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Recommendations on Dose Coefficients for Assessing Doses from Accidental Radionuclide Releases to the Environment

Prepared by a
Joint Working Group of
Radiation Protection Bureau, Health Canada
Atomic Energy Control Board
Atomic Energy of Canada Limited

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NOTICE to holders of the August 1998 version:

The following typographical corrections have been made:

Table 2:
Caesium
Cs-134 Adult inhalation dose coefficient has been corrected to read 6.6e-09 Sv Bq^{-1}

Americium
Am-241 3-months inhalation dose coefficient has been corrected to read 7.3e-05 Sv Bq^{-1}
Am-243 3-months inhalation dose coefficient has been corrected to read 7.2e-05 Sv Bq^{-1}

Abstract

This report summarises the recommendations of a Joint Working Group comprising representatives from the Radiation Protection Bureau of Health Canada, the Atomic Energy Control Board (AECB), and Atomic Energy of Canada Limited (AECL) on standard dose assessment parameters for use in Canada.

In 1990, the International Commission on Radiological Protection issued new recommendations on basic radiation protection principles (ICRP 1991). Changes to the terminology and formulation for assessing the health detriment from radiation exposure have a direct impact on the derivation of dose coefficients used in radiological protection and dose assessment. The objectives of the Working Group were to review published human physiological parameters and dose coefficients consistent with the latest ICRP guidance and to recommend default values for use in dose projections and assessments. The goal is to make the information widely available for use by various federal and provincial government agencies responsible for radiation protection in Canada, and by Canadian nuclear utilities and facilities, thereby providing a degree of standardisation reflecting the latest scientific knowledge.

This document contains the recommendations of the Working Group on appropriate human physiological and dosimetric parameters for use in assessing doses in the short-term following an accidental release of radioactive contamination to the atmosphere during a nuclear emergency. It focusses on the exposure pathways expected to deliver the greatest radiation dose under this scenario, namely, external irradiation by photons and electrons from radionuclides in the plume or deposited on the ground, and internal irradiation following inhalation of airborne radionuclides. Specifically, this document provides:

- age groups and recommended age-specific breathing rates for assessment of Canadian populations;
- recommended age-specific effective dose coefficients for internal exposures from inhalation, and external exposures from contaminated air and ground surfaces for all radionuclides of interest; and
- guidance on the use of the data

The ICRP has recently published age-specific breathing rates and inhalation dose coefficients for six age groups covering infants to adults (ICRP 1994, 1995b, 1996). The Working Group recommends the use of these parameters as default values in the assessment of inhalation doses from airborne radionuclides.

Radionuclide-specific dose coefficients for external irradiation from radionuclides distributed in the environment have not yet been published by the ICRP. As a result, the Working Group concentrated its effort on the review of published compilations of dose coefficients for cloudshine and groundshine exposures that incorporated the latest ICRP risk formulations for the assessment of health detriment. The Working Group concluded that the dose coefficients of Eckerman and Legett (1996) represented the best values currently available for cloudshine and groundshine dose

assessments. An extensive list of these external dose coefficients has been reproduced in this document.

The dose assessment parameters recommended in this report should be used as default values in the evaluation of the three critical pathways associated with accidental releases from nuclear facilities, or other radiological accident scenarios. These parameters are also applicable to non-emergency situations, notwithstanding that exposure scenarios and methodologies for calculating doses may be different. Modifying factors accounting for exposure scenarios that are different from those applicable to the default parameters were beyond the scope of this report, although these should be used where appropriate.

This report does not deal with the methodologies used to derive the environmental radionuclide concentrations from which doses are calculated. Other aspects of dose assessment, such as recommendations on modelling approaches or environmental parameters, were also beyond the scope of the Working Group.

Acknowledgements

The Working Group is indebted to Dr. Keith Eckerman of the Dosimetry Research Group, Oak Ridge National Laboratory, Oak Ridge, Tennessee, for granting permission to reproduce the external dose coefficients from DCFPAK (ORNL/TM-13347) in this document.

Comments or suggestions concerning this report should be sent to:

Chair, Working Group on Dose Assessment Parameters
Radiation Protection Bureau, Health Canada
Environmental Radiation Hazards Division, AL6302D1
775 Brookfield Rd.
Ottawa, Ontario K1A 1C1

Table of Contents

Abstract i

Acknowledgements ii

INTRODUCTION 1
Calculation of Dose from Atmospheric Releases of Radionuclides 2

DOSIMETRIC QUANTITIES 3

EXPOSURE PATHWAYS 5
Internal Exposure from Inhalation of Radionuclides in the Plume 5
Human Physiological Parameters 5
Inhalation Dose Coefficients 6
External Exposure from Radionuclides in the Plume and on the Ground 6
Dose Coefficients from Macdonald and Laverlock (1996) 7
Dose Coefficients from Eckerman and Legett (1996) 8
Comparison of the Macdonald - Laverlock and Eckerman - Leggett Data Sets 9
Figure 1 Frequency distributions of DC_{EL}:DC_{ML} for cloudshine and groundshine dose coefficients 9
Figure 2 Ratio of DC_{EL}:DC_{ML} versus DC_{EL} 10
Effect of Gender and Age on External Dose Coefficients 10
Other Modifying Factors 11

SUMMARY OF RECOMMENDED ASSESSMENT PARAMETERS 12
Table 1 Recommended breathing rates for the six ICRP age groups 13
Table 2 Recommended effective dose coefficients for internal and external exposures to selected radionuclides 14

REFERENCES 17

Appendix A: Working Group Membership 19

Appendix B: Considerations for Radionuclide Decay Chains and Example Calculations 20

Appendix C: Compilation of External Dose Rate Coefficients for Cloudshine and Groundshine 24

RECOMMENDATIONS ON DOSE COEFFICIENTS FOR ASSESSING DOSES FROM ACCIDENTAL RADIONUCLIDE RELEASES TO THE ENVIRONMENT

INTRODUCTION

In February 1997, a Joint Working Group comprising representatives from the Radiation Protection Bureau of Health Canada (RPB), the Atomic Energy Control Board (AECB), and Atomic Energy of Canada Limited (AECL) was established to review and recommend a standard set of human physiological parameters and dose coefficients for radiation dose assessments in Canada. The impetus for this work arose out of separate initiatives on the part of RPB and the AECB to incorporate this information into models for assessing public doses arising from routine and accidental releases of radioactivity to the environment. It was realised that there were significant advantages to ensuring that common data, where applicable, were used in these models, and that these reflected the latest recommendations of the International Commission on Radiological Protection (ICRP 1991). After initial discussions, the decision was made to limit the scope of work to parameters directly applicable to assessments in the short-term period following a nuclear emergency, on account of methodological differences between short-term accidental and long-term chronic exposure assessments (although some relevance will be found for the latter situation). The Joint Working Group membership is given in Appendix A.

This document contains the recommendations of the Working Group on appropriate human physiological and dosimetric parameters for use in assessing doses in the short-term following a release of radioactivity to the atmosphere during a nuclear emergency. Specifically, this document provides:

- age groups and recommended age-specific breathing rates for assessment of Canadian populations;
- recommended age-specific effective dose coefficients for internal exposures from inhalation, and external exposures from contaminated air and ground surfaces for all radionuclides of interest; and
- guidance on the use of the data

Due to the absence of an internationally recognised compilation of external dose coefficients for radionuclides distributed in the environment, the Working Group focussed its attention on the review of published collections of dose coefficients for cloudshine and groundshine exposures that incorporated the latest ICRP risk formulations for the assessment of health detriment.

In presenting its recommendations, the Working Group recognises the widespread use of guidance issued by the Canadian Standards Association in its N288 series of documents on Environmental Radiation Protection (CSA 1987, 1991). While not intended as a replacement to these documents, it is the aim of the Working Group that the recommendations in this report serve as a common source of updated parameters for the relevant aspects of dose assessment contained in the CSA guidelines.

Values recommended in this report are applicable to dose calculations for accidental releases from nuclear facilities, or other radiological accident scenarios. While calculational aspects of dose assessments for routine and emergency situations may differ, the breathing rates and dose coefficients recommended in this report are applicable to both types of assessments.

Calculation of Dose from Atmospheric Releases of Radionuclides

Following a release of radioactive material to the environment under either routine or accidental conditions, irradiation of members of the public can occur by a number of exposure pathways. These include immersion in radioactive airborne plumes or contaminated water, inhalation of airborne radioactivity, irradiation from deposited radionuclides and inhalation following their resuspension into the air, and ingestion of contaminated food and water. This report focusses on the assessment of those pathways expected to deliver the greatest radiation dose in the short-term following an accidental atmospheric release of radioactive contamination to the environment, namely, external irradiation by photons and electrons from radionuclides in the plume or deposited on the ground, and internal irradiation following inhalation of airborne radionuclides. These routes of exposure are typically referred to as the cloudshine, groundshine, and inhalation pathways.

Exposure to external irradiation from airborne radionuclides occurs only during the passage of the plume. The exposure period depends on the duration of the release, the meteorological conditions, and the residence times of the exposed individuals. Material deposited on the ground can give rise to exposures both during and after the passing of the plume. Radioactive material inhaled by individuals immersed in the plume can be retained in the body, and give rise to internal irradiation over a protracted period of time.

Under idealised exposure conditions, the effective dose rate to an exposed individual from external sources, $E_{ext}(t)$ (Sv s^{-1}), can generally be expressed as

$$E_{ext}(t) = \chi(t) \times DC_{ext} \qquad (1)$$

where $\chi(t)$ is the radionuclide activity concentration at time t in the air or deposited on the ground surface (Bq m^{-3} or Bq m^{-2}, respectively), and DC_{ext} is the instantaneous external dose rate factor per activity concentration, or the external dose coefficient for the given radionuclide (Sv s^{-1} Bq^{-1} m^3 for cloudshine; Sv s^{-1} Bq^{-1} m^2 for groundshine).

For inhalation doses, the committed effective dose rate (Sv s^{-1}) is given by

$$E_{int}(t) = \chi(t) \times B \times DC_{int} \qquad (2)$$

where $\chi(t)$ is the concentration in air, B is the *ventilation*, or breathing rate of the individual (m^3 s^{-1}), and DC_{int} is the dose coefficient per unit intake of inhaled radioactivity, or the inhalation dose coefficient (Sv Bq^{-1}). The radionuclide concentration is determined from environmental measurements, or predicted from environmental models.

This report focusses on the human physiological data and dose coefficients used in the above equations, namely the age-dependent effective dose coefficients for internal and external exposures, and age-dependent breathing rates. Methodologies for calculating activity concentrations in the various environmental media were beyond the scope of the Working Group.

This report does not address the ingestion pathway, and ingestion dose coefficients are not included, as the control of exposures due to the consumption of contaminated food and water, while potentially significant in some instances, is generally not considered urgent immediately following a radiological accident. If doses from the ingestion of contaminated food and water are assessed, ingestion dose coefficients from ICRP Publication 72 (1996) are recommended.

DOSIMETRIC QUANTITIES

In 1990, the International Commission on Radiological Protection issued recommendations on basic radiation protection principles in ICRP Publication 60 (1991), replacing its previous guidance (ICRP 1977). Changes made in the new guidance to the terminology and formulation for assessing the health detriment from radiation exposure have a direct impact on the derivation of dose coefficients used in radiological protection and dose assessment. The recommendations of this report are based on the definitions and terminology of ICRP Publication 60.

The fundamental dosimetric quantity is the absorbed dose, D, averaged over a tissue or organ. The probability of radiation effects depends not only on the absorbed dose, but also on the type and energy of radiation incident on the body, and the susceptibility to harm of the tissues and organs receiving the dose. Previously, the absorbed dose to all defined organs, weighted for the quality of the radiation and the sensitivity of the exposed tissue was referred to as the effective dose equivalent, H_E (ICRP 1977). Weighting factors representing the relative sensitivity of the irradiated tissue or organ were defined for six principal organ systems, and methods were provided to rank organs not explicitly assigned a value. The radiation quality factors and weighting factors for tissues and organs used to define effective dose equivalent characterised the health detriment in terms of the risk of fatal cancers and hereditary defects in the first two generations.

In its latest recommendations, the ICRP has changed the manner in which the health detriment arising from the irradiation of different organs and tissues by different types and energies of radiation is to be determined. Radiation weighting factors and tissue weighting factors have been defined. The product of the radiation weighting factor (for radiation incident on the body) and the absorbed dose in a given organ or tissue gives the equivalent dose for that organ or tissue. Multiplying this equivalent dose by the corresponding tissue weighting factor and summing the products for all organs or tissues gives the effective dose, E. The unit of absorbed dose is the gray (Gy), while for both the equivalent dose and the effective dose, it is the sievert (Sv).

Although the effective dose is, in principle, similar to the effective dose equivalent, the selection of the organs contributing to this risk-weighted quantity and their weighting factors have been changed. The ICRP now defines the human body in terms of 12 designated tissues and organs, and the remainder, consisting of 10 additional tissues and organs. Revised tissue weighting factors characterise the health detriment by a weighting of the risks for both fatal and non-fatal cancers, the risk of hereditary defects over all future generations, and the relative loss of life expectancy, given a fatal cancer or severe inherited disorder. They have been selected by the ICRP for a reference population of equal numbers of both sexes over a wide range of ages. Minor revisions to the specification of the remainder were made more recently in ICRP Publications 69 and 71 (1995a, 1995b).

For intakes of radionuclides, the ICRP has defined the committed effective dose as the sum of the tissue-weighted time integrals of the equivalent dose rates that will be received in the tissues and organs of an individual following intake. The period over which the dose is integrated is taken to be 50 years for workers, and up to age 70 years for members of the public. This quantity is an indirect measure of the potential total health detriment to an individual and offspring resulting from the intake of radioactive material.

The ICRP has published values of committed effective dose per unit intake of a radionuclide that incorporate the new risk formulations for the assessment of health detriment. These values are referred to as dose coefficients by the ICRP. Compendiums of dose coefficients for internal exposures resulting from inhalation and ingestion have been made available in ICRP Publications 67 - 69, 71, and 72 (1994a, 1995, 1995a, 1995b, 1996). Many of these values have been derived using the latest ICRP age-dependent model for the respiratory tract, and the gastro-intestinal tract model from ICRP Publication 30 (1979); those derived using older biokinetic models have taken account of variations in body size. Internal dose coefficients are available for both occupational and public exposure scenarios.

For external exposures, the impact of the new ICRP risk formulation on effective dose due to photon irradiation has been investigated by Zankl *et al* (1992). They found that, for the irradiation geometries studied, the changes in tissue weighting factors result in effective doses that are lower than the corresponding effective dose equivalents for photon energies above 15 keV. Many tabulations of external dose coefficients based on the previous ICRP (1977) definition of effective dose equivalent are available, such as the U.S. EPA’s Federal Guidance Report No. 12 (Eckerman and Ryman 1993); however, these findings show that values based on the new definitions should be used for dose assessment purposes.

The ICRP has recently published conversion coefficients for use in protection against external exposures based on a review of available data (ICRP 1996a). While reflecting the latest ICRP recommendations, they are primarily applicable to radiation fields found in occupational settings, rather than those arising from radionuclides distributed in the environment. As a result, the Working Group concentrated on the review of published compilations of dose coefficients for cloudshine and groundshine exposures that incorporated the current ICRP risk formulations.

EXPOSURE PATHWAYS

Internal Exposure from Inhalation of Radionuclides in the Plume

Individuals immersed in a radioactive plume can receive internal exposures following inhalation of airborne radioactive material. Inhaled radionuclides irradiate the tissues of the respiratory system, as well as those of other organs. The committed effective dose to an individual is determined by numerous physical, chemical, and biological factors, including the amount and type of material inhaled, its deposition and retention in the respiratory system, and the breathing rate of the individual.

In 1994, the ICRP published its new respiratory tract model, which incorporates many of the factors affecting the dose assessment of inhaled radioactivity (ICRP 1994). One of the major changes in this model is the replacement of the previously used average lung dose with the explicit calculation of dose to each of five separate respiratory regions. The scope of the model has also been extended to apply explicitly to all members of the population. Reference values for age-dependent parameters have been given for six age groups covering infants to adults. The ICRP has used this model to derive inhalation dose coefficients for a number of radionuclides.

Human Physiological Parameters

One of the features of the new respiratory tract model is the incorporation of respiratory physiology, which affects the rates and volumes of air inhaled and exhaled, and determines the amount of radioactive material deposited in, and cleared from, the respiratory tract (ICRP 1994). To account for age-dependency, the ICRP has defined a number of age-dependent parameters, including reference respiratory values such as *ventilation*, or breathing, rates for 3-month-old infants, 1-, 5-, 10- and 15-year-old children, and adults.

The Working Group compared the ICRP default breathing rates (ICRP 1994, 1995b) with those recommended by a Health Canada working group on reference values (Health Canada 1993). ICRP values are based on published respiratory data and surveys of average times spent at several activity levels (sleep, sitting, light exercise, heavy exercise) for various ages. Health Canada values were derived from the breathing rates specified for ICRP Reference Man (ICRP 1975) at two activity levels, with some adjustment to account for size differences in the Canadian population. Recommended age-adjusted values were then given for five age groups. The Working Group initially considered the Health Canada values as these attempted to represent Canadian populations. However, since these values are based on ICRP Reference Man rather than actual population surveys, and are given for age groups different from the current ICRP classifications, it was concluded that ICRP breathing rates were the most relevant and consistent. Recommended age groups and default breathing rates are reproduced in Table 1 (ICRP 1995b).

Inhalation Dose Coefficients

Age-dependent committed effective dose coefficients for inhalation by members of the public have been calculated using the new respiratory tract model and are compiled in ICRP Publication 72 (1996) for radioisotopes of 91 elements. Calculations for the public for inhaled particles are based on an activity median aerodynamic diameter of 1 µm, using the default breathing rates listed in Table 1. Age-specific biokinetic models describing tissue distribution, retention, and excretion of systemic activity are used for radioisotopes of 31 of these elements. For radioisotopes of the remaining 60 elements, biokinetic models are based on those given in ICRP Publication 30, Parts 1-4 (1979, 1980, 1981, 1988). Allowances were made for age-specific changes in gut uptake, body mass and geometry, and urinary excretion rates, but not in the biokinetics of systemic activity. Tissue and radiation weighting factors used to calculate effective dose coefficients are those given by ICRP in its 1990 recommendations (ICRP 1991).

The Working Group recommends that the dose coefficients for inhalation compiled in ICRP Publication 72 be used as the standard for assessing inhalation doses, as they represent the latest internationally recognised values. These dose coefficients have also been adopted in the International Basic Safety Series (IAEA 1996) and in the Euratom Directive (EC 1996). It is also recommended that age-dependent doses be explicitly calculated for the six ICRP age groups, using the age-specific breathing rates of Table 1 as default values.

Inhalation dose coefficients for radionuclides of potential importance following a radiological emergency are given in Table 2, based on the default lung absorption types (the rate of absorption from the respiratory tract to body fluids) recommended by the ICRP for those situations when no specific information is available on the chemical form of the radionuclide. The ICRP has developed a quality-assured database on CD-ROM of inhalation dose coefficients for the public and for workers for a range of particle sizes and integration times, as well as ingestion coefficients for various gut absorption values (ICRP 1998, in press). This database, or ICRP Publication 72, should be referred to when assessing the doses from radionuclides not listed in Table 2, or when a different lung absorption factor is assumed.

External Exposure from Radionuclides in the Plume and on the Ground

Reference conversion coefficients incorporating the latest ICRP recommendations have recently been compiled in ICRP Publication 74 (1996a) for irradiation by monoenergetic radiation. These coefficients are expressed as the effective dose per unit air kerma[1] for several parallel and non-parallel monoenergetic radiation field geometries applicable to occupational radiation exposure. The ICRP has not compiled radionuclide-specific effective dose coefficients for external irradiation from radionuclides distributed in the environment, with the exception of dose rate

[1] Kerma: Kinetic energy released per unit mass - the quotient of dE_{tr} by dm, where dE_{tr} is the expectation value of the sum of the initial kinetic energies of all charged ionising particles liberated by uncharged ionising particles in a volume of mass dm.

coefficients for the exposure of adults to inert gases (ICRP 1996)[2].

Since, in practice, radiation fields resulting from environmental radionuclide contamination are not monoenergetic, mean or effective conversion coefficients must be determined by integration over the entire radiation energy spectrum, and summed for all types of radiation present. Differences in the irradiation geometry can also be expected between uniform radiation fields, and radiation sources distributed in the environment. Finally, the units for conversion coefficients used in environmental dose assessments (effective dose per unit time-integrated exposure to a radionuclide) are not easily derived from effective dose per unit air kerma. Based on these considerations, the Working Group reviewed existing compilations of external dose coefficients that incorporated the recommendations and changes of ICRP Publication 60.

Two compilations of dose coefficients for cloudshine and groundshine were considered by the Working Group on account of their completeness, applicability, and availability, namely those of Macdonald and Laverlock (1996), and Eckerman and Leggett (1996), the latter which is an extension of the work of Eckerman and Ryman (1993). Both compilations are based on Monte Carlo modelling of the doses in the organs of a mathematical phantom, resulting from photons and electrons emitted by radionuclides distributed in air, water, soil, and on the ground surface.

Dose Coefficients from Macdonald and Laverlock (1996)

The data set of Macdonald and Laverlock (1996) is a revision to the work of Holford (1988, 1989). Holford calculated dose coefficients for the 24 organ systems of Reference Man (ICRP 1975) using the EDEFIS code of Barnard and D'Arcy (1986), and employing ICRP Publication 26 tissue weighting factors (ICRP 1977), but also including the later recommendation of a tissue weighting factor of 0.01 for the skin. Seven exposure scenarios were considered, including the three pathways of interest to the Working Group. Details of the computational method are given in Barnard and D'Arcy (1986). In brief,

- the absorbed dose rate to an element of the medium at the point of interest was calculated, and converted to a dose rate in an element of tissue-equivalent material at the body surface;
- this dose rate was multiplied by organ dose ratios computed by Monte Carlo simulations of the interaction of photons with a mathematical model of standard man, to determine the dose rates to individual organs. For electrons, only the skin dose was calculated;
- the effective dose equivalent was estimated from the individual organ dose coefficients.

The external dose from immersion in air was calculated for Reference Man assuming a centroid at 1 m from a surface in a semi-infinite volume, and an air density of 1.189 kg m^{-3}. Exposure from a contaminated ground surface was calculated assuming a two-dimensional distribution of the radionuclide on the surface, with a disc-shaped receptor suspended in parallel, 1.6 m from the surface.

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[2] An ICRP Committee 2 Task Group on dose coefficients for external irradiation from radionuclides in the environment was set up in 1997, but had not issued recommendations at the time of publication of this report.

In Macdonald and Laverlock's revision, effective dose coefficients were recalculated for external exposures by applying the new ICRP tissue weighting factors to the organ dose coefficients calculated by Holford (1989). A minor deviation was made from the ICRP (1991) guidance on the application of the tissue weighting factor for the remainder tissues under certain cases. Specifically, the ICRP weighting of the remainder fraction for exposure scenarios where one of the remainder organs receives an equivalent dose greater than in any of the principal organs was not used, based on the judgement that this type of dose distribution does not occur for external exposures.

Dose Coefficients from Eckerman and Legett (1996)

Eckerman and Legett (1996), and Eckerman and Ryman (1993) calculated coefficients for effective dose equivalent and effective dose for external exposures based respectively on ICRP Publications 26 and 60 tissue weighting specifications (ICRP 1977, 1991). Values conforming to ICRP Publication 26 appeared in Federal Guidance Report 12 of the U.S. Environmental Protection Agency (Eckerman and Ryman 1993), for use in radiation protection programs in the United States. Although not appearing in the EPA guidance, effective dose coefficients based on ICRP 60 methodologies were calculated using the same modelling techniques, and have been made available in the computer software package DCFPAK: Dose Coefficient Data File Package (Eckerman and Leggett 1996). The Working Group obtained this compilation and accompanying documentation directly from the authors.

Details of the calculational methods can be found in Eckerman and Ryman (1993), of which the three major steps were:

- computation of the distributions of the radiations incident on the body for a number of initial energies of monoenergetic sources distributed in environmental media of interest;
- evaluation of the transport and energy deposition in organs and tissues of the body of the incident radiations by Monte Carlo methods, for each of the initial energies considered; and
- calculation of the organ or tissue dose for specific radionuclides, considering the energies and intensities of the radiations emitted during nuclear transformations of those nuclides.

For photons, organ doses were computed at each of 12 monoenergetic photon energies for 25 organs in an adult hermaphrodite phantom (Christy and Eckerman 1987), modified to include the oesophagus, and to improve the modelling of the neck and thyroid. For electrons, values were tabulated for skin only. The computational methods were chosen to give an accurate characterisation of the energy and angular dependence of the radiation field incident on the body. The contribution from bremsstrahlung was also included for all exposure modes.

For each mono-energetic photon energy, coefficients for immersion in air were calculated assuming a semi-infinite cloud source containing a uniformly-distributed mono-energetic photon emitter surrounding a human phantom standing on the soil at the air-ground interface, under conditions of 40% relative humidity, a pressure of 760 mm Hg, air temperature of 20°C, and a density of 1.2 kg m^{-3}. Groundshine coefficients for a contaminated surface are based on an infinite isotropic source of monoenergetic photons, located at the air-ground interface, with a standing human phantom at the interface.

Comparison of the Macdonald - Laverlock and Eckerman - Leggett Data Sets

The two sets of external dose coefficients were compared in terms of both the calculated values for a number of radionuclides, and the quality of the models from which the values were derived. The models were compared based on the types of mathematical phantoms used, the types of processes considered (eg. bremsstrahlung), the material referenced by the authors, and the type and completeness of the models used.

Ratios of cloudshine and groundshine dose coefficients from Macdonald and Laverlock (DC_{ML}), and Eckerman and Legett (DC_{EL}) were calculated for 108 radionuclides, including those listed in CSA guideline documents N288.1 and N288.2 (CSA 1987, 1991) as being of potential radiological importance under normal and accidental situations, as well as their decay products. Radionuclides for which either source gave a value of zero were excluded from this comparison, although they were considered in the general analysis of the two data sets.

Figure 1 shows the frequency of occurrence of the various values of DC_{EL}:DC_{ML}, which are predominantly in the range of 1.00-1.25 for both exposure pathways, indicating a generally good agreement between the two data sets, although the values of DC_{EL} tend to be greater than those of DC_{ML}. From Figure 2, the best agreement occurs for those radionuclides which contribute the greatest effective dose per unit activity concentration, and are therefore of most importance in radiological assessments. Differences between the two data sources generally increase as the dose coefficient decreases. In some cases, Macdonald and Laverlock's values were significantly greater than those of Eckerman and Legett, particularly for low-energy beta emitters for which the dose per unit activity concentration is small. Such differences are expected due to the previously discussed differences in the models.

Figure 1 Frequency distributions of DC_{EL}:DC_{ML} for cloudshine and groundshine dose coefficients

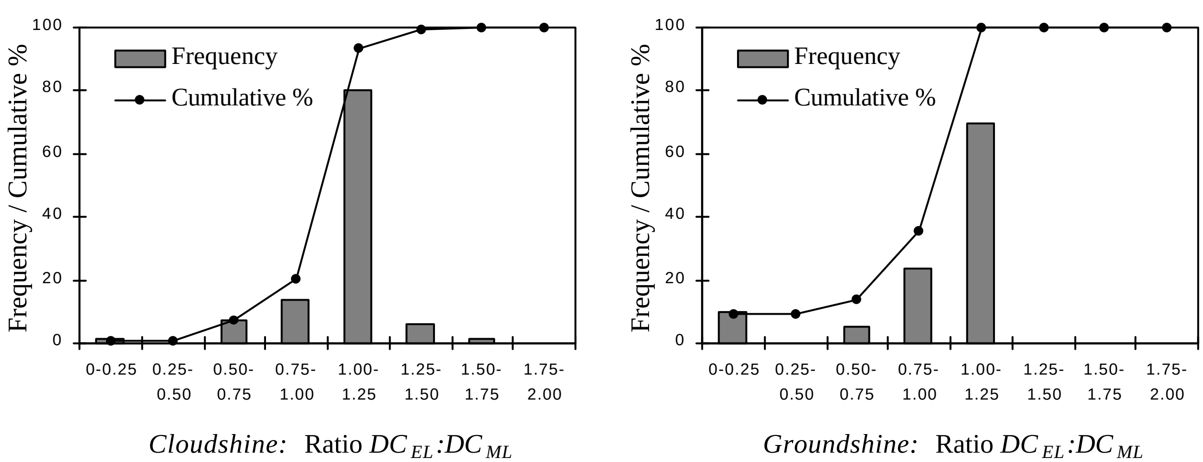
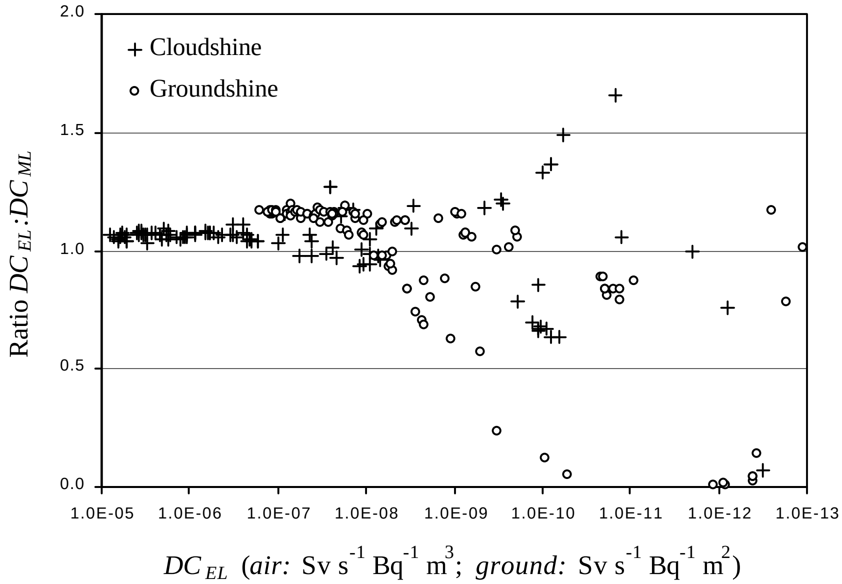


Figure 2 Ratio of DC_{EL}:DC_{ML} versus DC_{EL}



Eckerman and Ryman (1993) compared their data with other published results, and in general, agreement was good. Discrepancies were traced to differences in both the types of phantoms used, and certain features of the computational models. As a final check of the Eckerman and Legett data set, their dose coefficients based on ICRP Publication 26 (1977) were compared with those of Kocher (1983). Kocher's values were previously recommended for use in the Canadian Standards Association's N288 series of guidelines (CSA 1987, 1991). The two sets were in reasonable agreement, with the values of Eckerman and Legett typically 10-20% greater than those of Kocher, again due to the greater sophistication of their model.

Based on these considerations, the Working Group concluded that the dose coefficients of Eckerman and Legett (1996) represent the best values available to date for cloudshine and groundshine assessments. External dose coefficients for those radionuclides that might be of radiological importance following a nuclear accident are given in Table 2. Appendix C contains an extensive list of external dose coefficients reproduced from Eckerman and Legett's DCFPAK software, and should be referred to for dose coefficients of radionuclides not listed in Table 2.

Effect of Gender and Age on External Dose Coefficients

Organ equivalent dose coefficients and effective dose coefficients given by Eckerman and Legett were calculated for an hermaphrodite anthropomorphic adult phantom derived by Cristy (Cristy and Eckerman 1987) from ICRP Reference Man (ICRP 1975). Doses to individuals of different size and gender can be expected to be somewhat different due to differences in radiation transport through the body. In light of this, the Working Group reviewed the recommendation contained in the Canadian Standards Association's 1987 guidelines for derived release limit calculations (CSA

1987) to increase the values of the adult external dose coefficients by a factor of 1.5 when applied to infants.

Gender-specific and age-specific aspects of external dose have been investigated by several researchers, including Drexler *et al* (1989), Petoussi *et al* (1991), Yamaguchi (1994), and Schultz and Zoetelief (1997). Although dose coefficients in these studies are frequently given as air kerma to effective dose equivalent (or effective dose) conversion coefficients for monoenergetic photon radiation fields, the conclusions on gender and age dependency are relevant. These studies show that, typically, the dose to individual body organs increases with decreasing body size. This effect is more pronounced at low photon energies, and for organs located near the middle of the body, which are shielded by overlying tissues. This also applies to the differences arising from the use of hermaphroditic versus sex-specific phantoms, as discussed by Eckerman and Ryman (1993).

Petoussi *et al* (1991) have indicated that infant organ doses for cloudshine and groundshine may be as much as about 40% greater than those in the adult male at photon energies greater than 100 keV. Below 100 keV, the difference may approach a factor of 3 for deeper-seated organs. Yamaguchi (1994) calculated coefficients for anthropomorphic phantoms using the six ICRP age groups under 5 irradiation geometries. For isotropic radiation fields, effective dose coefficients for 0- and 1-year-old infants normalised to kerma in free air were about 20-30% higher than those for adults at energies above 115 keV. For lower energies, differences between infant and adult values approached factors of 3 to 4. From Schultz and Zoetelief (1997), ratios of child to adult effective dose coefficients for electrons ranged from about 2- to 20-fold for energies above 600 keV. The relative differences were less than 0.2% only for energies below 600 keV.

In light of these results, the modifying factor of 1.5 as recommended by the CSA (1987) is very conservative for some radionuclides and age groups. However, due to the complexity of deriving radionuclide- and age-specific corrections, the Working Group recommends that this factor be retained as a default to the external dose coefficients for the two youngest ICRP age groups (i.e. 3-month- and 1-year-old infants). Adult values should be used for the remaining four age groups. It is also recommended that if the identity of the nuclides and radiation spectra exposing the critical group are known, then a more appropriate factor may be calculated. The Working Group has chosen not to recommended a correction factor based on gender.

Other Modifying Factors

The Working Group considered the issue of modifying factors, such as shielding and exposure factors, and finite cloud corrections. It was decided that these were beyond the scope of the present report. More information on this topic can be found elsewhere, such as Kocher (1983), and Eckerman and Ryman (1993).

SUMMARY OF RECOMMENDED ASSESSMENT PARAMETERS

Age-dependent breathing rates recommended for the estimation of inhalation doses are given in Table 1 (ICRP 1995b). Recommended dose coefficients for internal and external exposures to those radionuclides that might be expected to be present in significant amounts following a radiological emergency are given in Table 2. This list has been harmonised with that in CSA guideline document N288.1 (CSA 1987), although many of these may not be released in significant quantities during emergency situations. Dose coefficients for inhalation are taken from ICRP Publication 72 (1996) for default lung absorption types, and the six recommended ICRP age groups. Breathing rates given in Table 1 should be used as default values for the assessment of these doses. Adult dose coefficients for cloudshine and groundshine are taken from Eckerman and Legett (1996). These should be multiplied by a factor of 1.5 when assessing doses to the 3-month- and 1-year-old age groups.

In general, dose coefficients do not reflect the contribution due to ingrowth of decay-chain members in the environment, although coefficients for internal exposures do reflect the contribution to dose from ingrowth in the body. However, in providing the short list of radionuclides given in Table 2, the Working Group has included the contributions from decay-chain members in the external dose coefficients for those cases where it is reasonable to assume that the parent and progeny will remain in equilibrium in the environment following release from the source. These include the following decay chains:

^{106}Ru - ^{106}Rh ^{132}Te - ^{132}I ^{137}Cs - ^{137m}Ba ^{144}Ce - $^{144/144m}$Pr

In these cases, it is almost always reasonable to assume that secular equilibrium between parent and progeny is maintained both in the plume and following deposition, due to the short half-lives of the daughters (less than a few hours). For these decay chains, external dose coefficients listed for the parent radionuclide in Table 2 were obtained by multiplying the dose coefficient for the progeny by the decay-branching fraction and adding to the coefficient for the parent.

In most cases, however, secular equilibrium between parent and daughter cannot be assumed. Examples include the complex decay chains of long-lived actinides, those involving noble gases and nuclides with non-zero deposition velocities, such as ^{88}Kr - ^{88}Rb, and those in which the parent and daughter are reasonably long-lived with similar half-lives (e.g. ^{95}Zr - ^{95}Nb). In these cases, the dose coefficients for the radionuclide and its progeny can be combined only after consideration of the equations describing production and decay of the daughter radionuclides over time, and differences in environmental behaviour (Kocher 1983). Some notes on the assessment of doses arising from decay-chain members are provided in Appendix B.

The Working Group has reproduced, with permission, an extensive list of external dose coefficients from Eckerman and Leggett (1996) in Appendix C that should be applicable to a broad range of accident scenarios. This list differs from Table 2 in that contributions to the external dose coefficients from radioactive progeny *have not been included* for any radionuclide. Contributions to dose from the ingrowth and decay of chain members in the environment must be accounted for by the user. As with Table 2, only adult values have been given for external dose coefficients. Infant values should be modified as appropriate. Age-dependent inhalation dose coefficients for radionuclides not listed in Table 2 should be obtained from either the ICRP CD-ROM database of dose coefficients (1998, in press), or ICRP Publication 72 (1996).

Dose assessment parameters recommended in this report should be employed as default values for the evaluation of the three critical pathways immediately following a nuclear emergency. However, in applying the parameters recommended in this report, it should be understood that their applicability to a particular exposure situation is influenced by any conditions that differ from those assumed by the modellers in their derivation. For example, the assumption of uniform radionuclide concentrations and semi-infinite or infinite sources may not apply under certain conditions, and thus, modifications to the external dose coefficients may be required..

Although beyond the scope of this report, modifying factors which account for changes in the radiation field, such as non-uniform or finite sources, shielding, or ground roughness, and factors associated with the duration of the exposure, should be used where appropriate in the assessment process. It is the task of the user to determine the adequacy of such factors to a particular exposure scenario.

Table 1 Recommended breathing rates for the six ICRP age groups

ICRP Age Group	Default Breathing Rate (m^3 d^{-1})
3 months (0-1 year)	2.86
1 year (1-2 years)	5.16
5 year (2-7 years)	8.72
10 year (7-12 years)	15.3
15 year (12-17 years)	20.1
Adult (> 17 years)	22.2

(Reference: ICRP Publication 71 (1995b), Table 6)

Table 2 Recommended effective dose coefficients for internal and external exposures to selected radionuclides

Nuclide		Inhalation Dose Coefficients (Sv Bq^{-1})						External Dose Coefficients [(a)]	
								Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
		3 months	1 Year	5 Years	10 Years	15 Years	Adult	5 Years - Adult	5 Years - Adult
a) Particulates									
Hydrogen	Tritium compounds	3.4e-10	2.7e-10	1.4e-10	8.2e-11	5.3e-11	4.5e-11	0	0
Carbon	C-14	8.3e-09	6.6e-09	4.0e-09	2.8e-09	2.5e-09	2.0e-09	2.60e-18	1.27e-20
Sodium	Na-24	2.3e-09	1.8e-09	9.3e-10	5.7e-10	3.4e-10	2.7e-10	2.08e-13	3.59e-15
Phosphorus	P-32	2.2e-08	1.5e-08	8.0e-09	5.3e-09	4.0e-09	3.4e-09	5.36e-16	8.52e-17
	P-33	6.1e-09	4.6e-09	2.8e-09	2.1e-09	1.9e-09	1.5e-09	1.45e-17	3.64e-20
Sulphur	S-35 (inorganic)	5.9e-09	4.5e-09	2.8e-09	2.0e-09	1.8e-09	1.4e-09	3.11e-18	1.33e-20
Scandium	Sc-46	2.8e-08	2.3e-08	1.4e-08	9.8e-09	8.4e-09	6.8e-09	9.36e-14	1.88e-15
Chromium	Cr-51	2.6e-10	2.1e-10	1.0e-10	6.6e-11	4.5e-11	3.7e-11	1.38e-15	2.97e-17
Manganese	Mn-54	5.2e-09	4.1e-09	2.2e-09	1.5e-09	9.9e-10	8.5e-10	3.83e-14	7.91e-16
Iron	Fe-55	1.9e-09	1.4e-09	9.9e-10	6.2e-10	4.4e-10	3.8e-10	0	0
	Fe-59	1.8e-08	1.3e-08	7.9e-09	5.5e-09	4.6e-09	3.7e-09	5.62e-14	1.10e-15
Cobalt	Co-58	7.3e-09	6.5e-09	3.5e-09	2.4e-09	2.0e-09	1.6e-09	4.44e-14	9.25e-16
	Co-60	4.2e-08	3.4e-08	2.1e-08	1.5e-08	1.2e-08	1.0e-08	1.19e-13	2.30e-15
Zinc	Zn-65	8.5e-09	6.5e-09	3.7e-09	2.4e-09	1.9e-09	1.6e-09	2.72e-14	5.41e-16
Arsenic	As-76	5.1e-09	4.6e-09	2.2e-09	1.4e-09	8.8e-10	7.4e-10	2.06e-14	5.24e-16
Rubidium	Rb-88	1.9e-10	1.2e-10	5.2e-11	3.2e-11	1.9e-11	1.6e-11	3.33e-14	7.41e-16
Strontium	Sr-89	3.3e-08	2.4e-08	1.3e-08	9.1e-09	7.3e-09	6.1e-09	4.37e-16	6.86e-17
	Sr-90	1.5e-07	1.1e-07	6.5e-08	5.1e-08	5.0e-08	3.6e-08	9.83e-17	1.64e-18
Yittrium	Y-90	1.3e-08	8.8e-09	4.2e-09	2.7e-09	1.8e-09	1.5e-09	7.92e-16	1.10e-16
	Y-91	4.3e-08	3.4e-08	1.9e-08	1.3e-08	1.0e-08	8.9e-09	6.22e-16	7.46e-17
Zirconium	Zr-95	2.0e-08	1.6e-08	9.7e-09	6.8e-09	5.9e-09	4.8e-09	3.36e-14	7.04e-16
Niobium	Nb-95	6.8e-09	5.2e-09	3.1e-09	2.2e-09	1.9e-09	1.5e-09	3.49e-14	7.28e-16
Molybdenum	Mo-99	6.0e-09	4.4e-09	2.2e-09	1.5e-09	1.1e-09	8.9e-10	6.99e-15	1.78e-16
Ruthenium	Ru-103	1.1e-08	8.4e-09	5.0e-09	3.5e-09	3.0e-09	2.4e-09	2.08e-14	4.49e-16
	Ru-106 [(b)]	1.4e-07	1.1e-07	6.4e-08	4.1e-08	3.1e-08	2.8e-08	1.06e-14	3.45e-16
Silver	Ag-110m	3.5e-08	2.8e-08	1.7e-08	1.2e-08	9.2e-09	7.6e-09	1.27e-13	2.58e-15

Nuclide		Inhalation Dose Coefficients (Sv Bq^{-1})						External Dose Coefficients [a] Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	External Dose Coefficients [a] Groundshine (Sv s^{-1} Bq^{-1} m^{2})
		3 months	1 Year	5 Years	10 Years	15 Years	Adult	5 Years - Adult	5 Years - Adult
Antimony	Sb-122	8.3e-09	5.7e-09	2.8e-09	1.8e-09	1.3e-09	1.0e-09	2.02e-14	4.85e-16
	Sb-124	3.1e-08	2.4e-08	1.4e-08	9.6e-09	7.7e-09	6.4e-09	8.62e-14	1.70e-15
	Sb-125	2.0e-08	1.6e-08	1.0e-08	6.8e-09	5.8e-09	4.8e-09	1.87e-14	4.09e-16
Tellurium	Te-132 [b]	1.6e-08	1.3e-08	6.4e-09	4.0e-09	2.6e-09	2.0e-09	1.17e-13	2.47e-15
Iodine	I-123	8.7e-10	7.9e-10	3.8e-10	1.8e-10	1.1e-10	7.4e-11	6.49e-15	1.53e-16
	I-125	2.0e-08	2.3e-08	1.5e-08	1.1e-08	7.2e-09	5.1e-09	3.73e-16	3.14e-17
	I-129	7.2e-08	8.6e-08	6.1e-08	6.7e-08	4.6e-08	3.6e-08	2.81e-16	1.95e-17
	I-131	7.2e-08	7.2e-08	3.7e-08	1.9e-08	1.1e-08	7.4e-09	1.69e-14	3.64e-16
	I-132	1.1e-09	9.6e-10	4.5e-10	2.2e-10	1.3e-10	9.4e-11	1.05e-13	2.20e-15
	I-133	1.9e-08	1.8e-08	8.3e-09	3.8e-09	2.2e-09	1.5e-09	2.76e-14	6.17e-16
	I-134	4.6e-10	3.7e-10	1.8e-10	9.7e-11	5.9e-11	4.5e-11	1.22e-13	2.53e-15
	I-135	4.1e-09	3.7e-09	1.7e-09	7.9e-10	4.8e-10	3.2e-10	7.54e-14	1.47e-15
Caesium	Cs-134	1.1e-08	7.3e-09	5.2e-09	5.3e-09	6.3e-09	6.6e-09	7.06e-14	1.48e-15
	Cs-135	1.7e-09	9.9e-10	6.2e-10	6.1e-10	6.8e-10	6.9e-10	9.50e-18	2.69e-20
	Cs-136	7.3e-09	5.2e-09	2.9e-09	2.0e-09	1.4e-09	1.2e-09	9.94e-14	2.03e-15
	Cs-137 [b]	8.8e-09	5.4e-09	3.6e-09	3.7e-09	4.4e-09	4.6e-09	2.55e-14	5.51e-16
Barium	Ba-140	2.7e-08	2.0e-08	1.1e-08	7.6e-09	6.2e-09	5.1e-09	8.07e-15	1.90e-16
Lanthanum	La-140	8.8e-09	6.3e-09	3.1e-09	2.0e-09	1.3e-09	1.1e-09	1.11e-13	2.16e-15
Cerium	Ce-141	1.4e-08	1.1e-08	6.3e-09	4.6e-09	4.1e-09	3.2e-09	3.10e-15	6.93e-17
	Ce-144 [b]	1.9e-07	1.6e-07	8.8e-08	5.5e-08	4.1e-08	3.6e-08	3.42e-15	1.82e-16
Promethium	Pm-147	2.1e-08	1.8e-08	1.1e-08	7.0e-09	5.7e-09	5.0e-09	8.67e-18	2.80e-20
Europium	Eu-152	1.1e-07	1.0e-07	7.0e-08	4.9e-08	4.3e-08	4.2e-08	5.28e-14	1.08e-15
	Eu-154	1.6e-07	1.5e-07	9.7e-08	6.5e-08	5.6e-08	5.3e-08	5.75e-14	1.17e-15
Mercury	Hg-203 (inorganic)	1.0e-08	7.9e-09	4.7e-09	3.4e-09	3.0e-09	2.4e-09	1.04e-14	2.22e-16
Uranium	U-234	1.5e-05	1.1e-05	7.0e-06	4.8e-06	4.2e-06	3.5e-06	6.11e-18	5.86e-19
	U-235	1.3e-05	1.0e-05	6.3e-06	4.3e-06	3.7e-06	3.1e-06	6.46e-15	1.40e-16
	U-238	1.2e-05	9.4e-06	5.9e-06	4.0e-06	3.4e-06	2.9e-06	2.50e-18	4.23e-19
Neptunium	Np-237	4.4e-05	4.0e-05	2.8e-05	2.2e-05	2.2e-05	2.3e-05	8.87e-16	2.52e-17
	Np-239	5.9e-09	4.2e-09	2.0e-09	1.4e-09	1.2e-09	9.3e-10	6.95e-15	1.54e-16
Plutonium	Pu-238	7.8e-05	7.4e-05	5.6e-05	4.4e-05	4.3e-05	4.6e-05	3.50e-18	6.26e-19
	Pu-239	8.0e-05	7.7e-05	6.0e-05	4.8e-05	4.7e-05	5.0e-05	3.48e-18	2.84e-19

Nuclide		Inhalation Dose Coefficients (Sv Bq^{-1})						External Dose Coefficients [a]	
								Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
		3 months	1 Year	5 Years	10 Years	15 Years	Adult	5 Years - Adult	5 Years - Adult
	Pu-240	8.0e-05	7.7e-05	6.0e-05	4.8e-05	4.7e-05	5.0e-05	3.42e-18	6.01e-19
	Pu-241	9.1e-07	9.7e-07	9.2e-07	8.3e-07	8.6e-07	9.0e-07	6.33e-20	1.72e-21
	Pu-242	7.6e-05	7.3e-05	5.7e-05	4.5e-05	4.5e-05	4.8e-05	2.90e-18	4.98e-19
	Pu-244	7.4e-05	7.2e-05	5.6e-05	4.5e-05	4.4e-05	4.7e-05	2.08e-18	4.16e-19
Americium	Am-241	7.3e-05	6.9e-05	5.1e-05	4.0e-05	4.0e-05	4.2e-05	6.74e-16	2.33e-17
	Am-243	7.2e-05	6.8e-05	5.0e-05	4.0e-05	4.0e-05	4.1e-05	1.85e-15	4.79e-17
Curium	Cm-242	2.2e-05	1.8e-05	1.1e-05	7.3e-06	6.4e-06	5.2e-06	4.02e-18	7.02e-19
	Cm-244	6.2e-05	5.7e-05	3.7e-05	2.7e-05	2.6e-05	2.7e-05	3.40e-18	6.44e-19
	Cm-247	6.7e-05	6.3e-05	4.7e-05	3.7e-05	3.7e-05	3.9e-05	1.38e-14	2.99e-16
b) Soluble or Reactive Gases and Vapours									
Hydrogen	Tritiated water	6.4e-11	4.8e-11	3.1e-11	2.3e-11	1.8e-11	1.8e-11	0	0
Carbon	C-14 dioxide	1.9e-11	1.9e-11	1.1e-11	8.9e-12	6.3e-12	6.2e-12	2.60e-18	1.27e-20
c) Noble Gases [c]									
Argon	Ar-41	-	-	-	-	-	-	6.13e-14	-
Krypton	Kr-85	-	-	-	-	-	-	2.55e-16	-
	Kr-85m	-	-	-	-	-	-	6.83e-15	-
	Kr-87	-	-	-	-	-	-	3.94e-14	-
	Kr-88	-	-	-	-	-	-	9.72e-14	-
Xenon	Xe-131m	-	-	-	-	-	-	3.70e-16	-
	Xe-133	-	-	-	-	-	-	1.39e-15	-
	Xe-133m	-	-	-	-	-	-	1.27e-15	-
	Xe-135	-	-	-	-	-	-	1.11e-14	-
	Xe-135m	-	-	-	-	-	-	1.85e-14	-
	Xe-138	-	-	-	-	-	-	5.44e-14	-

Reference: ICRP (1996), Eckerman and Legett (1996)

Notes: (a) External dose coefficients listed apply to the *5 Years - Adult* age groups. For *3 Month* and *1 Year* age groups, multiply values in Table 2 by 1.5

(b) External dose coefficients for these radionuclides include contributions from progeny, assuming secular equilibrium

(c) External dose coefficients for noble gases taken from ICRP (1996), Table A.4

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Appendix A: Working Group Membership

The Joint Working Group was comprised of representatives from the Radiation Protection Bureau of Health Canada, the Atomic Energy Control Board, and Atomic Energy of Canada Limited. Its members included:

Radiation Protection Bureau, Health Canada

B.A. Ahier (Chair)
B.L. Tracy

Atomic Energy Control Board

G. Poirier
B. Thériault
L. Truong

Atomic Energy of Canada Limited

B. Heinmiller

Appendix B: Considerations for Radionuclide Decay Chains and Example Calculations

Considerations for Radionuclide Decay Chains

In assessing doses from environmental exposures to radionuclides, it is important to realise that, in general, dose coefficients for radionuclides do not include any contribution to dose due to ingrowth of decay-chain members in the environment, although coefficients for internal exposures do reflect the contribution to dose from ingrowth in the body. In some cases, it is reasonable to assume that the parent and progeny are in equilibrium in the environment following release from the source. Decay chains where this assumption is often valid include:

^{106}Ru - ^{106}Rh ^{132}Te - ^{132}I ^{137}Cs - ^{137m}Ba ^{144}Ce - $^{144/144m}Pr$

In these cases, it is almost always reasonable to assume that secular equilibrium between parent and progeny is maintained both in the plume and following deposition, due to the short half-lives of the daughters (less than a few hours). In Table 2, external dose coefficients listed for the parent radionuclides of these four decay chains were obtained by multiplying the dose coefficient for the progeny by the decay-branching fraction and adding to the coefficient for the parent.

For most cases, it is not reasonable to assume secular equilibrium between the parent and its chain members. Examples include the complex decay chains of long-lived actinides, those involving noble gases and nuclides with non-zero deposition velocities, such as ^{88}Kr - ^{88}Rb, and those in which the parent and daughter are reasonably long-lived with similar half-lives (e.g. ^{95}Zr - ^{95}Nb). The contribution from each must be explicitly calculated by considering its production and decay, and any difference in environmental behaviour before dose coefficients for a radionuclide and its progeny can be combined (Kocher 1983).

The activity of a decay-chain member at any time, *t*, due to radioactive decay and ingrowth can be described by the Bateman equations (CRC 1982, CSA 1991, Eckerman and Ryman 1993). Using these equations, the activity at time *t* of the various chain members, $A_i(t)$, from the decay of an initial quantity of the parent, A_1^0, is given by (Eckerman and Ryman 1993)[3]

$$A_i(t) = A_1^0 \left(\prod_{j=1}^{i-1} (f_{j,j+1} \; \lambda_{j+1}) \right) \sum_{j=1}^{i} \frac{e^{-\lambda_j t}}{\prod_{\substack{k=1 \\ k \neq j}}^{i} (\lambda_k - \lambda_j)} \qquad \text{(B.1)}$$

where

$$\prod_{i=1}^{n} a_i = \begin{cases} a_1 \times a_2 \times \cdots a_n, \; if \; n \geq 1 \\ 1, \; if \; n = 0 \end{cases}$$

and $f_{j,j+1}$ = the fractional yield of chain member *j+1* from decay of member *j*

λ_j = decay constant of radionuclide *j*.

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[3] Equations B.1 and B.2 contain a correction in the subscript of term λ_{j+1} from that found in Eckerman and Ryman (1993), equations A.2 and A.3.

For exposures due to either submersion in, or inhalation of, the radioactive plume, the activities calculated using equation B.1 can be multiplied by the appropriate cloudshine dose coefficients, or the inhalation dose coefficients and breathing rates, to give the effective dose rate from each radionuclide at time, *t*. The effective dose is the integral of the dose rate over the period of interest. If it is assumed that radionuclide concentrations remain constant over the exposure period (the time for the radioactive plume to pass), the effective dose can be determined by multiplying the dose rate by the exposure time, *T*, and summing over the contribution from each radionuclide.

For ground contamination, where radioactive decay and ingrowth are more important due to the potentially longer exposure period, it is usually not justified to assume that radionuclide concentrations remain constant. In this case, the effective dose can be calculated by integrating equation B.1 over the exposure period, and applying the appropriate groundshine dose coefficients. For a single contamination event resulting in a ground surface activity concentration of $A_1^{\,0}$, the effective dose, *E* (Sv), over exposure period *T*, is given by (Eckerman and Ryman 1993)

$$E = A_1^0 \sum_{i=1}^{n} \left\{ DC_{ext,i} \left(\prod_{j=1}^{i-1} (f_{j,j+1} \; \lambda_{j+1}) \right) \sum_{j=1}^{i} \frac{1 - e^{-\lambda_j T}}{\lambda_j \prod_{\substack{k=1 \\ k \neq j}}^{i} (\lambda_k - \lambda_j)} \right\} \qquad \text{(B.2)}$$

where $DC_{ext,i}$ is the groundshine dose coefficient for radionuclide *i*.

Under the more general scenario where the initial activities of the progeny $A_2^{\,0}$, $A_3^{\,0}$ ... $A_n^{\,0} \neq 0$, the contribution due to each non-zero member, $A_i^{\,0}$, can be calculated from equation B.1 and B.2 by replacing $A_1^{\,0}$ with radionuclide $A_i^{\,0}$ as the parent of the sub-chain. Information on nuclear decay characteristics, including radioactive decay products and fractional yields is available from several sources, including ICRP (1983), Eckerman *et al* (1993), and Eckerman and Legett (1996).

Equations B.1 and B.2 apply to the specific scenarios described above, and only take account of changes in activity concentration due to nuclear decay transformations. As stated previously, changes due to differences in environmental behaviour should also be accounted for, where appropriate. Recommendations on this topic were beyond the scope of the Working Group.

Example Calculations

The following examples are intended to illustrate the how the information contained in this report may be used in the evaluation of effective doses to exposed individuals.

Example 1:

The concentration of ^{137}Cs in the atmosphere following an accidental release from a facility is estimated to be about 100 Bq m^{-3}. The time of exposure is estimated to be 3 hours. Estimate the effective doses to an adult from inhalation and submersion in the plume, assuming equilibrium between ^{137}Cs and its daughter, ^{137m}Ba.

From Table 1, the adult breathing rate is 22.2 m^3 d^{-1}. From Table 2, the adult inhalation and cloudshine dose coefficients for ^{137}Cs are:
inhalation: 4.6×10^{-9} Sv Bq^{-1}
cloudshine: 2.55×10^{-14} Sv s^{-1} Bq^{-1} m^3
The cloudshine dose coefficient includes the contribution from ^{137m}Ba in equilibrium with ^{137}Cs.

The effective dose is given by the product of the dose rate and the exposure duration. For submersion, the effective dose received during passage of the plume is given by

$$E_{sub} = (DC_{sub}\ C_{Cs})\ t$$
$$= 2.55\times10^{-14}\ \text{Sv s}^{-1}\ \text{Bq}^{-1}\ \text{m}^3 \times 100\ \text{Bq m}^{-3} \times 3\ \text{h} \times 3600\ \text{s h}^{-1}$$
$$= 2.8\times10^{-8}\ \text{Sv}$$

If the assumption of equilibrium was not valid, the contributions to external dose from the two radionuclides would have to be calculated separately using the dose coefficients from Appendix C.

For inhalation, the effective dose committed during the passage of the plume is given by

$$E_{inh} = (DC_{inh\_Cs}\ C_{Cs}\ B_{adult})\ t$$
$$= 4.6\times10^{-9}\ \text{Sv Bq}^{-1} \times 100\ \text{Bq m}^{-3} \times 22.2\ \text{m}^3\ \text{d}^{-1} \times 3\ \text{h} \times 0.04167\ \text{d h}^{-1}$$
$$= 1.3\times10^{-6}\ \text{Sv}$$

Example 2:

Assume that deposition of ^{95}Zr from an airborne plume results in a uniform ground surface contamination of 1 000 Bq m^{-2}. Calculate the effective dose to an adult in the first month following deposition, assuming that the exposure is continuous, and that radioactive decay is the only mechanism by which the contamination is removed.

The effective dose is the integral of the dose rate due to the decay of ^{95}Zr and its progeny, ^{95m}Nb and ^{95}Nb, which are assumed to be initially absent. The branching fractions for transformations ($f_{j,\,j+1}$) are 0.993 for ^{95}Zr → ^{95}Nb, 0.007 for ^{95}Zr → ^{95m}Nb, and 1.0 for ^{95m}Nb → ^{95}Nb. This can be approximated by assuming that f = 1 for the transformation of ^{95}Zr to ^{95}Nb, and ignoring the contribution from ^{95m}Nb.

In this example, the groundshine dose coefficients for ^{95}Zr and ^{95}Nb are treated separately. As given in Appendix C, the groundshine dose coefficients for adults are:

^{95}Zr: 7.04×10^{-16} Sv s^{-1} Bq^{-1} m^2
^{95}Nb: 7.28×10^{-16} Sv s^{-1} Bq^{-1} m^2

The decay constants for the two radionuclides are:

λ_{Zr95} = ln 2 / $T_{1/2}$
= 0.693 / (63.98 d × 86 400 s d^{-1})
= 1.25 ×10^{-7} s^{-1}

λ_{Nb95} = ln 2 / (35.15 d × 86 400 s d^{-1})
= 2.28 ×10^{-7} s^{-1}

From equation B.2, the effective dose from groundshine is given by

$$E_{gnd} = A^0_{Zr95} \left\{ DC_{Zr95} \frac{1 - e^{-\lambda_{Zr95} T}}{\lambda_{Zr95}} + DC_{Nb95} \frac{f_{Zr \rightarrow Nb} \lambda_{Nb95}}{(\lambda_{Nb95} - \lambda_{Zr95})} \left[\frac{1 - e^{-\lambda_{Zr95} T}}{\lambda_{Zr95}} - \frac{1 - e^{-\lambda_{Nb95} T}}{\lambda_{Nb95}} \right] \right\}$$

Substituting in the values defined above, the effective dose in the first 30 days following deposition is 1.97 × 10^{-6} Sv. If the $^{95}Zr \rightarrow {}^{95m}Nb \rightarrow {}^{95}Nb$ branch is explicitly included, additional terms appear in the above equation, which in this example are insignificant.

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Appendix C:
Compilation of External Dose Rate Coefficients for Cloudshine and Groundshine

This Appendix is available in electronic format as an ASCII, space-delimited file on the Health Canada Internet site at http://www.hc-sc.gc.ca/ehp/ehd/rpb/environ/impact/index.htm

Reference:

ICRP (1996) for noble gases.
Eckerman and Legett (1996) for particulates (reproduced with permission).

Application Notes:

External dose coefficients apply to the age groups from 5 Years to Adult. For 3 Month and 1 Year age groups, multiply values by 1.5 (default correction factor).

Radionuclide		Half-life	External Dose Coefficients	
			Cloudshine ($Sv\ s^{-1}\ Bq^{-1}\ m^3$)	Groundshine ($Sv\ s^{-1}\ Bq^{-1}\ m^2$)
NOBLE GASES				
Argon	Ar-37	35.0 d	4.75e-20	-
	Ar-39	269 y	1.27e-16	-
	Ar-41	1.83 h	6.13e-14	-
Krypton	Kr-74	11.5 min	5.21e-14	-
	Kr-76	14.8 h	1.85e-14	-
	Kr-77	74.7 min	4.51e-14	-
	Kr-79	1.46 d	1.12e-14	-
	Kr-81	2.10E+05 y	2.43e-16	-
	Kr-83m	1.83 h	2.43e-18	-
	Kr-85	10.7 y	2.55e-16	-
	Kr-85m	4.48 h	6.83e-15	-
	Kr-87	1.27 h	3.94e-14	-
	Kr-88	2.84 h	9.72e-14	-
Xenon	Xe-120	40.0 min	1.74e-14	-
	Xe-121	40.1 min	8.68e-14	-
	Xe-122	20.1 h	2.20e-15	-
	Xe-123	2.08 h	2.78e-14	-
	Xe-125	17.0 h	1.08e-14	-
	Xe-127	36.4 d	1.12e-14	-
	Xe-129m	8.0 d	9.38e-16	-
	Xe-131m	11.9 d	3.70e-16	-
	Xe-133m	2.19 d	1.27e-15	-
	Xe-133	5.24 d	1.39e-15	-
	Xe-135m	15.3 min	1.85e-14	-
	Xe-135	9.10 h	1.11e-14	-
	Xe-138	14.2 min	5.44e-14	-
PARTICULATES				
Hydrogen	H-3	12.3 y	0.00e+00	0.00e+00
Beryllium	Be-7	53.3 d	2.19e-15	4.72e-17
	Be-10	1.60E+06 y	1.38e-16	3.41e-18
Carbon	C-11	0.340 h	4.56e-14	1.01e-15
	C-14	5.73E+03 y	2.60e-18	1.27e-20
Fluorine	F-18	1.83 h	4.56e-14	9.82e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	 Groundshine (Sv s^{-1} Bq^{-1} m^2)
Sodium	Na-22	2.60 y	1.02e-13	2.05e-15
	Na-24	15.0 h	2.08e-13	3.59e-15
Magnesium	Mg-28	20.9 h	6.38e-14	1.26e-15
Aluminum	Al-26	7.16E+05 y	1.28e-13	2.47e-15
	Al-28	2.24 min	8.87e-14	1.71e-15
Silicon	Si-31	2.62 h	4.83e-16	7.14e-17
	Si-32	4.50E+02 y	8.68e-18	2.50e-20
Phosphorus	P-30	2.499 min	4.68e-14	1.13e-15
	P-32	14.3 d	5.36e-16	8.52e-17
	P-33	25.4 d	1.45e-17	3.64e-20
Sulphur	S-35	87.4 d	3.11e-18	1.33e-20
Chlorine	Cl-36	3.01E+05 y	1.66e-16	1.12e-17
	Cl-38	0.620 h	7.58e-14	1.43e-15
	Cl-39	0.927 h	6.90e-14	1.41e-15
Potassium	K-38	7.636 min	1.56e-13	2.97e-15
	K-40	1.28E+09 y	7.92e-15	2.04e-16
	K-42	12.4 h	1.48e-14	3.98e-16
	K-43	22.6 h	4.35e-14	9.41e-16
	K-44	0.369 h	1.14e-13	2.12e-15
	K-45	0.333 h	9.20e-14	1.76e-15
Calcium	Ca-41	1.40E+05 y	0.00e+00	0.00e+00
	Ca-45	163 d	1.53e-17	3.77e-20
	Ca-47	4.53 d	5.06e-14	1.00e-15
	Ca-49	8.716 min	1.66e-13	2.67e-15
Scandium	Sc-43	3.89 h	4.88e-14	1.07e-15
	Sc-44	3.93 h	9.87e-14	2.08e-15
	Sc-44m	2.44 d	1.24e-14	2.62e-16
	Sc-46	83.8 d	9.36e-14	1.88e-15
	Sc-47	3.35 d	4.67e-15	9.97e-17
	Sc-48	1.82 d	1.57e-13	3.11e-15
	Sc-49	0.956 h	7.16e-16	1.02e-16
Titanium	Ti-44	47.3 y	4.70e-15	1.18e-16
	Ti-45	3.08 h	3.89e-14	8.66e-16
Vanadium	V-47	0.543 h	4.49e-14	1.05e-15
	V-48	16.2 d	1.36e-13	2.72e-15
	V-49	330 d	0.00e+00	0.00e+00
Chromium	Cr-48	23.0 h	1.87e-14	4.04e-16
	Cr-49	0.702 h	4.68e-14	1.07e-15
	Cr-51	27.7 d	1.38e-15	2.97e-17
Manganese	Mn-51	0.770 h	4.51e-14	1.07e-15
	Mn-52	5.59 d	1.62e-13	3.22e-15
	Mn-52m	0.352 h	1.13e-13	2.36e-15
	Mn-53	3.70E+06 y	0.00e+00	0.00e+00
	Mn-54	312 d	3.83e-14	7.91e-16
	Mn-56	2.58 h	8.16e-14	1.62e-15
Iron	Fe-52	8.28 h	3.27e-14	7.11e-16
	Fe-55	2.70 y	0.00e+00	0.00e+00
	Fe-59	44.5 d	5.62e-14	1.10e-15
	Fe-60	1.00E+05 y	1.79e-18	1.17e-20
Cobalt	Co-55	17.5 h	9.16e-14	1.93e-15

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	 Groundshine (Sv s^{-1} Bq^{-1} m^2)
	Co-56	78.7 d	1.73e-13	3.23e-15
	Co-57	271 d	4.97e-15	1.08e-16
	Co-58	70.8 d	4.44e-14	9.25e-16
	Co-58m	9.15 h	6.06e-20	6.65e-21
	Co-60	5.27 y	1.19e-13	2.30e-15
	Co-60m	0.174 h	2.00e-16	4.38e-18
	Co-61	1.65 h	3.74e-15	1.29e-16
	Co-62m	0.232 h	1.30e-13	2.58e-15
Nickel	Ni-56	6.10 d	7.82e-14	1.62e-15
	Ni-57	1.50 d	9.12e-14	1.76e-15
	Ni-59	7.50E+04 y	0.00e+00	0.00e+00
	Ni-63	96.0 y	0.00e+00	0.00e+00
	Ni-65	2.52 h	2.67e-14	5.69e-16
	Ni-66	2.27 d	1.06e-17	2.83e-20
Copper	Cu-60	0.387 h	1.87e-13	3.64e-15
	Cu-61	3.41 h	3.72e-14	8.21e-16
	Cu-62	9.74 min	4.60e-14	1.11e-15
	Cu-64	12.7 h	8.50e-15	1.83e-16
	Cu-66	5.10 min	4.89e-15	2.03e-16
	Cu-67	2.58 d	4.90e-15	1.05e-16
Zinc	Zn-62	9.26 h	1.92e-14	4.15e-16
	Zn-63	0.635 h	5.00e-14	1.16e-15
	Zn-65	244 d	2.72e-14	5.41e-16
	Zn-69	0.950 h	1.99e-16	2.08e-17
	Zn-69m	13.8 h	1.84e-14	3.98e-16
	Zn-71m	3.92 h	6.99e-14	1.54e-15
	Zn-72	1.94 d	6.17e-15	1.34e-16
Gallium	Ga-65	0.253 h	5.28e-14	1.21e-15
	Ga-66	9.40 h	1.23e-13	2.25e-15
	Ga-67	3.26 d	6.49e-15	1.41e-16
	Ga-68	1.13 h	4.29e-14	9.99e-16
	Ga-70	0.353 h	8.40e-16	8.48e-17
	Ga-72	14.1 h	1.31e-13	2.48e-15
	Ga-73	4.91 h	1.39e-14	3.35e-16
Germanium	Ge-66	2.27 h	3.00e-14	6.50e-16
	Ge-67	0.312 h	6.45e-14	1.46e-15
	Ge-68	288 d	1.01e-19	4.10e-20
	Ge-69	1.63 d	3.99e-14	8.39e-16
	Ge-71	11.8 d	1.02e-19	4.15e-20
	Ge-75	1.38 h	1.78e-15	7.20e-17
	Ge-77	11.3 h	4.98e-14	1.09e-15
	Ge-78	1.45 h	1.23e-14	2.67e-16
Arsenic	As-69	0.253 h	4.61e-14	1.11e-15
	As-70	0.876 h	1.92e-13	3.90e-15
	As-71	2.70 d	2.53e-14	5.42e-16
	As-72	1.08 d	8.26e-14	1.81e-15
	As-73	80.3 d	1.55e-16	5.18e-18
	As-74	17.8 d	3.40e-14	7.47e-16
	As-76	1.10 d	2.06e-14	5.24e-16
	As-77	1.62 d	5.09e-16	1.41e-17

Radionuclide		Half-life	External Dose Coefficients Cloudshine ($Sv\ s^{-1}\ Bq^{-1}\ m^{3}$)	Groundshine ($Sv\ s^{-1}\ Bq^{-1}\ m^{2}$)
	As-78	1.51 h	6.03e-14	1.29e-15
Selenium	Se-70	0.683 h	4.40e-14	9.98e-16
	Se-73	7.15 h	4.78e-14	1.07e-15
	Se-73m	0.650 h	1.09e-14	2.52e-16
	Se-75	120 d	1.68e-14	3.61e-16
	Se-77m	17.45 s	3.63e-15	7.77e-17
	Se-79	6.50E+04 y	3.94e-18	1.64e-20
	Se-81	0.308 h	8.69e-16	8.14e-17
	Se-81m	0.954 h	5.48e-16	1.26e-17
	Se-83	0.375 h	1.14e-13	2.29e-15
Bromine	Br-74	0.422 h	2.26e-13	4.05e-15
	Br-74m	0.691 h	1.96e-13	3.82e-15
	Br-75	1.63 h	5.43e-14	1.22e-15
	Br-76	16.2 h	1.26e-13	2.44e-15
	Br-77	2.33 d	1.40e-14	2.99e-16
	Br-80	0.290 h	3.73e-15	1.04e-16
	Br-80m	4.42 h	2.37e-16	1.37e-17
	Br-82	1.47 d	1.21e-13	2.48e-15
	Br-83	2.39 h	5.34e-16	2.86e-17
	Br-84	0.530 h	9.02e-14	1.67e-15
Rubidium	Rb-79	0.382 h	6.08e-14	1.38e-15
	Rb-80	34 s	5.77e-14	1.38e-15
	Rb-81	4.58 h	2.73e-14	5.98e-16
	Rb-81m	0.533 h	1.63e-16	4.91e-18
	Rb-82	1.3 min	5.01e-14	1.20e-15
	Rb-82m	6.20 h	1.34e-13	2.74e-15
	Rb-83	86.2 d	2.21e-14	4.76e-16
	Rb-84	32.8 d	4.18e-14	8.74e-16
	Rb-86	18.7 d	4.94e-15	1.67e-16
	Rb-87	4.70E+10 y	3.30e-17	7.30e-20
	Rb-88	0.297 h	3.33e-14	7.41e-16
	Rb-89	0.253 h	1.01e-13	1.97e-15
Strontium	Sr-80	1.67 h	5.00e-18	1.60e-18
	Sr-81	0.425 h	6.24e-14	1.43e-15
	Sr-82	25.0 d	4.92e-18	1.57e-18
	Sr-83	1.35 d	3.60e-14	7.61e-16
	Sr-85	64.8 d	2.24e-14	4.84e-16
	Sr-85m	1.16 h	9.48e-15	2.02e-16
	Sr-87m	2.80 h	1.41e-14	3.04e-16
	Sr-89	50.5 d	4.37e-16	6.86e-17
	Sr-90	29.1 y	9.83e-17	1.64e-18
	Sr-91	9.50 h	3.27e-14	7.27e-16
	Sr-92	2.71 h	6.41e-14	1.23e-15
Yittrium	Y-86	14.7 h	1.69e-13	3.33e-15
	Y-86m	0.800 h	9.59e-15	2.04e-16
	Y-87	3.35 d	1.99e-14	4.31e-16
	Y-88	107 d	1.30e-13	2.41e-15
	Y-90	2.67 d	7.92e-16	1.10e-16
	Y-90m	3.19 h	2.77e-14	5.97e-16
	Y-91	58.5 d	6.22e-16	7.46e-17

Radionuclide		Half-life	External Dose Coefficients Cloudshine ($Sv\ s^{-1}\ Bq^{-1}\ m^3$)	 Groundshine ($Sv\ s^{-1}\ Bq^{-1}\ m^2$)
	Y-91m	0.828 h	2.37e-14	5.10e-16
	Y-92	3.54 h	1.32e-14	3.83e-16
	Y-93	10.1 h	5.28e-15	2.10e-16
	Y-94	0.318 h	5.39e-14	1.19e-15
	Y-95	0.178 h	4.66e-14	9.10e-16
Zirconium	Zr-86	16.5 h	1.17e-14	2.56e-16
	Zr-88	83.4 d	1.73e-14	3.77e-16
	Zr-89	3.27 d	5.31e-14	1.10e-15
	Zr-93	1.53E+06 y	0.00e+00	0.00e+00
	Zr-95	64.0 d	3.36e-14	7.04e-16
	Zr-97	16.9 h	8.90e-15	2.50e-16
Niobium	Nb-88	0.238 h	1.89e-13	4.02e-15
	Nb-89	2.03 h	6.62e-14	1.39e-15
	Nb-89m	1.10 h	8.65e-14	1.94e-15
	Nb-90	14.6 h	2.05e-13	3.79e-15
	Nb-93m	13.6 y	3.05e-18	6.82e-19
	Nb-94	2.03E+04 y	7.20e-14	1.49e-15
	Nb-95	35.1 d	3.49e-14	7.28e-16
	Nb-95m	3.61 d	2.74e-15	5.91e-17
	Nb-96	23.3 h	1.14e-13	2.34e-15
	Nb-97	1.20 h	2.99e-14	6.75e-16
	Nb-97m	60 s	3.31e-14	6.95e-16
	Nb-98	0.858 h	1.14e-13	2.37e-15
Molybdenum	Mo-90	5.67 h	3.64e-14	7.78e-16
	Mo-93	3.50E+03 y	1.73e-17	3.88e-18
	Mo-93m	6.85 h	1.06e-13	2.07e-15
	Mo-99	2.75 d	6.99e-15	1.78e-16
	Mo-101	0.244 h	6.48e-14	1.31e-15
Technetium	Tc-93	2.75 h	6.96e-14	1.32e-15
	Tc-93m	0.725 h	3.53e-14	6.30e-16
	Tc-94	4.88 h	1.22e-13	2.53e-15
	Tc-94m	0.867 h	8.64e-14	1.82e-15
	Tc-95	20.0 h	3.58e-14	7.50e-16
	Tc-95m	61.0 d	2.99e-14	6.32e-16
	Tc-96	4.28 d	1.14e-13	2.37e-15
	Tc-96m	0.858 h	2.09e-15	4.50e-17
	Tc-97	2.60E+06 y	2.26e-17	4.65e-18
	Tc-97m	87.0 d	3.72e-17	4.45e-18
	Tc-98	4.20E+06 y	6.41e-14	1.35e-15
	Tc-99	2.13E+05 y	2.87e-17	6.47e-20
	Tc-99m	6.02 h	5.25e-15	1.14e-16
	Tc-101	0.237 h	1.50e-14	3.65e-16
	Tc-104	0.303 h	9.61e-14	1.95e-15
Ruthenium	Ru-94	0.863 h	2.36e-14	5.00e-16
	Ru-97	2.90 d	9.91e-15	2.16e-16
	Ru-103	39.3 d	2.08e-14	4.49e-16
	Ru-105	4.44 h	3.56e-14	7.82e-16
	Ru-106	1.01 y	0.00e+00	0.00e+00
Rhodium	Rh-99	16.0 d	2.63e-14	5.66e-16
	Rh-99m	4.70 h	3.06e-14	6.39e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	Groundshine (Sv s^{-1} Bq^{-1} m^2)
	Rh-100	20.8 h	1.33e-13	2.49e-15
	Rh-101	3.20 y	1.09e-14	2.40e-16
	Rh-101m	4.34 d	1.29e-14	2.83e-16
	Rh-102	2.90 y	9.68e-14	2.02e-15
	Rh-102m	207 d	2.15e-14	4.77e-16
	Rh-103m	0.935 h	6.02e-18	8.86e-19
	Rh-105	1.47 d	3.47e-15	7.42e-17
	Rh-106	29.9 s	1.06e-14	3.45e-16
	Rh-106m	2.20 h	1.35e-13	2.75e-15
	Rh-107	0.362 h	1.41e-14	3.38e-16
Palladium	Pd-100	3.63 d	3.98e-15	1.06e-16
	Pd-101	8.27 h	1.42e-14	3.09e-16
	Pd-103	17.0 d	5.32e-17	7.67e-18
	Pd-107	6.50E+06 y	0.00e+00	0.00e+00
	Pd-109	13.4 h	4.20e-16	3.73e-17
Silver	Ag-102	0.215 h	1.57e-13	3.19e-15
	Ag-103	1.09 h	3.43e-14	7.45e-16
	Ag-104	1.15 h	1.23e-13	2.52e-15
	Ag-104m	0.558 h	5.48e-14	1.14e-15
	Ag-105	41.0 d	2.26e-14	4.90e-16
	Ag-106	0.399 h	3.18e-14	7.41e-16
	Ag-106m	8.41 d	1.29e-13	2.64e-15
	Ag-108	2.37 min	1.25e-15	8.96e-17
	Ag-108m	1.27E+02 y	7.24e-14	1.55e-15
	Ag-109m	39.6 s	1.59e-16	7.52e-18
	Ag-110	24.6 s	2.46e-15	1.63e-16
	Ag-110m	250 d	1.27e-13	2.58e-15
	Ag-111	7.45 d	1.38e-15	5.28e-17
	Ag-112	3.12 h	3.23e-14	7.46e-16
	Ag-115	0.333 h	3.46e-14	7.50e-16
Cadmium	Cd-104	0.961 h	1.04e-14	2.36e-16
	Cd-107	6.49 h	5.11e-16	2.33e-17
	Cd-109	1.27 y	2.28e-16	1.66e-17
	Cd-113	9.30E+15 y	2.53e-17	5.80e-20
	Cd-113m	13.6 y	9.06e-17	1.77e-18
	Cd-115	2.23 d	1.05e-14	2.43e-16
	Cd-115m	44.6 d	1.48e-15	9.24e-17
	Cd-117	2.49 h	5.14e-14	1.04e-15
	Cd-117m	3.36 h	9.89e-14	1.85e-15
Indium	In-109	4.20 h	2.98e-14	6.24e-16
	In-110	4.90 h	1.39e-13	2.88e-15
	In-110m	1.15 h	7.15e-14	1.53e-15
	In-111	2.83 d	1.68e-14	3.68e-16
	In-112	0.240 h	1.19e-14	2.74e-16
	In-113m	1.66 h	1.12e-14	2.43e-16
	In-114	71.9 s	1.59e-16	2.76e-18
	In-114m	49.5 d	3.89e-15	8.63e-17
	In-115	5.10E+15 y	6.55e-17	3.57e-19
	In-115m	4.49 h	6.86e-15	1.51e-16
	In-116m	0.902 h	1.18e-13	2.28e-15

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
	In-117	0.730 h	3.06e-14	6.64e-16
	In-117m	1.94 h	4.07e-15	1.25e-16
	In-119	2.4 min	3.53e-14	8.02e-16
	In-119m	0.300 h	1.26e-15	1.30e-16
Tin	Sn-110	4.00 h	1.25e-14	2.77e-16
	Sn-111	0.588 h	2.30e-14	5.01e-16
	Sn-113	115 d	3.15e-16	1.63e-17
	Sn-117m	13.6 d	6.11e-15	1.40e-16
	Sn-119m	293 d	7.04e-17	7.47e-18
	Sn-121	1.13 d	3.90e-17	8.84e-20
	Sn-121m	55.0 y	5.24e-17	3.60e-18
	Sn-123	129 d	6.98e-16	6.50e-17
	Sn-123m	0.668 h	6.14e-15	1.73e-16
	Sn-125	9.64 d	1.54e-14	3.82e-16
	Sn-126	1.00E+05 y	1.84e-15	4.82e-17
	Sn-127	2.10 h	9.03e-14	1.80e-15
	Sn-128	0.985 h	2.77e-14	6.25e-16
Antimony	Sb-115	0.530 h	4.02e-14	8.93e-16
	Sb-116	0.263 h	1.02e-13	2.03e-15
	Sb-116m	1.00 h	1.45e-13	2.93e-15
	Sb-117	2.80 h	7.15e-15	1.65e-16
	Sb-118m	5.00 h	1.19e-13	2.39e-15
	Sb-119	1.59 d	1.50e-16	1.56e-17
	Sb-120	5.76 d	1.14e-13	2.28e-15
	Sb-120	0.265 h	2.00e-14	4.67e-16
	Sb-122	2.70 d	2.02e-14	4.85e-16
	Sb-124	60.2 d	8.62e-14	1.70e-15
	Sb-124m	0.337 h	4.67e-19	5.07e-20
	Sb-125	2.77 y	1.87e-14	4.09e-16
	Sb-126	12.4 d	1.28e-13	2.72e-15
	Sb-126m	0.317 h	7.01e-14	1.55e-15
	Sb-127	3.85 d	3.12e-14	6.76e-16
	Sb-128	9.01 h	1.41e-13	2.98e-15
	Sb-128m	0.173 h	9.08e-14	1.99e-15
	Sb-129	4.32 h	6.71e-14	1.37e-15
	Sb-130	0.667 h	1.50e-13	3.14e-15
	Sb-131	0.383 h	8.84e-14	1.77e-15
Tellurium	Te-116	2.49 h	1.98e-15	6.06e-17
	Te-121	17.0 d	2.50e-14	5.47e-16
	Te-121m	154 d	8.99e-15	1.98e-16
	Te-123	1.00E+13 y	1.51e-16	1.42e-17
	Te-123m	120 d	5.81e-15	1.32e-16
	Te-125m	58.0 d	3.35e-16	2.66e-17
	Te-127	9.35 h	3.34e-16	1.03e-17
	Te-127m	109 d	1.12e-16	8.56e-18
	Te-129	1.16 h	2.86e-15	1.14e-16
	Te-129m	33.6 d	1.56e-15	5.70e-17
	Te-131	0.417 h	1.92e-14	4.74e-16
	Te-131m	1.25 d	6.55e-14	1.34e-15
	Te-132	3.26 d	9.32e-15	2.12e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	Groundshine (Sv s^{-1} Bq^{-1} m^2)
	Te-133	0.207 h	4.34e-14	9.59e-16
	Te-133m	0.923 h	1.07e-13	2.24e-15
	Te-134	0.696 h	3.94e-14	8.48e-16
Iodine	I-120	1.35 h	1.31e-13	2.62e-15
	I-120m	0.883 h	2.49e-13	5.01e-15
	I-121	2.12 h	1.78e-14	3.96e-16
	I-122	3.62 min	4.31e-14	1.02e-15
	I-123	13.2 h	6.49e-15	1.53e-16
	I-124	4.18 d	5.04e-14	1.04e-15
	I-125	60.1 d	3.73e-16	3.14e-17
	I-126	13.0 d	2.01e-14	4.42e-16
	I-128	0.416 h	4.33e-15	1.71e-16
	I-129	1.57E+07 y	2.81e-16	1.95e-17
	I-130	12.4 h	9.67e-14	2.05e-15
	I-131	8.04 d	1.69e-14	3.64e-16
	I-132	2.30 h	1.05e-13	2.20e-15
	I-132m	1.39 h	1.42e-14	3.11e-16
	I-133	20.8 h	2.76e-14	6.17e-16
	I-134	0.876 h	1.22e-13	2.53e-15
	I-135	6.61 h	7.54e-14	1.47e-15
Caesium	Cs-125	0.750 h	3.01e-14	6.85e-16
	Cs-126	1.64 min	4.96e-14	1.18e-15
	Cs-127	6.25 h	1.78e-14	3.95e-16
	Cs-128	3.9 min	4.06e-14	9.54e-16
	Cs-129	1.34 d	1.13e-14	2.62e-16
	Cs-130	0.498 h	2.30e-14	5.41e-16
	Cs-131	9.69 d	2.38e-16	1.79e-17
	Cs-132	6.48 d	3.11e-14	6.69e-16
	Cs-134	2.06 y	7.06e-14	1.48e-15
	Cs-134m	2.90 h	7.95e-16	2.25e-17
	Cs-135	2.30E+06 y	9.50e-18	2.69e-20
	Cs-135m	0.883 h	7.25e-14	1.51e-15
	Cs-136	13.1 d	9.94e-14	2.03e-15
	Cs-137	30.0 y	9.28e-17	2.99e-18
	Cs-138	0.536 h	1.15e-13	2.26e-15
Barium	Ba-126	1.61 h	6.41e-15	1.51e-16
	Ba-128	2.43 d	2.54e-15	6.78e-17
	Ba-131	11.8 d	1.92e-14	4.29e-16
	Ba-131m	0.243 h	2.64e-15	6.70e-17
	Ba-133	10.7 y	1.62e-14	3.73e-16
	Ba-133m	1.62 d	2.44e-15	5.97e-17
	Ba-135m	1.20 d	2.16e-15	5.38e-17
	Ba-137m	2.552 min	2.69e-14	5.79e-16
	Ba-139	1.38 h	2.54e-15	1.46e-16
	Ba-140	12.7 d	8.07e-15	1.90e-16
	Ba-141	0.305 h	3.92e-14	8.86e-16
	Ba-142	0.177 h	4.84e-14	1.01e-15
Lanthanum	La-131	0.983 h	2.91e-14	6.55e-16
	La-132	4.80 h	9.41e-14	1.90e-15
	La-134	6.67 min	3.15e-14	7.50e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
	La-135	19.5 h	7.75e-16	3.04e-17
	La-137	6.00E+04 y	3.00e-16	1.96e-17
	La-138	1.35E+11 y	5.84e-14	1.13e-15
	La-140	1.68 d	1.11e-13	2.16e-15
	La-141	3.93 h	2.88e-15	1.52e-16
	La-142	1.54 h	1.37e-13	2.49e-15
	La-143	0.237 h	5.78e-15	2.27e-16
Cerium	Ce-134	3.00 d	3.52e-16	2.15e-17
	Ce-135	17.6 h	7.93e-14	1.70e-15
	Ce-137	9.00 h	7.30e-16	2.98e-17
	Ce-137m	1.43 d	1.83e-15	4.72e-17
	Ce-139	138 d	5.97e-15	1.43e-16
	Ce-141	32.5 d	3.10e-15	6.93e-17
	Ce-143	1.38 d	1.21e-14	3.01e-16
	Ce-144	284 d	7.63e-16	1.84e-17
Praseodymium	Pr-136	0.218 h	9.72e-14	2.04e-15
	Pr-137	1.28 h	2.20e-14	4.97e-16
	Pr-138	1.45 min	3.72e-14	8.98e-16
	Pr-138m	2.10 h	1.13e-13	2.35e-15
	Pr-139	4.51 h	4.75e-15	1.17e-16
	Pr-142	19.1 h	3.50e-15	1.47e-16
	Pr-142m	0.243 h	0.00e+00	0.00e+00
	Pr-143	13.6 d	1.94e-16	2.06e-17
	Pr-144	0.288 h	2.65e-15	1.63e-16
	Pr-144m	7.2 min	2.20e-16	1.05e-17
	Pr-145	5.98 h	1.12e-15	9.38e-17
	Pr-147	0.227 h	3.90e-14	8.95e-16
Neodymium	Nd-136	0.844 h	1.15e-14	2.73e-16
	Nd-138	5.04 h	1.07e-15	3.75e-17
	Nd-139	0.495 h	1.77e-14	4.07e-16
	Nd-139m	5.50 h	7.12e-14	1.48e-15
	Nd-141	2.49 h	2.59e-15	6.84e-17
	Nd-141m	62.4 s	3.45e-14	7.32e-16
	Nd-147	11.0 d	5.72e-15	1.40e-16
	Nd-149	1.73 h	1.68e-14	4.06e-16
	Nd-151	0.207 h	4.21e-14	9.23e-16
Promethium	Pm-141	0.348 h	3.39e-14	7.73e-16
	Pm-142	40.5 s	4.01e-14	9.62e-16
	Pm-143	265 d	1.35e-14	2.97e-16
	Pm-144	363 d	6.95e-14	1.49e-15
	Pm-145	17.7 y	5.49e-16	2.61e-17
	Pm-146	5.53 y	3.34e-14	7.19e-16
	Pm-147	2.62 y	8.67e-18	2.80e-20
	Pm-148	5.37 d	2.76e-14	6.11e-16
	Pm-148m	41.3 d	9.01e-14	1.91e-15
	Pm-149	2.21 d	7.08e-16	4.04e-17
	Pm-150	2.68 h	6.77e-14	1.41e-15
	Pm-151	1.18 d	1.40e-14	3.18e-16
Samarium	Sm-141	0.170 h	6.44e-14	1.39e-15
	Sm-141m	0.377 h	9.07e-14	1.89e-15

Radionuclide		Half-life	External Dose Coefficients Cloudshine ($Sv\ s^{-1}\ Bq^{-1}\ m^3$)	Groundshine ($Sv\ s^{-1}\ Bq^{-1}\ m^2$)
	Sm-142	1.21 h	3.43e-15	8.95e-17
	Sm-145	340 d	1.26e-15	5.56e-17
	Sm-146	1.03E+08 y	0.00e+00	0.00e+00
	Sm-147	1.06E+11 y	0.00e+00	0.00e+00
	Sm-151	90.0 y	2.46e-20	3.54e-21
	Sm-153	1.95 d	2.04e-15	6.10e-17
	Sm-155	0.368 h	4.43e-15	1.56e-16
	Sm-156	9.40 h	4.93e-15	1.12e-16
Europium	Eu-145	5.94 d	6.78e-14	1.34e-15
	Eu-146	4.61 d	1.15e-13	2.35e-15
	Eu-147	24.0 d	2.14e-14	4.62e-16
	Eu-148	54.5 d	9.83e-14	2.06e-15
	Eu-149	93.1 d	1.95e-15	5.66e-17
	Eu-150	34.2 y	6.64e-14	1.42e-15
	Eu-150m	12.6 h	2.22e-15	6.78e-17
	Eu-152	13.3 y	5.28e-14	1.08e-15
	Eu-152m	9.32 h	1.36e-14	3.35e-16
	Eu-154	8.80 y	5.75e-14	1.17e-15
	Eu-155	4.96 y	2.14e-15	5.35e-17
	Eu-156	15.2 d	6.38e-14	1.24e-15
	Eu-157	15.1 h	1.09e-14	2.76e-16
	Eu-158	0.765 h	5.00e-14	1.08e-15
Gadolinium	Gd-145	0.382 h	1.09e-13	2.09e-15
	Gd-146	48.3 d	8.61e-15	2.22e-16
	Gd-147	1.59 d	5.98e-14	1.25e-15
	Gd-148	93.0 y	0.00e+00	0.00e+00
	Gd-149	9.40 d	1.75e-14	3.92e-16
	Gd-151	120 d	1.88e-15	5.57e-17
	Gd-152	1.08E+14 y	0.00e+00	0.00e+00
	Gd-153	242 d	3.11e-15	9.22e-17
	Gd-159	18.6 h	2.16e-15	6.48e-17
Terbium	Tb-147	1.65 h	7.29e-14	1.55e-15
	Tb-149	4.15 h	7.51e-14	1.50e-15
	Tb-150	3.27 h	7.75e-14	1.62e-15
	Tb-151	17.6 h	3.87e-14	8.38e-16
	Tb-153	2.34 d	8.86e-15	2.09e-16
	Tb-154	21.4 h	1.14e-13	2.08e-15
	Tb-155	5.32 d	4.84e-15	1.25e-16
	Tb-156	5.34 d	8.34e-14	1.69e-15
	Tb-156m	1.02 d	6.24e-16	2.21e-17
	Tb-156n	5.00 h	9.73e-17	3.15e-18
	Tb-157	1.50E+02 y	5.34e-17	2.20e-18
	Tb-158	1.50E+02 y	3.58e-14	7.49e-16
	Tb-160	72.3 d	5.19e-14	1.06e-15
	Tb-161	6.91 d	8.93e-16	2.95e-17
Dysprosium	Dy-155	10.0 h	2.56e-14	5.38e-16
	Dy-157	8.10 h	1.48e-14	3.33e-16
	Dy-159	144 d	9.93e-16	3.87e-17
	Dy-165	2.33 h	1.35e-15	6.91e-17
	Dy-166	3.40 d	1.21e-15	3.51e-17

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	 Groundshine (Sv s^{-1} Bq^{-1} m^2)
Holmium	Ho-155	0.800 h	1.65e-14	3.89e-16
	Ho-157	0.210 h	2.04e-14	4.61e-16
	Ho-159	0.550 h	1.43e-14	3.34e-16
	Ho-161	2.50 h	1.40e-15	5.14e-17
	Ho-162	0.250 h	6.70e-15	1.55e-16
	Ho-162m	1.13 h	2.54e-14	5.30e-16
	Ho-164	0.483 h	8.03e-16	3.38e-17
	Ho-164m	0.625 h	1.06e-15	3.90e-17
	Ho-166	1.12 d	1.72e-15	1.05e-16
	Ho-166m	1.20E+03 y	7.84e-14	1.65e-15
	Ho-167	3.10 h	1.59e-14	3.51e-16
Erbium	Er-161	3.24 h	4.11e-14	8.55e-16
	Er-165	10.4 h	8.96e-16	3.24e-17
	Er-169	9.30 d	2.97e-17	6.75e-20
	Er-171	7.52 h	1.64e-14	3.85e-16
	Er-172	2.05 d	2.29e-14	4.96e-16
Thulium	Tm-162	0.362 h	8.50e-14	1.63e-15
	Tm-166	7.70 h	8.78e-14	1.70e-15
	Tm-167	9.24 d	5.39e-15	1.31e-16
	Tm-170	129 d	3.67e-16	2.64e-17
	Tm-171	1.92 y	1.77e-17	5.55e-19
	Tm-172	2.65 d	2.30e-14	4.87e-16
	Tm-173	8.24 h	1.72e-14	3.88e-16
	Tm-175	0.253 h	4.81e-14	1.04e-15
Ytterbium	Yb-162	0.315 h	4.92e-15	1.22e-16
	Yb-166	2.36 d	2.35e-15	7.44e-17
	Yb-167	0.292 h	9.48e-15	2.37e-16
	Yb-169	32.0 d	1.13e-14	2.78e-16
	Yb-175	4.19 d	1.75e-15	3.74e-17
	Yb-177	1.90 h	8.82e-15	2.17e-16
	Yb-178	1.23 h	1.62e-15	3.60e-17
Lutetium	Lu-169	1.42 d	4.75e-14	9.56e-16
	Lu-170	2.00 d	1.21e-13	2.19e-15
	Lu-171	8.22 d	3.00e-14	6.54e-16
	Lu-172	6.70 d	8.64e-14	1.76e-15
	Lu-173	1.37 y	4.42e-15	1.16e-16
	Lu-174	3.31 y	4.94e-15	1.12e-16
	Lu-174m	142 d	1.84e-15	5.33e-17
	Lu-176	3.60E+10 y	2.11e-14	4.57e-16
	Lu-176m	3.68 h	7.65e-16	5.60e-17
	Lu-177	6.71 d	1.50e-15	3.21e-17
	Lu-177m	161 d	4.24e-14	9.31e-16
	Lu-178	0.473 h	7.12e-15	2.15e-16
	Lu-178m	0.378 h	4.80e-14	1.08e-15
	Lu-179	4.59 h	1.66e-15	7.67e-17
Hafnium	Hf-170	16.0 h	2.29e-14	5.11e-16
	Hf-172	1.87 y	3.40e-15	9.92e-17
	Hf-173	24.0 h	1.66e-14	3.73e-16
	Hf-175	70.0 d	1.54e-14	3.45e-16
	Hf-177m	0.856 h	9.67e-14	2.10e-15

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
	Hf-178m	31.0 y	1.03e-13	2.22e-15
	Hf-179m	25.1 d	3.84e-14	8.42e-16
	Hf-180m	5.50 h	4.33e-14	9.46e-16
	Hf-181	42.4 d	2.42e-14	5.25e-16
	Hf-182	9.00E+06 y	1.03e-14	2.23e-16
	Hf-182m	1.02 h	4.08e-14	8.78e-16
	Hf-183	1.07 h	3.39e-14	7.52e-16
	Hf-184	4.12 h	1.04e-14	2.46e-16
Tantalum	Ta-172	0.613 h	7.10e-14	1.49e-15
	Ta-173	3.65 h	2.55e-14	5.75e-16
	Ta-174	1.20 h	2.75e-14	6.15e-16
	Ta-175	10.5 h	4.24e-14	8.49e-16
	Ta-176	8.08 h	1.03e-13	1.93e-15
	Ta-177	2.36 d	2.15e-15	5.87e-17
	Ta-178	2.20 h	4.32e-14	9.53e-16
	Ta-178m	9.31 min	4.12e-15	9.61e-17
	Ta-179	1.82 y	9.00e-16	2.75e-17
	Ta-180	1.00E+13 y	2.35e-14	5.18e-16
	Ta-180m	8.10 h	1.43e-15	4.23e-17
	Ta-182	115 d	5.99e-14	1.20e-15
	Ta-182m	0.264 h	9.94e-15	2.25e-16
	Ta-183	5.10 d	1.19e-14	2.68e-16
	Ta-184	8.70 h	7.25e-14	1.55e-15
	Ta-185	0.816 h	8.23e-15	2.50e-16
	Ta-186	0.175 h	7.02e-14	1.58e-15
Tungsten	W-176	2.30 h	5.98e-15	1.54e-16
	W-177	2.25 h	3.91e-14	8.38e-16
	W-178	21.7 d	3.83e-16	1.14e-17
	W-179	0.625 h	1.50e-15	4.98e-17
	W-181	121 d	1.16e-15	3.44e-17
	W-185	75.1 d	4.97e-17	1.71e-19
	W-187	23.9 h	2.13e-14	4.68e-16
	W-188	69.4 d	1.10e-16	1.82e-18
Rhenium	Re-177	0.233 h	2.76e-14	5.95e-16
	Re-178	0.220 h	5.73e-14	1.15e-15
	Re-180	2.43 min	5.33e-14	1.12e-15
	Re-181	20.0 h	3.37e-14	7.20e-16
	Re-182	2.67 d	8.49e-14	1.73e-15
	Re-182m	12.7 h	5.39e-14	1.08e-15
	Re-184	38.0 d	3.99e-14	8.37e-16
	Re-184m	165 d	1.67e-14	3.59e-16
	Re-186	3.78 d	9.97e-16	4.42e-17
	Re-186m	2.00E+05 y	4.14e-16	1.28e-17
	Re-187	5.00E+10 y	0.00e+00	0.00e+00
	Re-188	17.0 h	3.13e-15	1.45e-16
	Re-188m	0.310 h	2.56e-15	6.77e-17
	Re-189	1.01 d	3.08e-15	8.41e-17
Osmium	Os-180	0.366 h	1.96e-15	5.39e-17
	Os-181	1.75 h	5.52e-14	1.13e-15
	Os-182	22.0 h	1.83e-14	4.06e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	 Groundshine (Sv s^{-1} Bq^{-1} m^{2})
	Os-185	94.0 d	3.18e-14	6.81e-16
	Os-189m	6.00 h	1.24e-19	4.83e-20
	Os-190m	9.9 min	7.03e-14	1.51e-15
	Os-191	15.4 d	2.78e-15	6.75e-17
	Os-191m	13.0 h	2.31e-16	6.40e-18
	Os-193	1.25 d	3.29e-15	9.59e-17
	Os-194	6.00 y	2.17e-17	9.55e-19
Iridium	Ir-182	0.250 h	6.07e-14	1.34e-15
	Ir-184	3.02 h	8.75e-14	1.78e-15
	Ir-185	14.0 h	2.74e-14	5.33e-16
	Ir-186	15.8 h	7.51e-14	1.51e-15
	Ir-186m	1.75 h	4.33e-14	9.16e-16
	Ir-187	10.5 h	1.54e-14	3.37e-16
	Ir-188	1.73 d	7.52e-14	1.42e-15
	Ir-189	13.3 d	2.77e-15	6.99e-17
	Ir-190	12.1 d	6.32e-14	1.36e-15
	Ir-190m	3.10 h	6.81e-14	1.47e-15
	Ir-190n	1.20 h	1.38e-19	5.32e-20
	Ir-192	74.0 d	3.61e-14	7.77e-16
	Ir-192m	2.41E+02 y	6.84e-15	1.47e-16
	Ir-194	19.1 h	4.73e-15	1.81e-16
	Ir-194m	171 d	1.04e-13	2.23e-15
	Ir-195	2.50 h	2.17e-15	7.37e-17
	Ir-195m	3.80 h	1.78e-14	3.98e-16
Platinum	Pt-186	2.00 h	3.27e-14	7.00e-16
	Pt-188	10.2 d	7.90e-15	1.82e-16
	Pt-189	10.9 h	1.34e-14	2.99e-16
	Pt-191	2.80 d	1.21e-14	2.78e-16
	Pt-193	50.0 y	4.07e-19	1.54e-19
	Pt-193m	4.33 d	3.76e-16	9.31e-18
	Pt-195m	4.02 d	2.44e-15	6.19e-17
	Pt-197	18.3 h	9.73e-16	2.39e-17
	Pt-197m	1.57 h	3.25e-15	7.28e-17
	Pt-199	0.513 h	9.32e-15	2.47e-16
	Pt-200	12.5 h	2.33e-15	5.46e-17
Gold	Au-193	17.6 h	6.03e-15	1.42e-16
	Au-194	1.65 d	4.94e-14	9.72e-16
	Au-195	183 d	2.73e-15	7.05e-17
	Au-195m	30.5 s	8.52e-15	1.84e-16
	Au-198	2.69 d	1.81e-14	4.07e-16
	Au-198m	2.30 d	2.39e-14	5.23e-16
	Au-199	3.14 d	3.67e-15	7.97e-17
	Au-200	0.807 h	1.32e-14	3.37e-16
	Au-200m	18.7 h	9.32e-14	1.98e-15
	Au-201	0.440 h	2.62e-15	9.03e-17
Mercury	Hg-193	3.50 h	7.70e-15	1.80e-16
	Hg-193m	11.1 h	4.69e-14	9.66e-16
	Hg-194	2.60E+02 y	6.23e-19	2.24e-19
	Hg-195	9.90 h	8.38e-15	1.85e-16
	Hg-195m	1.73 d	8.78e-15	1.93e-16

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^{3})	Groundshine (Sv s^{-1} Bq^{-1} m^{2})
	Hg-197	2.67 d	2.26e-15	5.79e-17
	Hg-197m	23.8 h	3.62e-15	8.12e-17
	Hg-199m	0.710 h	7.63e-15	1.67e-16
	Hg-203	46.6 d	1.04e-14	2.22e-16
Thallium	Tl-194	0.550 h	3.41e-14	7.35e-16
	Tl-194m	0.546 h	1.03e-13	2.23e-15
	Tl-195	1.16 h	5.94e-14	1.16e-15
	Tl-197	2.84 h	1.78e-14	3.77e-16
	Tl-198	5.30 h	9.47e-14	1.82e-15
	Tl-198m	1.87 h	5.26e-14	1.13e-15
	Tl-199	7.42 h	1.02e-14	2.27e-16
	Tl-200	1.09 d	5.98e-14	1.22e-15
	Tl-201	3.04 d	3.25e-15	7.96e-17
	Tl-202	12.2 d	2.00e-14	4.40e-16
	Tl-204	3.78 y	1.71e-16	1.08e-17
	Tl-206	4.20 min	3.95e-16	6.07e-17
	Tl-207	4.77 min	4.53e-16	5.56e-17
	Tl-208	3.07 min	1.69e-13	2.97e-15
	Tl-209	2.20 min	9.65e-14	1.92e-15
Lead	Pb-195m	0.263 h	7.12e-14	1.52e-15
	Pb-198	2.40 h	1.86e-14	4.06e-16
	Pb-199	1.50 h	6.83e-14	1.36e-15
	Pb-200	21.5 h	8.17e-15	1.86e-16
	Pb-201	9.40 h	3.35e-14	7.08e-16
	Pb-202	3.00E+05 y	4.96e-19	1.91e-19
	Pb-202m	3.62 h	9.29e-14	1.93e-15
	Pb-203	2.17 d	1.30e-14	2.86e-16
	Pb-205	1.43E+07 y	5.45e-19	2.08e-19
	Pb-209	3.25 h	1.00e-16	3.19e-18
	Pb-210	22.3 y	4.48e-17	2.13e-18
	Pb-211	0.601 h	2.59e-15	9.50e-17
	Pb-212	10.6 h	6.24e-15	1.35e-16
	Pb-214	0.447 h	1.09e-14	2.40e-16
Bismuth	Bi-200	0.606 h	1.08e-13	2.26e-15
	Bi-201	1.80 h	6.08e-14	1.28e-15
	Bi-202	1.67 h	1.24e-13	2.54e-15
	Bi-203	11.8 h	1.13e-13	2.18e-15
	Bi-205	15.3 d	7.98e-14	1.54e-15
	Bi-206	6.24 d	1.51e-13	3.06e-15
	Bi-207	38.0 y	7.04e-14	1.45e-15
	Bi-210	5.01 d	2.58e-16	3.51e-17
	Bi-210m	3.00E+06 y	1.12e-14	2.40e-16
	Bi-211	2.14 min	2.04e-15	4.40e-17
	Bi-212	1.01 h	8.95e-15	2.25e-16
	Bi-213	0.761 h	6.16e-15	1.68e-16
	Bi-214	0.332 h	7.25e-14	1.44e-15
Polonium	Po-203	0.612 h	7.59e-14	1.53e-15
	Po-205	1.80 h	7.29e-14	1.47e-15
	Po-207	5.83 h	6.08e-14	1.24e-15
	Po-210	138 d	3.89e-19	8.09e-21

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	Groundshine (Sv s^{-1} Bq^{-1} m^2)
	Po-218	3.05 min	4.21e-19	8.66e-21
Astantine	At-207	1.80 h	6.09e-14	1.22e-15
	At-211	7.21 h	1.37e-15	3.32e-17
Francium	Fr-220	27.4 s	4.40e-16	9.87e-18
	Fr-221	4.8 min	1.32e-15	2.84e-17
	Fr-222	0.240 h	5.79e-16	8.74e-17
	Fr-223	0.363 h	2.20e-15	7.76e-17
Radium	Ra-222	38 s	4.03e-16	8.66e-18
	Ra-223	11.4 d	5.47e-15	1.21e-16
	Ra-224	3.66 d	4.29e-16	9.15e-18
	Ra-225	14.8 d	2.40e-16	1.07e-17
	Ra-226	1.60E+03 y	2.84e-16	6.11e-18
	Ra-227	0.703 h	7.01e-15	1.82e-16
	Ra-228	5.75 y	0.00e+00	0.00e+00
Actinium	Ac-223	2.2 min	1.87e-16	4.42e-18
	Ac-224	2.90 h	8.01e-15	1.77e-16
	Ac-225	10.0 d	6.37e-16	1.47e-17
	Ac-226	1.21 d	5.57e-15	1.35e-16
	Ac-227	21.8 y	5.12e-18	1.41e-19
	Ac-228	6.13 h	4.49e-14	9.39e-16
Thorium	Th-226	0.515 h	3.21e-16	7.25e-18
	Th-227	18.7 d	4.43e-15	9.81e-17
	Th-228	1.91 y	8.10e-17	2.13e-18
	Th-229	7.34E+03 y	3.36e-15	7.89e-17
	Th-230	7.70E+04 y	1.48e-17	6.37e-19
	Th-231	1.06 d	4.58e-16	1.55e-17
	Th-232	1.40E+10 y	7.24e-18	4.55e-19
	Th-234	24.1 d	2.94e-16	7.49e-18
Protactinium	Pa-227	0.638 h	7.38e-16	1.81e-17
	Pa-228	22.0 h	5.16e-14	1.05e-15
	Pa-230	17.4 d	2.91e-14	6.07e-16
	Pa-231	3.27E+04 y	1.57e-15	3.78e-17
	Pa-232	1.31 d	4.26e-14	8.82e-16
	Pa-233	27.0 d	8.55e-15	1.86e-16
	Pa-234	6.70 h	8.72e-14	1.80e-15
	Pa-234m	1.17 min	1.21e-15	1.08e-16
Uranium	U-230	20.8 d	4.56e-17	1.55e-18
	U-231	4.20 d	2.56e-15	6.40e-17
	U-232	72.0 y	1.17e-17	8.07e-19
	U-233	1.58E+05 y	1.42e-17	5.99e-19
	U-234	2.44E+05 y	6.11e-18	5.86e-19
	U-235	7.04E+08 y	6.46e-15	1.40e-16
	U-236	2.34E+07 y	3.86e-18	5.03e-19
	U-237	6.75 d	5.29e-15	1.23e-16
	U-238	4.47E+09 y	2.50e-18	4.23e-19
	U-239	0.392 h	2.13e-15	8.25e-17
	U-240	14.1 h	5.87e-17	3.19e-18
Neptunium	Np-232	0.245 h	5.38e-14	1.13e-15
	Np-233	0.603 h	3.39e-15	7.79e-17
	Np-234	4.40 d	6.83e-14	1.31e-15

Radionuclide		Half-life	External Dose Coefficients Cloudshine (Sv s^{-1} Bq^{-1} m^3)	 Groundshine (Sv s^{-1} Bq^{-1} m^2)
	Np-235	1.08 y	4.19e-17	2.86e-18
	Np-236	1.15E+05 y	4.74e-15	1.11e-16
	Np-236m	22.5 h	1.92e-15	4.38e-17
	Np-237	2.14E+06 y	8.87e-16	2.52e-17
	Np-238	2.12 d	2.56e-14	5.34e-16
	Np-239	2.36 d	6.95e-15	1.54e-16
	Np-240	1.08 h	5.88e-14	1.24e-15
	Np-240m	7.4 min	1.55e-14	3.87e-16
Plutonium	Pu-234	8.80 h	2.49e-15	5.78e-17
	Pu-235	0.422 h	3.45e-15	8.00e-17
	Pu-236	2.85 y	4.68e-18	7.35e-19
	Pu-237	45.3 d	1.76e-15	4.25e-17
	Pu-238	87.7 y	3.50e-18	6.26e-19
	Pu-239	2.41E+04 y	3.48e-18	2.84e-19
	Pu-240	6.54E+03 y	3.42e-18	6.01e-19
	Pu-241	14.4 y	6.33e-20	1.72e-21
	Pu-242	3.76E+05 y	2.90e-18	4.98e-19
	Pu-243	4.95 h	9.61e-16	2.27e-17
	Pu-244	8.26E+07 y	2.08e-18	4.16e-19
	Pu-245	10.5 h	1.86e-14	4.06e-16
	Pu-246	10.9 d	5.35e-15	1.23e-16
Americium	Am-237	1.22 h	1.55e-14	3.38e-16
	Am-238	1.63 h	4.04e-14	8.27e-16
	Am-239	11.9 h	9.26e-15	2.08e-16
	Am-240	2.12 d	4.67e-14	9.57e-16
	Am-241	4.32E+02 y	6.74e-16	2.33e-17
	Am-242	16.0 h	6.09e-16	1.61e-17
	Am-242m	1.52E+02 y	2.49e-17	2.26e-18
	Am-243	7.38E+03 y	1.85e-15	4.79e-17
	Am-244	10.1 h	3.59e-14	7.60e-16
	Am-244m	0.433 h	3.63e-16	5.55e-17
	Am-245	2.05 h	1.45e-15	4.12e-17
	Am-246	0.650 h	3.06e-14	6.80e-16
	Am-246m	0.417 h	4.74e-14	9.95e-16
Curium	Cm-238	2.40 h	2.85e-15	6.56e-17
	Cm-240	27.0 d	4.17e-18	7.69e-19
	Cm-241	32.8 d	2.11e-14	4.65e-16
	Cm-242	163 d	4.02e-18	7.02e-19
	Cm-243	28.5 y	5.30e-15	1.18e-16
	Cm-244	18.1 y	3.40e-18	6.44e-19
	Cm-245	8.50E+03 y	3.49e-15	8.05e-17
	Cm-246	4.73E+03 y	3.10e-18	5.76e-19
	Cm-247	1.56E+07 y	1.38e-14	2.99e-16
	Cm-248	3.39E+05 y	2.35e-18	4.40e-19
	Cm-249	1.07 h	1.02e-15	3.32e-17
	Cm-250	6.90E+03 y	0.00e+00	0.00e+00
Berkelium	Bk-245	4.94 d	9.26e-15	2.06e-16
	Bk-246	1.83 d	4.27e-14	8.88e-16
	Bk-247	1.38E+03 y	4.20e-15	9.42e-17
	Bk-249	320 d	4.68e-19	5.34e-21

Radionuclide		Half-life	External Dose Coefficients Cloudshine ($Sv\ s^{-1}\ Bq^{-1}\ m^3$)	Groundshine ($Sv\ s^{-1}\ Bq^{-1}\ m^2$)
	Bk-250	3.22 h	4.12e-14	8.43e-16
Californium	Cf-244	0.323 h	4.74e-18	8.19e-19
	Cf-246	1.49 d	3.92e-18	5.73e-19
	Cf-248	334 d	3.25e-18	5.58e-19
	Cf-249	3.50E+02 y	1.45e-14	3.15e-16
	Cf-250	13.1 y	3.09e-18	5.32e-19
	Cf-251	8.98E+02 y	5.01e-15	1.13e-16
	Cf-252	2.64 y	3.63e-18	5.24e-19
	Cf-253	17.8 d	1.75e-17	5.17e-20
	Cf-254	60.5 d	1.01e-20	1.73e-21
Einsteinium	Es-250	2.10 h	1.76e-14	3.65e-16
	Es-251	1.38 d	3.65e-15	8.39e-17
	Es-253	20.5 d	1.60e-17	6.63e-19
	Es-254	276 d	1.57e-16	9.76e-18
	Es-254m	1.64 d	2.11e-14	4.58e-16
Fermium	Fm-252	22.7 h	3.45e-18	5.41e-19
	Fm-253	3.00 d	3.12e-15	7.14e-17
	Fm-254	3.24 h	4.76e-18	5.99e-19
	Fm-255	20.1 h	8.82e-17	6.29e-18
	Fm-257	101 d	4.15e-15	9.50e-17
Mendelevium	Md-257	5.20 h	4.52e-15	1.01e-16
	Md-258	55.0 d	3.89e-17	3.32e-18