R-06-68

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July 2006

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ISSN 1402-3091
SKB Rapport R-06-68

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Keywords: Dose, Dose coefficients, SRCAN, Biosphere, Safety, Human, Model.

This report is a result of a joint project between Posiva Oy, Finland and SKB.
This report will also be printed as Posiva Working Report 2006-56.

Abstract

This report describes methods and data for calculation of doses to man to be used in , safety assessments of repositories for nuclear fuel. The methods are based on the latest recommendations from the ICRP; the EU and the national radiation protection authorities.

Equations are given for calculation of doses from ingestion of contaminated water and food, inhalation of contaminated air and external exposure from radionuclides in the ground. With the exception of the exposure from food ingestion, the equations are the same used in previous safety assessments. A general equation is suggested for estimation of the exposure from food ingestion, in which the annual demand of carbon is used instead of the annual ingestion of different food-stuffs, which was earlier applied.

The report contains tables with recommended values for physiological characteristics such as water intake, food intake and inhalation rates, based on information summarised in an Appendix. Furthermore, tables are given with recommended age dependent dose conversion factors for ingestion and inhalation for a number of nuclides of interest for safety assessments. The most recently published dose conversion factors for external exposure from contaminated ground are also given.

An overview of the implementation of the methodology in Pandora, which is the tool that SKB and Posiva currently use for biosphere modelling, is also provided. The work presented in the report is a result from a joint project commissioned by SKB and Posiva.

Sammanfattning

Denna rapport beskriver metoder och data för att beräkna dos till människor för användning vid säkerhetsanalyser för slutförvar av kärnbränsle. Metoderna bygger på de senaste rekommendationerna från ICRP, EU och de nationella strålskyddsmyndigheterna.

Rapporten visar ekvationer för att beräkna doser från intag av kontaminerat vatten och kontaminerad föda, inandning av kontaminerad luft och extern exponering från radionuklider i marken. Med undantag av exponering via födoämnen är de föreslagna ekvationerna jämförbara med de som tidigare använts. För exponering via föda föreslås ett generellt uttryck med ett årligt behov av kol istället för den årliga fördelningen av olika födoämnen, som tidigare använts.

Rapporten innehåller tabeller med rekommenderade värden för fysiologiska karaktäristika såsom konsumtion av vatten och föda samt inhalationshastigheter, baserat på bakgrundsinformationen given i bilagan. Vidare ges tabeller med åldersspecifika dosomvandlingsfaktorer för intag och inhalation av ett antal nuklider av intresse för säkerhetsanalyser. Dessutom redovisas de senast publicerade dosomvandlingsfaktorerna för extern exponering från kontaminerad mark.

Slutligen ges också en översikt om hur metoderna implementeras i Pandora, det verktyg som SKB och Posiva för närvarande använder för biosfärsmodellering. Arbetet som presenteras i denna rapport är ett resultat från ett gemensamt SKB och Posiva projekt.

Contents

1 Introduction

In safety assessments of radioactive waste repositories the risk to man from calculated potential releases into the biosphere is estimated by performing calculations of the doses that individuals of the most exposed group may receive from use of the environment to which the radionuclides have leaked.. The method for dose calculations that has been used in previous safety assessments by SKB and Posiva is described in /Bergström et al. 1999/. This methodology considers the main exposure pathways that may arise from a continuous input of radionuclides into the environment with contaminated groundwater, which is the release scenario of most relevance for safety assessment of geologic repositories.

During 2005 a revision of the methodology for dose calculations was carried out within a joint project commissioned by SKB and Posiva. This included a compilation of the dose coefficients for ingestion, and inhalation and an updating of the dose coefficients for external exposure. In addition, physiological characteristics to be used in dose calculations, such as water intake, food intake and inhalation rate were reviewed and summarised. The methodology was implemented in Pandora /Åstrand et al. 2005/, which is a modelling tool that has been developed in the frame of the cooperation between SKB and Posiva, and is used by both organisations for biosphere modelling.

The present report describes the revised methodology and includes tables with updated values of the parameters needed for performing the dose calculations. An overview of the implementation of the methodology in Pandora is also given. In the Appendix supporting information used in the revision of the recommended parameter values is presented.

This report is a result of a joint project between Posiva Oy, Finland and SKB. This report will also be printed as Posiva Working Report 2006-56.

2 Exposure pathways

Man can be exposed both externally and internally to radionuclides in the environment. The external exposure comes from radiation emitted by the radionuclides in surrounding environmental media, air, water and soils. Previous safety assessments of planned geologic repositories in Sweden and Finland /Bergström et al. 1999/ and /Karlsson and Bergström 2000/ have shown that for most radionuclides of concern the external exposure gives a minor contribution to the total dose. The external exposure from air and water is negligible for all radionuclides of concern, while for radionuclides with high gamma-energy and low bioavailability, such as Nb-94, the external exposure to radionuclides accumulated in the ground (soil) could give an important contribution to the total dose. Hence, exposure from radionuclides accumulated in the ground is the only external exposure pathway included in this methodology. The exposure to radionuclides in the ground will be lower indoors due to the shielding effects of buildings. In the methodology it is conservatively assumed that man is exposed from activity outdoors hundred percent of time.

The internal exposure is always preceded by incorporation of radionuclides into the human body. This can occur mainly by inhalation of contaminated air, or ingestion of contaminated water and food. Other pathways for radionuclide penetration into the human body, for example through the skin, are irrelevant for the context of this methodology. The exposure via inhalation of contaminated air can occur both outdoors and indoors. However, exposure indoors may be lower than outdoors due to the filtering effects of buildings. This methodology will consider only outdoor exposure hundred percent of time, which in most cases gives a conservative estimate, as the radionuclide contamination of the air comes from resuspension of soil particles. The situation could, however, be different for isotopes of elements that can exist in gas form in the environment, such as radon and iodine.

The methodology also considers the internal exposure via oral intake of radionuclides. This exposure will, among other things, depend on the fraction of contaminated food and water consumed and the level of activity in the foodstuffs and water. In this methodology it is assumed that the annual demand of water and food is contaminated, but other situations can be easily be addressed by introducing corrections to account for the fraction of consumed water and food that is not contaminated. The diet composition can also have an impact on the internal exposure, as different food can have different contamination levels. However, for long-term assessments it is difficult to postulate a particular diet composition, as the human habits and choices may change. Hence, no assumptions have been made regarding food preferences and instead the calculations are based on values of food energy intake given by the ICRP for the reference man /ICRP 1975, 2004/.

3 Doses from ingestion of water and water

The internal dose from water ingestion can be calculated with the following equation:

$$D^{j}_{ingWater} = IR_{W} * C^{j}_{water} * DCC^{j}_{ing} \qquad (1)$$

where,

$D^{j}_{ingWater}$ is the dose from the *j-th* radionuclide via ingestion of water [Sv/y],

IR_W is the yearly consumption of water by an individual [m^3/y],

C^{j}_{water} is the concentration of the *j-th* radionuclide in drinking water [Bq/m^3]

DCC^{j}_{ing} is the dose coefficient for ingestion of the *j-th* radionuclide [Sv/Bq].

The water consumption value used in equation (1) should not include the water that is contained in the food, since its contribution to man's water balance is indirectly included in the calculations of the internal dose from food ingestion (equation 2). The reference values in /ICRP 2004/ are given for the total water intake with food and fluids (see Table A-1 in the Appendix). Daily consumption of water in fluids and food varies markedly from one person to another, depending on individual habits, such as dietary habits and exercise, and environmental factors such as air temperature and humidity, as well as age and gender. A study on an adult population in France /Antoine et al. 1986/ quoted in /ICRP 2004/ estimated "visible" water intakes such as tap water (650 ml/day) and other drinks (678 ml/day), i.e. a total of 0.5 m3/y of water consumption with fluids (drinking). A study in the US /Ershow and Cantor 1989/ quoted in /ICRP 2004/ showed total values of water consumption with fluids by adults of 0.4–0.6 m3/y, including intake of drinking water, water added to beverages and water added to food during preparation, but not water intrinsic in food as purchased. The values reported in the above studies, as well as in /ICRP 1975/, are close to the value of 0.6 m3/y that have been used in previous assessments and we therefore recommend to continue using this value in future assessments (see Table 3-1).

The internal dose from food ingestion can be calculated with the following equation:

$$D^{j}_{ingFood} = IR_{C} * C^{j}_{Diet} * DCC^{j}_{ing} \qquad (2)$$

where,

D^{j}_{ing} is the dose from the *j-th* radionuclide via ingestion of food [Sv/y],

IR_C is the yearly intake of carbon by an individual [kg C/y],

$C^{j}_{Dateriet}$ is the concentration of the *j-th* radionuclide in the diet [Bq/kg C]

DCC^{j}_{ing} is the dose coefficient for ingestion of the *j-th* radionuclide [Sv/Bq].

Table 3-1. Recommended values of man physiological properties needed as parameters for calculation of doses via water ingestion, food ingestion, inhalation and external exposure. All values are chosen at the high end of the range of values in, or estimated from, ICRP recommendations.

Parameter	Units	Value	Comments
Intake rate of water by an individual IR_W (Used in Equation 1)	m^3/y	0.6	Intake rate of water by adults, excluding water consumed with food. /ICRP 1975, 2004/
Intake rate of carbon by an individual IR_C (Used in Equation 2)	kg C/y	110	Estimated from the intake of protein, carbohydrates and fats by adult males given in /ICRP 1975/
Inhalation rate InhR (Used in Equation 3)	m^3/h	1	Based on values of total ventilation during a day for adult males given in /ICRP 1975, 2004/

The total intake of carbon by an individual is related to the food energy intake, 10 kcal is approximately equivalent to 1 g C. Total energy expenditure is age and gender dependent (see Table A-1 in the Appendix) and varies widely due to individual differences in activity, body size and body composition. The reference value of energy expenditure by an adult male given in /ICRP 2004/ is 2.8E03 kcal/day (Table A-1 in the Appendix) and since usage of metabolic fuel is normally balanced by variations in food intake /ICRP 2004/, we can estimate that the yearly carbon intake is around 102 kg. The same calculation for adult females gives a value of 66 kg C/year. The carbon intake by male adults can also be estimated from the values of protein intake (0.095 kg/day), carbohydrate intake (0.39 kg/day) and fat intake (0.12 kg/day) given in /ICRP 1975/ and the carbon content in proteins, carbohydrates and fats: 0.53, 0.44 and 0.66 kg C/kg, respectively /Altman and Ditmer 1964, Dyson 1978, Robert J et al. 1991/. This gives a value of around 110 kg C/year for male adults (recommended value in Table 3-1). The same calculation for adult females gives a value of around 76 kg C/year.

Equation 2 is equivalent to the equation used in previous assessments for estimation of internal doses from food ingestion see /Bergström et al. 1999/. Indeed the equation used in /Bergström et al. 1999/ and further in /Karlsson and Bergström 2000/ can be obtained from equation (2) by assuming a specific diet composition and making appropriate substitutions. The use of equation (2) is consistent with the assumptions behind the dose coefficients and does not require a priori assumptions about the diet composition. The activity concentration in food in units of Bq/kg C can be easily obtained from values in Bq/kg fresh weight by multiplying the commonly known values of protein, carbohydrates and fat content in different food types by their corresponding carbon content (see above).

3.1 Dose coefficients for ingestion

The dose coefficient for internal exposure via ingestion (DCC^j_{ing}), expressed in Sv/Bq, is defined as the committed effective dose to an individual from unit intake of the *j-th* radionuclide orally with food or water. The dose is integrated over 50 years for adults and up to 70 years for the group with ages of between 0 and 1 year. Hence, the dose coefficients correspond to life-time doses. Recommended values of the DCC^j_{ing} are presented in Table 3-2. For radionuclides with decay chains the values include the contribution from short lived daughter radionuclides, assuming equilibrium.

All recommended values, with the exception of the values for Rn-222, are taken from the European Union recommendations /EUR 1996/. The DCC values are given for several age groups: 0–1 years, 1–2 years, 2–7 years, 7–12 years, 12–17 years and adults. Values for radon, Rn-222, are missing in the European Union recommendations and were taken from /NRC 1999/.

Table 3-2. Recommended values of dose coefficients (Sv/Bq) for ingestion for various age groups based on /EUR 1996/ and /NRC 1999/ for Rn-222.

Nuclide	Adults	0–1 years	1–2 years	2–7 years	7–12 years	12–17 years
H-3	1.8E–11	6.4E–11	4.8E–11	3.1E–11	2.3E–11	1.8E–11
Be-10	1.1E–09	1.4E–08	8.0E–09	4.1E–09	2.4E–09	1.4E–09
C-14	5.8E–10	1.4E–09	1.6E–09	9.9E–10	8.0E–10	5.7E–10
Cl-36	9.3E–10	9.8E–09	6.3E–09	3.2E–09	1.9E–09	1.2E–09
Ca-41	1.9E–10	1.2E–9	5.2E–10	3.9E–10	4.8E–10	5.0E–10
Co-60	3.4E–09	5.4E–08	2.7E–08	1.7E–08	1.1E–08	7.9E–09
Ni-59	6.3E–11	6.4E–10	3.4E–10	1.9E–10	1.1E–10	7.3E–11
Ni-63	1.5E–10	1.6E–09	8.4E–10	4.6E–10	2.8E–10	1.8E–10
Se-79	2.9E–09	4.1E–08	2.8E–08	1.9E–08	1.4E–08	4.1E–09
Sr-90	2.8E–08	2.3E–07	7.3E–08	4.7E–08	6.0E–08	8.0E–08
Zr-93	1.1E–09	1.2E–09	7.6E–10	5.1E–10	5.8E–10	8.6E–10
Nb-94	1.7E–09	1.5E–08	9.7E–09	5.3E–09	3.4E–09	2.1E–09
Mo-93	3.1E–09	7.9E–09	6.9E–09	5.0E–09	4.0E–09	3.4E–09
Tc-99	6.4E–10	1.0E–08	4.8E–09	2.3E–09	1.3E–09	8.2E–10
Pd-107	3.7E–11	4.4E–10	2.8E–10	1.4E–10	8.1E–11	4.6E–11
Ag-108m	2.3E–09	2.1E–08	1.1E–08	6.5E–09	4.3E–09	2.8E–09
I-129	1.1E–07	1.8E–07	2.2E–07	1.7E–07	1.9E–07	1.4E–07
Cs-134	1.9E–08	2.6E–08	1.6E–08	1.3E–08	1.4E–08	1.9E–08
Cs-135	2.0E–09	4.1E–09	2.3E–09	1.7E–09	1.7E–09	2.0E–09
Cs-137	1.3E–08	2.1E–08	1.2E–08	9.6E–09	1.0E–08	1.3E–08
Sm-151	9.8E–11	1.5E–09	6.4E–10	3.3E–10	2.0E–10	1.2E–10
Eu-152	1.4E–09	1.6E–08	7.4E–09	4.1E–09	2.6E–09	1.7E–09
Eu-154	2.0E–09	2.5E–08	1.2E–08	6.5E–09	4.1E–09	2.5E–09
Eu-155	3.2E–10	4.3E–09	2.2E–09	1.1E–09	6.8E–10	4.0E–10
Ho-166m	2.0E–09	2.6E–08	9.3E–09	5.3E–09	3.5E–09	2.4E–09
Pb-210	6.9E–07	8.4E–06	3.6E–06	2.2E–06	1.9E–06	1.9E–06
Po-210	1.2E–06	2.6E–05	8.8E–06	4.4E–06	2.6E–06	1.6E–06
Rn-222	3.5E–09	–	–	–	–	–
Ra-226	2.8E–07	4.7E–06	9.6E–07	6.2E–07	8.0E–07	1.5E–06
Ac-227	1.1E–06	3.3E–05	3.1E–06	2.2E–06	1.5E–06	1.2E–06
Th-229	4.9E–07	1.1E–05	1.0E–06	7.8E–07	6.2E–07	5.3E–07
Th-230	2.1E–07	4.1E–06	4.1E–09	3.1E–07	2.4E–07	2.2E–07
Th-232	2.3E–07	4.6E–06	4.5E–07	3.5E–07	2.9E–07	2.5E–07
Pa-231	7.1E–07	1.3E–05	1.3E–06	1.1E–06	9.2E–07	8.0E–07
U-233	5.1E–08	3.8E–07	1.4E–07	9.2E–08	7.8E–08	7.8E–08
U-234	4.9E–08	3.7E–07	1.3E–07	8.8E–08	7.4E–08	7.4E–08
U-235	4.7E–08	3.5E–07	1.3E–07	8.5E–08	7.1E–08	7.0E–08
U-236	4.7E–08	3.5E–07	1.3E–07	8.4E–08	7.0E–08	7.0E–08
U-238	4.5E–08	3.4E–07	1.2E–07	8.0E–08	6.8E–08	6.7E–08
Np-237	1.1E–07	2.0E–06	2.1E–07	1.4E–07	1.1E–07	1.1E–07
Pu-238	2.3E–07	4.0E–06	4.0E–07	3.1E–07	2.4E–07	2.2E–07
Pu-239	2.5E–07	4.2E–06	4.2E–07	3.3E–07	2.7E–07	2.4E–07
Pu-240	2.5E–07	4.2E–06	4.2E–07	3.3E–07	2.7E–07	2.4E–07
Pu-241	4.8E–09	5.6E–08	5.7E–09	5.5E–09	5.1E–09	4.8E–09
Pu-242	2.4E–07	4.0E–06	4.0E–07	3.2E–07	2.6E–07	2.3E–07
Am-241	2.0E–07	3.7E–06	3.7E–07	2.7E–07	2.2E–07	2.0E–07
Am-242m	1.9E–07	3.1E–06	3.0E–07	2.3E–07	2.0E–07	1.9E–07
Am-243	2.0E–07	3.6E–06	3.7E–07	2.7E–07	2.2E–07	2.0E–07
Cm-244	1.2E–07	2.9E–06	2.9E–07	1.9E–07	1.4E–07	1.2E–07
Cm-245	2.1E–07	3.7E–06	3.7E–07	2.8E–07	2.3E–07	2.1E–07
Cm-246	2.1E–07	3.7E–06	3.7E–07	2.8E–07	2.2E–07	2.1E–07

4 Doses from inhalation

The internal dose from inhalation of atmospheric air can be calculated with the following equation:

$$D^{j}_{inh} = C^{j}_{air} * InhR * H * DCC^{j}_{inh} \qquad (3)$$

where,

D^{j}_{inh} is the dose from the *j-th* radionuclide via inhalation [Sv/y],

C^{j}_{air} is the concentration of the *j-th* radionuclide in air [Bq/m^3],

InhR is the inhalation rate by an individual [m^3/h],

H is the exposure time to contaminated air [h/y],

DCC $^{j}_{inh}$ is the dose coefficient inhalation of the *j-th* radionuclide [Sv/Bq].

The inhalation rates (*InhR*) of an individual vary during the day depending on the activities and time expend outdoors and indoors. In /ICRP 2004/ reference values of total ventilation during a day are provided for members of the public at various ages (see Table A-1 in the Appendix). The highest value, 22 m^3/day, is for adult males, which is close to the value used in previous assessments, i.e. 1 m^3/h or 24 m^3/day and we therefore recommend continue using this value in future assessments (see Table 3-1).

The exposure time to the contaminated air (H) depends on the exposure context and in particular the type of human activity leading to the exposure. For pessimistic assessments a value of 8,760 h/year can be used, which also applies to external exposure (see Chapter 5), implying 100% percent exposure time.

4.1 Dose coefficients for inhalation

The dose coefficient for internal exposure via inhalation (DCC^{j}_{inh}), expressed in Sv/Bq, is defined as the committed effective dose to an individual from unit intake of the *j-th* radionuclide with inhaled air. The dose is integrated over 50 years for adults and up to 70 years for the age 0–1 years. Hence, the dose coefficients for internal exposure via inhalation also correspond to life-time doses. Recommended values of the DCC^{j}_{inh} based on /EUR 1996/ are presented in Table 4-1. For radionuclides with decay chains the values include the contribution from short lived daughter radionuclides, assuming equilibrium.

In the European recommendations three values are given, one for each class of absorption in the lungs (see Table A-2 in the Appendix): F (fast), M (moderate) and S (slow). The slow retention causes the highest exposure for most radionuclides, but there are exceptions, for example for isotopes of the actinides Np, Pu, Am and Cm the highest exposure is observed for fast absorption. The highest value for each isotope across different classes of absorption was chosen as recommended value (Table 4-1). The European recommendations do not provide a value for radon. The /ICRP 1993/ recommends a mean value of 2.1E-08 Sv/y per Bq/m^3. It should be taken into account that epidemiological studies have shown a large variability in the risk from radon inhalation, depending on factors as smoking habits, time spent indoor and outdoor.

Table 4-1. Recommended dose coefficients (Sv/Bq) for inhalation for various age groups based on /EUR 1996/. The recommended value is the highest value across classes of absorption given in /EUR 1996/ (see Table A-2 in the Appendix). For I-129 the value given for adults refers to the soluble gas form.

Nuclide	Adults	1–2 years	2–7 years	7–12 years	12–17 years
H-3	2.6E-10	1.0E-09	6.3E-10	3.8E-10	2.8E-10
Be-10	3.5E-08	9.1E-08	6.1E-08	4.2E-08	3.7E-08
C-14	5.8E-09	1.7E-08	1.1E-08	7.4E-09	6.4E-09
Cl-36	7.3E-09	2.6E-08	1.5E-08	1.0E-08	8.8E-09
Ca-41	1.8E-10	6.0E-10	3.8E-10	3.3E-10	3.3E-10
Co-60	3.1E-08	8.6E-08	5.9E-08	4.0E-08	3.4E-08
Ni-59	4.4E-10	1.5E-09	9.5E-10	5.9E-10	4.6E-10
Ni-63	1.3E-09	4.3E-09	2.7E-09	1.7E-09	1.3E-09
Se-79	6.8E-09	2.0E-08	1.3E-08	8.7E-09	7.6E-09
Sr-90	1.6E-07	4.0E-07	2.7E-07	1.8E-07	1.6E-07
Zr-93	2.5E-08	4.8E-09	5.3E-09	9.7E-09	1.8E-08
Nb-94	4.9E-08	1.2E-07	8.3E-08	5.8E-08	5.2E-08
Mo-93	2.3E-09	5.8E-09	4.0E-09	2.8E-09	2.4E-09
Tc-99	1.3E-08	3.7E-08	2.4E-08	1.7E-08	1.5E-08
Pd-107	5.9E-10	2.0E-09	1.3E-09	7.8E-10	6.2E-10
Ag-108m	3.7E-08	8.7E-08	6.2E-08	4.4E-08	3.9E-08
I-129*	9.8E-09	8.6E-08	6.1E-08	6.7E-08	4.6E-08
Cs-134	2.0E-08	6.3E-08	4.1E-08	2.8E-08	2.3E-08
Cs-135	8.6E-09	2.4E-08	1.6E-08	1.1E-08	9.5E-09
Cs-137	3.9E-08	1.0E-07	7.0E-08	4.8E-08	4.2E-08
Sm-151	4.0E-09	1.0E-08	6.7E-09	4.5E-09	4.0E-09
Eu-152	4.2E-08	1.0E-07	7.0E-08	4.9E-08	4.3E-08
Eu-154	5.3E-08	1.5E-07	9.7E-08	6.5E-08	5.6E-08
Eu-155	6.9E-09	2.3E-08	1.4E-08	9.2E-09	7.6E-09
Ho-166m	1.2E-07	2.5E-07	1.8E-07	1.3E-07	1.2E-07
Pb-210	5.6E-06	1.8E-05	1.1E-05	7.2E-06	5.9E-06
Po-210	4.3E-06	1.4E-05	8.6E-06	5.9E-06	5.1E-06
Ra-226	9.5E-06	2.9E-05	1.9E-05	1.2E-05	1.0E-05
Ac-227	5.5E-04	1.6E-03	1.0E-03	7.2E-04	5.6E-04
Th-229	2.4E-04	5.1E-04	3.6E-04	2.9E-04	2.4E-04
Th-230	1.0E-04	2.0E-04	1.4E-04	1.1E-04	9.9E-05
Th-232	1.1E-04	2.2E-04	1.6E-04	1.3E-04	1.2E-04
Pa-231	1.4E-04	2.3E-04	1.9E-04	1.5E-04	1.5E-04
U-233	9.6E-06	3.0E-05	1.9E-05	1.2E-05	1.1E-05
U-234	9.4E-06	2.9E-05	1.9E-05	1.2E-05	1.0E-05
U-235	8.5E-06	2.6E-05	1.7E-05	1.1E-05	9.2E-06
U-236	8.7E-06	2.7E-05	1.8E-05	1.1E-05	9.5E-06
U-238	8.0E-06	2.5E-05	1.6E-05	1.0E-05	8.7E-06
Np-237	5.0E-05	9.3E-05	6.0E-05	5.0E-05	4.7E-05
Pu-238	1.1E-04	1.9E-04	1.4E-04	1.1E-04	1.0E-04
Pu-239	1.2E-04	2.0E-04	1.5E-04	1.2E-04	1.1E-04
Pu-240	1.2E-04	2.0E-04	1.5E-04	1.2E-04	1.1E-04
Pu-241	2.3E-06	2.9E-06	2.6E-06	2.4E-06	2.2E-06
Pu-242	1.1E-04	1.9E-04	1.4E-04	1.2E-04	1.1E-04
Am-241	9.6E-05	1.8E-04	1.2E-04	1.0E-04	9.2E-05
Am-242m	9.2E-05	1.5E-04	1.1E-04	9.4E-05	8.8E-05
Am-243	9.6E-05	1.7E-04	1.2E-04	1.0E-04	9.1E-05
Cm-244	5.7E-05	1.3E-04	8.3E-05	6.1E-05	5.3E-05
Cm-245	9.9E-05	1.8E-04	1.2E-04	1.0E-04	9.4E-05
Cm-246	9.8E-05	1.8E-04	1.2E-04	1.0E-04	9.4E-05

5 Doses from external exposure

The external dose from exposure to radionuclides in the ground can be calculated with the following equation:

$$D^j_{ext} = C^j_{soil} * \rho_{soil} * H * DCC^j_{ext} \qquad (4)$$

where,

D^j_{ext} is the dose from the *j-th* radionuclide via external exposure [Sv/y],

C^j_{soil} is the concentration of the *j-th* radionuclide in soil [Bq/kg dw],

ρ_{soil} is the soil density [kg/m^3],

H is the exposure time to external radiation [h/y],

DCC^j_{ext} is the dose coefficient for external exposure of the *j-th* radionuclide [Sv/h per Bq/m^3].

As for inhalation, equation (4) considers only outdoor exposure and if assuming being outdoors hundred percent of time, this will give a conservative estimate, since indoor exposure to radiation from the ground will be reduced by the shielding provided by buildings. As shown below, the values of the dose coefficients for external exposure from the ground depend among other things on the radionuclide vertical distribution in the ground. Hence, concentrations of radionuclides in soil that are consistent with the chosen DCC_{ext} should be used. In practice, a homogeneous radionuclide distribution in a soil layer of infinite depth is usually assumed with concentrations representative of the most contaminated soil layer, which is conservative.

5.1 Dose coefficients for external exposure

The dose coefficient for external exposure (DCC^j_{ext}), expressed in Sv/h per Bq/m^3, is defined as the dose rate to which an individual is exposed from unit volumetric concentration in soil of the *j-th* radionuclide. Recommended values of the DCC^j_{ext} are presented in Table 5-1. For radionuclides with decay chains the values include the contribution from short lived daughter radionuclides, assuming equilibrium.

The recommended values are taken from /Eckerman and Legget 1996/ for the case of homogeneous distribution of the radionuclide in a soil layer of infinite depth. /Eckerman and Legget 1996/ provide values even for other radionuclide distributions in soil: surface contamination, homogeneous distribution in 0.01 m, 0.05 m and 0.15 m layers (see Table A-3 in the Appendix). All values were derived from calculations for a typical silt soil with a density of 1,600 kg/m^3, 20 % air and 30 % water content reported in /Eckerman and Ryman 1993/ taking into account the latest values of tissue weighting factors recommended by /ICRP 1996/.

The dose coefficients for external exposure that have been used by SKB and Posiva in safety assessments performed before 2006 were based on values reported in /Svensson 1979/. These values have also been used in calculations of conversion factors relating unit releases to dose used in assessments of doses to the critical group from atmospheric releases by Swedish nuclear facilities /Bergström et al. 2001/. The values reported in /Svensson 1979/ for homogenous distribution of activity in soil were compared to those reported in /Eckerman and Legget 1996/ (see Table A-4 in the Appendix). For most radionuclides the values agree within a factor of 3. For a few radionuclides, Sm-151, Po-210, U-234 and Pu-238, the values in /Eckerman and Legget 1996/ were up-to 300 times lower. However, these radionuclides have low energies and give low external exposure doses and therefore have low values of the dose conversion coefficient.

Table 5-1. Recommended dose coefficients (Sv/h per Bq/m^3) for external exposure taken from /Eckerman and Legget 1996/. The values are based on the case of homogeneous distribution in soil (see Table A-3 in the Appendix).

Nuclide	DCC
H-3	–0.0E+00
Be-10	1.9E–17
C-14	2.1E–19
Cl-36	4.8E–17
Ca-41	0.0E+00
Co-60	3.0E–13
Ni-59	0.0E+00
Ni-63	0.0E+00
Se-79	3.0E–19
Sr-90	1.2E–17
Zr-93	0.0E+00
Nb-94	1.8E–13
Mo-93	8.0E–18
Tc-99	2.1E–18
Ag-108m	1.7E–13
I-129	1.8E–16
Cs-134	1.7E–13
Cs-135	6.2E–19
Cs-137	6.5E–14
Sm-151	1.3E–20
Eu-152	1.3E–13
Eu-154	1.4E–13
Eu-155	3.1E–15
Ho-166m	1.9E–13
Pb-210	3.8E–17
Po-210	9.5E–19
Rn-222	4.2E–17
Ra-226	5.6E–16
Ac-227	8.6E–18
Th-229	5.6E–15
Th-230	2.1E–17
Th-232	8.8E–18
Pa-231	3.4E–15
U-233	2.4E–17
U-234	6.6E–18
U-235	1.3E–14
U-236	3.4E–18
U-238	1.5E–18
Np-237	1.3E–15
Pu-238	2.2E–18
Pu-239	5.1E–18
Pu-240	2.2E–18
Pu-241	1.0E–19
Pu-242	1.9E–18
Am-241	7.2E–16
Am-242m	2.8E–17
Am-243	2.4E–15
Cm-244	1.7E–18
Cm-245	5.9E–15
Cm-246	1.6E–18

6 Implementation in Pandora

The methodology for dose calculation was implemented in Pandora /Åstrand et al. 2005/, which is the tool used by SKB and Posiva for biosphere modelling in safety assessment of radioactive waste repositories. Figure 6-1 provides an overview of the implementation in Pandora of the calculation of doses from ingestion of water (Equation 1), ingestion of food (Equation 2), inhalation (Equation 3) and external exposure (Equation 4).

The Pandora Function block (grey rectangles) is the basic building block used in the implementation, where the corresponding equation is evaluated using the inputs and parameter values. The green ellipses represent inputs, which can be signals coming from other Pandora blocks, or any Matlab/Simulink© (www.mathworks.com) block. Two types of parameters are used: (i) radionuclide specific, such as the DCC and (ii) element independent parameters such as the Intake Rate of Carbon. The dimension of the radionuclide specific parameters is controlled by the Pandora Radionuclide Manager, which facilitates simulating multiple radionuclides in a biosphere model. The outputs (red ellipses) are signals, which dimensions depend on the dimensions of the corresponding inputs. The output signals can be used in other blocks for further calculations.

The function blocks and their corresponding outputs, together with the needed input and parameters, can be used in any sub-model to produce "local" dose values, for example for an ecosystem or object of the landscape. The local dose values can be further combined with each other, for example for estimating doses from exposure to several landscape objects.

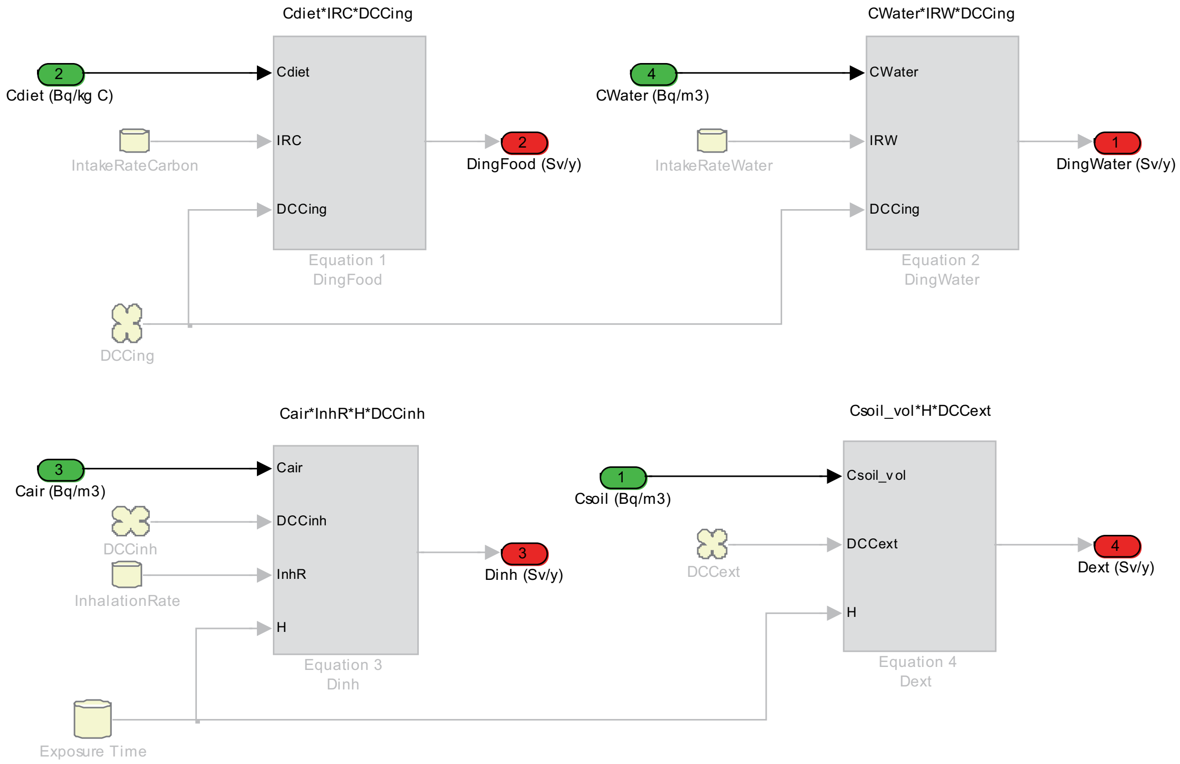

Figure 6-1. Overview of the implementation in Pandora of the methodology for dose calculations.

7 Concluding remarks

The report presents a revised methodology valid for calculation of doses from exposures to radionuclides in the environment starting from radionuclide concentrations in environmental media, air, water, food and soil. The methodology considers the main exposure pathways that may arise from a continuous input of radionuclides into the biosphere with contaminated groundwater, which is the release scenario of most relevance for the safety assessment of geologic repositories. The report also describes the methodology implementation in Pandora, which is the tool currently used by SKB and Posiva for biosphere modelling.

Revised recommended values are provided for all required parameters taking into account the latest recommendations of the ICRP, the EU and the competent national authorities. Cautious, but still realistic values are recommended for the parameters. The dose estimations obtained using these values, can then be considered pessimistic, but still realistic lifetime dose estimates in most relevant exposure situations. An exception might be the case of exposure via inhalation to isotopes of nuclides that can be in gas form, such as iodine and radon. For this case, exposure indoors may give higher doses, than outdoor exposures, as assumed in the methodology. This exposure pathway requires further investigation.

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Appendix 1

Table A-1. Summary of physiological data extracted from ICRP recommendations /ICRP 1975, 2004/.

Parameter	Males	Females
Water intake in food and fluids (ml/day)	2,600	1,960
Water produced from oxidation of food (ml/day)	300	225
Water intake with milk (ml/day)	300	200
Tap water intake (ml/day)	150	100
Water intake with other fluids (ml/day)	1,500	1,100
Water intake with free water in food (ml/day)	700	450
Total energy expenditure (kcal/day)		
New born	500	500
1 year	800	750
5 years	1,600	1,400
10 years	1,900	1,700
15 years	2,400	1,800
adult	2,800	1,800
Protein intake by adults (kg/day)	0.095	0.066
Carbohydrate intake by adults (kg/day)	0.39	0.27
Fat intake by adults (kg/day)	0.12	0.08
Daily air intake (m^3/day)		
3 months	2.8	2.8
1 year	5.1	5.1
5 years	8.8	8.8
10 years	15.2	15.2
15 years	20.1	15.8
adult	22.2	18.2

Table A-2. Committed effective dose coefficients (Sv/Bq) for inhalation given for various ages and classes of absorption: F, M and S (Fast, Moderate or Slow absorption in the lung). The highest value across classes of absorption in each age group are marked bold /EUR 1996/.

Nuclide	Adult Class S	Adult Class M	Adult Class F	1–2 y Class S	1–2 y Class M	1–2 y Class F	2–7 y Class S	2–7 y Class M	2–7 y Class F	7–12 y Class S	7–12 y Class M	7–12 y Class F	12–17 y Class S	12–17 y Class M	12–17 y Class F
H-3	**2.6E–10**	4.5E–11	6.2E–11	**1.0E–09**	2.7E–10	2.0E–11	**6.3E–10**	1.4E–10	1.1E–11	**3.8E–10**	8.2E–11	8.2E–12	**2.8E–10**	5.3E–11	5.9E–11
Be-10	**3.5E–08**	9.6E–09		**9.1E–08**	3.4E–10		**6.1E–08**	2.0E–08		**4.2E–08**	1.3E–08		**3.7E–08**	1.1E–08	
C-14	**5.8E–09**	2.0E–09	2.0E–10	**1.7E–08**	6.6E–09	6.7E–10	**1.1E–08**	4.0E–09	3.6E–10	**7.4E–09**	2.8E–09	2.9E–10	**6.4E–09**	2.5E–09	1.9E–10
Cl-36		**7.3E–09**	3.3E–10		**2.6E–08**	2.6E–09		**1.5E–08**	1.1E–09		**1.0E–08**	7.1E–10		**8.8E–09**	3.9E–10
Ca-41	**1.8E–10**	9.5E–11	1.7E–10	**6.0E–10**	2.6E–10	3.8E–10	**3.8E–10**	1.7E–10	2.6E–10	2.4E–10	1.7E–10	**3.3E–10**	1.9E–10	1.6E–10	**3.3E–10**
Co-60	**3.1E–08**	1.0E–08	5.2E–09	**8.6E–08**	3.4E–08	2.3E–08	**5.9E–08**	2.1E–08	1.4E–08	**4.0E–08**	1.5E–08	8.9E–09	**3.4E–08**	1.2E–08	6.1E–09
Ni-59	**4.4E–10**	1.3E–10	1.8E–10	**1.5E–09**	6.2E–10	8.1E–10	**9.5E–10**	3.4E–10	4.4E–10	**5.9E–10**	2.1E–10	2.8E–10	**4.6E–10**	1.4E–10	1.9E–10
Ni-63	**1.3E–09**	4.8E–10	4.4E–10	**4.3E–09**	1.9E–09	2.0E–09	**2.7E–09**	1.1E–09	1.1E–09	**1.7E–09**	7.0E–10	6.7E–10	**1.3E–09**	5.3E–10	4.6E–10
Se-79	**6.8E–09**	2.6E–09	1.1E–09	**2.0E–08**	1.1E–08	1.3E–08	**1.3E–08**	6.9E–09	7.7E–09	**8.7E–09**	4.9E–09	5.6E–09	**7.6E–09**	3.3E–09	1.5E–09
Sr-90	**1.6E–07**	3.6E–08	2.4E–08	**4.0E–07**	1.1E–07	5.2E–08	**2.7E–07**	6.5E–08	3.1E–08	**1.8E–07**	5.1E–08	4.1E–08	1.6E–07	5.0E–08	5.3E–08
Zr-93	3.3E–09	1.0E–08	**2.5E–08**	6.4E–09	3.1E–09	**4.8E–09**	4.5E–09	2.8E–09	**5.3E–09**	3.3E–09	4.1E–09	**9.7E–09**	3.3E–09	7.5E–09	**1.8E–08**
Nb-94	**4.9E–08**	1.1E–07	5.8E–09	**1.2E–07**	3.7E–08	2.7E–08	**8.3E–08**	2.3E–08	1.5E–08	**5.8E–08**	1.6E–08	1.0E–08	**5.2E–08**	1.3E–08	6.7E–09
Mo-93	**2.3E–09**	5.9E–10	1.0E–09	**5.8E–09**	1.8E–09	2.6E–09	**4.0E–09**	1.1E–09	1.7E–09	**2.8E–09**	7.9E–10	1.3E–09	**2.4E–09**	6.6E–10	1.1E–09
Tc-99	**1.3E–08**	4.0E–09	2.9E–10	**3.7E–08**	1.3E–08	2.5E–09	**2.4E–08**	8.0E–09	1.0E–09	**1.7E–08**	5.7E–09	5.9E–10	**1.5E–08**	5.0E–09	3.6E–10
Pd-107	**5.9E–10**	8.5E–11	2.5E–11	**2.0E–09**	5.0E–10	1.8E–10	**1.3E–09**	2.6E–10	8.2E–11	**7.8E–10**	1.5E–10	5.2E–11	**6.2E–10**	1.0E–10	3.1E–11
Ag-108m	**3.7E–08**	7.4E–09	6.1E–09	**8.7E–08**	2.7E–08	2.8E–08	**6.2E–08**	1.7E–08	1.6E–08	**4.4E–08**	1.1E–8	1.0E–08	**3.9E–08**	8.6E–09	6.9E–09
I-129*	9.8E–09	1.5E–08	**3.6E–08**	2.6E–08	3.3E–08	**8.6E–08**	1.8E–08	2.4E–08	**6.1E–08**	1.3E–08	2.4E–08	**6.7E–08**	1.1E–08	1.9E–08	**4.6E–08**
Cs-134	**2.0E–08**	9.1E–09	6.6E–09	**6.3E–08**	2.6E–08	7.3E–09	**4.1E–08**	1.6E–08	5.2E–09	**2.8E–08**	1.2E–08	5.3E–09	**2.3E–08**	1.1E–08	6.3E–09
Cs-135	**8.6E–09**	3.1E–09	6.9E–10	**2.4E–08**	9.3E–09	9.9E–10	**1.6E–08**	5.7E–09	6.2E–10	**1.1E–08**	4.1E–09	6.1E–10	**9.5E–09**	3.8E–09	6.8E–10
Cs-137	**3.9E–08**	9.7E–09	4.6E–09	**1.0E–07**	2.9E–08	5.4E–09	**7.0E–08**	1.8E–08	3.6E–09	**4.8E–08**	1.4E–08	3.7E–09	**4.2E–08**	1.1E–08	4.4E–09
Sm-151		4.0E–09			1.0E–08			6.7E–09			4.5E–09			4.0E–09	
Eu-152		4.2E–08			1.0E–07			7.0E–08			4.9E–08			4.3E–08	
Eu-154		5.3E–08			1.5E–07			9.7E–08			6.5E–08			5.6E–08	
Eu-155		6.9E–09			2.3E–08			1.4E–08			9.2E–09			7.6E–09	
Ho-166m		1.2E–07			2.5E–07			1.8E–07			1.3E–07			1.2E–07	
Pb-210	**5.6E–06**	1.1E–06	9.0E–07	**1.8E–05**	3.7E–06	2.9E–06	**1.1E–05**	2.2E–06	1.5E–06	**7.2E–06**	1.5E–06	1.4E–06	**5.9E–06**	1.3E–06	1.3E–06

Nuclide	Adult Class S	Adult Class M	Adult Class F	1–2 y Class S	1–2 y Class M	1–2 y Class F	2–7 y Class S	2–7 y Class M	2–7 y Class F	7–12 y Class S	7–12 y Class M	7–12 y Class F	12–17 y Class S	12–17 y Class M	12–17 y Class F
Po-210	**4.3E–06**	3.3E–06	6.1E–07	**1.4E–05**	1.1E–05	4.8E–06	**8.6E–06**	6.7E–06	2.2E–06	**5.9E–06**	4.6E–06	1.3E–06	**5.1E–06**	4.0E–06	7.7E–07
Ra-226	**9.5E–06**	3.5E–06	3.6E–07	**2.9E–05**	1.1E–05	9.4E–07	**1.9E–05**	7.0E–06	5.5E–07	1.2E–05	4.9E–06	**7.2E–07**	**1.0E–05**	4.5E–06	1.3E–06
Ac-227	7.2E–05	2.2E–04	**5.5E–04**	2.0E–04	5.5E–04	**1.6E–03**	1.3E–04	3.9E–04	**1.0E–03**	8.7E–05	2.6E–04	**7.2E–04**	7.6E–05	2.3E–04	**5.6E–04**
Th-229	7.1E–05	1.1E–04	**2.4E–04**	1.9E–04	2.1E–04	**5.1E–04**	1.3E–04	1.6E–04	**3.6E–04**	8.7E–05	1.2E–04	**2.9E–04**	7.6E–05	1.1E–04	**2.4E–04**
Th-230	1.4E–05	4.3E–05	**1.0E–04**	3.5E–05	7.4E–05	**2.0E–04**	2.4E–05	5.5E–05	**1.4E–04**	1.6E–05	4.3E–05	**1.1E–04**	1.5E–05	4.2E–05	**9.9E–05**
Th-232	2.5E–05	4.5E–05	**1.1E–04**	5.0E–05	8.1E–05	**2.2E–04**	3.7E–05	6.3E–05	**1.6E–04**	2.6E–05	5.0E–05	**1.3E–04**	2.5E–05	4.7E–05	**1.2E–04**
Pa-231	3.4E–05	**1.4E–04**		6.9E–05	**2.3E–04**		5.2E–05	**1.9E–04**		3.9E–05	**1.5E–04**		3.6E–05	**1.5E–04**	
U-233	**9.6E–06**	3.6E–06	5.8E–07	**3.0E–05**	1.1E–05	1.4E–06	**1.9E–05**	7.2E–06	9.4E–07	**1.2E–05**	4.9E–06	8.4E–07	**1.1E–05**	4.3E–06	8.6E–07
U-234	**9.4E–06**	3.5E–06	5.6E–07	**2.9E–05**	1.1E–05	1.4E–06	**1.9E–05**	7.0E–06	9.0E–07	**1.2E–05**	4.8E–06	8.0E–07	**1.0E–05**	4.2E–06	8.2E–07
U-235	**8.5E–06**	3.1E–06	5.2E–07	**2.6E–05**	1.0E–05	1.3E–06	**1.7E–05**	6.3E–06	8.5E–07	**1.1E–05**	4.3E–06	7.5E–07	**9.2E–06**	3.7E–06	7.7E–07
U-236	**8.7E–06**	3.2E–06	5.3E–07	**2.7E–05**	1.0E–05	1.3E–06	**1.8E–05**	6.5E–06	8.5E–07	**1.1E–05**	4.5E–06	7.5E–07	**9.5E–06**	3.9E–06	7.8E–07
U-238	**8.0E–06**	2.9E–06	**5.0E–07**	**2.5E–05**	9.4E–06	1.3E–06	**1.6E–05**	5.9E–06	8.2E–07	**1.0E–05**	4.0E–06	7.3E–07	**8.7E–06**	3.4E–06	7.4E–07
Np-237	1.2E–05	2.3E–05	**5.0E–05**	3.2E–05	4.0E–05	**9.3E–05**	2.1E–05	2.8E–05	**6.0E–05**	1.4E–05	2.2E–05	**5.0E–05**	1.3E–05	2.2E–05	**4.7E–05**
Pu-238	1.6E–05	4.6E–05	**1.1E–04**	4.0E–05	7.4E–05	**1.9E–04**	2.7E–05	5.6E–05	**1.4E–04**	1.9E–05	4.4E–05	**1.1E–04**	1.7E–05	4.3E–05	**1.0E–04**
Pu-239	1.6E–05	5.0E–05	**1.2E–04**	3.9E–05	7.7E–05	**2.0E–04**	2.7E–05	6.0E–05	**1.5E–04**	1.9E–05	4.8E–05	**1.2E–04**	1.7E–05	4.7E–05	**1.1E–04**
Pu-240	1.6E–05	5.0E–05	**1.2E–04**	3.9E–05	7.7E–05	**2.0E–04**	2.7E–05	6.0E–05	**1.5E–04**	1.9E–05	4.8E–05	**1.2E–04**	1.7E–05	4.7E–05	**1.1E–04**
Pu-241	1.7E–07	9.0E–07	**2.3E–06**	2.3E–07	9.7E–07	**2.9E–06**	2.0E–07	9.2E–07	**2.6E–06**	1.7E–07	8.3E–07	**2.4E–06**	1.7E–07	8.6E–07	**2.2E–06**
Pu-242	1.5E–05	4.8E–05	**1.1E–04**	3.6E–05	7.3E–05	**1.9E–04**	2.5E–05	5.7E–05	**1.4E–04**	1.7E–05	4.5E–05	**1.2E–04**	1.6E–05	4.5E–05	**1.1E–04**
Am-241	1.6E–05	4.2E–05	**9.6E–05**	4.0E–05	6.9E–05	**1.8E–04**	2.7E–05	5.1E–05	**1.2E–04**	1.9E–05	4.0E–05	**1.0E–04**	1.7E–05	4.0E–05	**9.2E–05**
Am-242m	1.1E–05	3.7E–05	**9.2E–05**	2.4E–05	5.3E–05	**1.5E–04**	1.7E–05	4.1E–05	**1.1E–04**	1.2E–05	3.4E–05	**9.4E–05**	1.1E–05	3.5E–05	**8.8E–05**
Am-243	1.5E–05	4.1E–05	**9.6E–05**	3.9E–05	6.8E–05	**1.7E–04**	2.6E–05	5.0E–05	**1.2E–04**	1.8E–05	4.0E–05	**1.0E–04**	1.6E–05	4.0E–05	**9.1E–05**
Cm-244	1.3E–05	2.7E–05	**5.7E–05**	3.8E–05	5.7E–05	**1.3E–04**	2.5E–05	3.7E–05	**8.3E–05**	1.7E–05	2.7E–05	**6.1E–05**	1.5E–05	2.6E–05	**5.3E–05**
Cm-245	1.6E–05	4.2E–05	**9.9E–05**	4.0E–05	6.9E–05	**1.8E–04**	2.7E–05	5.1E–05	**1.2E–04**	1.9E–05	4.1E–05	**1.0E–04**	1.7E–06	4.1E–05	**9.4E–05**
Cm-246	1.6E–05	4.2E–05	**9.8E–05**	4.0E–05	6.9E–05	**1.8E–04**	2.7E–05	5.1E–05	**1.2E–04**	1.9E–05	4.1E–05	**1.0E–04**	1.7E–06	4.1E–05	**9.4E–05**

* For I-129 the value given for adults (9.6E–8 Sv/Bq) refers to the soluble gas form.

Table A-3. External dose coefficients for different distributions of activity in soil /Eckerman and Legget 1996/.

Nuclide	Surface (Sv/h per Bq/m^2)	0.01 m depth (Sv/h per Bq/m^3)	0.05 m depth (Sv/h per Bq/m^3)	0.15 m depth (Sv/h per Bq/m^3)	Homogenous distribution (Sv/h per Bq/m^3)
H-3	–	–	–	–	–
Be-10	1.2E–14	7.1E–18	1.5E–17	1.9E–17	1.9E–17
C-14	4.6E–17	1.2E–19	2.0E–19	2.1E–19	2.1E–19
Cl-36	4.0E–14	1.8E–17	3.5E–17	4.6E–17	4.8E–17
Ca-41	–	–	–	–	–
Co-60	8.3E–12	5.3E–14	1.5E–13	2.5E–13	3.0E–13
Ni-59	–	–	–	–	–
Ni-63	–	–	–	–	–
Se-79	5.9E–17	1.7E–19	2.7E–19	2.9E–19	2.9E–19
Sr-90	5.9E–15	4.5E–18	9.8E–18	1.2E–17	1.2E–17
Zr-93	–	–	–	–	–
Nb-94	5.4E–12	3.4E–14	9.8E–14	1.5E–13	1.8E–13
Mo-93	1.4E–14	8.1E–18	8.0E–18	8.0E–18	8.0E–18
Tc-99	2.3E–16	9.0E–19	1.8E–18	2.1E–18	2.1E–18
Pd-107	–	–	–	–	–
Ag-108m	5.6E–12	3.5E–14	1.0E–13	1.6E–13	1.7E–13
I-129	7.0E–14	1.6E–16	1.8E–16	1.8E–16	1.8E–16
Cs-134	5.3E–12	3.4E–14	9.7E–14	1.5E–13	1.7E–13
Cs-135	9.7E–17	3.1E–19	5.6E–19	6.2E–19	6.2E–19
Cs-137	1.1E–14	7.5E–18	1.3E–17	1.6E–17	1.6E–17
Sm-151	1.3E–17	1.3E–20	1.3E–20	1.3E–20	1.3E–20
Eu-152	3.9E–12	2.4E–14	6.9E–14	1.1E–13	1.3E–13
Eu-154	4.2E–12	2.6E–14	7.6E–14	1.2E–13	1.4E–13
Eu-155	1.9E–13	1.1E–15	2.5E–15	3.1E–15	3.1E–15
Ho-166m	5.9E–12	3.7E–14	1.1E–13	1.7E–13	1.9E–13
Pb-210	7.7E–15	2.4E–17	3.8E–17	3.8E–17	3.8E–17
Po-210	2.9E–17	1.8E–19	5.3E–19	8.3E–19	9.5E–19
Rn-222	1.4E–15	8.7E–18	2.5E–17	3.8E–17	4.2E–17
Ra-226	2.2E–14	1.4E–16	3.9E–16	5.4E–16	5.6E–16
Ac-227	5.1E–16	2.5E–18	6.5E–18	8.5E–18	8.6E–18
Th-229	2.8E–13	1.7E–15	4.2E–15	5.5E–15	5.6E–15
Th-230	2.3E–15	7.4E–18	1.7E–17	2.0E–17	2.1E–17
Th-232	1.6E–15	3.6E–18	7.4E–18	8.7E–18	8.8E–18
Pa-231	1.4E–13	7.8E–16	2.2E–15	3.2E–15	3.4E–15
U-233	2.2E–15	7.0E–18	1.7E–17	2.4E–17	2.4E–17
U-234	2.1E–15	3.0E–18	5.6E–18	6.6E–18	6.6E–18
U-235	5.0E–13	3.2E–15	8.8E–15	1.2E–14	1.3E–14
U-236	1.8E–15	1.9E–18	3.0E–18	3.4E–18	3.4E–18
U-238	1.5E–15	1.2E–18	1.5E–18	1.5E–18	1.5E–18
Np-237	9.1E–14	4.5E–16	1.1E–15	1.3E–15	1.3E–15
Pu-238	2.3E–15	1.7E–18	2.1E–18	2.2E–18	2.2E–18
Pu-239	1.0E–15	1.7E–18	3.6E–18	4.9E–18	5.1E–18
Pu-240	2.2E–15	1.7E–18	2.0E–18	2.2E–18	2.2E–18
Pu-241	6.2E–18	3.2E–20	7.9E–20	1.0E–19	1.0E–19
Pu-242	1.8E–15	1.4E–18	1.8E–18	1.9E–18	1.9E–18
Am-241	8.4E–14	3.5E–16	6.7E–16	7.2E–16	7.2E–16
Am-242m	8.1E–15	1.2E–17	2.3E–17	2.8E–17	2.8E–17
Am-243	1.7E–13	9.5E–16	2.1E–15	2.4E–15	2.4E–15
Cm-244	2.3E–15	1.7E–18	1.7E–18	1.7E–18	1.7E–18
Cm-245	2.9E–13	1.7E–15	4.5E–15	5.9E–15	5.9E–15
Cm-246	2.1E–15	1.5E–18	1.6E–18	1.6E–18	1.6E–18

Table A-4. Comparison of external dose coefficients (Sv/h per Bq/m^3) reported in /Svensson 1979/ with values reported in /Eckerman and Legget 1996/ for the case of homogeneous radionuclide distribution in soil.

Nuclide	Eckerman and Legget A	Svensson B	A/B
H-3	–	–	–
Be-10	1.9E–17	–	–
C-14	2.1E–19	–	–
Cl-36	4.8E–17	–	–
Ca-41	–	–	–
Co-60	3.0E–13	2.8E–13	1.1
Ni-59	–	1.3E–15	–
Se-79	3.0E–19	–	–
Sr-90	1.2E–17	–	–
Zr-93	0.0E+00	–	–
Nb-94	1.8E–13	1.6E–13	1.1
Mo-93	8.0E–18	–	–
Tc-99	2.1E–18	1.9E–18	1.1
Ag-108m	1.7E–13	1.6E–13	1.1
I-129	1.8E–16	3.4E–16	0.5
Cs-134	1.7E–13	1.6E–13	1.1
Cs-135	6.2E–19	–	–
Cs-137	6.5E–14	5.6E–14	1.2
Sm-151	1.3E–20	4.6E–18	0.003
Eu-152	1.3E–13	1.5E–13	0.85
Eu-154	1.4E–13	1.3E–13	1.1
Eu-155	3.1E–15	3.9E–15	0.80
Ho-166m	1.9E–13	1.6E–13	1.2
Pb-210	3.8E–17	7.2E–17	0.53
Po-210	9.5E–19	2.7E–17	0.035
Rn-222	4.2E–17	–	–
Ra-226	5.6E–16	6.0E–16	0.94
Ac-227	8.6E–18	–	–
Th-229	5.6E–15	2.0E–15	2.8
Th-230	2.1E–17	3.5E–17	0.59
Th-232	8.8E–18	1.5E–17	0.59
Pa-231	3.4E–15	1.8E–15	1.9
U-233	2.4E–17	5.9E–17	0.41
U-234	6.6E–18	3.1E–17	0.21
U-235	1.3E–14	1.1E–14	1.2
U-236	3.4E–18	–	–
U-238	1.5E–18	–	–
Np-237	1.3E–15	1.8E–15	0.74
Pu-238	2.2E–18	1.3E–17	0.17
Pu-239	5.1E–18	6.6E–18	0.77
Pu-240	2.2E–18	–	–
Pu-241	1.0E–19	–	–
Pu-242	1.9E–18	–	–
Am-241	7.2E–16	1.1E–15	0.65
Am-242m	2.8E–17	1.5E–17	1.8
Am-243	2.4E–15	2.9E–15	0.8
Cm-244	1.7E–18	–	–
Cm-245	5.9E–15	2.3E–15	2.6
Cm-246	1.6E–18	–	–