^{-3}	5.7×10^{-3}	6.4×10^{-3}	6.6×10^{-3}	1.2×10^{-2}
^{234}U	2.4×10^{-4}	3.9×10^{-5}	5.3×10^{-4}	9.5×10^{-4}	2.2×10^{-4}	6.3×10^{-4}	2.3×10^{-4}	4.1×10^{-4}	3.2×10^{-4}	3.7×10^{-4}	3.6×10^{-4}	6.5×10^{-4}
^{238}U[c]	2.1×10^{-4}	3.3×10^{-5}	4.5×10^{-4}	8.1×10^{-4}	1.9×10^{-4}	5.3×10^{-4}	2.0×10^{-4}	3.5×10^{-4}	2.8×10^{-4}	3.1×10^{-4}	3.1×10^{-4}	5.5×10^{-4}
^{239}Pu	3.0×10^{-3}	4.9×10^{-4}	6.4×10^{-3}	1.2×10^{-2}	2.6×10^{-3}	7.3×10^{-3}	2.8×10^{-3}	4.9×10^{-3}	3.7×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	7.9×10^{-3}
^{240}Pu	3.0×10^{-3}	4.9×10^{-4}	6.4×10^{-3}	1.2×10^{-2}	2.6×10^{-3}	7.3×10^{-3}	2.8×10^{-3}	4.9×10^{-3}	3.7×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	7.9×10^{-3}
^{241}Am	2.5×10^{-3}	4.1×10^{-4}	5.4×10^{-3}	9.7×10^{-3}	2.2×10^{-3}	6.1×10^{-3}	2.3×10^{-3}	4.1×10^{-3}	3.1×10^{-3}	3.5×10^{-3}	3.6×10^{-3}	6.6×10^{-3}

[a] The world-average value is based on a world average population density given in table 3 together with a world-average consumption rate for terrestrial foods (table 7).

[b] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[c] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 29. Local and regional components of collective dose for discharges to atmosphere for low population density sites

These collective dose estimates are for locations with a low population density out to 1,500 km and are based on a population density of 5 km^{-2}. They apply to the world as a whole and are intended for use for uranium mines and mill tailings sites

Radionuclide	*Collective dose integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (man Sv)*	
	Local component	*Regional component*
$^{3}H^{a}$	1.0×10^{-9}	8.4×10^{-9}
^{14}C	7.5×10^{-8}	3.8×10^{-7}
^{35}S	2.2×10^{-7}	1.0×10^{-6}
^{41}Ar	3.8×10^{-11}	2.0×10^{-16}
^{54}Mn	2.9×10^{-8}	1.4×10^{-7}
^{58}Co	7.3×10^{-8}	3.4×10^{-7}
^{60}Co	2.9×10^{-6}	1.4×10^{-5}
^{65}Zn	1.0×10^{-6}	4.7×10^{-6}
^{85}Kr	8.6×10^{-13}	7.2×10^{-12}
$^{90}Sr^{b}$	6.8×10^{-6}	3.2×10^{-5}
$^{106}Ru^{b}$	3.7×10^{-7}	1.8×10^{-6}
^{129}I	1.1×10^{-5}	5.4×10^{-5}
^{131}I	2.9×10^{-7}	1.0×10^{-6}
$^{133}Xe^{b}$	1.0×10^{-11}	5.1×10^{-11}
^{135}Xe	5.3×10^{-11}	1.1×10^{-11}
$^{138}Xe^{b}$	1.2×10^{-13}	1.1×10^{-32}
^{134}Cs	2.4×10^{-6}	1.1×10^{-5}
$^{137}Cs^{b}$	2.7×10^{-6}	1.3×10^{-5}
^{210}Pb	2.0×10^{-5}	9.6×10^{-5}
^{210}Po	3.3×10^{-5}	1.5×10^{-4}
$^{222}Rn^{b}$	2.5×10^{-8}	1.1×10^{-7}
^{226}Ra	2.9×10^{-5}	1.4×10^{-4}
^{230}Th	3.6×10^{-5}	1.7×10^{-4}
$^{232}Th^{b}$	1.9×10^{-4}	8.9×10^{-4}
^{234}U	1.0×10^{-5}	4.8×10^{-5}
$^{238}U^{b}$	8.6×10^{-6}	4.1×10^{-5}
^{239}Pu	1.2×10^{-4}	5.8×10^{-4}
^{240}Pu	1.2×10^{-4}	5.8×10^{-4}
^{241}Am	1.0×10^{-4}	4.9×10^{-4}

[a] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[b] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 30. Collective dose for discharges to small and large rivers

Values are for small and large rivers situated in the regions shown in figure II. The results for large rivers are also assumed to apply for lakes

Radio-nuclide	*Collective doses integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (man Sv)*													
	Africa		*Asia and Pacific*		*Europe*		*Latin America*		*North America*		*West Asia*		*World average*[a]	
	Small	*Large*	*Small*	*Large*	*Small*	*Large*	*Small*	*Large*	*Small*	*Large*	*Small*	*Large*	*Small*	*Large*
^{3}H[b]	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}	1.9×10^{-7}
^{14}C	2.3×10^{-3}	1.2×10^{-3}	2.3×10^{-3}	1.2×10^{-3}	2.3×10^{-3}	1.2×10^{-3}	2.3×10^{-3}	1.2×10^{-3}	2.3×10^{-3}	1.2×10^{-3}	2.3×10^{-3}	1.4×10^{-3}	2.3×10^{-3}	1.2×10^{-3}
^{35}S	7.4×10^{-6}	4.5×10^{-6}	7.4×10^{-6}	4.8×10^{-6}	7.4×10^{-6}	4.6×10^{-6}	7.4×10^{-6}	4.3×10^{-6}	7.4×10^{-6}	5.2×10^{-6}	7.4×10^{-6}	1.7×10^{-5}	7.4×10^{-6}	4.8×10^{-6}
^{54}Mn	1.5×10^{-6}	9.2×10^{-7}	1.5×10^{-6}	9.8×10^{-7}	1.5×10^{-6}	9.4×10^{-7}	1.5×10^{-6}	8.8×10^{-7}	1.5×10^{-6}	1.1×10^{-6}	1.5×10^{-6}	3.6×10^{-6}	1.5×10^{-6}	9.7×10^{-7}
^{58}Co	1.6×10^{-6}	1.3×10^{-6}	1.6×10^{-6}	1.4×10^{-6}	1.6×10^{-6}	1.3×10^{-6}	1.6×10^{-6}	1.3×10^{-6}	1.6×10^{-6}	1.4×10^{-6}	1.6×10^{-6}	3.1×10^{-6}	1.6×10^{-6}	1.4×10^{-6}
^{60}Co	7.2×10^{-6}	6.4×10^{-6}	7.2×10^{-6}	6.8×10^{-6}	7.2×10^{-6}	6.5×10^{-6}	7.2×10^{-6}	6.1×10^{-6}	7.2×10^{-6}	7.2×10^{-6}	7.2×10^{-6}	2.2×10^{-5}	7.2×10^{-6}	6.7×10^{-6}
^{65}Zn	1.4×10^{-4}	6.1×10^{-5}	1.4×10^{-4}	6.1×10^{-5}	1.4×10^{-4}	6.1×10^{-5}	1.4×10^{-4}	6.0×10^{-5}	1.4×10^{-4}	6.2×10^{-5}	1.4×10^{-4}	9.2×10^{-5}	1.4×10^{-4}	6.1×10^{-5}
^{90}Sr[c]	7.2×10^{-5}	1.0×10^{-4}	7.2×10^{-5}	1.2×10^{-4}	7.2×10^{-5}	1.1×10^{-4}	7.2×10^{-5}	8.8×10^{-5}	7.2×10^{-5}	1.4×10^{-4}	7.2×10^{-5}	9.8×10^{-4}	7.2×10^{-5}	1.2×10^{-4}
^{106}Ru[c]	1.4×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.2×10^{-5}	1.4×10^{-5}	1.5×10^{-5}	1.4×10^{-5}	1.2×10^{-5}
^{129}I	3.1×10^{-4}	3.8×10^{-4}	3.1×10^{-4}	4.5×10^{-4}	3.1×10^{-4}	4.0×10^{-4}	3.1×10^{-4}	3.4×10^{-4}	3.1×10^{-4}	5.3×10^{-4}	3.1×10^{-4}	3.3×10^{-3}	3.1×10^{-4}	4.4×10^{-4}
^{131}I	5.7×10^{-6}	5.3×10^{-6}	5.7×10^{-6}	5.4×10^{-6}	5.7×10^{-6}	5.4×10^{-6}	5.7×10^{-6}	5.3×10^{-6}	5.7×10^{-6}	5.5×10^{-6}	5.7×10^{-6}	9.1×10^{-6}	5.7×10^{-6}	5.4×10^{-6}
^{134}Cs	3.5×10^{-4}	7.8×10^{-5}	3.5×10^{-4}	8.7×10^{-5}	3.5×10^{-4}	8.1×10^{-5}	3.5×10^{-4}	7.1×10^{-5}	3.5×10^{-4}	9.8×10^{-5}	3.5×10^{-4}	4.9×10^{-4}	3.5×10^{-4}	8.5×10^{-5}
^{137}Cs[c]	2.4×10^{-4}	5.5×10^{-5}	2.4×10^{-4}	6.3×10^{-5}	2.4×10^{-4}	5.7×10^{-5}	2.4×10^{-4}	5.0×10^{-5}	2.4×10^{-4}	7.2×10^{-5}	2.4×10^{-4}	3.9×10^{-4}	2.4×10^{-4}	6.1×10^{-5}
^{210}Pb	1.3×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	2.5×10^{-3}	1.3×10^{-3}	1.3×10^{-3}
^{210}Po	2.3×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.1×10^{-3}
^{226}Ra	4.9×10^{-4}	5.9×10^{-4}	4.9×10^{-4}	6.6×10^{-4}	4.9×10^{-4}	6.1×10^{-4}	4.9×10^{-4}	5.4×10^{-4}	4.9×10^{-4}	7.5×10^{-4}	4.9×10^{-4}	3.8×10^{-3}	4.9×10^{-4}	6.5×10^{-4}
^{230}Th	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.0×10^{-4}	2.7×10^{-4}	2.0×10^{-4}	2.0×10^{-4}
^{232}Th[c]	1.5×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.5×10^{-3}	4.3×10^{-3}	1.5×10^{-3}	1.6×10^{-3}
^{234}U	4.7×10^{-5}	5.1×10^{-5}	4.7×10^{-5}	5.3×10^{-5}	4.7×10^{-5}	5.1×10^{-5}	4.7×10^{-5}	4.9×10^{-5}	4.7×10^{-5}	5.7×10^{-5}	4.7×10^{-5}	1.7×10^{-4}	4.7×10^{-5}	5.3×10^{-5}
^{238}U[c]	4.6×10^{-5}	5.0×10^{-5}	4.6×10^{-5}	5.2×10^{-5}	4.6×10^{-5}	5.1×10^{-5}	4.6×10^{-5}	4.8×10^{-5}	4.6×10^{-5}	5.5×10^{-5}	4.6×10^{-5}	1.6×10^{-4}	4.6×10^{-5}	5.2×10^{-5}
^{239}Pu	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	3.3×10^{-4}	2.3×10^{-4}	2.2×10^{-4}
^{240}Pu	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	2.2×10^{-4}	2.3×10^{-4}	3.3×10^{-4}	2.3×10^{-4}	2.2×10^{-4}
^{241}Am	3.1×10^{-4}	1.8×10^{-4}	3.1×10^{-4}	1.8×10^{-4}	3.1×10^{-4}	1.8×10^{-4}	3.1×10^{-4}	1.8×10^{-4}	3.1×10^{-4}	1.9×10^{-4}	3.1×10^{-4}	3.1×10^{-4}	3.1×10^{-4}	1.8×10^{-4}

[a] The world-average collective dose is calculated using world-average values for irrigation (tables 11, 12 and 17) (note that the catch data for unit river length is the same for all regions and the world-average).

[b] For ^{3}H the calculated doses include a contribution from HTO and OBT as discussed in section III.A.3.

[c] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

Table 31. Local and regional components of collective dose for discharges to a marine environment

These results are for discharges to a marine environment for the regions shown in figure II

Radio-nuclide	*Collective dose integrated to 100 years from a year's continuous discharge at a rate of 1 Bq/s (man Sv)*													
	Africa		*Asia and Pacific*		*Europe*		*Latin America*		*North America*		*West Asia*		*World average*[a]	
	Local	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*	*Local*	*Regional*
^{3}H	8.5×10^{-13}	4.8×10^{-14}	3.4×10^{-12}	5.8×10^{-14}	6.0×10^{-13}	4.7×10^{-14}	1.4×10^{-12}	2.8×10^{-14}	1.1×10^{-12}	1.8×10^{-14}	1.0×10^{-12}	5.7×10^{-14}	2.2×10^{-12}	3.1×10^{-14}
^{14}C	5.5×10^{-7}	3.3×10^{-8}	2.2×10^{-6}	4.0×10^{-8}	3.9×10^{-7}	3.2×10^{-8}	9.2×10^{-7}	1.9×10^{-8}	6.9×10^{-7}	1.2×10^{-8}	6.5×10^{-7}	3.9×10^{-8}	1.4×10^{-6}	2.1×10^{-8}
^{35}S	4.9×10^{-11}	5.0×10^{-13}	2.7×10^{-10}	6.6×10^{-13}	3.9×10^{-11}	4.9×10^{-13}	9.7×10^{-11}	3.0×10^{-13}	6.3×10^{-11}	2.0×10^{-13}	5.4×10^{-11}	5.9×10^{-13}	1.8×10^{-10}	3.6×10^{-13}
^{54}Mn	5.1×10^{-7}	1.5×10^{-9}	3.9×10^{-6}	5.2×10^{-9}	4.5×10^{-7}	1.4×10^{-9}	1.2×10^{-6}	1.8×10^{-9}	7.2×10^{-7}	1.1×10^{-9}	5.1×10^{-7}	1.7×10^{-9}	2.6×10^{-6}	3.3×10^{-9}
^{58}Co	2.5×10^{-7}	3.7×10^{-10}	1.6×10^{-6}	9.9×10^{-10}	1.9×10^{-7}	3.4×10^{-10}	5.8×10^{-7}	3.9×10^{-10}	3.8×10^{-7}	2.5×10^{-10}	2.8×10^{-7}	4.2×10^{-10}	1.1×10^{-6}	6.1×10^{-10}
^{60}Co	1.4×10^{-6}	7.6×10^{-9}	8.8×10^{-6}	2.0×10^{-8}	1.0×10^{-6}	7.0×10^{-9}	3.1×10^{-6}	8.0×10^{-9}	2.1×10^{-6}	5.2×10^{-9}	1.5×10^{-6}	8.7×10^{-9}	5.8×10^{-6}	1.3×10^{-8}
^{65}Zn	2.7×10^{-5}	3.1×10^{-8}	1.0×10^{-4}	1.1×10^{-7}	1.2×10^{-5}	1.7×10^{-8}	5.3×10^{-5}	5.5×10^{-8}	4.7×10^{-5}	4.8×10^{-8}	3.5×10^{-5}	4.0×10^{-8}	7.0×10^{-5}	7.2×10^{-8}
^{90}Sr[b]	7.6×10^{-9}	2.4×10^{-10}	4.1×10^{-8}	3.3×10^{-10}	5.6×10^{-9}	2.3×10^{-10}	1.5×10^{-8}	1.5×10^{-10}	1.0×10^{-8}	9.8×10^{-11}	8.6×10^{-9}	2.8×10^{-10}	2.7×10^{-8}	1.8×10^{-10}
^{106}Ru[b]	5.7×10^{-8}	8.9×10^{-11}	4.1×10^{-7}	5.1×10^{-10}	4.7×10^{-8}	7.7×10^{-11}	1.4×10^{-7}	1.7×10^{-10}	8.4×10^{-8}	1.1×10^{-10}	5.9×10^{-8}	9.6×10^{-11}	2.7×10^{-7}	3.3×10^{-10}
^{129}I	3.4×10^{-8}	2.8×10^{-9}	1.6×10^{-7}	3.3×10^{-9}	3.0×10^{-8}	2.7×10^{-9}	5.6×10^{-8}	1.6×10^{-9}	3.6×10^{-8}	1.0×10^{-9}	3.8×10^{-8}	3.3×10^{-9}	1.0×10^{-7}	1.7×10^{-9}
^{131}I	2.4×10^{-10}	6.1×10^{-13}	1.1×10^{-9}	7.2×10^{-13}	2.1×10^{-10}	6.0×10^{-13}	3.9×10^{-10}	3.4×10^{-13}	2.5×10^{-10}	2.2×10^{-13}	2.7×10^{-10}	7.1×10^{-13}	7.1×10^{-10}	3.8×10^{-13}
^{134}Cs	5.9×10^{-8}	3.9×10^{-9}	2.1×10^{-7}	4.6×10^{-9}	4.6×10^{-8}	3.9×10^{-9}	8.7×10^{-8}	2.2×10^{-9}	6.3×10^{-8}	1.4×10^{-9}	7.0×10^{-8}	4.6×10^{-9}	1.4×10^{-7}	2.4×10^{-9}
^{137}Cs[b]	4.1×10^{-8}	3.6×10^{-9}	1.5×10^{-7}	4.1×10^{-9}	3.2×10^{-8}	3.5×10^{-9}	6.0×10^{-8}	2.0×10^{-9}	4.4×10^{-8}	1.3×10^{-9}	4.9×10^{-8}	4.2×10^{-9}	9.4×10^{-8}	2.2×10^{-9}
^{210}Pb[b]	2.5×10^{-3}	1.1×10^{-5}	1.2×10^{-2}	2.9×10^{-5}	1.4×10^{-3}	8.9×10^{-6}	5.3×10^{-3}	1.3×10^{-5}	4.2×10^{-3}	1.0×10^{-5}	3.2×10^{-3}	1.3×10^{-5}	7.9×10^{-3}	1.8×10^{-5}
^{210}Po	7.6×10^{-4}	2.6×10^{-6}	3.8×10^{-3}	5.0×10^{-6}	4.6×10^{-4}	2.4×10^{-6}	1.6×10^{-3}	2.2×10^{-6}	1.2×10^{-3}	1.6×10^{-6}	9.2×10^{-4}	3.1×10^{-6}	2.5×10^{-3}	2.9×10^{-6}
^{226}Ra[b]	2.6×10^{-3}	1.2×10^{-5}	1.2×10^{-2}	3.2×10^{-5}	1.4×10^{-3}	9.7×10^{-6}	5.3×10^{-3}	1.4×10^{-5}	4.3×10^{-3}	1.1×10^{-5}	3.2×10^{-3}	1.5×10^{-5}	8.0×10^{-3}	2.0×10^{-5}
^{230}Th	8.7×10^{-6}	3.5×10^{-7}	3.8×10^{-5}	4.4×10^{-7}	5.8×10^{-6}	3.4×10^{-7}	1.6×10^{-5}	2.1×10^{-7}	1.2×10^{-5}	1.4×10^{-7}	1.0×10^{-5}	4.1×10^{-7}	2.5×10^{-5}	2.4×10^{-7}
^{232}Th[b]	3.1×10^{-5}	7.3×10^{-7}	1.4×10^{-4}	1.0×10^{-6}	1.8×10^{-5}	7.0×10^{-7}	5.9×10^{-5}	4.7×10^{-7}	4.7×10^{-5}	3.2×10^{-7}	3.8×10^{-5}	8.6×10^{-7}	9.0×10^{-5}	5.5×10^{-7}
^{234}U	2.9×10^{-8}	1.9×10^{-10}	1.9×10^{-7}	5.3×10^{-10}	2.2×10^{-8}	1.8×10^{-10}	6.7×10^{-8}	2.1×10^{-10}	4.4×10^{-8}	1.3×10^{-10}	3.2×10^{-8}	2.2×10^{-10}	1.3×10^{-7}	3.3×10^{-10}
^{238}U[b]	1.7×10^{-7}	6.1×10^{-9}	7.9×10^{-7}	7.9×10^{-9}	1.2×10^{-7}	5.9×10^{-9}	3.2×10^{-7}	3.7×10^{-9}	2.4×10^{-7}	2.4×10^{-9}	2.0×10^{-7}	7.1×10^{-9}	5.2×10^{-7}	4.3×10^{-9}
^{239}Pu	1.1×10^{-5}	9.0×10^{-8}	8.4×10^{-5}	2.4×10^{-7}	9.9×10^{-6}	8.8×10^{-8}	2.6×10^{-5}	8.9×10^{-8}	1.5×10^{-5}	5.3×10^{-8}	1.1×10^{-5}	1.0×10^{-7}	5.5×10^{-5}	1.5×10^{-7}
^{240}Pu	1.1×10^{-5}	9.0×10^{-8}	8.4×10^{-5}	2.4×10^{-7}	9.9×10^{-6}	8.8×10^{-8}	2.6×10^{-5}	8.9×10^{-8}	1.5×10^{-5}	5.3×10^{-8}	1.1×10^{-5}	1.0×10^{-7}	5.5×10^{-5}	1.5×10^{-7}
^{241}Am	4.4×10^{-6}	6.3×10^{-8}	2.7×10^{-5}	1.1×10^{-7}	3.3×10^{-6}	6.0×10^{-8}	9.7×10^{-6}	4.8×10^{-8}	6.5×10^{-6}	3.1×10^{-8}	4.9×10^{-6}	7.3×10^{-8}	1.8×10^{-5}	6.6×10^{-8}

[a] The world-average value is calculated using the world-average annual catch of fish, crustacea and molluscs from table 21.

[b] For these radionuclides the calculated doses include a contribution from the ingrowth of progeny (see appendix for details).

VII. CONCLUSIONS

151. An important aspect of the Committee's work is the periodic assessment of global and regional radiation exposures to the public from discharges of radionuclides to the environment. Such studies require a robust, generic methodology that is defensible and takes into account developments in the field. The methodology used by the Committee for many years has proved to meet its needs for worldwide exposure assessments but, as previously, before any major evaluation of exposures, the methodology has been reviewed by the Committee to ensure its continued validity. An important factor for the current review was the decision by the Committee to update its evaluations of human radiation exposures from all significant types of electrical energy production. Following the review, the Committee decided to make some changes to parts of the methodology, while retaining other parts that it felt were still appropriate for its purposes. Previously, the results had often been expressed in terms of dose per unit of electricity generated but, for flexibility, it was agreed that the results be presented in terms of dose per unit of activity discharged.

152. The updated methodology can be used to estimate characteristic individual doses (typical of the average person living in the area around the source) and collective doses due to discharges to atmosphere, to freshwater bodies (small and large rivers or a lake) and to the sea. A wide range of radionuclides are included to enable exposures to be assessed for nuclear and non-nuclear forms of electrical energy production. The methodology applies to routine, continuous discharges only and it cannot be used for accidental releases; nor is it suitable for detailed site-specific assessments of doses to representative persons for regulatory purposes. As previously mentioned, local, regional and global components of collective dose are estimated, as appropriate. However, it is now possible to gain additional insight for discharges to atmosphere on collective doses within different distance bands from the discharge point. Global components of collective dose are now also available for integration times of 100, 500 and 10,000 years.

153. The methodology now includes factors for population densities and for food consumption rates that vary with geographical region. The Committee added this detail because non-nuclear power stations are found throughout the world where population densities and patterns of food consumption are significantly different from a generic world average. However, the geographical regions adopted are still very large and the inclusion of such region-specific data does not mean that the methodology is suitable for site-specific assessments. Another addition to the methodology is the inclusion of doses due to the irrigation of terrestrial foods with fresh water into which radionuclides had been discharged. The extent and nature of irrigation is very variable throughout the world but, for the purposes of this methodology, a simplified generic approach has been adopted for estimating exposures due to irrigation.

154. This scientific annex describes the methodology, outlines changes from previous versions and discusses its limitations and particular areas of uncertainty. Where possible, the results from applying the methodology have been compared with those from other methodologies and published studies. Although the purpose of the other studies would have influenced the developers' choice of models and parameter values and hence the estimated doses, the comparisons still helped to give confidence that the Committee's methodology is fit for its purposes.

155. The methodology has been implemented in a series of Excel® workbooks to ensure that it is transparent for use by the Committee in any future studies. It should also be relatively easy to update the methodology using such a system. The workbooks enable the user to obtain information on the important exposure pathways and radionuclides to gain insight for the Committee's work. The workbooks have been checked and verified by people not involved in their development.

156. The Committee considers that the methodology should also be transparent to the wider community and therefore, in addition to the information presented here, further detail is provided in electronic attachments available on the UNSCEAR website (http://www.unscear.org/unscear/en/publications/2016.html). The Committee is satisfied that the methodology, as implemented in the workbooks, is robust, builds on the strong position of the previous versions of the methodology and is suitable for assessing worldwide exposures due to routine discharges of radionuclides to the environment. It can be used to assess—in a consistent way—exposures due to releases from non-nuclear and nuclear sites of electricity generation including the related fuel-cycle sites (e.g. uranium mining and milling, nuclear fuel reprocessing and nuclear power stations that are being decommissioned).

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Expert group

Co-chairs: E. Waller (Canada)

Members: T. Anderson (United Kingdom), L. Anspaugh (United States), H. Grogan (United States), G. Hirth (Australia), K. Jones (United Kingdom), L. Hubbard (Sweden), R. Michel (Germany), J. Simmonds (United Kingdom)

Observer: G. Proehl (IAEA)

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APPENDIX A. IMPLEMENTATION OF THE METHODOLOGY

A1. The aim of this appendix is to provide more details of how the Committee has implemented the methodology as a set of Excel® workbooks by describing the workbook design (including the end points considered, the mathematical equations to implement the methodology in the workbooks, and information on how the workbooks can be used to assess exposures from different types of discharge), details of how radioactive progeny have been treated, and quality assurance.

I. WORKBOOK DESIGN

A2. The methodology has been implemented as a series of Excel® workbooks from which dose calculation factors (i.e. the calculated individual and collective doses from unit discharge of radionuclides under a set of defined conditions) can be derived. The series includes a workbook for each environment into which a discharge can be made (i.e. atmosphere, freshwater bodies, and marine environments); a further workbook summarizes the doses due to discharges into each of the three environments, and another provides dose values for globally circulating radionuclides. Table A1 summarizes the various end points that are produced by the workbooks, and how the relevant populations and pathways are treated.

A3. The workbook for each environment into which a discharge is made comprises a number of interlinked worksheets. An initial status worksheet describes the purpose of the workbook and provides key information about its format and contents, version and quality control. Other worksheets contain values of the model input parameters (radionuclide-specific ones and others such as habit data); intermediate calculations (e.g. of activity concentrations of radionuclides as a function of distance for discharges to atmosphere); and output values for the end points (i.e. dose calculation factors).

A4. *Discharges to atmosphere.* The workbook first calculates activity concentrations of radionuclides in air at a number of distances from the point of discharge. Deposition rates and activity concentrations of radionuclides on the ground surface, in soil and in crops, meat and milk are derived for each distance. These activity concentrations are used to calculate characteristic individual and collective doses due to inhalation of the plume, and due to external exposure from radionuclides in the plume and deposited on the ground. Consumption rates of terrestrial food for different geographical regions are used to calculate characteristic individual and collective doses from consumption of foods. Table A2 lists the equations that are implemented for discharges to an atmospheric environment that give rise to exposure through terrestrial pathways.

A5. *Discharges to a freshwater environment.* The workbook calculates activity concentrations of radionuclides in water for two sizes of river (the results for a large river are also applied for a lake). Concentration factors are used to derive activity concentrations in freshwater fish, and irrigation rates are used to calculate activity concentrations in irrigated crops. Activity concentrations of radionuclides in riverbank sediment are assumed to be the same as those in riverbed sediment. These values are used to derive characteristic individual and collective doses from consumption of irrigated foods and water

abstracted from the river, consumption of fish caught from the river and individual doses from external exposure to radioactive material in riverbank sediments. Table A3 lists the equations implemented for discharges to a freshwater environment.

A6. *Discharges to a marine environment.* The workbook is based on the assumption that radionuclides are discharged to a relatively small, local compartment and water in the local compartment is exchanged with that in a larger, regional compartment. Activity concentrations in water are calculated for each compartment, and activity concentrations in fish, crustaceans, molluscs and beach sediment are derived. The workbook calculates individual doses from external exposure to beach sediment, and individual and collective doses from consumption of shellfish harvested in the local compartment and consumption of fish caught in both compartments. Table A4 lists the relevant equations for discharges to a marine environment.

A7. *Summary workbook.* This is linked to the above workbooks for each environment into which a discharge is made and, for this reason, must be saved in the same electronic folder as them. It presents characteristic individual and collective doses for each geographical region from discharges to atmospheric, freshwater and marine environments. The doses from discharges of radionuclides with very short-lived progeny (e.g. ^{137}Cs and ^{137m}Ba) include the contributions from radioactive progeny. In other cases (i.e. radionuclides with longer-lived progeny), the contribution from the progeny are considered separately (see section II below). If the degree of equilibrium between different members of the radionuclide chain is significantly different from that assumed here, then the doses from the parent and progeny have to be summed once the activity of radionuclides in the discharge and the degree of equilibrium are specified.

A8. *Globally circulating radionuclides.* The final workbook includes calculation factors for collective doses from the global circulation of the relevant radionuclides for 100, 500 and 10,000 years following unit discharge. These factors have been derived using the PC-CREAM 08 computer system [S8], which implements each of the global circulation models adopted by the Committee.

A9. The results can be scaled by the actual rates of discharge of each radionuclide from a particular site and then summed over all relevant radionuclides to give the overall characteristic individual and collective doses. Results are produced for sites located in different regions of the world, with additional results for coastal and inland nuclear sites and sites situated in areas of low population density.

II. TREATMENT OF RADIOACTIVE PROGENY

A10. For most radionuclides the workbooks for atmospheric, freshwater and marine environments provide the relevant dose factors separately for the parent and any progeny. (This permits the workbooks to be used when non-equilibrium conditions apply). Tables A5, A6 and A7 contain further details on how dose contributions from radioactive progeny have been treated for terrestrial, freshwater and marine pathways respectively, following the general principles outlined in section II.D.2. The summary workbook contains summed values based on the assumptions detailed in those tables. However, for radionuclides that are in secular equilibrium with their short-lived progeny, the doses presented and clearly marked in the workbooks are the sums of the doses from the parent and progeny.

III. QUALITY ASSURANCE

A11. A systematic review of the completed workbooks was carried out for quality assurance purposes, firstly by the workbook developers and then by independent reviewers. This included a comparison of the parameter values and variables with source data, and the workbook equations with the agreed calculation methodology, defined by the lists of equations and data presented below in tables A2-A4. This ensured that the workbooks had implemented the methodology agreed by the Committee.

A12. As further verification, a workbook was created that compared a sample of the results of the workbooks with those published in the UNSCEAR 2000 Report [U6]. The results are discussed in detail in electronic attachment 1.

TABLES

Table A1. Summary of end points, populations and pathways considered

(a) Characteristic individual dose

End point/pathway	*Key features of methodology*	*Integration considerations*
DISCHARGE TO ATMOSPHERE		
Characteristic individual dose	Total dose from all exposure pathways assuming location 5 km distant from site of discharge	Time integration: 100 years Individual dose in 100th year following 100 years continuous discharge
External irradiation (beta + gamma radiation from plume, and gamma radiation from deposited radionuclides)	Activity concentrations of radionuclides in plume derived using approach in [U6] Time-integrated activity concentrations in soil from [S8] Dose factors (table A3 below)	
Inhalation	Activity concentrations of radionuclides in plume derived using approach in [U6]	
Ingestion of terrestrial foods	Activity concentrations of radionuclides in terrestrial foods per unit deposition rate from [S8] Approaches for ^{14}C and ^{3}H based on [I5]	
DISCHARGE TO FRESHWATER ENVIRONMENT		
Characteristic individual dose	Total dose from all exposure pathways assuming complete instantaneous mixing For two situations: discharge into large and small rivers (for nuclear and mines/non-nuclear discharges, respectively)	Time integration: 100 years Individual dose in 100th year following 100 years continuous discharge
External irradiation from occupancy on freshwater sediments	Time-integrated activity concentrations of radionuclides in sediment from [S8] 5 km distant from discharge point	
Drinking water	Ingestion rate from [U6]	
Fish ingestion	Region-specific consumption rates from [F3]	
Ingestion of irrigated terrestrial foods	Deposition rate related to generic irrigation rate and growing period appropriate for grain [W2] Approaches for ^{14}C and ^{3}H derived from [C1]	
DISCHARGE TO MARINE ENVIRONMENT		
Characteristic individual dose	Total dose from exposure pathways calculated using a two-compartment model Activity concentrations of radionuclides in seawater in local marine compartment	Time integration: 100 years Individual dose in 100th year following 100 years continuous discharge
External irradiation from occupancy on marine sediments	Time-integrated activity concentrations of radionuclides in sediments within the local marine box [S8]	
Ingestion of marine foods (fish, crustaceans and molluscs)	Ingestion of crustaceans and molluscs from the local compartment (25%) and regional compartment (75%)	

(b) Collective dose

Component	*Key features of methodology*	*Integration considerations*
DISCHARGE TO ATMOSPHERE		
Local component	Based on individual dose at midpoint and number of people in annuli around discharge point derived from population density information from [F1] for nuclear sites or using a population density of 5 km^{-2} for sites in areas of low population (see electronic attachment 3)	Time integration: 100 years Distance integration: using activity concentrations of radionuclides and individual doses at centre point of annular area, 0–100 km
Regional component	Based on individual dose and number of people in annuli around discharge point for nuclear sites (see electronic attachment 3) or derived from weighted population density information from [F1]	Time integration: 100 years, 500 years Distance integration: using activity concentrations of radionuclides and individual doses at centre point of following annular areas: 100–500, 500–1 000 and 1 000–1 500 km For discharge continuing for 100 years and integration times of 100 years
Global component	Based on collective dose from globally dispersed radionuclides [S8], which implements models referred to in [U6]	Time integration: 100 years, 500 years and 10 000 years
DISCHARGE TO FRESHWATER ENVIRONMENT		
Local and regional components from freshwater pathways (external irradiation from exposure on freshwater sediment not included)	Based on total collective intakes from abstraction of drinking water and freshwater fish-catch data from specified lengths of small and large rivers Consumption of irrigated terrestrial foods based on generalized yield data and areas of land equipped for irrigation as function of region (from [F1])	Time integration: 100 years
Global component	Based on collective dose from globally dispersed radionuclides [S8], which implements models referred to in [U6]	
DISCHARGE TO MARINE ENVIRONMENT		
Regional component (External exposure on marine sediment not included)	Based on total collective intake from seafood-catch data derived from the representative regional marine compartment	Time integration: 100 years
Global component	Based on collective dose from globally dispersed radionuclides [S8], which implements models referred to in [U6]	

Table A2. Parameter and equation list: Atmospheric discharge and terrestrial environment

Parameter	*Symbol*	*Value*	*Units*	*Reference*
ATMOSPHERIC DISPERSION				
Activity concentration in air at a specified distance calculated using: $C_{\mathrm{air},i}(x) = D_1 \cdot Q \cdot x^{-n} e^{-\lambda_i x/u_a}$ (T1)				
Activity concentration of radionuclide, i, in air at distance, x, from discharge point	$C_{\mathrm{air},i}(x)$	Equation (T1)	Bq/m^3	—
Dilution factor at 1 km	D_1	5.3×10^{-7}	s/m^3	[U6]
Discharge rate	Q	Unit discharge rate = 1	Bq/s	—
Downwind distance from discharge point	x	5, 50, 300, 750, 1 250	km	—
Empirical index	n	Noble gases, tritium: 1.2 ^{14}C: 1.4 All others: 1.42	—	[U6]
Radioactive decay constant of radionuclide, i	λ_i	Radionuclide-specific	s^{-1}	[I9]
Geometric mean of wind speed at the height of release representative of one year	u_a	2×10^{-3}	km/s	[I2]
Activity concentration in air of ^{135}Cs (progeny of ^{135}Xe) and ^{138}Cs (progeny of ^{138}Xe) calculated using: $C_{air,progeny}(x) = C_{air,parent}(x) \frac{\lambda_{\mathrm{progeny}}}{\lambda_{\mathrm{progeny}} - \lambda_{\mathrm{parent}}} \left(1 - e^{-(\lambda_{\mathrm{progeny}} - \lambda_{\mathrm{parent}})\left(\frac{x}{u_a}\right)}\right)$ (T2) (note this equation is valid for one progeny and does not include a branching fraction)				
Activity concentration of progeny in air at distance, x, from discharge point	$C_{\mathrm{air,progeny}}(x)$	Equation (T2)	Bq/m^3	—
Activity concentration of parent in air at distance, x, from discharge point	$C_{\mathrm{air,parent}}(x)$	Equation (T1)	Bq/m^3	—
Radioactive decay constant of parent/progeny	$\lambda_{\mathrm{parent}}$, $\lambda_{\mathrm{progeny}}$	Radionuclide-specific	s^{-1}	[I9]
Downwind distance from discharge point	x	5, 50, 300, 750, 1 250	km	—
Geometric mean of wind speed at the height of release representative of one year	u_a	2×10^{-3}	km/s	[I2]
Deposition rate at a specified distance calculated using: $\dot{d}_i(x) = V_T C_{\mathrm{air},i}(x)$ (T3)				
Total daily-average deposition rate at distance, x, of radionuclide, i, from both wet and dry processes	$\dot{d}_i(x)$	Equation (T3)	Bq/(m^2 s)	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Total deposition velocity (wet and dry)	V_T	Noble and non-reactive gases: 0 Tritium: 0 ^{14}C: 0 All others: 0.002	m/s	[U6]
Activity concentration of radionuclide, i, in air at distance, x, from discharge point	$C_{\text{air},i}(x)$	Equations (T1), (T2)	Bq/m^3	—
ENVIRONMENTAL TRANSFER				
Activity concentration in terrestrial food calculated using: $C_{f,i}(x) = C_{f,\text{unit},i}\,\dot{d}_i(x)$ (T4)				
Activity concentration of radionuclide, i, in terrestrial food, f, at distance, x, from discharge point	$C_{f,i}(x)$	Equation (T4)	Bq/kg or Bq/L	—
Activity concentration of radionuclide, i, in year 100 in terrestrial food, f, per unit deposition rate for continuous deposition	$C_{f,\text{unit},i}$	PC-CREAM output [S8]	Bq/kg per Bq/(m^2 s) or Bq/L per Bq/(m^2 s)	—
Total daily average deposition rate at distance, x, of radionuclide, i, from both wet and dry processes	$\dot{d}_i(x)$	Equation (T3)	Bq/(m^2 s)	—
^{14}C activity concentration in terrestrial food (cereal, vegetables and pasture) calculated using: $C_{f,^{14}C}(x) = C_{\text{air},^{14}C}(x) \cdot \frac{S_p}{S_{\text{air}}}$ (T5)				
Activity concentration of ^{14}C in food, and pasture, f, at distance, x, from discharge point	$C_{f,^{14}C}(x)$	Equation (T5)	Bq/kg	[I5]
Activity concentration of ^{14}C in air at distance, x, from discharge point	$C_{\text{air},^{14}C}(x)$	Equation (T1)	Bq/m^3	—
Concentration of stable carbon in the plant (fresh weight)	S_p	Cereal: 3.9×10^2 Vegetables: 30 Pasture: 1×10^2	g C/kg	[I5]
Concentration of stable carbon in air	S_{air}	0.2	g C/m^3	[I5]
^{14}C activity concentration in terrestrial food (animal products) calculated using: $C_{f,^{14}C}(x) = \frac{f_C \cdot C_{\text{pasture},^{14}C}(x) \cdot S_a}{S_p}$ (T6)				
Activity concentration of ^{14}C in food, f, at distance, x, from discharge point	$C_{f,^{14}C}(x)$	Equation (T6)	Bq/kg	[I5]
Fraction of animal feed that is contaminated	f_C	1	—	[I5]
Activity concentration of ^{14}C in pasture at distance, x, from discharge point	$C_{\text{pasture},^{14}C}(x)$	Equation (T5)	Bq/kg	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Concentration of stable carbon in the animal product (fresh weight)	S_a	Milk: 65 Beef: 200	g/kg	[I5]
Concentration of stable carbon in the plant (fresh weight)	S_p	Pasture: 1×10^2	g/kg	[I5]
Activity concentration of HTO in soil water calculated using: $$C_{\text{sw,HTO}}(x) = \frac{\text{CR}_{\text{s-a}} \cdot C_{\text{air,HTO}}(x)}{H_a}$$ (T7)				
Activity concentration of HTO in soil water at distance, x, from discharge point	$C_{\text{sw,HTO}}(x)$	Equation (T7)	Bq/L	[I5]
Empirical constant	$\text{CR}_{\text{s-a}}$	0.3	—	[I5]
Activity concentration of HTO in air at distance, x, from discharge point	$C_{\text{air,HTO}}(x)$	Equation (T1)	Bq/m³	—
Absolute humidity	H_a	6×10^{-3}	L/m³	[I5]
Calculated using: $$C_{f,\text{HTO}}(x) = \text{WC}_p \cdot \left[\text{RH} \frac{C_{\text{air,HTO}}(x)}{H_a} + (1 - \text{RH}) C_{\text{sw,HTO}}(x) \right] \Big/ \gamma$$ (T8)				
Activity concentration of HTO in food, f, at distance, x, from discharge point (fresh weight)	$C_{f,\text{HTO}}(x)$	Equation (T8)	Bq/kg	[I5]
Fractional water content of the plant (fresh weight)	WC_p	Cereal: 0.12 Vegetables: 0.92 Pasture: 0.76	L/kg	[I5]
Relative humidity	RH	0.7	—	[I4]
Activity concentration of HTO in air at distance, x, from discharge point	$C_{\text{air,HTO}}(x)$	Equation (T1)	Bq/m³	—
Absolute humidity	H_a	6×10^{-3}	L/m³	[I2]
Activity concentration of HTO in soil water at distance, x, from discharge point	$C_{\text{sw,HTO}}(x)$	Equation (T7)	Bq/L	[I5]
Ratio of HTO vapour pressure to H_2O vapour pressure	γ	0.909	—	[I5]
Weighted concentration of HTO in drinking water and feed calculated using: $$\text{CR}_{f,\text{HTO}}(x) = 0.5 \cdot C_{\text{sw,HTO}}(x) + 0.5 \cdot \frac{C_{\text{pasture,HTO}}(x)}{\text{WC}_p}$$ (T9)				
Weighted concentration of HTO in drinking water and of water in feed (assumes that 50% intake is drinking water and 50% is pasture)	$\text{CR}_{f,\text{HTO}}(x)$	Equation (T9)	Bq/L	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration of HTO in soil water at distance, *x*, from discharge point	$C_{\mathrm{sw,HTO}}(x)$	Equation (T7)	Bq/L	[I5]
Activity concentration of HTO in pasture at distance, *x*, from discharge point (fresh weight)	$C_{\mathrm{pasture,HTO}}(x)$	Equation (T8)	Bq/kg	[I5]
Fractional water content of the plant	WC_p	0.76	L/kg	[I5]
HTO activity concentration in terrestrial food (animal products) calculated using: $C_{f,\mathrm{HTO}}(x) = \mathrm{CR}_{a,\mathrm{HTO}} \cdot \mathrm{CR}_{f,\mathrm{HTO}}(x)$ (T10)				
Activity concentration of HTO in food, *f*, at distance, *x*, from discharge point	$C_{f,\mathrm{HTO}}(x)$	Equation (T10)	Bq/kg	[I5]
Concentration ratio: concentration of HTO in product (fresh weight) divided by concentration of HTO in water intake	$\mathrm{CR}_{a,\mathrm{HTO}}$	Milk: 0.87 Beef: 0.66	L/kg	[I5]
Weighted concentration of HTO in drinking water and of water in feed	$\mathrm{CR}_{f,\mathrm{HTO}}(x)$	Equation (T9)	Bq/L	—
OBT activity concentration in terrestrial food (cereal, vegetables and pasture) calculated using: $C_{f,\mathrm{OBT}}(x) = (1-\mathrm{WC}_p) \cdot \frac{\mathrm{WEQ}_p \cdot R_p \cdot C_{f,\mathrm{HTO}}(x)}{\mathrm{WC}_p}$ (T11)				
Activity concentration of OBT in food, *f*, at distance, *x*, from discharge point	$C_{f,\mathrm{OBT}}(x)$	Equation (T11)	Bq/kg	[I5]
Fractional water content of the plant (fresh weight)	WC_p	Cereal: 0.12 Vegetables: 0.92 Pasture: 0.76	L/kg	[I5]
Water equivalent factor	WEQ_p	Cereal: 0.56 Vegetables: 0.51 Pasture: 0.56	L/kg	[I5]
Partition factor	R_p	0.54	—	[I5]
Activity concentration of HTO in food, *f*, at distance, *x*, from discharge point	$C_{f,\mathrm{HTO}}(x)$	Equation (T8)	Bq/kg	[I5]
OBT activity concentration in terrestrial food (animal products) $C_{f,\mathrm{OBT}}(x) = \mathrm{CR}_{a,\mathrm{OBT}} \cdot C_{\mathrm{pasture,OBT}}(x)$ (T12)				
Activity concentration of OBT in food, *f*, at distance, *x*, from discharge point	$C_{f,\mathrm{OBT}}(x)$	Equation (T12)	Bq/kg	[I5]
Concentration ratio: concentration of OBT in milk (fresh weight) divided by concentration of OBT in intake (dry weight)	$\mathrm{CR}_{a,\mathrm{OBT}}$	Milk: 0.24 Beef: 0.40	kg/L	[I5]
Mean concentration of OBT in feed	$C_{\mathrm{pasture,OBT}}(x)$	Equation (T11)	Bq/kg	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
INDIVIDUAL DOSE CALCULATIONS				
Effective dose from inhalation at a specified distance calculated using: $$H_{E(\text{inh}),i}(x) = C_{\text{air},i}(x) \cdot D_{\text{inh},i} \cdot \frac{I_{\text{inh}}}{86\,400} \cdot O_{\text{ann}} \quad \text{(T13)}$$				
Effective dose from inhalation of radionuclide, i, at distance, x, from discharge point	$H_{E(\text{inh}),i}(x)$	Equation (T13)	Sv	—
Activity concentration of radionuclide, i, in air at distance, x, from discharge point	$C_{\text{air},i}(x)$	Equation (T1)	Bq/m^3	—
Dose coefficient for inhalation of radionuclide, i, (see equation (T14) for calculation of dose coefficient for ^{222}Rn plus short-lived progeny)	$D_{\text{inh},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Adult inhalation rate	I_{inh}	20	m^3/d	[U6]
Conversion factor		86 400	s/d	—
Annual occupancy at location	O_{ann}	3.15×10^7 (rounded)	s	—
Dose coefficient for inhalation of radon and its short-lived progeny calculated using: $$D_{\text{inh},^{222}\text{Rn}} = 24 \cdot \frac{\text{DC}_{^{222}\text{Rn}}\left(\text{EF}_{^{222}\text{Rn,in}} \cdot O_{^{222}\text{Rn,in}} + \text{EF}_{^{222}\text{Rn,out}} \cdot O_{^{222}\text{Rn,out}}\right)}{I_{\text{inh}}} \quad \text{(T14)}$$				
Dose coefficient for inhalation of ^{222}Rn plus short-lived progeny	$D_{\text{inh},^{222}\text{Rn}}$	Equation (T14)	Sv/Bq	[U6]
Conversion factor		24	h/d	—
Dose conversion factor for radon	$\text{DC}_{^{222}\text{Rn}}$	9×10^{-9}	Sv per (Bq h/m^3)	[U6]
Indoor equilibrium factor for radon	$\text{EF}_{^{222}\text{Rn,in}}$	0.4	—	[U6]
Indoor occupancy factor	$O_{^{222}\text{Rn,in}}$	0.8	—	[U6]
Outdoor equilibrium factor for radon	$\text{EF}_{^{222}\text{Rn,out}}$	0.6	—	[U6]
Outdoor occupancy factor	$O_{^{222}\text{Rn,out}}$	0.2	—	[U6]
Adult inhalation rate	I_{inh}	20	m^3/d	[U6]
Dose from external exposure from immersion in the plume at a specified distance calculated using: $$H_{E(\text{ex,cloud}),i}(x) = C_{\text{air},i}(x) \cdot D_{\text{ex,cloud},i} \cdot O_{\text{ann}} \cdot \left(O_{\text{out}} + (1 - O_{\text{out}}) L_{\text{cloud}}\right) \quad \text{(T15)}$$				
Effective gamma dose from external exposure to radionuclide, i, at distance, x, from discharge point	$H_{E(\text{ex,cloud}),i}(x)$	Equation (T15)	Sv	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration of radionuclide, i, in air at distance, x, from discharge point	$C_{\text{air},i}(x)$	Equation (T1)	Bq/m^3	—
External dose coefficient for immersion in the plume	$D_{\text{ex,cloud},i}$	Dependent on radionuclide	Sv per (Bq s/m^3)	[E2, P2]
Annual occupancy at location	O_{ann}	3.15×10^7 (rounded)	s	—
Fraction of occupancy that is outdoors	O_{out}	0.2	—	[U4]
Building shielding factor in plume (location factor)	L_{cloud}	0.2	—	
Dose from external exposure from deposits calculated using: $$H_{E(\text{ex,deposit}),i}(x) = \dot{d}_i(x) \cdot t_{\text{discharge}} \cdot D_{\text{ex,deposit},i} \cdot \left(O_{\text{out}} + (1 - O_{\text{out}}) L_{\text{deposit}}\right) \quad \text{(T16)}$$				
Annual effective dose from the deposited radionuclide, i, at distance, x, from discharge point	$H_{E(\text{ex,deposit}),i}(x)$	Equation (T16)	Sv	—
Total daily average deposition rate at distance, x, of radionuclide, i, from both wet and dry processes	$\dot{d}_i(x)$	Equation (T3)	Bq s/m^2	—
Duration of deposition	$t_{\text{discharge}}$	3.15×10^7 (rounded)	s	1 year
Dose coefficient for external exposure from deposited material, integrated to 100 years (time dependence taken into account using equation given by [G2])	$D_{\text{ex,deposit},i}$	Dependent on radionuclide	Sv per (Bq/m^2)	[E2, P2]
Fraction of occupancy that is outdoors	O_{out}	0.2	—	[U4]
Building shielding factor from deposited material (location factor)	L_{deposit}	0.1	—	
Effective dose from ingestion calculated using: $$H_{E(\text{ing}),f,r,i}(x) = C_{f,i}(x) \cdot D_{\text{ing},i} \cdot F_{\text{local}} \cdot I_{f,r} \quad \text{(T17)}$$				
Annual effective dose from the ingestion of food, f, containing radionuclide, i, at distance, x, from discharge point in region r	$H_{E(\text{ing}),f,r,i}(x)$	Equation (T17)	Sv	—
Activity concentration of radionuclide, i, in terrestrial food, f, at distance, x, from discharge point	$C_{f,i}(x)$	Equations (T4), (T5), (T6), (T8), (T10), (T11), (T12)	Bq/kg or Bq/L	—
Dose coefficient for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Fraction of food that is locally produced	F_{local}	Individual dose: 0.25 Collective dose: 1.0	—	
Amount of food, f, ingested per caput in a year in region, r	$I_{f,r}$	Dependent on region and food	kg or L	[W2]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Total effective dose from ingestion calculated using: $$H_{E(\text{ing}),r,i}(x)=\sum_f H_{E(\text{ing}),f,r,i}(x)$$ (T18)				
Total annual effective dose in region, r, from ingestion of radionuclide, i, in food at distance, x, from discharge point	$H_{E(\text{ing}),r,i}(x)$	Equation (T18)	Sv	—
Annual effective dose from ingestion of food, f, containing radionuclide, i, at distance, x, from discharge point in region, r	$H_{E(\text{ing}),f,r,i}(x)$	Equation (T17)	Sv	—
Total individual effective dose calculated using: $$H_{E(\text{atmos}),r,i}(x)=H_{E(\text{inh}),i}(x)+H_{E(\text{ex,cloud}),i}(x)+H_{E(\text{ex,deposit}),i}(x)+H_{E(\text{ing}),r,i}(x)$$ (T19)				
Total effective dose in region, r, from radionuclide, i, at distance, x, from discharge point	$H_{E(\text{atmos}),r,i}(x)$	Equation (T19)	Sv	—
Effective dose from inhalation of radionuclide, i, at distance, x, from discharge point	$H_{E(\text{inh}),i}(x)$	Equation (T13)	Sv	—
Effective dose from external exposure to radionuclide, i, at distance, x, from discharge point	$H_{E(\text{ex,cloud}),i}(x)$	Equation (T15)	Sv	—
Effective dose from the deposited radionuclide, i, at distance, x, from discharge point	$H_{E(\text{ex,deposit}),i}(x)$	Equation (T16)	Sv	—
Total effective dose in region, r, from ingestion of radionuclide, i, in food at distance, x, from discharge point	$H_{E(\text{ing}),r,i}(x)$	Equation (T18)	Sv	—
COLLECTIVE DOSE CALCULATIONS				
Collective effective dose calculated using: $$S_{E(\text{atmos}),r,i}(x_k,x_{k+1})=N_r(x_k,x_{k+1})\cdot H_{E(\text{atmos}),r,i}(x)$$ (T20)				
Collective effective dose in region, r, in the annulus limited by x_k and x_{k+1}	$S_{E(\text{atmos}),r,i}(x_k,x_{k+1})$	Equation (T20)	man Sv	—
Total population in region, r, in the annulus limited by x_k and x_{k+1}	$N_r(x_k,x_{k+1})$	Dependent on region		see electronic attachment 3 and [F1]
Annular distances (the outer distance for each annuli)	(x_1,x_2,x_3,x_4,x_5)	$\{0,100,500,1\,000,1\,500\}$	km	—
Total effective dose from radionuclide, i, at distance, x, from discharge point where x is the midpoint between x_k and x_{k+1}	$H_{E(\text{atmos}),r,i}(x)$	Equation (T19)	Sv	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Local collective effective dose calculated using: $$S_{E(\text{atmos}),r,i}(\text{local}) = \sum_{k=1}^{2} S_{E(\text{atmos}),r,i}(x_k, x_{k+1})$$ (T21)				
Local (0 km to 100 km) collective effective dose in region, r, from radionuclide, i	$S_{E(\text{atmos}),r,i}(\text{local})$	Equation (T21)	man Sv	—
Total annual collective effective dose in region, r, from radionuclide, i, in the annulus limited by x_k and x_{k+1}	$S_{E(\text{atmos}),r,i}(x_k, x_{k+1})$	Equation (T20)	man Sv	—
Regional component of collective effective dose $$S_{E(\text{atmos}),r,i}(\text{regional}) = \sum_{k=3}^{5} S_{E(\text{atmos}),r,i}(x_k, x_{k+1})$$ (T22)				
Regional component (100 km to 1500 km) of collective effective dose in region, r, from radionuclide, i	$S_{E(\text{atmos}),r,i}(\text{regiona}$	Equation (T21)	man Sv	—
Total annual collective effective dose in region, r, from radionuclide, i, in the annulus limited by x_k and x_{k+1}	$S_{E(\text{atmos}),r,i}(x_k, x_{k+1}$	Equation (T20)	man Sv	—
GLOBAL DISPERSION				
Collective doses from tritium, ^{14}C, ^{85}Kr and ^{129}I were calculated by PC-CREAM (incorporates global dispersion models referenced in [U6])				

Table A3. Parameter and equation list: Freshwater environment

Parameter	*Symbol*	*Value*	*Units*	*Reference*
FRESHWATER DISPERSION				
Activity concentration in unfiltered water calculated using: $$C_{\mathrm{uw},s} = \frac{Q}{F_{\mathrm{river},s}}$$ (F1)				
Activity concentration in unfiltered water	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—
Annual discharge rate of radionuclide, i	Q	1	Bq/s	—
Volumetric flow rate of river of size, s	$F_{\mathrm{river},s}$	Large: 1 000 Small: 10	m^3/s	—
Activity concentration in filtered water calculated using: $$C_{\mathrm{fw},s,i} = \frac{C_{\mathrm{uw},s}}{1 + K_{d,i} \cdot \alpha_s}$$ (F2)				
Activity concentration of radionuclide, i, in filtered water from river of size, s	$C_{\mathrm{fw},s,i}$	Equation (F2)	Bq/m^3	—
Activity concentration in unfiltered water	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—
Sediment–water distribution factor	$K_{d,i}$	Dependent on element	m^3/t	[I2, I5]
Suspended sediment load in river of size, s	α_s	Large: 5×10^{-4} Small: 2×10^{-5}	t/m^3	[O1]
ENVIRONMENTAL TRANSFERS				
Activity concentrations in freshwater fish calculated using: $$C_{\mathrm{fish},s,i} = \frac{C_{\mathrm{fw},s,i} \cdot B_{\mathrm{fish},i}}{1\,000}$$ (F3)				
Activity concentration of radionuclide, i, in freshwater fish	$C_{\mathrm{fish},s,i}$	Equation (F3)	Bq/kg	—
Activity concentration of radionuclide, i, in filtered water from river of size, s	$C_{\mathrm{fw},s,i}$	Equation (F2)	Bq/m^3	—
Concentration factor for freshwater fish (fresh weight)	$B_{\mathrm{fish},i}$	Dependent on food and element	Bq/kg per Bq/L	[I5]
Conversion factor		1 000	L/m^3	—
Activity concentration of HTO in fish calculated using: $$C_{\mathrm{fish},s,\mathrm{HTO}} = \frac{\mathrm{WC}_f \cdot C_{\mathrm{fw},s,\mathrm{HTO}}}{1\,000}$$ (F4)				
Activity concentration of HTO in freshwater fish	$C_{\mathrm{fish},s,\mathrm{HTO}}$	Equation (F4)	Bq/kg	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Fractional water content of fish (fresh weight)	WC_f	0.78	L/kg	[I5]
Activity concentration of HTO in filtered water from river of size, *s*	$C_{\mathrm{fw},s,\mathrm{HTO}}$	Equation (F2)	Bq/m^3	—
Conversion factor		1 000	L/m^3	—
Activity concentration of OBT in fish calculated using: $$C_{\mathrm{fish},s,\mathrm{OBT}} = \frac{\left(1-\mathrm{WC}_f\right)\cdot \mathrm{WEQ}_f \cdot R_f \cdot C_{\mathrm{fw},s,\mathrm{HTO}}}{1\,000} \quad \text{(F5)}$$				
Activity concentration of OBT in freshwater fish	$C_{\mathrm{fish},s,\mathrm{OBT}}$	Equation (F5)	Bq/kg	—
Fractional water content of fish (fresh weight)	WC_f	0.78	L/kg	[I5]
Water equivalent factor for fish	WEQ_f	0.65	—	[I5]
Partition factor for fish (geometric mean, fresh weight)	R_f	6.6×10^{-4}	kg/kg	[I5]
Activity concentration of HTO in filtered water from river of size, *s*	$C_{\mathrm{fw},s,\mathrm{HTO}}$	Equation (F2)	Bq/m^3	—
Conversion factor		1 000	L/m^3	—
Activity concentrations of ^{14}C in fish calculated using: $$C_{\mathrm{fish},s,^{14}\mathrm{C}} = \frac{C_{\mathrm{fw},s,^{14}\mathrm{C}} \cdot B_{\mathrm{fish},^{14}\mathrm{C}}}{1\,000} \quad \text{(F6)}$$				
Activity concentration of ^{14}C in freshwater fish (adapted from Equation (F3))	$C_{\mathrm{fish},s,^{14}\mathrm{C}}$	Equation (F6)	Bq/kg	—
Activity concentration of ^{14}C in filtered water from river of size, s	$C_{\mathrm{fw},s,^{14}\mathrm{C}}$	Equation (F2)	Bq/m^3	—
Concentration factor for ^{14}C in freshwater fish	$B_{\mathrm{fish},^{14}\mathrm{C}}$	5×10^4	Bq/kg per Bq/L	[I5]
Conversion factor		1 000	L/m^3	—
Deposition rate from irrigation calculated using $$\dot{d}_{\mathrm{irr},s} = C_{\mathrm{uw},s} \cdot I_{\mathrm{irr}} \cdot F_{\mathrm{irr}} \quad \text{(F7)}$$				
Total daily average deposition rate of radionuclide, i, from irrigation	$\dot{d}_{\mathrm{irr},s}$	Equation (F7)	Bq/m^2	—
Average concentration of radionuclide, i, in river water used for irrigation	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—
Daily irrigation rate	I_{irr}	0.005	m^3/m^2	[N2]
Fraction of the year for which irrigation occurs	F_{irr}	$\frac{150}{365}$=0.41	—	[N2]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration in terrestrial food (cereals, vegetables) calculated using: $$C_{f,s,i} = \frac{C_{f,\text{unit},i} \cdot \dot{d}_{\text{irr},s}}{86\,400}$$ (F8)				
Activity concentration of radionuclide, i, in irrigated, terrestrial food, f	$C_{f,s,i}$	Equation (F8)	Bq/kg	—
Activity concentration of radionuclide, i, in terrestrial food, f, per unit deposition rate	$C_{f,\text{unit},i}$	PC-CREAM output	Bq/kg per Bq s/m^2	—
Total daily average deposition rate of radionuclide, i, from irrigation	$\dot{d}_{\text{irr},s}$	Equation (F7)	Bq/m^2	—
Conversion factor		86 400	s/d	—
Activity concentration of HTO in soil water calculated using: $$C_{\text{sw},s,\text{HTO}} = \frac{I_{\text{irr}} \cdot C_{\text{uw},s}}{P + 1\,000 \cdot I_{\text{irr}}}$$ (F9)				
Activity concentration of HTO in soil water irrigated from river of size, s	$C_{\text{sw},s,\text{HTO}}$	Equation (F9)	Bq/L	[I4]
Daily irrigation rate (averaged over 150-day growing season)	I_{irr}	0.005	m^3/m^2	[N2]
Average concentration of radionuclide, i, in river water used for irrigation	$C_{\text{uw},s}$	Equation (F1)	Bq/m^3	—
Daily precipitation rate (averaged over 150-day growing season)	P	5	L/m^2	[U6]
Conversion factor		1 000	L/m^3	—
HTO activity concentration in terrestrial food (cereals, vegetables) calculated using: $$C_{f,s,\text{HTO}} = \text{WC}_p \cdot \left[\text{RH} \cdot C_{\text{am}} + (1 - \text{RH}) \cdot C_{\text{sw},s,\text{HTO}}\right] / \gamma$$ (F10)				
Activity concentration of HTO in food, f	$C_{f,s,\text{HTO}}$	Equation (F10)	Bq/kg	[I5]
Fractional water content of the plant	WC_p	Cereal: 0.12 Vegetables: 0.92	L/kg	[I5]
Relative humidity	RH	0.7	—	[I4]
HTO concentration in air moisture	C_{am}	Assumed approximately equal to $C_{\text{sw},s,\text{HTO}}$	Bq/L	[I4]
Activity concentration of HTO in soil water	$C_{\text{sw},s,\text{HTO}}$	Equation (F9)	Bq/L	—
Ratio of HTO vapour pressure to H_2O vapour pressure	γ	0.909	—	[I5]
Activity concentration of OBT in terrestrial food (cereals, vegetables) calculated using: $$C_{f,s,\text{OBT}} = (1 - \text{WC}_p) \cdot \frac{\text{WEQ}_p \cdot R_p \cdot C_{f,s,\text{HTO}}}{\text{WC}_p}$$ (F11)				

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration of OBT in terrestrial food	$C_{f,s,\mathrm{OBT}}$	Equation (F11)	Bq/kg	—
Fractional water content of plant (fresh weight)	WC_p	Cereal: 0.12 Vegetables: 0.92	L/kg	[I5]
Water equivalent factor for plant	WEQ_p	Cereal: 0.56 Vegetables: 0.51	L/kg	[I5]
Partition factor	R_p	0.54	—	[I5]
Activity concentration of HTO in food, f	$C_{f,s,\mathrm{HTO}}$	Equation (F10)	Bq/kg	[I5]
Specific activity of ^{14}C in plant calculated using: $\mathrm{SA}_p = \mathrm{SA}_{\mathrm{air}} = \mathrm{CD}_c \cdot \frac{I_{\mathrm{irr}} \cdot C_{\mathrm{uw},s}}{F_c}$ (F12)				
Specific activity of ^{14}C in plant	SA_p	Equation (F12)	Bq/(g C)	[I4]
Specific activity of ^{14}C in air	SA_{air}	Equation (F12)	Bq/(g C)	[I4]
Canopy dilution factor	CD_c	0.15	—	[I4]
Daily irrigation rate (averaged over growing season)	I_{irr}	0.005	m^3/m^2	[N2]
Activity concentration of dissolved radionuclide i in unfiltered water	$C_{uw,s}$	Equation (F1)	Bq/m^3	—
Average production rate of carbon by decomposition of crop residues	F_c	0.66	$(g\ C)/m^2$	[I4]
^{14}C activity concentration in terrestrial food (cereals, vegetables) calculated using: $C_{f,s,^{14}\mathrm{C}} = \frac{C_{\mathrm{air},^{14}\mathrm{C}}}{S_{\mathrm{air}}} \cdot S_p = \mathrm{SA}_{\mathrm{air}} \cdot S_p$ (F13)				
^{14}C activity concentration in food, f, irrigated from river of size, s	$C_{f,s,^{14}\mathrm{C}}$	Equation (F13)	Bq/kg	[I4]
Specific activity of ^{14}C in air	SA_{air}	Equation (F12)	Bq/(g C)	[I4]
Concentration of stable carbon in the plant	S_p	Cereal: 3.9×10^2 Vegetables: 30	(g C)/kg	[I5]
INDIVIDUAL DOSE CALCULATIONS				
Individual dose from ingestion of drinking water calculated using $H_{E(\mathrm{water}),s,i} = C_{\mathrm{uw},s} \cdot D_{\mathrm{ing},i} \cdot I_{\mathrm{water}} \cdot F_{\mathrm{WT}} \cdot P_{\mathrm{river}}$ (F14)				
Annual effective dose from the ingestion of radionuclide, i, in drinking water	$H_{E(\mathrm{water}),s,i}$	Equation (F14)	Sv	—
Average activity concentration of radionuclide, i, in water assuming complete mixing	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Dose coefficient for ingestion of radionuclide, i	$D_{\text{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Amount of water ingested in one year	I_{water}	0.5	m^3	[U6]
Drinking water treatment removal factor	F_{WT}	Dependent on element	—	[B7]
Fraction of individual water intake from river	P_{river}	1	—	—
Dose from external exposure from freshwater sediments calculated using: $H_{E(\text{ex,riverbank}),s,i} = C_{\text{sed},s,i} \cdot \rho_{\text{sed}} \cdot t_{\text{sed}} \cdot F_{\text{geom}} \cdot D_{\text{ex,deposit}} \cdot O_{\text{riverbank}}$ (F15)				
Annual effective dose from radionuclide, i, from occupancy on river banks	$H_{E(\text{ex,riverbank}),s,i}$	Equation (F15)	Sv	—
Activity concentration of radionuclide, i, in freshwater riverbank sediment based on discharge rate of 1 Bq/s (assumed to be the same as bed sediment) (dry weight)	$C_{\text{sed},s,i}$	PC-CREAM output	Bq/kg	—
Density of riverbank sediment	ρ_{sed}	1 200	kg/m^3	[I2]
Thickness of riverbank sediment	t_{sed}	0.05	m	[I2]
Geometry factor for river banks for external dose coefficients	F_{geom}	0.2 (rounded)	—	[A2]
Integrated dose coefficient for irradiation from surface deposits	$D_{\text{ex,deposit}}$	Dependent on radionuclide	Sv/s per Bq/m^2	[E2]
River bank occupancy	$O_{\text{riverbank}}$	1.8×10^5 (50 hours)	s	Assumed value
Ingestion of freshwater fish $H_{E(\text{ing,fish}),s,r,i} = C_{\text{fish},s,i} \cdot D_{\text{ing},i} \cdot F_{\text{local}} \cdot I_{\text{fish},r}$ (F16)				
Annual effective dose from radionuclide, i, from ingestion of freshwater fish in region, r	$H_{E(\text{ing,fish}),s,r,i}$	Equation (F16)	Sv	—
Average activity concentration of radionuclide, i, in freshwater fish	$C_{\text{fish},s,i}$	Equations (F3), (F4), (F5), (F6)	Bq/kg	—
Dose coefficient for adults for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Fraction of food that is locally produced	F_{local}	0.25	—	See para.11 [U12]
Amount of freshwater fish ingested in a year in region, r	$I_{\text{fish},r}$	Dependent on region	kg	[F3]
Dose from ingestion of irrigated, terrestrial foods calculated using: $H_{E(\text{ing,irr}),f,s,r,i} = C_{f,s,i} \cdot D_{\text{ing},i} \cdot F_{\text{local}} \cdot F_{\text{spray},s,r} \cdot I_{f,r}$ (F17)				
Annual effective dose from the ingestion of irrigated, terrestrial food, f, containing radionuclide, i, in region, r	$H_{E(\text{ing,irr}),f,s,r,i}$	Equation (F17)	Sv	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration of radionuclide, i, in irrigated, terrestrial food, f	$C_{f,s,i}$	Equations (F8), (F10), (F11), (F13)	Bq/kg	—
Adult dose coefficient for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Fraction of food that is locally produced	F_{local}	0.25	—	See para.11 [U12]
Fraction of food that is spray irrigated	$F_{\text{spray},s,r}$	Small rivers: 0 Large rivers: dependent on region	—	[I7]
Amount of food, f, ingested in a year in region, r	$I_{f,r}$	Dependent on region and food	kg	[W2]
Total effective dose from ingestion of irrigated, terrestrial foods calculated using: $H_{E(\text{ing,irr}),s,r,i} = \sum_f H_{E(\text{ing,irr}),f,s,r,i}$ (F18)				
Total effective dose in region, r, from ingestion of irrigated, terrestrial food containing radionuclide, i	$H_{E(\text{ing,irr}),s,r,i}$	Equation (F18)	Sv	—
Annual effective dose from the ingestion of irrigated, terrestrial food, f, containing radionuclide i in region, r	$H_{E(\text{ing,irr}),f,s,r,i}$	Equation (F17)	Sv	—
Total individual dose from freshwater pathways calculated using: $H_{E(\text{fw}),s,r,i} = H_{E(\text{water}),s,i} + H_{E(\text{ex,riverbank}),s,i} + H_{E(\text{fish}),s,r,i} + H_{E(\text{ing,irr}),s,r,i}$ (F19)				
Total individual dose from freshwater pathways	$H_{E(\text{fw}),s,r,i}$	Equation (F19)	Sv	—
Annual effective dose from the ingestion of radionuclide, i, in drinking water	$H_{E(\text{water}),s,i}$	Equation (F14)	Sv	—
Annual effective dose from radionuclide, i, from occupancy on river banks	$H_{E(\text{ex,riverbank}),s,i}$	Equation (F15)	Sv	—
Annual effective dose from radionuclide, i, from ingestion of freshwater fish in region, r	$H_{E(\text{fish}),s,r,i}$	Equation (F16)	Sv	—
Total effective dose in region, r, from ingestion of irrigated, terrestrial food containing radionuclide, i	$H_{E(\text{ing,irr}),s,r,i}$	Equation (F18)	Sv	—
COLLECTIVE DOSE CALCULATIONS				
Volumetric abstraction rate of water calculated using: $V_{\text{irr,surface},s,r} = F_{\text{river},s} \cdot F_{\text{irr,surface},r}$ (F20)				
Volumetric abstraction rate of surface water from river of size, s, in region, r	$V_{\text{irr,surface},s,r}$	Equation (F20)	m^3/s	—
Volumetric flow rate of river of size, s	$F_{\text{river},s}$	Large: 1 000 Small: 10	m^3/s	—
Fraction of surface water withdrawn for irrigation in region, r	$F_{\text{irr,surface},r}$	Dependent on region	m^2 a/m^3	[F4]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Area irrigated by abstracted water calculated using: $$A_{\mathrm{irr,surface},s,r} = 3.15\times10^{7}\cdot A_{\mathrm{irr,unit},r}\cdot V_{\mathrm{irr,surface},s,r}$$ (F21)				
Area irrigated by water abstracted from river of size, s, in region, r	$A_{\mathrm{irr,surface},s,r}$	Equation (F21)	m^2	—
Area irrigated per unit volume water withdrawn in a year in region, r	$A_{\mathrm{irr,unit},r}$	Dependent on region	m^2 a/m^3	[F4]
Volumetric abstraction rate of surface water from river of size, s, in region, r	$V_{\mathrm{irr,surface},s,r}$	Equation (F20)	m^3/s	—
Conversion factor		3.15×10^7 (rounded)	s/a	
Irrigation rate calculated using: $$\dot{d}_{\mathrm{irr,surface},s,r} = \frac{C_{\mathrm{uw},s}\cdot V_{\mathrm{irr,surface},s,r}}{A_{\mathrm{irr,surface},s,r}}$$ (F22)				
Irrigation rate, assumed to be the same volume of water with the same activity concentration abstracted from river of size, s, in region, r	$\dot{d}_{\mathrm{irr,surface},s,r}$	Equation (F22)	Bq s/m^2	—
Activity concentration in unfiltered water	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—
Volumetric abstraction rate of surface water from river of size, s, in region, r	$V_{\mathrm{irr,surface},s,r}$	Equation (F20)	m^3/s	—
Area irrigated by water abstracted from river of size, s, in region, r	$A_{\mathrm{irr,surface},s,r}$	Equation (F21)	m^2	—
Activity concentration in irrigated, terrestrial foods calculated using: $$C_{\mathrm{cereal},s,r,i} = C_{\mathrm{cereal,unit},i}\cdot\dot{d}_{\mathrm{irr,surface},s,r}$$ (F23)				
Activity concentration of radionuclide, i, in terrestrial food (represented by cereal) irrigated from river of size, s, in region, r	$C_{\mathrm{cereal},s,r,i}$	Equation (F23)	Bq/kg	—
Activity concentration of radionuclide, i, in terrestrial food, f, per unit deposition rate	$C_{\mathrm{cereal,unit},i}$	PC-CREAM output	Bq/kg per Bq s/m^2	
Irrigation rate	$\dot{d}_{\mathrm{irr,surface},s,r}$	Equation (F22)	Bq s/m^2	—
Activity concentration of ^{14}C in cereals calculated using: $$C_{\mathrm{cereal},s,r,^{14}\mathrm{C}} = \frac{C_{\mathrm{air},^{14}\mathrm{C}}}{S_{\mathrm{air}}}\cdot S_p = \mathrm{SA}_{\mathrm{air}} = \mathrm{CD}_c\cdot\frac{C_{\mathrm{uw},s}}{365\cdot A_{\mathrm{irr,unit},r}\cdot F_c}\cdot S_p$$ (F24)				
Activity concentration of ^{14}C in food, f, irrigated from river of size, s	$C_{\mathrm{cereal},s,r,^{14}\mathrm{C}}$	Equation (F24)	Bq/kg	Equations (F13) & (F12)
Canopy dilution factor	CD_c	0.15	—	[I4]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration in unfiltered water	$C_{\mathrm{uw},s}$	Equation (F1)	Bq/m^3	—
Area irrigated per unit volume in region, r	$A_{\mathrm{irr,unit},r}$	Dependent on region	m^2 a/m^3	[F4]
Average daily production rate of carbon by decomposition of crop residues	F_c	0.66	(g C)/m^2	[I4]
Concentration of stable carbon in the plant	S_p	3.9×10^2	(g C)/kg	[I5]
Conversion factor		365	d/a	—
Collective dose from ingestion of irrigated, terrestrial food calculated using: $S_{E(\mathrm{ing,irr}),s,r,i} = C_{\mathrm{cereal},s,r,i} \cdot Y_{\mathrm{cereal},r} \cdot F_{\mathrm{spray},s,r} \cdot A_{\mathrm{irr,surface},s,r} \cdot D_{\mathrm{ing},i}$ (F25)				
Collective dose from consumption of food (represented by major food group, cereal) in region, r	$S_{E(\mathrm{ing,irr}),s,r,i}$	Equation (F25)	man Sv	—
Activity concentration of radionuclide, i, in terrestrial food (represented by cereal) irrigated from river of size, s, in region, r	$C_{\mathrm{cereal},s,r,i}$	Equations (F23), (F10), (F11), (F24)	Bq/kg	—
Yield per unit area of cereal in region, r	$Y_{\mathrm{cereal},r}$	Dependent on region	kg/m^3	[F1]
Fraction of food that is spray irrigated	$F_{\mathrm{spray},s,r}$	Small rivers: 0 Large rivers: dependent on region	—	[I7]
Area irrigated by water abstracted from river of size, s, in region, r	$A_{\mathrm{irr,surface},s,r}$	Equation (F21)	m^2	—
Adult dose coefficient for ingestion	$D_{\mathrm{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Collective dose from drinking water calculated using: $S_{E(\mathrm{water}),s,i} = C_{\mathrm{uw},i} \cdot D_{\mathrm{ing},i} \cdot F_{\mathrm{river},s} \cdot T_{\mathrm{dw}} \cdot A_{\mathrm{mun}} \cdot F_{\mathrm{dw}} \cdot F_{\mathrm{WT}}$ (F26)				
Collective dose from drinking water for river of size, s	$S_{E(\mathrm{water}),s,i}$	Equation (F26)	man Sv	—
Activity concentration of dissolved radionuclide, i, in unfiltered water	$C_{\mathrm{uw},i}$	Equation (F1)	Bq/m^3	—
Dose coefficient for ingestion of radionuclide, i	$D_{\mathrm{ing},i}$	Dependent on radionuclide	Sv/ q	[I14]
Volumetric flow rate of river of size, s	$F_{\mathrm{river},s}$	Large: 1 000 Small: 10	m^3/s	—
Duration of abstraction	T_{dw}	3.15×10^7 (rounded)	S	—
Abstraction fraction for municipal water	A_{mun}	0.01	—	—
Fraction of municipal water that is drunk	F_{dw}	0.01	—	—
Drinking water treatment removal factor	F_{WT}	Dependent on element	—	[B7]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Collective dose from freshwater fish ingestion calculated using: $S_{E(\text{ing,fish}),s,i} = C_{\text{fish},s,i} \cdot D_{\text{ing},i} \cdot Y_{\text{fish},s} \cdot L_{\text{river},s}$ (F27)				
Collective dose from ingestion of freshwater fish from river of size, s	$S_{E(\text{ing,fish}),s,i}$	Equation (F27)	man Sv	—
Activity concentration of radionuclide, i, in filtered water from river of size, s	$C_{\text{fish},s,i}$	Equations (F3), (F4), (F5), (F6)	Bq/m^3	—
Dose coefficient for ingestion of radionuclide, i	$D_{\text{ing},i}$	Dependent on radionuclide	Sv/Bq	[I14]
Representative freshwater fish catch in river of size, s	$Y_{\text{fish},s}$	Large: 10^4 Small: 10^3	kg/km	[F1]
Length of river of size, s	$L_{\text{river},s}$	Large: 5×10^2 Small: 1×10^2	km	[I2]
Total collective dose from all freshwater pathways calculated using: $S_{E(\text{fw}),s,r,i} = S_{E(\text{ing,irr}),s,r,i} + S_{E(\text{water}),s,i} + S_{E(\text{ing,fish}),s,i}$ (F28)				
Total collective dose in region, r, from discharges into river of size, s	$S_{E(\text{fw}),s,r,i}$	Equation (F28)	man Sv	—
Collective dose from consumption of food (represented by major food group, cereal) in region, r	$S_{E(\text{ing,irr}),s,r,i}$	Equation (F25)	man Sv	—
Collective dose from drinking water for river of size, s	$S_{E(\text{water}),s,i}$	Equation (F26)	man Sv	—
Collective dose from ingestion of freshwater fish of size, s	$S_{E(\text{ing,fish}),s,i}$ $S_{E(\text{fish}),s,i}$	Equation (F27)	man Sv	—
GLOBAL DISPERSION				
Collective doses from tritium, ^{14}C, ^{85}Kr and ^{129}I were calculated by PC-CREAM (incorporates global dispersion models referenced in [U6])				

Table A4. Parameter and equation list: Marine environment

Parameter	*Symbol*	*Value*	*Units*	*Reference*
MARINE DISPERSION				
Sedimentation decay constant $$\lambda_{s,c,i} = \frac{K_{d,c,i} \cdot S_c}{h_c \cdot \left(1 + K_{d,c,i} \cdot \alpha_c\right)}$$				(M38)
Sedimentation decay constant for compartment, c	$\lambda_{s,c,i}$	Equation (M38)	a^{-1}	[C2]
Marine sediment distribution factor for compartment c and radionuclide, i	$K_{d,c,i}$	Dependent on radionuclide	$m^3\ t^{-1}$	[I3]
Sedimentation rate in compartment, c	S_c	Local: 1.0×10^{-4} Regional: 1.0×10^{-5}	$t\ m^{-2}\ a^{-1}$	(see section III.C of main text)
Depth of compartment, c	h_c	Local: 10 Regional: 1000	m	(see section III.C of main text)
Suspended sediment load in compartment, c	α_c	Local: 2.0×10^{-4} Regional: 1.0×10^{-7}	$t\ m^{-3}$	(see section III.C of main text)
Flow rate constant, local to regional $$\lambda_{l,r} = \frac{\Delta V_{l,r}}{V_l}$$				(M39)
Flow rate constant, local compartment to regional compartment	$\lambda_{l,r}$	Equation (M39)	a^{-1}	(see section III.C of main text)
Volumetric exchange between regional compartment and global oceans	$\Delta V_{l,r}$	2×10^{10}	$m^3\ a^{-1}$	(see section III.C of main text)
Volume of local compartment	V_l	10^9	m^3	(see section III.C of main text)
Flow rate constant, regional compartment to global oceans $$\lambda_{r,g} = \frac{\Delta V_{r,g}}{V_r}$$				(M40)
Flow rate constant, regional compartment to global oceans	$\lambda_{r,g}$	Equation (M40)	a^{-1}	(see section III.C of main text)
Volumetric exchange between local and regional compartments	$\Delta V_{r,g}$	10^{15}	$m^3\ a^{-1}$	(see section III.C of main text)
Volume of regional compartment	V_l	10^{15}	m^3	(see section III.C of main text)
Combined decay constant, local to regional $$\Lambda_{l,i} = \lambda_i + \lambda_{s,l,i} + \lambda_{l,r}$$				(M41)
Combined decay constant for local compartment and radionuclide, i	$\Lambda_{l,i}$	Equation (M41)	a^{-1}	[C2]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Radioactive decay constant for radionuclide, i	λ_i	Dependent on radionuclide	a^{-1}	[I9]
Sedimentation decay constant for local compartment	$\lambda_{s,l,i}$	Equation (M38)	a^{-1}	[C2]
Flow rate constant, local compartment to regional compartment	$\lambda_{l,r}$	Equation (M39)	a^{-1}	(see section III.C of main text)
Combined decay constant, regional compartment to global oceans $\Lambda_{r,i} = \lambda_i + \lambda_{s,r,i} + \lambda_{r,g}$				(M42)
Combined decay constant for regional compartment and radionuclide, i	$\Lambda_{r,i}$	Equation (M42)	a^{-1}	[C2]
Radioactive decay constant for radionuclide, i	λ_i	Dependent on radionuclide	a^{-1}	[I9]
Sedimentation decay constant for regional compartment	$\lambda_{s,r,i}$	Equation (M38)	a^{-1}	[C2]
Flow rate constant, regional compartment to global oceans	$\lambda_{r,g}$	Equation (M40)	a^{-1}	(see section III.C of main text)
Activity in local compartment $A_{l,i}(t) = \frac{Q}{\Lambda_{l,r}}\left(1 - e^{-\Lambda_{l,r} \cdot t}\right)$				(M43)
Activity of radionuclide, *i*, in local compartment at time, *t*	$A_{l,i}(t)$	Equation (M43)	Bq	[C2]
Discharge rate	Q	3.15×10^7 (rounded)	Bq a^{-1}	= 1 Bq s^{-1}
Combined decay constant for local compartment and radionuclide, i	$\Lambda_{l,r}$	Equation (M41)	a^{-1}	[C2]
Duration of discharge	t	100	a	—
Activity in regional compartment $A_{r,i}(t) = \frac{\lambda_{l,r} \cdot A_{l,i}(t)}{\Lambda_{l,r}}\left(1 - e^{-\Lambda_{l,r} \cdot t}\right)$				(M44)
Activity of radionuclide, i, in regional compartment at time, *t*	$A_{r,i}(t)$	Equation (M44)	Bq	[C2]
Rate constant for movement of water from local compartment to regional compartment	$\lambda_{l,r}$	20	a^{-1}	(see section III.C of main text)
Activity of radionuclide, i, in local compartment at time, *t*	$A_{l,i}(t)$	Equation (M43)	Bq	[C2]
Combined decay constant for regional compartment and radionuclide, i	$\Lambda_{l,r}$	Equation (M41)	a^{-1}	[C2]
Duration of discharge	t	100	a	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Activity concentration in water $C_{c,i}(t) = \frac{A_{c,i}(t)}{V_c}$ (M45)				
Activity concentration of radionuclide, i, in water in compartment, c, at time, t	$C_{c,i}(t)$	Equation (M45)	Bq m^{-3}	—
Activity of radionuclide, i, in compartment, c, at time, t	$A_{c,i}(t)$	Equations (M43), (M44)	Bq	[C2]
Volume of compartment, c	V_c	Local: 1.0×10^9 Regional: 1.0×10^{15}	m^3	(see section III.C of main text)
ENVIRONMENTAL TRANSFERS				
Activity concentrations in marine foods $C_{f,c,i} = \frac{C_{c,i} \cdot B_{f,i}}{1\,000}$ (M46)				
Activity concentration of radionuclide, i, in marine food, f, in compartment, c	$C_{f,c,i}$	Equation (M46)	Bq kg^{-1}	—
Activity concentration of radionuclide, i, in water at time, t	$C_{c,i}$	Equation (M45)	Bq m^{-3}	—
Bioaccumulation factor for marine food, f, concentration in marine food (fresh weight) divided by concentration in seawater	$B_{f,i}$	Dependent on food and element	L kg^{-1}	[I3]
Conversion factor		1 000	L m^{-3}	—
Activity concentration in beach sediment $C_{\text{beach},i} = 0.1 \cdot t_{\text{sed}} \cdot \rho_{\text{sed}} \cdot K_{d,\text{local},i} \cdot C_{\text{local},i}$ (M47)				
Activity concentration per unit area in beach sediment	$C_{\text{beach},i}$	Equation (M47)	Bq m^{-2}	—
K_d adjustment factor for coarser grains (i.e. sand rather than fine bed sediment)	—	0.1	—	[S7]
Average thickness of beach sediment	t_{sed}	0.05	m	[I2]
Average density of beach sediment	ρ_{sed}	1.2	t m^{-3}	[I2]
Marine sediment distribution factor in local compartment for radionuclide, i	$K_{d,\text{local},i}$	Dependent on radionuclide	m^3 t^{-1} (L kg^{-1})	[I3]
Activity concentration of radionuclide, i, in water	$C_{\text{local},i}$	Equation (M45)	Bq m^{-3}	—
INDIVIDUAL DOSE CALCULATIONS				
External dose from beach occupancy $H_{E(\text{ex,beach}),i} = C_{\text{beach},i} \cdot F_{\text{geom}} \cdot D_{\text{ex,deposit},i} \cdot O_{\text{beach}}$ (M48)				

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Effective dose from radionuclide, i, from beach occupancy	$H_{E(\text{ex,beach}),i}$	Equation (M48)	Sv	—
Activity concentration of radionuclide, i, in beach sediment	$C_{\text{beach},i}$	Equation (M47)	Bq m^{-2}	—
Geometry factor for beaches for external dose coefficients	F_{geom}	0.5	—	[E2]
Dose coefficient for irradiation from surface deposits	$D_{\text{ex,deposit},i}$	Dependent on radionuclide	Sv s^{-1} Bq^{-1} m^2	[E2]
Beach occupancy (typical rather than critical)	O_{beach}	3.6×10^5	s	[R1]
Ingestion of marine food $$H_{E(\text{ing,marine}),f,r,i} = \left(C_{f,\text{local},i} \cdot f_{f,\text{local}} + C_{f,\text{regional},i} \cdot f_{f,\text{regional}}\right) \cdot D_{\text{ing},i} \cdot I_{f,r} \quad \text{(M49)}$$				
Annual effective dose from radionuclide, i, from ingestion of freshwater fish in region, r	$H_{E(\text{ing,marine}),f,r}$	Equation (M49)	Sv	—
Average activity concentration of radionuclide, i, in food, f, in the local marine compartment	$C_{f,\text{local},i}$	Equation (M46)	Bq kg^{-1}	—
Fraction of food, f, that is caught in the local marine compartment	$f_{f,\text{local}}$	Fish: 0.25 Crustaceans: 1.0 Molluscs: 1.0	—	Fish: consistent with freshwater and terrestrial Crustaceans and molluscs: [S7]
Average activity concentration of radionuclide, i, in food, f, in the regional marine compartment	$C_{f,\text{regional},i}$	Equation (M46)	Bq kg^{-1}	—
Fraction of food, f, that is caught in the regional marine compartment	$f_{f,\text{regional}}$	Fish: 0.75 Crustaceans: 0.0 Molluscs: 0.0	—	Fish: consistent with freshwater and terrestrial environments Crustaceans & molluscs: [S7]
Adult dose coefficient for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv Bq^{-1}	[I14]
Amount of marine food, f, ingested in a year in region, r	$I_{f,r}$	Dependent on region	kg	[W2]
Total effective dose from ingestion of marine foods $$H_{E(\text{ing,marine}),r,i} = \sum_f H_{E(\text{ing,marine}),f,r,i} \quad \text{(M50)}$$				
Total effective dose in region, r, from ingestion of marine food containing radionuclide, i	$H_{E(\text{ing,marine}),r,i}$	Equation (M50)	Sv	—
Effective dose from the ingestion of marine food f containing radionuclide, i, in region, r	$H_{E(\text{ing,marine}),f,r}$	Equation (M49)	Sv	—

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Total individual dose from marine pathways $$H_{E(\text{marine}),r,i} = H_{E(\text{ex,beach}),i} + H_{E(\text{ing,marine}),r,i}$$ (M51)				
Total individual dose from marine pathways in region, r	$H_{E(\text{marine}),r,i}$	Equation (M51)	Sv	—
Effective dose from beach occupancy	$H_{E(\text{ex,beach}),i}$	Equation (M48)	Sv	—
Effective dose from the ingestion of radionuclide, i, in marine foods in region, r	$H_{E(\text{ing,marine}),r,i}$	Equation (M50)	Sv	—
COLLECTIVE DOSE CALCULATIONS				
Collective dose from ingestion of marine fish $$S_{E(\text{ing,marine}),\text{fish},c,r,i} = C_{\text{fish},c,i} \cdot Y_{\text{fish},r} \cdot F_{\text{ed,fish}} \cdot A_c \cdot D_{\text{ing},i}$$ (M52)				
Collective dose from ingestion of marine fish for radionuclide, i	$S_{E(\text{ing,marine}),\text{fish},}$	Equation (M52)	man Sv	—
Activity concentration of radionuclide, i, in fish in compartment, c	$C_{\text{fish},c,i}$	Equation (M46)	Bq kg^{-1}	—
Fish catch in 1 year in region, r	$Y_{\text{fish},r}$	Dependent on region	kg km^{-2}	[F2]
Edible fraction of catch	$F_{\text{ed,fish}}$	0.5	—	[S6]
Area of compartment, c	A_c	Local: 1×10^2 Regional: 1×10^6	km^2	(see section III.C of main text)
Adults dose coefficient for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv Bq^{-1}	[I14]
Collective dose from ingestion of shellfish $$S_{E(\text{ing,marine}),f,c,r,i} = C_{f,c,i} \cdot Y_{f,r} \cdot F_{\text{ed},f} \cdot L_c \cdot D_{\text{ing},i}$$ (M53)				
Collective dose from ingestion of marine food, f, (where $f \in \{\text{molluscs, crustaceans}\}$) in compartment, c, for radionuclide, i	$S_{E(\text{ing,marine}),f,c,}$	Equation (M53)	man Sv	—
Activity concentration of radionuclide, i, in marine food, f, in compartment, c	$C_{f,c,i}$	Equation (M46)	Bq kg^{-1}	—
Harvest of marine food, f, in 1 year per unit length of coastline in region, r	$Y_{f,r}$	Dependent on region	kg km^{-1}	[F2]
Edible fraction of catch for marine food, f	$F_{\text{ed},f}$	Crustaceans: 0.35 Molluscs: 0.15	—	[S6]
Length of coastline in compartment, c	L_c	Local: 10 Regional: 1 000	km	(see section III.C of main text)
Adults dose coefficient for ingestion	$D_{\text{ing},i}$	Dependent on radionuclide	Sv Bq^{-1}	[I14]

Parameter	*Symbol*	*Value*	*Units*	*Reference*
Total collective dose from all marine pathways $S_{E(\text{marine}),c,r,i} = \sum_f S_{E(\text{ing,marine}),f,c,r,i}$				(M54)
Total collective dose in compartment, *c*	$S_{E(\text{marine}),c,r,i}$	Equation (M54)	man Sv	—
Collective dose from consumption of food, *f*, in compartment, *c*	$S_{E(\text{ing,marine}),f,c,}$	Equations (M52) and (M53)	man Sv	—
GLOBAL DISPERSION				
Collective doses from tritium, ^{14}C, ^{85}Kr and ^{129}I calculated by PC-CREAM (incorporates global dispersion models referenced in UNSCEAR 2000 Report [U6])				

Table A5. Treatment of progeny for atmospheric and terrestrial pathways

Half-lives are given in brackets to two significant figures [I9]

Discharged parent	*Progeny*	*Exposure pathway*		
		Plume (external irradiation and inhalation)	*Deposited material (external irradiation)*	*Food (ingestion)*
^{90}Sr (29 a)	^{90}Y (64 h)	Dose coefficient for inhalation of parent accounts for progeny. Activity concentration of progeny assumed equal to parent for estimating external exposure	Deposition and dose rates calculated for parent and progeny separately	Dose coefficient for ingestion of parent accounts for progeny
^{106}Ru (370 d)	^{106}Rh (30 s)	Secular equilibrium assumed. Dose rates calculated for both parent and progeny	Deposition and dose rates calculated for parent and progeny separately	Dose coefficient for ingestion of parent accounts for progeny
^{135}Xe (9.1h)	^{135}Cs (2.3×10^6 a)	Activity concentrations of progeny in air calculated explicitly based on transit time	Deposition and dose rate calculated for progeny	Activity concentration calculated from deposition rate for progeny
^{138}Xe (14 m)	^{138}Cs (32 min)	Activity concentration of progeny in air calculated explicitly based on transit time	Deposition and dose rate calculated for progeny	Activity concentration calculated from deposition rate for progeny
^{137}Cs (30 a)	^{137m}Ba (2.6 min)	Dose coefficient for inhalation of parent accounts for progeny. Activity concentration of progeny calculated at yield of 94.6% for estimating external exposure	Deposition and dose rates calculated for parent and progeny separately	Dose coefficient for ingestion of parent accounts for progeny
^{210}Pb (22 a)	^{210}Bi (5.0 d) ^{210}Po (140 d)	Ingrowth insignificant during plume transit; progeny not considered	Negligible dose from progeny following ingrowth after deposition of ^{210}Pb; not considered	Ingrowth following deposition of ^{210}Pb to soil and plant, but activity concentration of ^{210}Po in terrestrial foods significantly lower than for deposition of ^{210}Po; subsequent small doses compared to those from ^{210}Pb; ingrowth not considered
^{222}Rn (3.8 d)	^{218}Po (3.1 min) ^{214}Pb (27 min) ^{214}Bi (20 min) ^{214}Po (164 μs) ^{210}Pb (22 a) ^{210}Bi (5.0 d) ^{210}Po (140 d)	Dose coefficient for inhalation of ^{222}Rn includes contribution from four immediate short-lived progeny [U9]. Longer lived progeny (^{210}Pb, ^{210}Bi and ^{210}Po) will not grow in during plume transit and so not considered	Negligible contributions to dose from deposition of progeny compared with dose from inhalation; not considered	Because of time taken for ingrowth and reduced activities of long-lived progeny compared to ^{222}Rn, negligible doses from ingestion of progeny in terrestrial foods; not considered

Discharged parent	*Progeny*	*Exposure pathway*		
		Plume (external irradiation and inhalation)	*Deposited material (external irradiation)*	*Food (ingestion)*
^{226}Ra (1 600 a)	^{222}Rn (3.8 d) ^{218}Po (3.1 min) ^{214}Pb (27 min) ^{214}Bi (20 min) ^{214}Po (164 μs) ^{210}Pb (22a) ^{210}Bi (5.0 d) ^{210}Po (140 d)	Ingrowth insignificant during plume transit; progeny not considered	Ingrowth following deposition of ^{226}Ra, but radon gas largely emitted to atmosphere and further diluted. Small doses from progeny compared with parent; not included	Ingrowth following deposition of ^{226}Ra, but radon gas largely emitted to atmosphere and further diluted. Small doses from progeny compared with parent; not included
^{232}Th (1.4×10^{10} a)	^{228}Ra (5.8 a) ^{228}Ac (6.1 h) ^{228}Th (1.9 a) ^{212}Pb (11 h)	Secular equilibrium assumed; activity concentration in air assumed equal to parent	Deposition rate calculated for each progeny in secular equilibrium	Activity concentration of parent in air used as proxy for secular equilibrium in soil after 100 years. Only ^{228}Ra, ^{228}Th and ^{212}Pb included
^{234}U (2.4×10^{5} a)	^{230}Th (7.7×10^{4} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years		
^{238}U (4.5×10^{9} a)	^{234}Th (24 d) ^{234m}Pa (1.2 min)	Secular equilibrium assumed; activity concentration in air assumed equal to parent	Deposition rate calculated for each progeny	Activity concentration of parent in air used as proxy for secular equilibrium in soil after 100 years. Only ^{234}Th included
^{239}Pu (2.4×10^{4} a)	^{235}U (7.0×10^{8} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years		
^{240}Pu (6 500 a)	^{236}U (2.3×10^{7} a)			
^{241}Am (430 a)	^{237}Np (2.1×10^{6} a)			

Table A6. Treatment of progeny for freshwater pathways

Half-lives are given in brackets to two significant figures [I9]

Discharged parent	*Progeny*	*Exposure pathway*			
		Riverbank occupancy	*Freshwater fish*	*Drinking water*	*Irrigated food*
^{90}Sr (29 a)	^{90}Y (64 h)	Secular equilibrium assumed[a]	Dose coefficient for ingestion of parent accounts for progeny		
^{106}Ru (370 d)	^{106}Rh (30 s)	Secular equilibrium assumed[a]			
^{137}Cs (30 a)	^{137m}Ba (2.6 min)	^{137m}Ba activity concentration in filtered water calculated at yield of 94.6%[a]			
^{210}Pb (22 a)	^{210}Bi (5.0 d) ^{210}Po (140 d)	Negligible doses from ingrowth compared with total dose for ^{210}Pb; not considered	Ingrowth limited during transit time in freshwater body; doses from progeny not included		
^{226}Ra (1 600 a)	^{222}Rn (3.8 d) ^{218}Po (3.1 min) ^{214}Pb (27 min) ^{214}Bi (20 min) ^{214}Po (164 μs) ^{210}Pb (22 a) ^{210}Bi (5.0 d) ^{210}Po (140 d)	^{222}Rn gas mainly emitted to atmosphere; contributions from subsequent progeny omitted			
^{232}Th (1.4×10^{10} a)	^{228}Ra (5.8 a) ^{228}Ac (6.1 h) ^{228}Th (1.9 a) ^{212}Pb (11 h)	Secular equilibrium assumed[a]	Secular equilibrium assumed in water[a]	Secular equilibrium assumed in untreated water[a]	Deposition rate of parent used as proxy for secular equilibrium in soil after 100 years. Only ^{228}Ra, ^{228}Th and ^{212}Pb included
^{234}U (2.4×10^{5} a)	^{230}Th (7.7×10^{4} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years			
^{238}U (4.5×10^{9} a)	^{234}Th (24 d) ^{234m}Pa (1.2 min)	Secular equilibrium assumed[a]	Secular equilibrium assumed in water[a]	Secular equilibrium assumed in untreated water[a]	Deposition rate of parent used as proxy for secular equilibrium in soil after 100 years. Only ^{234}Th included
^{239}Pu (2.4×10^{4} a)	^{235}U (7.0×10^{8} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years			
^{240}Pu (6 500 a)	^{236}U (2.3×10^{7} a)				
^{241}Am (430 a)	^{237}Np (2.1×10^{6} a)				

[a] Dose rates calculated from parent and each progeny separately.

Table A7. Treatment of progeny for marine pathways

Half-lives are given in brackets to two significant figures [I9]

Discharged parent	*Progeny*	*Exposure pathway*	
		Beach occupancy	*Marine food*
^{90}Sr (29 a)	^{90}Y (64 h)	Secular equilibrium assumed[a]	Dose coefficient for ingestion of parent accounts for progeny
^{106}Ru (370 d)	^{106}Rh (30 s)		
^{137}Cs (30 a)	^{137m}Ba (2.6 min)	^{137m}Ba activity in local/regional compartment and on beach calculated at yield of 94.6%[a]	
^{210}Pb (22 a)	^{210}Bi (5.0 d) ^{210}Po (140 d)	Secular equilibrium assumed[a]	Secular equilibrium assumed in water; bioaccumulation factors for parent and progeny explicitly applied
^{226}Ra (1 600 a)	^{222}Rn (3.8 d) ^{218}Po (3.1 min) ^{214}Pb (27 min) ^{214}Bi (20 m) ^{214}Po (164 µs) ^{210}Pb (22 a) ^{210}Bi (5.0 d) ^{210}Po (140 d)	Most radon is assumed not emitted to atmosphere; secular equilibrium assumed [a]	Secular equilibrium assumed in water; bioaccumulation factors for parent and progeny explicitly applied
^{232}Th (1.4×10^{10} a)	^{228}Ra (5.8 a) ^{228}Ac (6.1 h) ^{228}Th (1.9 a) ^{212}Pb (11 h)	Secular equilibrium assumed [a]	Secular equilibrium assumed in water; bioaccumulation factors for parent and progeny explicitly applied
^{234}U (2.4×10^{5} a)	^{230}Th (7.7×10^{4} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years	
^{238}U (4.5×10^{9} a)	^{234}Th (24 d) ^{234m}Pa (1.2 min)	Secular equilibrium assumed [a]	Secular equilibrium assumed in water; bioaccumulation factors for parent and progeny explicitly applied
^{239}Pu (2.4×10^{4} a)	^{235}U (7.0×10^{8} a)	Parent half-life sufficiently long that ingrowth not relevant at 100 years	
^{240}Pu (6 500 a)	^{236}U (2.3×10^{7} a)		
^{241}Am (430 a)	^{237}Np (2.1×10^{6} a)		

[a] Dose rates from external exposure calculated from parent and each progeny separately.

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