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User's Manual for RESRAD-BUILD Code Version 4

Vol. 1 – Methodology and Models Used in RESRAD-BUILD Code

Environmental Science Division

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by
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December 2022

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USER'S MANUAL FOR RESRAD-BUILD CODE VERSION 4
VOL. 1 – METHODOLOGY AND MODELS USED IN RESRAD-BUILD CODE

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ABSTRACT

The RESRAD-BUILD computer code models radionuclide release and transport in indoor environments and performs pathway analyses to evaluate the potential radiological dose and risk incurred by an individual who works or lives in a building contaminated with radioactive material or housing radioactively contaminated furniture or equipment. The code provides four geometries to characterize a radiation source: point, line, area, and volume, in which radionuclides are homogeneously distributed. Radionuclides contained in a source are considered to be released to the indoor air due to various processes including erosion (mechanically or weathering), diffusion (for tritium and radon in a volume source), or emanation (radon in a point, line, or area source). The release can proceed through different time phases with different rates. In RESRAD-BUILD Version 4.0, a dynamic ventilation model is implemented to simulate the fate and transport of source material particles and radionuclides after their releases. This dynamic ventilation model considers (1) air exchange between rooms in the building and between the rooms and the outdoor environment, (2) deposition from air to floor, (3) resuspension from the floor to the air, and (4) periodical vacuuming that reduces the floor deposition. The fate and transport modeling provides estimates of radionuclide concentrations in the source, in the air, and on the floor at different times, which are then integrated over the exposure duration for the calculation of radiation doses and cancer risks. A single run of the RESRAD-BUILD code can model a building with up to 9 rooms, 10 sources, and 10 receptors. The potential radiation dose and cancer risk incurred by each receptor are calculated for seven exposure pathways: (1) external radiation directly from the sources (accounting for shielding), (2) external radiation from radioactive particles deposited on the floors, (3) external radiation from airborne radionuclides, (4) inhalation of airborne radionuclides, (5) inhalation of radon and radon progenies, (6) inadvertent ingestion of radioactive particles directly from the source, and (7) ingestion of radioactive particles deposited on the floors. Various exposure scenarios can be modeled with RESRAD-BUILD, including but are not limited to, office worker, renovation worker, decontamination worker, building visitor, and resident. Both deterministic and probabilistic analyses can be performed to obtain results in both text reports and graphic displays.

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1 INTRODUCTION

RESRAD-BUILD is part of the RESRAD family of codes that Argonne National Laboratory developed for the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission. The RESRAD family of codes includes five (5) codes that are actively maintained and updated to run on various computer systems. These 5 codes are RESRAD-ONSITE, RESRAD-OFFSITE, RESRAD-BUILD, RESRAD-BIOTA, and RESRAD-RDD. Descriptions of these codes and their supporting documents can be found on the RESRAD website (https://resrad.evs.anl.gov). This report is Volume 1 of the RESRAD-BUILD User's Manual that documents the methodology, models, and radionuclide-specific data used in RESRAD-BUILD code Version 4.0. Volume 2 of the RESRAD-BUILD User's Manual is called the User's Guide for RESRAD-BUILD code, which describes how to use RESRAD-BUILD code Version 4.0; it contains screen shots and parameter information.

1.1 OVERVIEW OF RESRAD-BUILD

The RESRAD-BUILD computer code models radionuclide release and transport in indoor environments and links a radiation source to individual receptors at specific locations inside a building via pathway analyses to evaluate the potential radiation doses and cancer risks incurred by those receptors. The code provides four types of geometry to characterize a radiation source: point, line, area, and volume, in which radionuclides are homogeneously distributed. The radionuclides in a source are considered to be released into the indoor air due to erosion (mechanically or weathering), diffusion (for tritium and radon in a volume source), or simply emanation (for radon in a point, line, or area source). The release rates are tracked to calculate the remaining contamination in the source and are used in an air ventilation model to simulate the transport of contaminated source particles and radionuclides within the building from one compartment (room) to another. In addition to air exchanges between compartments and between the compartments and the outside environment, the air ventilation model also considers deposition and resuspension of dust particles, floor vacuuming, as well as radiological ingrowth and decay to quantify radionuclide concentrations in the air and on the floors over the time frame of analysis. The time-varying concentrations of radionuclide in the source, in the air, and on the floors are integrated over the exposure duration to calculate the radiation dose and cancer risk associated with different exposure pathways. Seven exposure pathways are considered by RESRAD-BUILD: (1) external radiation directly from the sources (accounting for shielding), (2) external radiation from radioactive particles deposited on the floors, (3) external radiation from airborne radionuclides, (4) inhalation of airborne radionuclides, (5) inhalation of radon and its progenies, (6) inadvertent ingestion of radioactive particles directly from the source, and (7) ingestion of radioactive particles deposited on the floors.

The design of RESRAD-BUILD is similar to that of RESRAD-ONSITE and RESRAD-OFFSITE. It incorporates a user-friendly interface for (1) entering data to construct an exposure scenario with appropriate input parameter values; (2) accessing the independent Dose Conversion Factor (DCF) Editor to view and create a dose and risk coefficient library to be used in dose/risk calculations, if so desired; (3) performing deterministic and sensitivity analysis calculations and viewing calculation results; and (4) performing probabilistic calculations and viewing the results generated. The interface is equipped with general and context-specific help files as well as the User's Manual including the User's Guide (Volume 1 and 2 of this report) that can be retrieved at any time to guide the use of the computer code. A single run of the RESRAD-BUILD code can model a building with up to 9 compartments (rooms), 10 sources, and 10 receptors. Because of the level of detail in input specifications as well as the precision in mathematical formulations and solutions, RESRAD-BUILD can be applied to evaluate radiation dose and cancer risk associated with building occupancy (residents, office workers, and occasional visitors) that typically involve slow releases of the contaminants, as well as with building decontamination and renovation (decontamination and renovation workers) that could involve quick removal of the contamination.

Version 4.0 of RESRAD-BUILD has quite a few modeling enhancements and new features over the previously released versions; the major enhancements include:

1. Provision of a choice between ICRP-107 and ICRP-38 radiological transformation database, along with an input of cut-off half-life, for use to construct radiological decay chains, and choices of compatible dose and risk coefficient libraries for use in dose and risk calculations.

2. Modeling of complete decay chains, including branches, and evaluating each progeny separately for their contributions to direct external radiation.

3. Implementation of a new dynamic ventilation model that forgoes the steady-state assumption as used in previous versions, to conserve mass balance and improve accuracy in the predicted radionuclide concentrations in the air and on the floor over time.

4. Increments in the number of compartments (rooms) in the building from 3 to 9 with allowance for air exchange between any pair of rooms and between any room and the outdoor.

5. Consideration of periodical vacuuming and its efficiency to remove floor deposition of contaminated materials.

6. Consideration of up to 10 release phases with user-defined begin time, end time, and source removal fraction for each phase for point, line, and area sources, to factor into account different source removal rates and intermittent releases.

7. Implementation of both analytical and numerical solutions to time-integration and use of the analytical solutions to reduce calculation time whenever feasible or per user's choice.

8. Redefining the basis for volume source coordinates, as the center of the contaminated region, and adding a new direction of erosion parameter, for precise determination of the receptor-source distance at any time.

9. Generation of output files containing intermediate calculation results per user's choice, for obtaining insights to the modeling.

10. Addition of new appearance for several input forms, to facilitate input data collection, while maintaining the traditional appearance (as in Version 3.5), which can continue to be used if preferred by users.

11. Linking the code to Version 3.3 of the DCF Editor that has an expanded database (including air submersion dose and risk coefficients) and is equipped with improved interactive help entries.

12. Provision of context-specific help entries and the User's Manual (including User's Guide) in pdf format to guide the use of the code.

13. Streamlining the selection of DCF libraries to ensure proper pairing of external and internal dose coefficient libraries.

The new appearance of input forms, as mentioned in item (10) above, are associated with the inputs regarding evaluation times, graphic display of source-receptor locations, details of air flow, and details of point, line, or area sources. The choice of using the new input forms or traditional input forms (those with Version 3.5) for data entry can be made with the "Advanced" menu options in the main user's interface. This choice does not affect the look of the layout of the main interface; however, it affects the functionality of the code as described in items (3)–(9). The RESRAD-BUILD User's Guide for Version 4.0 (Volume 2 of this report) provides detailed instructions on manipulating the interface to complete the evaluation of an exposure scenario with the code.

RESRAD-BUILD Version 3.5 was released before Windows 10 became available. The compatibility issues seen with Version 3.5 have been resolved in Version 4.0.

1.2 ORGANIZATION OF MANUAL

The building geometry, sources, and receptors modeled by the code and exposure pathways for building occupancy and building renovation scenarios are described in Chapters 2 and 3 of this report (Volume 1 of the User's Manual). Details about the formulations in the models and the information in the data sources are described in detail in Appendices A through J of this report. A User's Guide that describes the user interface is included in Volume 2 of the User's Manual. There are also appendices describing the different analyses that can be performed using the code and the verification and benchmarking of the code.

The information presented in this report is organized as follows:

- Chapter 1: Introduction
- Chapter 2: Descriptions of sources, buildings, and receptors
- Chapter 3: Descriptions of exposure scenarios and pathways
- Chapter 4: Verification and benchmarking
- Chapter 5: References

- Appendix A: Radionuclides, dose conversion factors, and slope factors database
- Appendix B: Modeling the fate of radioactivity
- Appendix C: External radiation exposure
- Appendix D: Inhalation of radioactive airborne dust particles
- Appendix E: Radon release model and inhalation exposure
- Appendix F: Tritium release model and exposure
- Appendix G: Ingestion of radioactive particulates
- Appendix H: Uncertainty analysis
- Appendix I: Parameter descriptions
- Appendix J: Benchmarking of RESRAD-BUILD Version 4.0

2 DESCRIPTION OF BUILDINGS, SOURCES, AND RECEPTORS

The RESRAD-BUILD code is designed to evaluate the radiological doses to individuals who live or work inside a building that is contaminated with radioactive material. The contamination could be (1) on the surfaces of the floors, walls, or ceilings; (2) within the building material, such as in the drywall, concrete floors, steel I-beams, metal pipes, or wires; and (3) accumulated inside the building, such as in the air exchange filter or drain. RESRAD-BUILD Version 4.0 can model up to nine compartments in a building. A compartment can be one room or several rooms on the same floor with free air exchange among the rooms. External radiation penetrating the walls, ceilings, or floors is calculated based on user input for the shielding material type, thickness, and density. Internal (inhalation and ingestion) exposures are calculated based on an air quality model that considers the air exchange between rooms and with outdoor air.

The RESRAD-BUILD code can be applied to evaluate the potential exposure of an individual standing or working outside a contaminated building by assuming that the outdoor space is a large room (compartment) adjacent to the contaminated building. The building, source of contamination, and receptors modeled in the RESRAD-BUILD code are discussed in detail in the following sections.

2.1 BUILDING DESCRIPTION

In the RESRAD-BUILD Version 4.0 model, the building is conceptualized as a structure composed of up to nine compartments. Air exchange is assumed between all compartments. All compartments can exchange air with the outdoor atmosphere. An air quality model was developed to calculate the contaminant concentration in each compartment. A detailed description of the air quality model is presented in Appendix B.

Examples of typical building geometries with up to 3 rooms that can be modeled by the RESRAD-BUILD code are illustrated in Figure 2-1. An example of a 9-room building is shown in Figure 2-2. A coordinate system is used in RESRAD-BUILD to define the location of the sources and receptor points inside the building. The origin of the coordinate system can be at any location and the axes can be in any direction. The origin, however, is usually located at the bottom-left corner of the lowest level, with the x-axis measuring the horizontal distance to the right of the origin and coinciding with the bottom edge of the building (see Figure 2-3); the y-axis being perpendicular to the x-axis and pointing into the building; and the z-axis measuring the vertical distance from the left edge of the building.

The RESRAD-BUILD Version 4.0 code can model the building being cleaned periodically. This is accomplished with vacuuming parameters for efficiency and frequency. See Appendix B and User's Guide (Volume 2 of this report) for a more detailed discussion of the model and parameters.

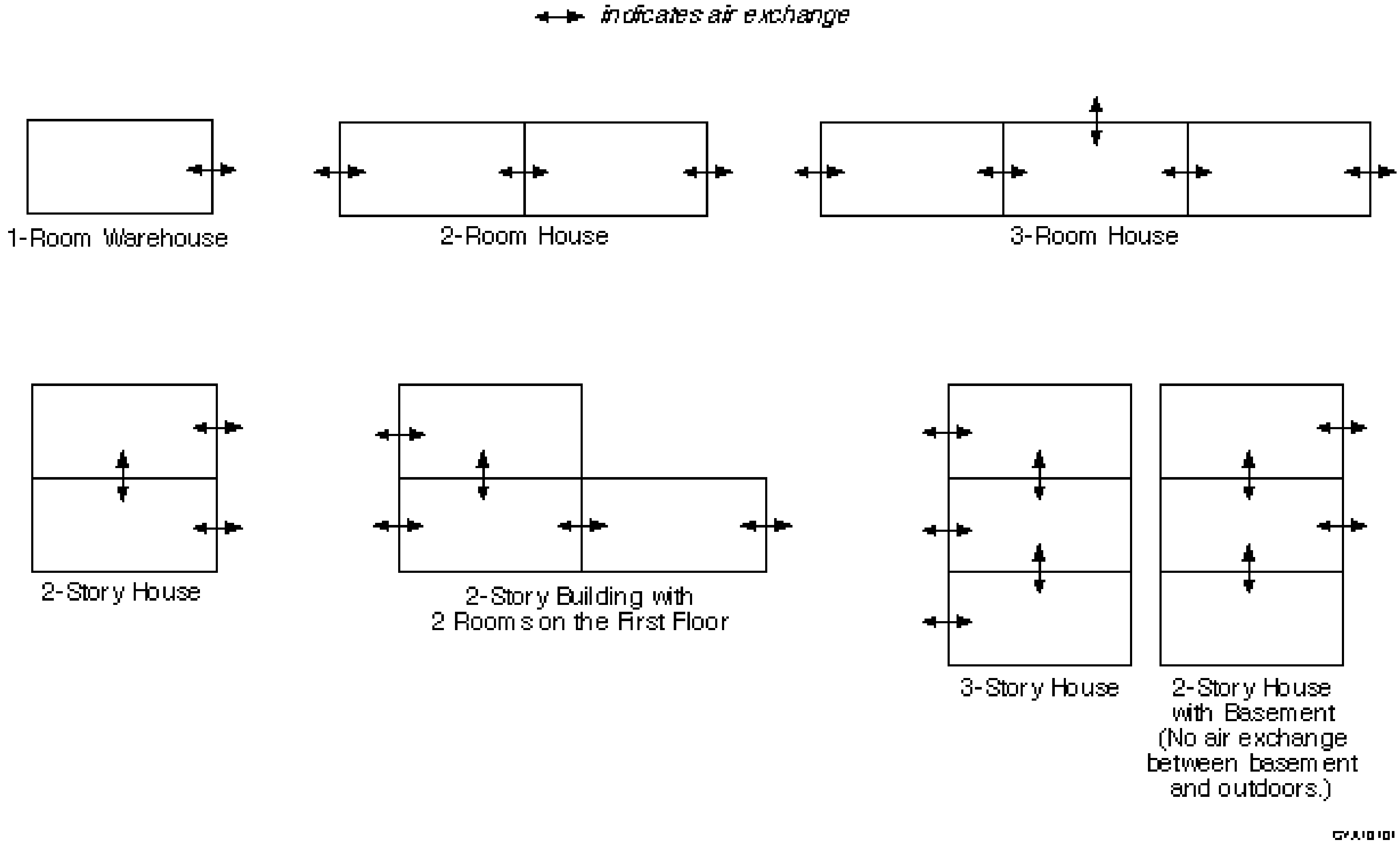

Figure 2-1 Vertical View of Possible 3-Room Building Geometries for the RESRAD-BUILD Code

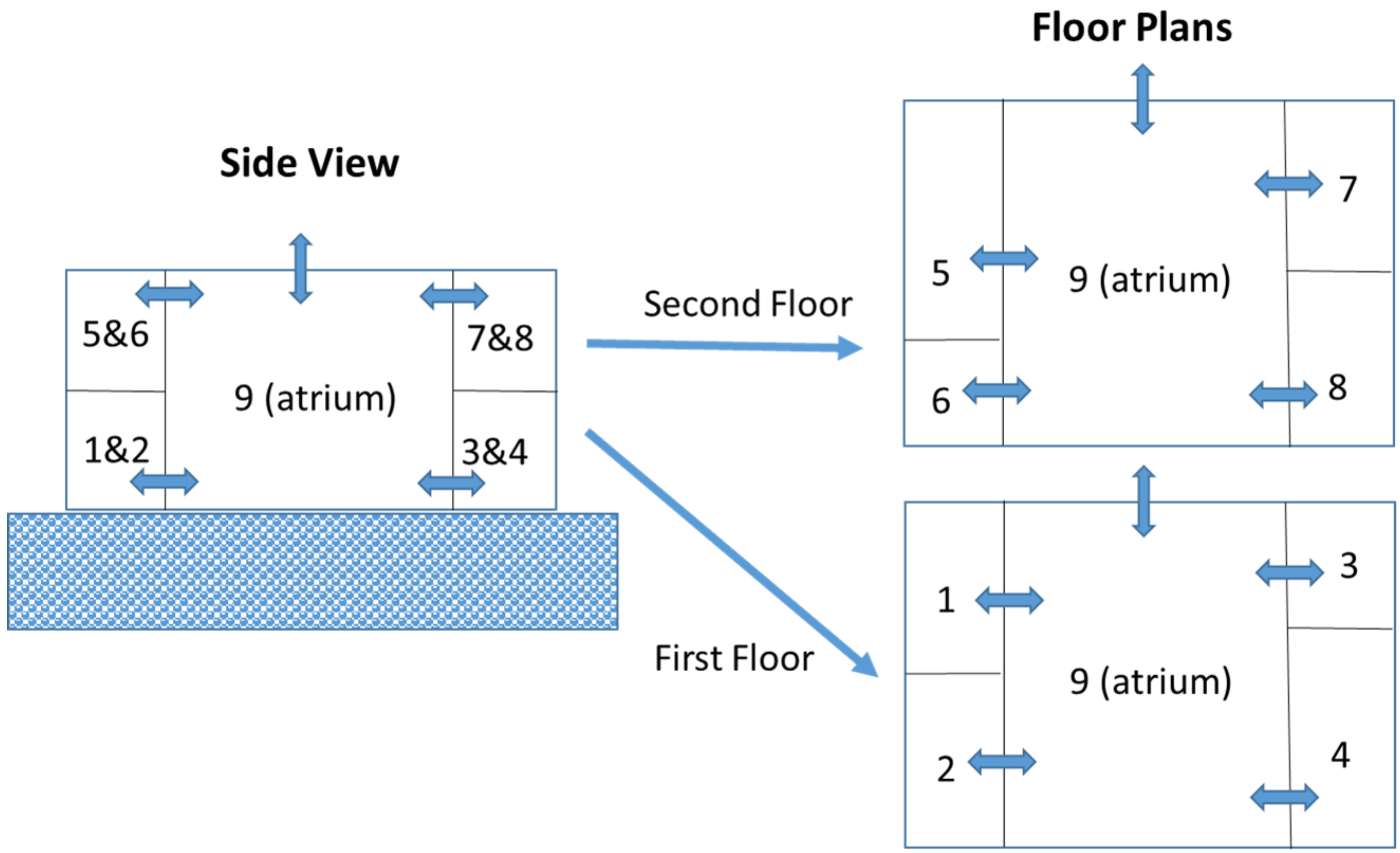

Figure 2-2 The Layout of a 9-Room Building as an Example of What Can Be Modeled in RESRAD-BUILD. The atrium is similar to an HVAC system in that it collects and redistributes air between all rooms. Direct airflow could also be modeled between the smaller offices.

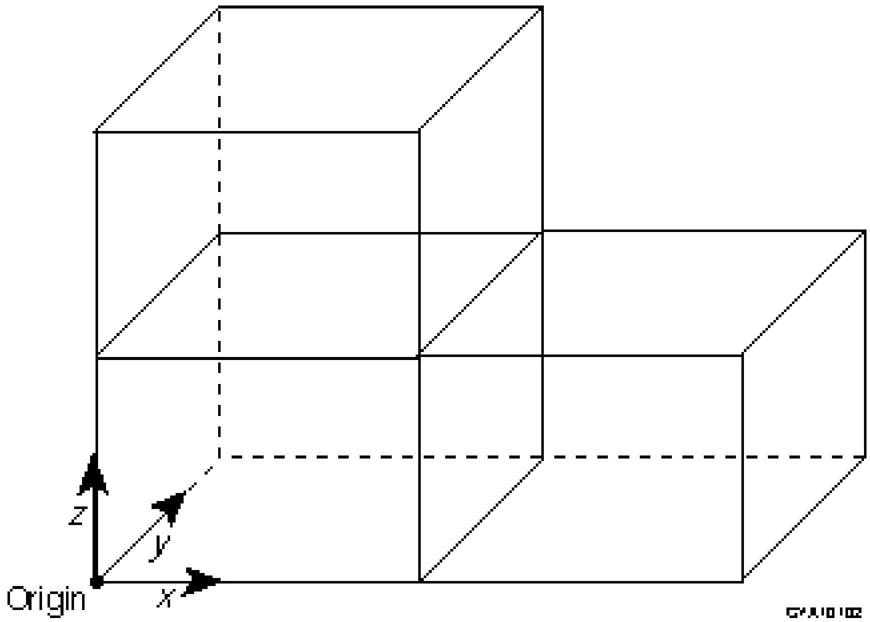

Figure 2-3 Example of a Coordinate System Used in the RESRAD-BUILD Code

The user can specify the locations of the sources and receptors and the amount of time the receptor spends in each compartment, so the radiological dose to the receptor can be calculated for any type of building use, including residential, commercial, or industrial. Therefore, the building model approach used in RESRAD-BUILD is quite flexible.

2.2 SOURCE DESCRIPTION

The building is assumed to be contaminated with radioactive materials located at a defined number of places within the structure of the building. Each contaminated location is considered as a distinct source, and as many as 10 sources can be specified in a single run of RESRAD-BUILD. Depending on its geometric appearance, the source can be defined as a volume, area, line, or point source. The distinctions among these types of sources are rather arbitrary and reflect the modeling objective of simplifying the overall configuration whenever justifiable. The proper classification of each source is left to the user's best judgment. For example, if the distance between the receptor and a small area source is much greater (say, five times greater) than the largest dimension of the area source, then this small area source may be modeled as a point source.

In general, each source is initially characterized by defining its type, the compartment in which it is located, and the coordinates of its center of contamination, according to the system of coordinates used for the building compartments (see Figure 2-3). The number of different radionuclides and their initial concentrations are also defined for each source. Depending on the type of the source, other geometric parameters may also be defined: the area/length, shape, and direction of the source. For either a volume or surface source, the area can be circular or rectangular. The area for a circular source is defined as the surface area of the source facing the open air. The area for a rectangular source is the product of the two lengths. Source direction is defined as the vector perpendicular to the exposed area. This direction should be coincident with one of the axes (x, y, or z). For a line source, the length parameter is defined as the length of the segment of line forming the source, and direction is given by the direction of the line itself. Again, the direction of the line source must be coincident with an axis. For a point source, neither the direction nor the area or length parameter is used.

Mechanical removal and erosion of the source material, when its surface is exposed to open air, may result in the transport of part of its mass directly into the indoor air environment, resulting in airborne contaminants. Because of the air exchange processes among all compartments of the building, the airborne particulates being loaded into the indoor air of a compartment are then transported to the indoor air of all compartments of the building.

A contaminated area in the building should be considered a volume source, if it can be clearly represented in a three-dimensional configuration. A segment of a building wall contaminated with radioactive materials is an example of a possible volume source. The volume source is assumed to release any particulates, radon, or tritiated water vapor into the compartment it was assigned. Currently, the releases of tritiated water are estimated only for the primary side. The radon releases are from both sides, but the fluxes go in the same compartment as the source. In the RESRAD-BUILD model, the volume source can be composed of up to five distinct parallel regions (or layers) located along the direction parallel to the partition, each consisting of homogeneous and isotropic materials. Each layer is defined by its physical properties, such as thickness, density, porosity, radon diffusion coefficient, radon emanation fraction, erosion rate, and concentration of radioactive contaminants. For modeling releases of tritiated water vapor, the uncontaminated regions between the release surface (the face from which emissions flow out to the indoor air) and the contaminated region need to be lumped into one single region. The definition of a volume source must also identify to which compartment the emissions flow and the direction from the center of contamination to the release surface. Finally, the rate of inadvertent ingestion of loose materials directly from the source must be defined.

The definition of a surface source considers those cases of surface contamination in which the thickness of the contaminated layer is considerably smaller than the affected area exposed to open air. An example would be a spill of radioactive materials over an area of relatively large dimensions, with very little penetration of the spilled substance into the matrix of the contaminated medium. Each surface source is associated with a set of timed removable fractions and air release fractions and a time-independent direct ingestion rate. The unit of radionuclide concentration for area sources used in RESRAD-BUILD is picocuries per square meter (pCi/m^2) or becquerels per square meter (Bq/m^2).

A line source can be defined for those cases in which one dimension, such as length, is clearly larger than any other dimension of the source. A pipe carrying radioactive materials or the wall/floor joint edge with accumulated contaminated substances could be considered a line source. The unit of radionuclide concentration for line sources is pCi/m or Bq/m.

Contaminated locations in the building where the radioactive materials are concentrated in regions of small dimensions (compared with the dimensions of the compartment and the distance to the receptor) could be approximated as point sources. The unit of radionuclide concentration for point sources is pCi or Bq.

2.3 RECEPTOR DESCRIPTION

The receptors considered in the RESRAD-BUILD model include office worker, resident, industrial worker, renovation worker, building visitor, or any individual spending some time inside the contaminated building. The RESRAD-BUILD code was designed with flexibility and simplicity in mind, so that the model can simulate diverse exposure scenarios, such as office work, building cleaning and maintenance work, building renovation, building visiting, and continuous residency. The exact location (coordinates) of the receptor is required to calculate external exposure. The receptor location should be the midpoint of the person. For example, if the receptor is standing on a contaminated floor, the receptor location should be 1 m above the floor. For other pathways, only the information about the room in which the receptor is located is required by the code, because the air quality model assumes that the air is homogeneously mixed in each compartment. To calculate the external dose, the shielding material type and its density and thickness need to be input into the code, in addition to the receptor location. The orientation of the receptor to the source may affect the external dose. For example, when the receptor is facing the source (anterior-posterior [AP]), the external dose may be greater than it is when the receptor is in the rotational or back-to-the-source (posterior-anterior [PA]) orientation. In most situations, the receptor is moving around and is not in a fixed position facing the source. Therefore, the external dose conversion factors (DCFs) for rotational orientation are used in the RESRAD-BUILD code.

Up to 10 receptor points can be specified in the RESRAD-BUILD code. The time fraction spent at each receptor point needs to be input. The total time fraction can exceed unity. These criteria allow RESRAD-BUILD to evaluate total (collective) worker dose as well as the total individual dose in a single run of the code.

3 DESCRIPTION OF EXPOSURE SCENARIOS AND PATHWAYS

3.1 EXPOSURE SCENARIOS

Before a contaminated building can be released for use without radiological restrictions, the potential future use of the building must be evaluated. That potential future use of a building depends on many factors, such as the current use, age, condition, location, and size of the building and the extent of contamination.

The potential uses of a building are referred to as exposure scenarios, which can be classified into two major categories: building occupancy and building renovation. Building occupancy scenarios include residents, office workers, industrial workers, and visitors. Building renovation scenarios include decontamination workers, building renovation workers, and building demolition workers. The building occupancy scenarios usually involve rather long-term chronic exposures, whereas building renovation scenarios usually involve short-term exposures. Building decontamination and renovation activity scenarios usually result in a higher amount of contaminant removal than do building occupancy scenarios. However, decontamination and renovation are usually performed under controlled conditions, and contaminated materials are removed from the building. Therefore, the actual amount of contaminants released into the indoor air may or may not be greater than the amount that is released under building occupancy scenarios. The building occupancy scenarios may result in the release of contaminants into the air as a result of normal use and cleaning of the building, such as washing the walls or vacuuming the floors. Building renovation includes such activities as sanding a contaminated floor, chipping concrete, and removing or installing drywall.

The differences among these scenarios are associated with the exposure durations, the amounts of contaminants, the rates at which they are released into air, and the pathways involved. The RESRAD-BUILD code is designed to model all these exposure scenarios. If the user inputs appropriate parameters for the exposure duration and the amount and rate of contaminants released into the air and selects appropriate pathways, RESRAD-BUILD can model all scenarios. The exposure pathways considered in RESRAD-BUILD code are discussed in Section 3.2. Input template files for the building occupancy scenario are provided in Section 3.3. If a building is demolished, the dose to workers demolishing the building can be evaluated with the RESRAD-BUILD code. If the demolished building material is buried, the RESRAD-ONSITE and RESRAD-OFFSITE computer codes (Yu et al. 2001, Kamboj et al. 2018, Yu et al. 2020) can be used to evaluate the dose for future use of the site. If building material (such as steel I-beams) is recycled, the RESRAD-RECYCLE code (Cheng et al. 2000) can be used to evaluate the dose to workers and the general public.

3.2 EXPOSURE PATHWAYS

External and internal exposure pathways are considered. Internal exposure includes both inhalation and ingestion pathways. Figure 3-1 illustrates all the pathways considered in the RESRAD-BUILD code:

- External exposure to penetrating radiation emitted directly from the source,
- External exposure to penetrating radiation emitted from radioactive particulates deposited on the floors of the compartments,
- External exposure to penetrating radiation due to submersion in airborne radioactive particulates,
- Inhalation of airborne radioactive particulates,
- Inhalation of aerosol indoor radon decay products and tritiated water vapor,
- Inadvertent ingestion of radioactive material contained in removable material directly from the source, and
- Inadvertent ingestion of airborne radioactive particulates deposited on the surfaces of the building.

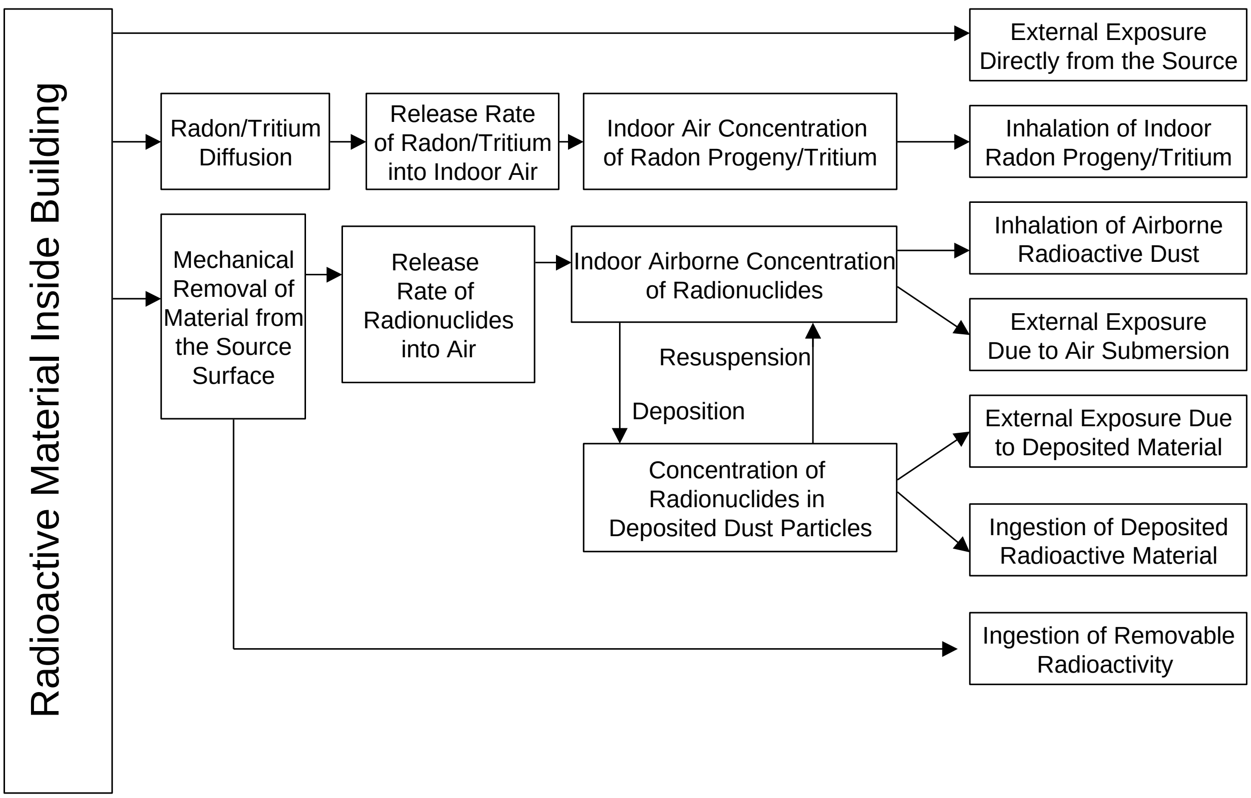

Figure 3-1 Exposure Pathways Incorporated into the RESRAD-BUILD Code

The first three pathways would result in external exposure, and the last four would result in internal exposure due to internal contamination of the exposed individual. Other possible exposure pathways to be considered in a radiological analysis of a contaminated building would include internal contamination due to puncture wounds and dermal absorption of radionuclides deposited on the skin. However, the radiation doses caused by these two pathways would be much smaller than the doses caused by the other potential pathways already considered for most radionuclides (Kennedy and Strenge 1992). Therefore, dermal pathways are not included in the current version of RESRAD-BUILD. However, the dermal absorption of tritium is considered by increasing the inhalation dose and risk conversion factors by 50%.

3.3 INPUT DATA TEMPLATE

The NUREG/CR-5512 (Beyeler et al. 1999) describes a generic modeling analysis used by the U.S. Nuclear Regulatory Commission (NRC) to translate radiological contamination in a building to radiation dose for decommissioning purposes. Table 3-1 lists the key parameter values to use if the RESRAD-BUILD code is used to simulate the exposures associated with the building occupancy scenario considered in the NUREG/CR-5512 document, assuming the surface contamination exists only on the floor, with an area of 36 m^2, and centered at (0,0,0). The other input parameters not listed or mentioned should assume either site-specific values or be kept at RESRAD-BUILD defaults. To consider variation in input parameter values that can impact the radiation dose, an uncertainty analysis can be conducted. Appendix I provides detailed descriptions of RESRAD-BUILD input parameters and their default distributions.

Table 3-1 Key Parameter Values for Simulating the NUREG/CR-5512 Building Occupancy Scenario

Parameter	Unit	Parameter Values	Remarks
Exposure duration	days (d)	365.25	To match the occupancy period of 365.25 days in NUREG/CR-5512 building occupancy scenario (Beyeler et al. 1999).
Indoor fraction	–[a]	0.267	To match the 97.5 d/yr time in building in NUREG/CR-5512 building occupancy scenario (Beyeler et al. 1999).
Receptor location	m	0, 0, 1	At 1-m from the center of the source.
Receptor inhalation rate	m^3/d	33.6	For building occupancy scenario, it matches with 1.4 m^3/h breathing rates in NUREG/CR-5512 (Beyeler et al. 1999).
Receptor indirect ingestion rate	m^2/h	1.12×10^{-4}	Value for the building occupancy scenario is the mean value from the distribution (Appendix I).
Source type	–	Area	For the building occupancy scenario, it is assumed that contamination is only on the floor (i.e., is an area source).
Direct ingestion rate	1/h (area)	3.06×10^{-6}	Calculated from the default ingestion rate of 1.1×10^{-4} m^2/h in NUREG/CR-5512 building occupancy scenario (Beyeler et al. 1999).
Air release fraction	–	0.357	For the building occupancy scenario, it is the mean value from the parameter distribution (Appendix I).
Removable fraction	–	0.1	10% of the contamination is removable (NUREG/CR-5512 building occupancy scenario default).
Time for source removal or source lifetime	d	10,000	Value for the building occupancy scenario is the most likely value from the parameter distribution (Appendix I).

[a] A dash indicates that the parameter is dimensionless.

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4 VERIFICATION AND BENCHMARKING OF THE RESRAD-BUILD CODE

As part of the RESRAD quality assurance (QA) program, RESRAD-BUILD has undergone extensive review, testing, benchmarking, and verification. Many models used in the RESRAD-BUILD code have been benchmarked against other codes. For example, the external dose models have been benchmarked against the Monte Carlo N-particle (MCNP) code (Briesmeister 1993), and the radon model used in the RESRAD-BUILD code has been compared with the radon model used in RESRAD-ONSITE (Yu et al. 2001). The NRC compared the DandD code Version 1.0 with the RESRAD-ONSITE Version 5.61 and RESRAD-BUILD Version 1.5 codes (Haaker et al. 1999). A verification of RESRAD-BUILD Version 3.0 using Microsoft Excel spreadsheets was conducted when Version 3.0 was released (Kamboj et al. 2001). Additional benchmarking of the RESRAD-BUILD Version 4.0 external exposure model with MCNP code was conducted, and the results are presented in Section J.3 of Appendix J. An independent verification of the RESRAD-BUILD models and parameters was also conducted (Tetra Tech NUS, Inc. 2003). The differences between RESRAD-BUILD Version 3.5 and Version 4.0 are presented in Appendix J. Additional benchmarking/comparison of RESRAD-BUILD Version 4.0 with the NRC DandD code and the U.S. Environmental Protection Agency (EPA) Building Preliminary Remediation Goals (BPRG) Calculator was done, and the results are summarized in Section 4.1. More detailed results and discussions are presented in Appendix J.

4.1 TESTING AND VERIFICATION PROCEDURE

Verification of the RESRAD-BUILD code was conducted with an initial check of all the input parameters for correctness. Verification of the calculations was performed external to the RESRAD-BUILD code with Microsoft Excel to verify all the major portions of the code. Following RESRAD QA program requirements, test cases were prepared to test the design and performance objectives of the RESRAD-BUILD code. All the results from these test cases are documented as a record when the code is officially released.

4.2 COMPARISON AND BENCHMARKING

There are many modeling enhancements and new features in RESRAD-BUILD Version 4.0 compared to Version 3.5. The major changes are:

- Modeling of all branches of the radiological decay chain, with any specified logical cut-off half-life to reduce calculation time;
- Evaluating individual progeny radionuclides for their contributions to direct external dose and risk;
- Implementing a new dynamic air quality model that includes up to nine compartments (rooms) and allows periodical vacuuming to remove part of the deposited contamination;

- Implementing both numerical and analytical solutions to compute the transient concentrations of particulates, suspended in air and deposited on the floor, and the radionuclides attached to those particulates;
- Addition of expanded versions for several input forms to accommodate additional parameters;
- Allowing up to 10 release phases for point, line, and area sources;
- Performing time integration analytically, when possible, to reduce execution time;
- Performing time integration numerically, when necessary, to user-specified convergence criteria using a larger number of time points, while still reducing the execution time;
- Ensuring direct source ingestion does not exceed the released source material available for ingestion;
- Redefining the basis for volume source coordinates;
- Generating intermediate calculation results;
- Updating the Dose Conversion Factor (DCF) Editor to include air submersion dose coefficients and slope factors; and
- Streamlining the selection of DCF and risk libraries.

RESRAD-BUILD models the removal and disposition of the material removed from the source. Version 4.0 has a dynamic air quality model that considers air exchanges between all compartments and the outside to calculate air concentration and particulates deposited in each compartment. The dynamic air quality model includes resuspension of the deposited contamination to the air and periodical vacuuming to remove part of the deposited contamination from the floor, and it allows consideration of up to 10 release phases with different source removal rates for each phase (see Appendix B). Version 3.5 implements a pseudo steady-state air quality model. A detailed comparison of the radionuclide concentrations calculated with RSERAD-BUILD 4.0 and 3.5 is presented in Section J.1 of Appendix J.

The NRC DandD code (McFadden et al. 2001) and the EPA BPRG Calculator (EPA 2019) are designed to evaluate building contamination with radionuclides. A detailed comparison of RESRAD-BUILD 4.0, DandD, and BPRG is presented in Appendix J. The comparison of the methodologies and features of these three codes is summarized below.

The DandD code, developed by Sandia National Laboratories for the NRC, converts contamination levels in a building to the annual dose for building occupancy and residential scenarios (McFadden et al. 2001). The building occupancy scenario computes the yearly average dose from surface contamination in buildings for light industrial use. The exposure starts immediately after release of the building for occupancy. The building occupancy scenario considers direct external exposure from surface sources, exposure by breathing indoor air contaminated by resuspension of radionuclides from surface contamination, and inadvertent ingestion of surface contamination.

The BPRG Calculator, developed by EPA (EPA 2019), is used to calculate building preliminary remediation goals (BPRG) for radionuclides in buildings for resident and indoor worker exposure. The BPRG Calculator estimates radionuclide concentrations in dust settled on surfaces, radionuclide concentrations in the air inside the building, and direct external exposure from radionuclide concentrations on six surfaces/inside walls of different room sizes that are protective of humans over a lifetime for a selected risk level. The Calculator does not consider any relationship between the concentration deposited on surfaces with the concentration in the air inside the building (i.e., no air model or deposition model). The Calculator has three options for calculating BPRGs: 1) assumes secular equilibrium throughout the chain (no decay) (default assumption), 2) does not assume secular equilibrium, but provides results for progeny throughout chain (with decay); and 3) does not assume secular equilibrium, and no progeny included. Similar equations are used for both resident and indoor worker exposure, the only difference is in the parameters used. If media concentrations are input in the BPRG Calculator for dust, air, soil, and ground plane, it also calculates risk from dust settled on surfaces, ambient air concentration, and direct external exposure. For estimating radionuclide concentrations in air inside the building at a target risk level, the BPRG Calculator considers two exposure routes: inhalation and air submersion. For estimating radionuclide surface or volumetric concentrations inside the building at a target risk level, the BPRG Calculator considers direct external exposure from surface or volumetric contamination. It assumes all six inside sides of the building (walls, floor, and ceiling) are uniformly contaminated. The room surface factor accounts for the exposure to multiple contaminated surfaces of different finite sizes (length, width, depth, material) compared to infinite size. Table J-2 in Appendix J compares the main features and options in RESRAD-BUILD Version 4.0, the BPRG Calculator, and DandD.

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APPENDIX A:

RADIONUCLIDE TRANSFORMATION DATABASE AND DOSE AND RISK COEFFICIENT LIBRARIES

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APPENDIX A:

RADIONUCLIDE TRANSFORMATION DATABASE AND DOSE AND RISK COEFFICIENT LIBRARIES

This appendix discusses the radionuclide transformation databases and the dose and risk coefficient libraries used by the RESRAD-BUILD code, Version 4.0, for the calculations of radiological dose and cancer risk. The radionuclide transformation data from International Commission on Radiation Protection Publication 107 (ICRP-107) and from International Commission on Radiation Protection Publication 38 (ICRP-38) are in two plain text files, ICRP-07.NDXand NewICRP38.idx. The standard libraries of dose and risk coefficients are in two corresponding database files, Master_dcf_ICRP07.mdb and Master_dcf_2k.mdb, which are installed in the same directory as the Dose Conversion Factor (DCF) Editor during installation. These libraries can be viewed or be used as the basis for creating custom libraries using the DCF Editor. The transformation data is not accessible in the DCF Editor as they are not to be modified.

A.1 RADIONUCLIDE TRANSFORMATION DATABASE IN RESRAD-BUILD

RESRAD-BUILD performs pathway analyses to calculate potential radiation dose and cancer risk a receptor could incur from spending time inside a building contaminated with radioactive materials, i.e., radiation sources. The potential radiation dose and cancer risk are calculated for exposures incurred at the current time as well as at future times. The projection of radiation dose and cancer risk at a future time factor into account the presence of progenies of the initial radionuclides due to radiological transformation, thereby including the dose/risk contributions from the progenies. The radionuclide transformation data in the International Commission on Radiation Protection Publication 38 (ICRP-38) (ICRP 1983) and International Commission on Radiation Protection Publication 107 (ICRP-107) (ICRP 2008) can be used to establish the decay chains and to calculate the radioactivity of progenies over time.

To simplify the calculations concerning ingrowth of progenies, radionuclides are categorized as “principal” or “associated” nuclides depending on their radiological decay half-life, compared with a cut-off value. Radionuclides with a half-life greater than the cut-off value are called principal nuclides. When principal nuclides are involved in the decay of an initially present radionuclide, their activities and dose/risk contributions over time are separately tracked and calculated. Radionuclides with a half-life shorter than or equal to the cut-off value are called associated nuclides. When associated nuclides are involved in the decay of an initially present radionuclide, they are assumed to have the same activity, i.e., in secular equilibrium, as the preceding principal nuclide. For internal exposures, the dose/risk contributions from associated nuclides are not separately tracked and calculated; rather, their contributions are included in the dose/risk calculated for the preceding principal nuclide. In terms of designation, the suffix “+D” is added to the name of a principal nuclide in this manual whose calculated dose/risk includes contributions from its associated progenies. In practice, the doses/risks for +D principal nuclides are calculated using the sum of the branch fraction weighted dose/risk coefficients of the principal nuclide itself and its associated progenies. The user has the option to specify any cut-off half-life in the code. Only radionuclides with a half-life greater than the selected cut-off half-life can be chosen as initially present for the dose/risk calculations.

The ICRP-38 database (ICRP 1983) contains radiological transformation data for 838 radionuclides and ICRP-107 database (ICRP 2008) contains radiological transformation data for 1252 radionuclides. Based on the selected radiological transformation database and the input cut-off half-life, the RESRAD-BUILD code will list all the principal radionuclides for inclusion in a radiation source. Any of the listed radionuclides can be selected for dose/risk calculations.

Table A-1 (1st column) lists the principal radionuclides that can be specified as initially present in a radiation source in the RESRAD-BUILD Version 4.0, when a cut-off half-life of 30 days and the ICRP-38 transformation database are selected. Column 3 lists the short-lived progenies that are associated with each principal nuclide in column 1 and their branch fractions; their decay half-lives are < 30 days. The stable nuclide(s)/principal radionuclide that each principal nuclide in column 1 is considered to decay to is listed in 4th column.

Table A-2 lists principal radionuclides with half-life of at least 30 days with their associated radionuclides when ICRP-107 database is used.

Table A-1 Principal and Associated Radionuclide with a Cut-off Half-life of at Least 30 Days from ICRP-38 Database

<table>
<tr><th colspan="2">Principal Radionuclide[a]</th><th rowspan="2">Associated Decay Chain[b]</th><th colspan="3">Terminal Nuclide or Progeny Principal Radionuclide[c]</th></tr>
<tr><th>Species</th><th>Half-life (yr)</th><th>Species</th><th>Half-life (yr)</th><th>Fraction</th></tr>
<tr><td>Ac-227+D</td><td>2.18E+01</td><td>(Th-227 9.8620E-01), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (Tl-207 9.9720E-01), (Po-211 2.8000E-03), (Fr-223 1.3800E-02)</td><td>Pb-207</td><td>*</td><td></td></tr>
<tr><td>Ag-105</td><td>1.12E-01</td><td>—[d]</td><td>Pd-105</td><td>*</td><td></td></tr>
<tr><td>Ag-108m+D</td><td>1.27E+02</td><td>(Ag-108 8.9000E-02)</td><td>Pd-108, Cd-108</td><td>*</td><td></td></tr>
<tr><td>Ag-110m+D</td><td>6.84E-01</td><td>(Ag-110 1.3300E-02)</td><td>Cd-110, Pd-110</td><td>*</td><td></td></tr>
<tr><td>Al-26</td><td>7.16E+05</td><td>—</td><td>Mg-26</td><td>*</td><td></td></tr>
<tr><td>Am-241</td><td>4.32E+02</td><td>—</td><td>Np-237</td><td>2.14E+06</td><td></td></tr>
<tr><td rowspan="2">Am-242m+D</td><td rowspan="2">1.52E+02</td><td rowspan="2">(Am-242 0.9952), (Np-238 0.0048)</td><td>Cm-242</td><td>4.46E-01</td><td>8.23E-01</td></tr>
<tr><td>Pu-238</td><td>8.77E+01</td><td>1.78E-01</td></tr>
<tr><td>Am-243+D</td><td>7.38E+03</td><td>Np-239</td><td>Pu-239</td><td>2.41E+04</td><td></td></tr>
<tr><td>Ar-37</td><td>9.59E-02</td><td>—</td><td>Cl-37</td><td>*</td><td></td></tr>
<tr><td>Ar-39</td><td>2.69E+2</td><td>—</td><td>K-39</td><td>*</td><td></td></tr>
<tr><td>As-73</td><td>2.20E-01</td><td>—</td><td>Ge-73</td><td>*</td><td></td></tr>
<tr><td>Au-195</td><td>5.01E-01</td><td>—</td><td>Pt-195</td><td>*</td><td></td></tr>
<tr><td>Ba-133</td><td>1.07E+01</td><td>—</td><td>Cs-133</td><td>*</td><td></td></tr>
<tr><td>Be-10</td><td>1.60E+06</td><td>—</td><td>B-10</td><td>*</td><td></td></tr>
<tr><td>Be-7</td><td>1.46E-01</td><td>—</td><td>Li-7</td><td>*</td><td></td></tr>
<tr><td>Bi-207</td><td>3.80E+01</td><td>—</td><td>Pb-207</td><td>*</td><td></td></tr>
<tr><td>Bi-210m+D</td><td>3.00E+06</td><td>Tl-206</td><td>Pb-206</td><td>*</td><td></td></tr>
<tr><td>Bk-247</td><td>1.38E+03</td><td>—</td><td>Am-243m+D</td><td>7.38E+03</td><td></td></tr>
<tr><td rowspan="4">Bk-249+D</td><td rowspan="4">8.76E-01</td><td rowspan="4">(Am-245 1.45E-5)</td><td>SF</td><td></td><td>4.70E-10</td></tr>
<tr><td>Cm-245</td><td>8.50E+03</td><td>1.45E-05</td></tr>
<tr><td>Cf-249</td><td>3.51E+02</td><td></td></tr>
<tr><td>SF</td><td></td><td>5.20E-09</td></tr>
</table>

Table A-1 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Progeny Principal Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
C-14	5.73E+03	—	N-14	*	
Ca-41	1.40E+05	—	K-41	*	
Ca-45	4.46E-01	—	Sc-45	*	
Cd-109	1.27E+00	—	Ag-109	*	
Cd-113	9.30E+15	—	In-113	*	
Cd-113m	1.36E+01	—	In-113	*	
Cd-115m	1.22E-01	—	In-115	5.10E+15	
Ce-139	3.77E-01	—	La-139	*	
Ce-141	8.90E-02	—	Pr-141	*	
Ce-144+D	7.78E-01	(Pr-144m 0.0178), Pr-144	Nd-144	*	
Cf-248	9.13E-01	—	SF		2.90E-05
			Cm-244	1.81E+01	1.00E+00
Cf-249	3.51E+02	—	SF		5.20E-09
			Cm-245	8.50E+03	1.00E+00
Cf-250	1.31E+01	—	SF		7.70E-04
			Cm-246	4.73E+03	9.99E-01
Cf-251	8.98E+02	—	Cm-247+D	1.56E+07	
Cf-252	2.64E+00	—	SF		3.09E-02
			Cm-248	3.39E+05	9.69E-01
Cf-254	1.66E-01	—	SF		0.9969
			Cm-250	6.90E+03	0.0031
Cl-36	3.01E+05	—	Ar-36, S-36	*	
Cm-241	8.98E-02	—	Am-241	4.32E+02	9.90E-01
			Pu-237	1.24E-01	1.00E-02
Cm-242	4.46E-01	—	SF		6.80E-08
			Pu-238	8.77E+01	1.00E+00
Cm-243	2.85E+01	—	Am-243	7.38E+03	2.40E-03
			Pu-239	2.41E+04	9.98E-01
Cm-244	1.81E+01	—	SF		1.35E-06
			Pu-240	6.54E+03	1.00E+00
Cm-245	8.50E+03	—	Pu-241	1.44E+01	1.00E+00
Cm-246	4.73E+03	—	SF		2.61E-04
			Pu-242	3.76E+05	1.00E+00
Cm-247+D	1.56E+07	Pu-243	Am-243+D	7.38E+03	
Cm-248	3.39E+05	—	SF		8.26E-02
			Pu-244	8.26E+07	9.17E-01
Cm-250	6.9E+03	(Pu-246 0.25), (Am-246 0.25), (Bk-250 0.14)	SF		0.61
			Cm-246	4.73E+03	0.25
			Cf-250		0.14
Co-56	2.16E-01	—	Fe-56	*	
Co-57	7.42E-01	—	Fe-57	*	
Co-58	1.94E-01	—	Fe-58	*	
Co-60	5.27E+00	—	Ni-60	*	
Cs-134	2.06E+00	—	Ba-134, Xe-134	*	
Cs-135	2.30E+06	—	Ba-135	*	
Cs-137+D	3.00E+01	(Ba-137m 0.946)	Ba-137	*	
Dy-159	3.95E-01	—	Tb-159	*	
Es-254+D	7.55E-01	Bk250	Cf-250	1.31E+01	1.00E+00

Table A-1 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Progeny Principal Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Eu-148	1.49E-01	—	Sm-148	*	
			Pm-144	9.94E-01	9.40E-09
Eu-149	2.55E-01	—	Sm-149	*	
Eu-150b	3.42E+01	—	Sm-150	*	
Eu-152	1.33E+01	—	Sm-152	*	7.21E-01
			Gd-152	1.08E+14	2.79E-01
Eu-154	8.80E+00	—	Gd-154, Sm-154	*	
Eu-155	4.96E+00	—	Gd-155	*	
Fe-55	2.70E+00	—	Mn-55	*	
Fe-59	1.22E-01	—	Co-59	*	
Fe-60+D	1.00E+05	Co-60m	Ni-60	*	2.50E-03
			Co-60	5.27E+00	9.98E-01
Fm-257+D	2.75E-01	Cf-253, (Es-253 9.9690E-01), (Cm-249 3.1000E-03)	SF		8.67E-08
			Bk-249		1.00E+00
Gd-146+D	1.32E-01	Eu-146	Sm-146	1.03E+08	
Gd-148	9.30E+01	—	Sm-144	*	
Gd-151	3.29E-01	—	Eu-151	*	
			Sm147	0.00E+00	
Gd-152	1.08E+14	—	Sm-148	*	
Gd-153	6.63E-01	—	Eu-153	*	
Ge-68+D	7.89E-01	Ga-68	Zn-68	*	
H-3	1.24E+01	—	He-3	*	
Hf-172+D	1.87E+00	Lu-172	Yb-172	*	
Hf-175	1.92E-01	—	Lu-175	*	
Hf-178m	3.10E+01	—	Hf-178	*	
Hf-181	1.16E-01	—	Ta-181	*	
Hf-182	9.00E+06	—	Ta-182	3.15E-01	
Hg-194+D	2.60E+02	Au-194	Pt-194	*	
Hg-203	1.28E-01	—	Tl-203	*	
Ho-166m	1.20E+03	—	Er-166	*	
I-125	1.65E-01	—	Te-125	*	
I-129	1.57E+07	—	Xe-129	*	
In-114m+D	1.36E-01	(In-114 0.957)	Cd-114, Sn-114	*	
In-115	5.10E+15	—	Sn-115	*	
Ir-192	2.03E-01	—	Os-192, Pt-192	*	
Ir-192m	2.41E+02	—	Ir-192	2.03E-01	
Ir-194m	4.68E-01	—	Pt-194	*	
K-40	1.28E+09	—	Ca-40, Ar-40	*	
Kr-81	2.10E+05	—	Br-81	*	
Kr-85	10.72	—	Rb-85	*	
La-137	6.00E+04	—	Ba-137	*	
La-138	1.35E+11	—	Ba-138, Ce-138	*	
Lu-173	1.37E+00	—	Yb-173	*	
Lu-174	3.31E+00	—	Yb-174	*	
Lu-174m	3.89E-01	—	Yb-174	*	7.00E-03
			Lu-174	3.31E+00	9.93E-01
Lu-176	3.60E+10	—	Hf-176	*	

Table A-1 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Progeny Principal Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Lu-177m+D	4.41E-01	(Lu-177 0.21)	Hf-177	*	
Md-258	1.51E-01		Es-254	7.55E-01	1.00E+00
Mn-53	3.70E+06	—	Cr-53	*	
Mn-54	8.56E-01	—	Cr-54	*	
Mo-93	3.50E+03	—	Nb-93	*	
Na-22	2.60E+00	—	Ne-22	*	
Nb-93m	1.36E+01	—	Nb-93	*	
Nb-94	2.03E+04	—	Mo-94	*	
Nb-95	9.62E-02	—	Mo-95	*	
Ni-59	7.50E+04	—	Co-59	*	
Ni-63	9.60E+01	—	Cu-63	*	
Np-235	1.08E+00	—	U-235	7.04E+08	1.00E+00
			Pa-231	3.28E+04	1.40E-05
Np-236a	1.15E+05	—	U-236		9.11E-01
			Pu-236	2.85E+00	8.90E-02
Np-237+D	2.14E+06	Pa-233	U-233	1.59E+05	
Os-185	2.57E-01	—	Re-185	*	
Os-194+D	6.00E+00	Ir-194	Pt-194	*	
Pa-231	3.28E+04	—	Ac-227+D	2.18E+01	
Pb-202+D	3.00E+05	Tl-202	Hg-202	*	
Pb-205	1.43E+07	—	Tl-205	*	
Pb-210+D	2.23E+01	Bi-210	Po-210	3.79E-01	
Pd-107	6.50E+06	—	Ag-107	*	
Pm-143	7.26E-01	—	Nd-143	*	
Pm-144	9.94E-01	—	Nd-144	*	
Pm-145	1.77E+01	—	Nd-145	*	
Pm-146	5.53E+00	—	Nd-146	*	6.41E-01
			Sm-146	1.03E+08	3.59E-01
Pm-147	2.62E+00	—	Sm-147	1.06E+11	
Pm-148m+D	1.13E-01	(Pm-148 0.046)	Sm-148	*	
Po-209	1.02E+02	—	Pb-205	1.43E+07	0.9974
			Bi-209	*	0.0026
Po-210	3.79E-01	—	Pb-206	*	
Pt-193	5.00E+01	—	Ir-193	*	
Pu-236	2.85E+00	—	SF		8.10E-10
			U-232	7.20E+01	1.00E+00
Pu-237	1.24E-01	—	Np-237+D	2.14E+06	1.00E+00
			U-233	1.59E+05	5.00E-05
Pu-238	8.77E+01	—	SF		1.84E-09
			U-234	2.45E+05	1.00E+00
Pu-239	2.41E+04	—	U-235	7.04E+08	
Pu-240	6.54E+03	—	SF		4.95E-08
			U-236	2.34E+07	1.00E+00
Pu-241+D	1.44E+01	(U-237 0.0000245)	Am-241	4.32E+02	1.00E+00
			Np-237	2.14E+06	2.45E-05
Pu-242	3.76E+05	—	SF		5.50E-06
			U-238	4.47E+09	1.00E+00
Pu-244+D	8.26E+07	(U-240 0.9988), (Np-240m 0.9988)	SF		1.25E-03

Table A-1 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Progeny Principal Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
			Pu-240	6.54E+03	9.99E-01
Ra-226+D	1.60E+03	Rn-222,Po-218, (Pb-214 9.9980E-01), Bi-214, (Po-214 9.9980E-01), (Tl-210 2.0000E-04), (At-218 2.0000E-04)	Pb-210	2.23E+01	
Ra-228+D	5.75E+00	Ac-228	Th-228+D	1.91E+00	
Rb-83+D	2.36E-01	(Kr-83m 0.76199)	Kr-83	*	
Rb-84	8.97E-02	—	Sr-84, Kr-84	*	
Rb-87	4.70E+10	—	Sr-87	*	
Re-184	1.04E-01	—	W-184	*	
Re-184m	4.52E-01	—	W-184	*	2.53E-01
			Re-184	1.04E-01	7.47E-01
Re-186m+D	2.00E+05	Re-186	W-186, Os-186	*	
Re-187	5.00E+10	—	Os-187	*	
Rh-101	3.20E+00	—	Ru-101	*	
Rh-102	2.90E+00	—	Ru-102	*	
Rh-102m	5.67E-01	—	Ru-102, Pd-102	*	9.50E-01
			Rh-102	2.90E+00	5.00E-02
Ru-103+D	1.08E-01	(Rh-103m 0.997)	Rh-103	*	
Ru-106+D	1.01E+00	Rh-106	Pd-106	*	
S-35	2.39E-01	—	Cl-35	*	
Sb-124	1.65E-01	—	Te-124	*	
Sb-125	2.77E+00	—	Te-125	*	7.72E-01
			Te-125m	1.59E-01	2.28E-01
Sc-46	2.30E-01	—	Ti-46	*	
Se-75	3.28E-01	—	As-75	*	
Se-79	6.50E+04	—	Br-79	*	
Si-32+D	4.50E+02	P-32	S-32	*	
Sm-145	9.31E-01	—	Pm-145	1.77E+01	
Sm-146	1.03E+08	—	Nd-142	*	
Sm-147	1.06E+11	—	Nd-143	*	
Sm-151	9.00E+01	—	Eu-151	*	
Sn-113+D	3.15E-01	In-113m	In-113	*	
Sn-119m	8.02E-01	—	Sn-119	*	
Sn-121m+D	5.50E+01	(Sn-121 0.776)	Sb-121	*	
Sn-123	3.54E-01	—	Sb-123	*	
Sn-126+D	1.00E+05	Sb-126m, (Sb-126 0.14)	Te-126	*	
Sr-85	1.78E-01	—	Rb-85	*	
Sr-89	1.38E-01	—	Y-89	*	
Sr-90+D	2.91E+01	Y-90	Zr-90	*	
Ta-179	1.82E+00	—	Hf-179	*	
Ta-180	1.00E+13	—	W-180	*	
Ta-182	3.15E-01	—	W-182	*	
Tb-157	1.50E+02	—	Gd-157	*	
Tb-158	1.50E+02	—	Gd-158, Dy-158	*	
Tb-160	1.98E-01	—	Dy-160	*	
Tc-95m+D	1.67E-01	(Tc-95 0.04)	Mo-95	*	
Tc-97	2.60E+06	—	Mo-97	*	

Table A-1 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Progeny Principal Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Tc-97m	2.38E-01	—	Tc-97	2.60E+06	
Tc-98	4.20E+06	—	Ru-98	*	
Tc-99	2.13E+05	—	Ru-99	*	
Te-121m+D	4.22E-01	(Te-121 0.886)	Sb-121	*	
Te-123	1.00E+13	—	Sb-123	*	
Te-123m	3.28E-01	—	Te-123	1.00E+13	
Te-125m	1.59E-01	—	Te-125	*	
Te-127m+D	2.98E-01	(Te-127 0.976)	I-127	*	
Te-129m+D	9.20E-02	(Te-129 0.65)	I-129	1.57E+07	
Th-228+D	1.91E+00	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 0.6407), (Tl-208 0.3593)	Pb-208	*	
Th-229+D	7.34E+03	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 0.9784), (Tl-209 0.0216), Pb-209	Bi-209	*	
Th-230	7.70E+04	—	Ra-226+D	1.60E+03	
Th-232	1.41E+10	—	Ra-228+D	5.75E+00	
Ti-44+D	4.73E+01	Sc-44	Ca-44	*	
Tl-204	3.78E+00	—	Pb-204, Hg-204	*	
Tm-170	3.52E-01	—	Er-170, Yb-170	*	
Tm-171	1.92E+00	—	Yb-171	*	
U-232	7.20E+01	—	Th-228+D	1.91E+00	
U-233	1.59E+05	—	Th-229+D	7.34E+03	
U-234	2.45E+05	—	Th-230	7.70E+04	
U-235+D	7.04E+08	Th-231	Pa-231	3.28E+04	
U-236	2.34E+07	—	Th-232	1.41E+10	
U-238+D	4.47E+09	Th-234, (Pa-234m 0.998), (Pa-234 0.0033)	SF		5.40E-05
			U-234	2.45E+05	
V-49	9.04E-01	—	Ti-49	*	
W-181	3.32E-01	—	Ta-181	*	
W-185	2.06E-01	—	Re-185	*	
W-188+D	1.90E-01	Re-188	Os-188	*	
Xe-127	9.9685E-02	—	I-127	*	
Y-88	2.92E-01	—	Sr-88	*	
Y-91	1.60E-01	—	Zr-91	*	
Yb-169	8.76E-02	—	Tm-169	*	
Zn-65	6.68E-01	—	Cu-65	*	
Zr-88	2.28E-01	—	Y-88	2.92E-01	
Zr-93	1.53E+06	—	Nb-93m	1.36E+01	
Zr-95+D	1.75E-01	(Nb-95m 0.007)	Nb-95	9.62E-02	

[a] Radionuclides with half-lives greater than 30 days. If short-lived progeny are involved, the +D symbol is added along with the radionuclide name (e.g., Ac-227+D).

[b] The associated progeny with half-lives shorter than 30 days are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] The principal radionuclide or stable nuclide that terminates an associated decay chain. Stable nuclides are indicated by an asterisk (*) in place of the half-life. If a radionuclide has spontaneous fission, it is indicated by SF. If the branching fraction is anything other than 1, the fraction is listed.

[d] Indicates there is no associated radionuclide.

Table A-2 Principal and Associated Radionuclides with a Cut-off Half-life of at least 30 Days from ICRP-107 Database

Principal Radionuclide[a]			Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)	Associated Decay Chain[b]	Species	Half-life (yr)	Fraction
Ac-227+D	2.18E+01	(Th-227 9.8620E-01), (Ra-223 1.0000E+00), (Rn-219 1.0000E+00), Po-215, Pb-211, Bi-211, (Tl-207 9.9724E-01), (Po-211 2.7600E-03), (Fr-223 1.3800E-02), (At-219 8.2800E-07), (Bi-215 8.2800E-07)	Pb-207	*	
Ag-105	1.13E-01	—[d]	Pd-105	*	
Ag-108m+D	4.18E+02	(Ag-108 8.7000E-02)	Pd-108, Cd-108	*	
Ag-110m+D	6.84E-01	(Ag-110 1.3600E-02)	Cd-110, Pd-110	*	
Al-26	7.17E+05	—	Mg-26	*	
Am-241	4.32E+02	—	Np-237	2.14E+06	
Am-242m+D	1.41E+02	(Am-242 0.9955) (Np-238 0.0045)	Cm-242	4.46E-01	8.23E-01
			Pu-242	3.75E+05	1.72E-01
			Pu-238	8.77E+01	4.50E-03
Am-243+D	7.37E+03	Np-239	Pu-239	2.41E+04	
Ar-37	9.59E-02	—	Cl-37	*	
Ar-39	2.69E+02	—	K-39	*	
Ar-42	3.29E+01	K-42	Ca-42	*	
As-73	2.20E-01	—	Ge-73	*	
Au-195	5.10E-01	—	Pt-195	*	
Ba-133	1.05E+01	—	Cs-133	*	
Be-10	1.51E+06	—	B-10	*	
Be-7	1.46E-01	—	Li-7	*	
Bi-207	3.29E+01	—	Pb-207	*	
Bi-208	3.68E+05	—	Pb-208	*	
Bi-210m+D	3.04E+06	Tl-206	Pb-206	*	
Bk-247	1.38E+03	—	Am-243m	7.37E+03	1.00E+00
Bk-249+D	9.04E-01	(Am-245 1.45E-05)	Cf-249	3.51E+02	1.00E+00
			Cm-245	8.50E+03	1.45E-05
C-14	5.70E+03	—	N-14	*	
Ca-41	1.02E+05	—	K-41	*	
Ca-45	4.45E-01	—	Sc-45	*	
Cd-109	1.26E+00	—	Ag-109	*	
Cd-113	7.70E+15	—	In-113	*	
			Cd-113	7.70E+15	1.40E-03
Cd-113m	1.41E+01	—	In-113	*	9.99E-01
Cd-115m+D	1.22E-01	(In-115m 1.06E-04)	In-115	4.41E+14	1.00E+00
Ce-139	3.77E-01	—	La-139	*	
Ce-141	8.90E-02	—	Pr-141	*	
Ce-144+D	7.80E-01	(Pr-144 9.9999E-01), (Pr-144m 9.7699E-03)	Nd-144	2.29E+15	
Cf-248	9.14E-01	—	SF		2.90E-05
			Cm-244	1.81E+01	1.00E+00
Cf-249	3.51E+02	—	SF		5.02E-09
			Cm-245	8.50E+03	1.00E+00

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Cf-250	1.31E+01	—	SF		7.70E-04
			Cm-246	4.76E+03	9.99E-01
Cf-251	9.00E+02	—	Cm-247	1.56E+07	
Cf-252	2.65E+00	—	SF		3.09E-02
			Cm-248	3.48E+05	9.69E-01
Cf-254	1.66E-01	—	SF		9.97E-01
			Cm-250	8.30E+03	3.10E-03
Cl-36	3.01E+05	—	Ar-36, S-36	*	
Cm-241	8.98E-02	—	Am-241	4.32E+02	9.90E-01
			Pu-237	1.24E-01	1.00E-02
Cm-242	4.46E-01	—	SF		6.37E-08
			Pu-238	8.77E+01	1.00E+00
Cm-243	2.91E+01	—	Am-243	7.37E+03	2.40E-03
			Pu-239	2.41E+04	9.98E-01
Cm-244	1.81E+01	—	SF		1.37E-06
			Pu-240	6.56E+03	1.00E+00
Cm-245	8.50E+03	—	SF		6.10E-09
			Pu-241	1.44E+01	1.00E+00
Cm-246	4.76E+03	—	SF		2.63E-04
			Pu-242	3.75E+05	1.00E+00
Cm-247+D	1.56E+07	Pu-243	Am-243	7.37E+03	1.00E+00
Cm-248	3.48E+05	—	SF		8.39E-02
			Pu-244	8.00E+07	9.16E-01
Cm-250+D	8.30E+03	(Pu-246 0.18), (Am-246m 0.18), (Bk-250 0.08)	SF		7.40E-01
			Cf-250	1.31E+01	8.00E-02
			Cm-246	4.76E+03	1.80E-01
Co-56	2.11E-01	—	Fe-56	*	
Co-57	7.44E-01	—	Fe-57	*	
Co-58	1.94E-01	—	Fe-58	*	
Co-60	5.27E+00	—	Ni-60	*	
Cs-134	2.07E+00	—	Ba-134, Ce-134	*	
Cs-135	2.30E+06	—	Ba-135	*	
Cs-137+D	3.02E+01	(Ba-137m 9.4399E-01)	Ba-137	*	
Dy-154	3.00E+06	—	Gd-150	1.79E+06	1.00E+00
Dy-159	3.95E-01	—	Tb-159	*	
Es-254+D	7.55E-01	(Fm-254 1.7390E-06), (Bk-250 1.0000E+00)	SF		3.00E-08
			SF		1.03E-09
			Cf-250	13.08	1.00E+00
Es-255+D	1.09E-01	(Fm-255 0.92), (Bk-251 0.08)	SF		4.52E-05
			SF		2.30E-07
			Cf-251	9.00E+02	1.00E+00
Eu-148	1.49E-01	—	Sm-148	7.00E+15	1.00E+00
			Pm-144	9.94E-01	9.40E-09
Eu-149	2.55E-01	—	Sm-149	*	
Eu-150	3.69E+01	—	Sm-150	*	
Eu-152	1.35E+01	—	Sm-152	*	7.21E-01
			Gd-152	1.08E+14	2.79E-01

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Eu-154	8.59E+00	—	Gd-154, Sm-154	*	
Eu-155	4.76E+00	—	Gd-155	*	
Fe-55	2.74E+00	—	Mn-55	*	
Fe-59	1.22E-01	—	Co-59	*	
Fe-60+D	1.50E+06	Co-60m	Ni-60	*	2.40E-03
			Co-60	5.27E+00	9.98E-01
Fm-257+D	2.75E-01	(Cf-253 0.9979), (Es-253 0.9948), (Cm-249 0.0031)	SF		2.10E-03
			SF		7.96E-08
			Bk-249	9.04E-01	9.98E-01
Gd-146+D	1.32E-01	Eu-146	Sm-146	1.03E+08	
Gd-148	7.46E+01	—	Sm-144	*	
Gd-150	1.79E+06	—	Sm-146	1.03E+08	1.00E+00
Gd-151	3.40E-01	—	Eu-151	*	1.00E+00
			Sm-147	1.06E+11	1.00E-08
Gd-152	1.08E+14	—	Sm-148	7.00E+15	
Gd-153	6.58E-01	—	Eu-153	*	
Ge-68+D	7.42E-01	Ga-68	Zn-68	*	
H-3	1.23E+01	—	He-3	*	
Hf-172+D	1.87E+00	Lu-172m Lu-172	Yb-172	*	
Hf-174	2.00E+15	—	Yb-170	*	
Hf-175	1.92E-01	—	Lu-175	*	
Hf-178m	3.10E+01	—	Hf-178	*	
Hf-181	1.16E-01	—	Ta-181	*	
Hf-182	9.00E+06	—	Ta-182	3.13E-01	
Hg-194+D	4.40E+02	Au-194	Pt-194	*	
Hg-203	1.28E-01	—	Tl-203	*	
Ho-163	4.57E+03	—	Dy-163	*	
Ho-166m	1.20E+03	—	Er-166	*	
I-125	1.63E-01	—	Te-125	*	
I-129	1.57E+07	—	Xe-129	*	
In-114m+D	1.36E-01	(In-114 0.9675)	Cd-114, Sn-114	*	
In-115	4.41E+14	—	Sn-115	*	
Ir-192	2.02E-01	—	Os-192, Pt-192	*	
Ir-192n	2.41E+02	—	Ir-192	2.02E-01	
Ir-194m	4.68E-01	—	Pt-194	*	
K-40	1.25E+09	—	Ca-40, Ar-40	*	
Kr-81	2.29E+05	—	Br-81	*	
Kr-85	1.0756E+01	—	Rb-85	*	
La-137	6.00E+04	—	Ba-137	*	
La-138	1.02E+11	—	Ba-138, Ce-138	*	
Lu-173	1.37E+00	—	Yb-173	*	
Lu-174	3.31E+00	—	Yb-174	*	
Lu-174m	3.89E-01	—	Yb-174	*	6.20E-03
			Lu-174	3.31E+00	9.94E-01

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Lu-176	3.85E+10	—	Hf-176	*	*
Lu-177m+D	4.39E-01	(Lu-177 2.1700E-01)	Hf-177	*	
Mn-53	3.70E+06	—	Cr-53	*	
Mn-54	8.55E-01	—	Cr-54, Fe-54	*	
Mo-93	4.00E+03	—	Nb-93	*	1.20E-01
			Nb-93m	1.61E+01	8.80E-01
Na-22	2.60E+00	—	Ne-22	*	
Nb-91	6.80E+02	—	Zr-91	*	
Nb-91m	1.67E-01	—	Zr-91	*	3.40E-02
			Nb-91	6.80E+02	9.66E-01
Nb-92	3.47E+07	—	Zr-92	*	
Nb-93m	1.61E+01	—	Nb-93	*	
Nb-94	2.03E+04	—	Mo-94	*	
Nb-95	9.58E-02	—	Mo-95	*	
Nd-144	2.29E+15	—	Ce-140	*	
Ni-59	1.01E+05	—	Co-59	*	
Ni-63	1.00E+02	—	Cu-63	*	
Np-235+D	1.08E+00	(U-235m 3.9934E-03)	Pa-231	3.28E+04	2.60E-05
			U-235	7.04E+08	1.00E+00
Np-236+D	1.54E+05	(Pa-232 1.6E-3)	U-236	2.34E+07	8.73E-01
			Pu-236	2.86E+00	1.25E-01
			Th-232	1.405E+10	4.80E-08
			U-232	6.89E+01	1.60E-03
Np-237+D	2.14E+06	Pa-233	U-233	1.59E+05	
Os-185	2.56E-01	—	Re-185	*	
Os-186	2.00E+15	—	W-182	*	
Os-194+D	6.00E+00	Ir-194	Pt-194	*	
Pa-231	3.28E+04	—	Ac-227	2.18E+01	
Pb-202+D	5.25E+04	(Tl-202 9.9000E-01)	Hg-202	*	
Pb-205	1.53E+07	—	Tl-205	*	
Pb-210+D	2.22E+01	Bi-210, (Hg-206 1.9E-08), (Tl-206 1.339E-06)	Po-210	3.79E-01	1.00E+00
Pd-107	6.50E+06	—	Ag-107	*	
Pm-143	7.26E-01	—	Nd-143	*	
Pm-144	9.94E-01	—	Nd-144	2.29E+15	
Pm-145	1.77E+01	—	Nd-145	*	
Pm-146	5.53E+00	—	Nd-146	*	
			Sm-146	1.03E+08	
Pm-147	2.62E+00	—	Sm-147	1.06E+11	
Pm-148m+D	1.13E-01	(Pm-148 4.2000E-02)	Sm-148	7.00E+15	
Po-208	2.90E+00	—	Pb-204	*	
			Bi-208	3.68E+05	2.23E-05
Po-209	1.02E+02	—	Pb-205	1.53E+07	9.95E-01
			Bi-209	*	4.80E-03
Po-210	3.79E-01	—	Pb-206	*	
Pt-190	6.50E+11	—	Os-186	2.00E+15	1.00E+00
Pt-193	5.00E+01	—	Ir-193	*	
Pu-236	2.86E+00	—	SF		1.37E-09

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
			U-232	6.89E+01	1.00E+00
Pu-237	1.24E-01	—	Np-237	2.14E+06	1.00E+00
			U-233	1.59E+05	4.20E-05
Pu-238	8.77E+01	—	SF		1.85E-09
			U-234	2.46E+05	1.00E+00
Pu-239+D	2.41E+04	(U-235m 9.9940E-01)	U-235	7.04E+08	
Pu-240	6.56E+03	—	SF		5.75E-08
			U-236	2.34E+07	1.00E+00
Pu-241+D	1.44E+01	(U-237 2.45E-05)	Am-241	4.32E+02	1.00E+00
			Np-237	2.14E+06	2.45E-05
Pu-242	3.75E+05	—	SF		5.54E-06
			U-238	4.47E+09	1.00E+00
Pu-244+D	8.00E+07	U-240, Np-240m, (Np-240 1.1000E-03)	SF		1.21E-03
			Pu-240	6.56E+03	9.99E-01
Ra-226+D	1.60E+03	Rn-222, Po-218, (Pb-214 9.9980E-01), (Bi-214 1.0E+00), (Po-214 9.9979E-01), (Tl-210 2.1E-04), (At-218 2.0E-04), (Rn-218 2.0E-07)	Pb-210	2.22E+01	1.00E+00
Ra-228+D	5.75E+00	Ac-228	Th-228	1.91E+00	
Rb-83+D	2.36E-01	(Kr-83m 7.4292E-01)	Kr-83	*	
Rb-84	8.97E-02	—	Sr-84, Kr-84	*	
Rb-87	4.92E+10	—	Sr-87	*	
Re-183	1.92E-01	—	W-183	*	
Re-184	1.04E-01	—	W-184	*	
Re-184m	4.63E-01	—	W-184	*	2.46E-01
			Re-184	1.04E-01	7.54E-01
Re-186m+D	2.00E+05	Re-186	W-186	*	7.47E-02
			Os-186	2.00E+15	9.25E-01
Re-187	4.12E+10	—	Os-187	*	
Rh-101	3.30E+00	—	Ru-101	*	
Rh-102	5.67E-01	—	Ru-102, Pd-102	*	
Rh-102m	3.74E+00	—	Ru-102	*	9.98E-01
			Rh-102	5.67E-01	2.33E-03
Ru-103+D	1.08E-01	(Rh-103m 0.988)	Rh-103	*	
Ru-106+D	1.02E+00	Rh-106	Pd-106	*	
S-35	2.40E-01	—	Cl-35	*	
Sb-124	1.65E-01	—	Te-124	*	
Sb-125	2.76E+00	—	Te-125	*	7.69E-01
			Te-125m	1.57E-01	2.31E-01
Sc-46	2.29E-01	—	Ti-46	*	
Se-75	3.28E-01	—	As-75	*	
Se-79	2.95E+05	—	Br-79	*	
Si-32+D	1.32E+02	P-32	S-32	*	
Sm-145	9.31E-01	—	Pm-145	1.77E+01	
Sm-146	1.03E+08	—	Nd-142	*	
Sm-147	1.06E+11	—	Nd-143	*	
Sm-148	7.00E+15	—	Nd-144	2.29E+15	

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
Sm-151	9.00E+01	—	Eu-151	*	
Sn-113+D	3.15E-01	In-113m	In-113	*	
Sn-119m	8.03E-01	—	Sn-119	*	
Sn-121m+D	4.39E+01	(Sn-121 7.7600E-01)	Sb-121	*	
Sn-123	3.54E-01	—	Sb-123	*	
Sn-126+D	2.30E+05	Sb-126m, (Sb-126 1.4000E-01)	Te-126	*	
Sr-85	1.78E-01	—	Rb-85	*	
Sr-89	1.38E-01	—	Y-89	*	
Sr-90+D	2.88E+01	Y-90	Zr-90	*	
Ta-179	1.82E+00	—	Hf-179	*	
Ta-182	3.13E-01	—	W-182	*	
Tb-157	7.10E+01	—	Gd-157	*	
Tb-158	1.80E+02	—	Gd-158, Dy-158	*	
Tb-160	1.98E-01	—	Dy-160	*	
Tc-95m+D	1.67E-01	(Tc-95 3.8800E-02)	Mo-95	*	
Tc-97	2.60E+06	—	Mo-97	*	
Tc-97m	2.47E-01	—	Tc-97	2.60E+06	
Tc-98	4.20E+06	—	Ru-98	*	
Tc-99	2.11E+05	—	Ru-99	*	
Te-121m+D	4.22E-01	(Te-121 8.8600E-01)	Sb-121	*	
Te-123	6.00E+14	—	Sb-123	*	
Te-123m	3.27E-01	—	Te-123	6.00E+14	
Te-125m	1.57E-01	—	Te-125	*	
Te-127m+D	2.98E-01	(Te-127 9.7600E-01)	I-127	*	
Te-129m+D	9.20E-02	(Te-129 6.3000E-01)	I-129	1.57E+07	
Th-228+D	1.91E+00	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 6.4060E-01), (Tl-208 3.5940E-01)	Pb-208	*	
Th-229+D	7.34E+03	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 9.7910E-01), Pb-209, (Tl-209 2.0900E-02)	Bi-209	*	
Th-230	7.54E+04	—	Ra-226	1.60E+03	1.00E+00
Th-232	1.41E+10	—	Ra-228	5.75E+00	
Ti-44+D	6.00E+01	Sc-44	Ca-44	*	
Tl-204	3.78E+00	—	Pb-204, Hg-204	*	
Tm-168	2.55E-01	—	Er-168, Yb-168	*	
Tm-170	3.52E-01	—	Er-170, Yb-170	*	
Tm-171	1.92E+00	—	Yb-171	*	
U-232	6.89E+01	—	Th-228	1.91E+00	
U-233	1.59E+05	—	Th-229	7.34E+03	
U-234	2.46E+05	—	Th-230	7.54E+04	
U-235+D	7.04E+08	Th-231	Pa-231	3.28E+04	
U-236	2.34E+07	—	Th-232	1.41E+10	
U-238+D	4.47E+09	Th-234, Pa-234m, (Pa-234 1.6000E-03)	SF		5.45E-07
			U-234	2.46E+05	

Table A-2 (Cont.)

Principal Radionuclide[a]		Associated Decay Chain[b]	Terminal Nuclide or Radionuclide[c]		
Species	Half-life (yr)		Species	Half-life (yr)	Fraction
V-49	9.04E-01	—	Ti-49	*	
V-50	1.50E+17	—	Ti-50, Cr-50	*	
W-181	3.32E-01	—	Ta-181	*	
W-185	2.06E-01	—	Re-185	*	
W-188+D	1.91E-01	Re-188	Os-188	*	
Xe-127	9.97E-02	—	I-127	*	
Y-88	2.92E-01	—	Sr-88	*	
Y-91	1.60E-01	—	Zr-91	*	
Yb-169	8.77E-02	—	Tm-169	*	
Zn-65	6.68E-01	—	Cu-65	*	
Zr-88	2.28E-01	—	Y-88	2.92E-01	
Zr-93	1.53E+06	—	Nb-93	*	
			Nb-93m	1.61E+01	2.50E-02
Zr-95+D	1.75E-01	(Nb-95m 1.08E-02)	Mo-95	*	
			Nb-95	9.58E-02	9.99E-01

[a] Radionuclides with half-lives longer than 30 days. If short-lived progeny are involved, the +D symbol is added along with the radionuclide name (e.g., Ac-227+D).

[b] The associated progeny with half-lives shorter than 30 days are listed. If the branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] The principal radionuclide or stable nuclide that terminates an associated decay chain. Stable nuclides are indicated by an asterisk (*) in place of the half-life. If a radionuclide has spontaneous fission, it is indicated by SF. If the branching fraction is anything other than 1, the fraction is listed.

[d] Indicates there is no associated radionuclide.

For some isomers, the notation in ICRP-107 has changed from ICRP-38 notations. In ICRP-107, isomers of energy above the ground state are identified by appending “m,” “n,” “p,” or “q” to the mass number, whereas the information during the preparation of ICRP-38 was insufficient to identify the ground and excited states of a few radionuclides. Several radionuclides that did not have sufficient information were assigned an *ad-hoc* designation based on their physical half-life. Table A-3 shows the correspondence between the ICRP-38 and ICRP-107 isomers. Some radionuclides in ICRP-38 are not in the ICRP-107 database (see footnote b in Table A-3). If any of the radionuclides not in ICRP-107 were selected using the ICRP-38 radionuclide transformation data and if the transformation database is later changed to ICRP-107 then these nuclides will be deleted from the analysis.

Table A-3 Identification of ICRP-38 and ICRP-107 Isomers

ICRP-38 Notation[a,b]		ICRP-107 Notation[a]	
ICRP-38[c]	$T_{1/2}$	ICRP-107	$T_{1/2}$
Nb-89a	66 m	Nb-89m	66 m
Nb-89b	122 m	Nb-89	2.03 h
Nb-98	51.5 m	Nb-98m	51.3 m
Rh-102	2.9 y	Rh-102m	3.742 y
Rh-102m	207 d	Rh-102	207 d
In-110a	69.1 m	In-110m	69.1 m
In-110b	4.9 h	In-110	4.9 h
Sb-120a	15.89 m	Sb-120	15.89 m
Sb-120b	5.76 d	Sb-120m	5.76 d
Sb-128a	10.4 m	Sb-128m	10.4 m
Sb-128b	9.01 h	Sb-128	9.01 h
Eu-150a	12.62 h	Eu-150m	12.8 h
Eu-150b	34.2 y	Eu-150	36.9 y
Ta-178a	9.31 m	Ta-178	9.31 m
Ta-178b	2.2 h	Ta-178m	2.36 h
Ta-180m	8.1 h	Ta-180	8.152 h
Ta-180	1.0E13 y	Ta-180m	—[e]
Re-182a	12.7 h	Re-182m	12.7 h
Re-182b	64.0 h	Re-182	64.0 h
Ir-186b	1.75 h	Ir-186m	1.92 h
Ir-186a	15.8 h	Ir-186	16.64 h
Ir-192m	241 y	Ir-192n[d]	241 y
Np-236b	22.5 h	Np-236m	22.5 h
Np-236a	115E3 y	Np-236	1.54E5 y
Es-250	2.1 h	Es-250m	2.22 h

[a] Half-life ($T_{½}$) units: m—minute(s); h—hour(s); d—day(s); y—year(s).

[b] Nb-97m (60 s), W-176 (2.3 h), Re-177 (14 m), Md-257 (5.2 h), and Md-258 (55 d) were in ICRP-38 ($T_{1/2}$ values from ICRP-38) but are not in ICRP-107.

[c] Ad-hoc notation "a" and "b" used in ICRP-38 database.

[d] Metastable state of higher energy than the first metastable state.

[e] Ta-180m, $T_{1/2}$ in excess of 1.2E15 y; decay has not been observed (i.e., observationally stable).

A.2 DOSE COEFFICIENT LIBRARIES

The RESRAD-BUILD code is linked to a stand-alone utility program called the DCF Editor. This DCF Editor manages an array of dose coefficient (dose conversion factor) and risk coefficient (slope factor) libraries developed based on different radionuclide transformation databases and with different methodologies (see Sections A.3 and A.5 for more information). The RESRAD-BUILD code can access and retrieve data in specific dose and risk coefficient libraries that are specified by the users for use in dose/risk calculations. The dose and risk coefficient libraries managed by the DCF Editor include base libraries taken directly from ICRP and federal government publications as well as user-created libraries. The user-created libraries are libraries created by modifying one of the base libraries and are named by the users. Chapter 5 of the RESRAD-BUILD User's Guide (Volume 2 of this report) provides detailed instructions on creating a user DCF library.

There are two sets of base dose coefficient libraries developed with the ICRP-38 radionuclide transformation database. One set was developed using the ICRP-26/30 methodology (ICRP 1977, 1979) and published in Federal Guidance Reports (FGRs) No. 11 (Eckerman et al. 1988) and No.12 (Eckerman and Ryman 1993). These base libraries only include dose coefficients for adult members of the public. The other set of base libraries was developed using the ICRP-60 methodology (ICRP 1991) and published in the ICRP-72 report (ICRP 1996). These libraries include dose coefficients for six different age groups (infant, 1, 5, 10, 15, and adult) of the general public. There is one set of base dose coefficient library developed with the ICRP-107 radionuclide transformation database. This library also includes dose coefficients for six different age groups (infant, 1, 5, 10, 15, and adult) of the general public and for the DOE-STD-1196-2011 Reference Person. The reference person is defined as a hypothetical aggregation of human (male and female) physical and physiological characteristics arrived at by international consensus for standardizing radiation dose calculations. The reference person dose coefficients are derived using age-specific dose coefficients coupled with information on the age and gender structure of the U.S. population in 2000 census data and age- and gender-specific intakes (DOE 2011).

A.2.1 ICRP-26/30-Based Dose Coefficient Libraries Developed with ICRP-38 Radionuclide Transformation Database

FGR No.12 (Eckerman and Ryman 1993) lists dose coefficients for external exposure to photons and electrons emitted by radionuclides distributed in air, water, and soil. These dose coefficients relate the absorbed doses adjusted for radiation type, i.e., dose equivalent, to different organs and tissues of the body, as well as the effective dose equivalent to the whole body, from an entire year of external exposure to an environmental medium with a unit concentration of radionuclides. The RESRAD-BUILD code uses only the dose coefficients for the whole body for exposure to radionuclides in air (for the air submersion pathway) and in soil (for the direct external and deposition pathways). Appendix C provides discussions on the methodology implemented in the code for external dose calculations.

FGR 11 (Eckerman et al. 1988) lists dose coefficients for internal exposure to the radiation emitted by radionuclides that enter a human body through inhalation and ingestion. A dose coefficient for inhalation relates the committed dose, i.e., the total dose over 50 years after the intake of radionuclides, to a unit intake of radionuclides through inhalation. Like the external exposure, the RESRAD-BUILD code uses only the committed effective dose equivalent for the whole body. The amount of radionuclides that will reach and distribute in the respiratory system after inhalation intake depends on the size of the particles that carry the radionuclides. The committed dose equivalent to different issues and organs, thereby the committed effective dose equivalent to the whole body, also depends on how fast the radionuclides will be cleared from the lungs after the intake. The dose coefficients for inhalation were developed for the dust particles with an activity median aerodynamic diameter (AMAD) of 1 µm. Values are available for different inhalation classes D, W, and Y, referring to the different rates of clearance from the lungs, which correspond to retention half-times of less than 10 days, 10 to 100 days, and more than 100 days, respectively. These different values are included in the base library and can be viewed with the DCF Editor. By default, the largest dose coefficient is selected for use in dose calculations, unless the user chooses a different value and saves it to a user-created library for use by the code. Appendix E discusses the calculations of radiation dose for the inhalation pathway using the inhalation dose coefficients.

A dose coefficient for ingestion is the dose/exposure ratio for the committed dose that an individual would incur from a unit intake of radionuclide by ingestion. The ingestion dose coefficient of a radionuclide depends on its chemical form, which determines the fraction of the radionuclide entering the gastrointestinal tract that would enter the body fluid, i.e., fraction of uptake. FGR 11 includes committed dose equivalents for different organs or tissues as well as committed effective dose equivalents for the whole body; the whole-body dose coefficients are used by RESRAD-BUILD in dose calculations. Some radionuclides (those of antimony, tungsten, mercury, uranium, and plutonium) can assume different chemical forms; therefore, they have different dose coefficients for ingestion in the base library. By default, the largest dose coefficient is selected for use in dose calculations, unless the user chooses a different value and saves it to a user-created library for use by the code. Appendix H discusses the calculations of radiation dose for the ingestion pathway using the ingestion dose coefficients.

Table A-4 lists the default ingestion, inhalation, and air submersion dose coefficients used in the RESRAD-BUILD code for calculating the radiation dose associated with the exposure to each principal radionuclide with half-life of at least 30 days. The listed values include the contributions from associated progenies, if applicable; in that case, the listed values are different from the default values stored in the FGR 11/12 base library that can be displayed and viewed with the DCF Editor. The direct external pathway dose coefficients are provided in Appendix C.

Table A-4 Default Ingestion, Inhalation, and Air Submersion Dose Coefficients for at least 30 Day Half-life Radionuclides from FGR 11 and FGR 12 in RESRAD-BUILD Code

Radionuclide[a]	Associated Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Ac-227+D	(Th-227 9.8620E-01), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (Tl-207 9.9720E-01), (Po-211 2.8000E-03), (Fr-223 1.3800E-02)	1.48E-02	6.72E+00	2.16E-03
Ag-105	—[c]	2.04E-06	4.66E-06	2.86E-03
Ag-108m+D	(Ag-108 8.9000E-02)	7.62E-06	2.83E-04	9.11E-03
Ag-110m+D	(Ag-110 1.3300E-02)	1.08E-05	8.03E-05	1.59E-02
Al-26	—	1.46E-05	7.96E-05	1.59E-02
Am-241	—	3.64E-03	4.44E-01	9.55E-05
Am-242m+D	(Am-242 0.9952), (Np-238 0.0048)	3.51E-03	4.26E-01	9.02E-05
Am-243+D	Np-239	3.62E-03	4.40E-01	1.15E-03
Ar-37	—	0.00E+00	0.00E+00	1.48E-08
Ar-39	—	0.00E+00	0.00E+00	1.06E-06
As-73	—	7.07E-07	3.46E-06	2.22E-05
Au-195	—	1.06E-06	1.30E-05	3.75E-04
Ba-133	—	3.40E-06	7.81E-06	2.08E-03
Be-10	—	4.66E-06	3.54E-04	1.31E-06
Be-7	—	1.28E-07	3.21E-07	2.75E-04
Bi-207	—	5.48E-06	2.00E-05	8.80E-03
Bi-210m+D	Tl-206	9.58E-05	7.58E-03	1.43E-03
Bk-247	—	4.70E-03	5.73E-01	5.50E-04
Bk-249+D	(Am-245 1.45E-5)	1.20E-05	1.39E-03	1.21E-08
C-14	—	2.09E-06	2.09E-06	2.61E-08
Ca-41	—	1.27E-06	1.35E-06	0.00E+00
Ca-45	—	3.16E-06	6.62E-06	1.01E-07
Cd-109	—	1.31E-05	1.14E-04	3.43E-05
Cd-113	—	1.74E-04	1.67E-03	1.69E-07
Cd-113m	—	1.61E-04	1.53E-03	8.10E-07
Cd-115m	—	1.62E-05	7.21E-05	1.37E-04
Ce-139	—	1.14E-06	9.07E-06	7.85E-04
Ce-141	—	2.90E-06	8.95E-06	4.00E-04
Ce-144+D	(Pr-144m 0.0178), Pr-144	2.11E-05	3.74E-04	3.28E-04
Cf-248	—	3.34E-04	5.07E-02	5.52E-07
Cf-249	—	4.74E-03	5.77E-01	1.84E-03
Cf-250	—	2.13E-03	2.62E-01	5.25E-07
Cf-251	—	4.85E-03	5.88E-01	6.51E-04
Cf-252	—	1.08E-03	1.57E-01	5.91E-07
Cf-254	—	2.42E-03	2.93E-01	1.72E-09
Cl-36	—	3.03E-06	2.19E-05	2.60E-06
Cm-241	—	4.48E-06	1.47E-04	2.70E-03
Cm-242	—	1.15E-04	1.73E-02	6.64E-07
Cm-243	—	2.51E-03	3.07E-01	6.86E-04
Cm-244	—	2.02E-03	2.48E-01	5.73E-07
Cm-245	—	3.74E-03	4.55E-01	4.62E-04
Cm-246	—	3.70E-03	4.51E-01	5.21E-07
Cm-247+D	Pu-243	3.42E-03	4.14E-01	1.87E-03
Cm-248	—	1.36E-02	1.65E+00	3.96E-07

Table A-4 (Cont.)

Radionuclide[a]	Associated Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Cm-250	(Pu-246 0.25), (Am-246 0.25), (Bk-250 0.14)	7.77E-02	9.40E+00	2.36E-03
Co-56	—	1.26E-05	3.96E-05	2.14E-02
Co-57	—	1.18E-06	9.07E-06	6.55E-04
Co-58	—	3.58E-06	1.09E-05	5.56E-03
Co-60	—	2.69E-05	2.19E-04	1.47E-02
Cs-134	—	7.33E-05	4.62E-05	8.83E-03
Cs-135	—	7.07E-06	4.55E-06	6.59E-08
Cs-137+D	(Ba-137m 0.946)	5.00E-05	3.19E-05	3.18E-03
Dy-159	—	4.44E-07	2.43E-06	1.46E-04
Es-254+D	Bk250	3.14E-04	4.11E-02	5.14E-03
Eu-148	—	5.74E-06	1.43E-05	1.24E-02
Eu-149	—	4.59E-07	1.89E-06	2.63E-04
Eu-150	—	6.36E-06	2.68E-04	8.37E-03
Eu-152	—	6.48E-06	2.21E-04	6.59E-03
Eu-154	—	9.55E-06	2.86E-04	7.17E-03
Eu-155	—	1.53E-06	4.14E-05	2.91E-04
Fe-55	—	6.07E-07	2.69E-06	0.00E+00
Fe-59	—	6.70E-06	1.48E-05	6.97E-03
Fe-60+D	Co-60m	1.52E-04	7.47E-04	2.54E-05
Fm-257+D	Cf-253, (Es-253 9.9690E-01), (Cm-249 3.1000E-03)	1.99E-04	3.05E-02	5.47E-04
Gd-146	Eu-146	9.84E-06	4.20E-05	1.55E-02
Gd-148	—	2.18E-04	3.30E-01	0.00E+00
Gd-151	—	8.25E-07	8.88E-06	2.57E-04
Gd-152	—	1.61E-04	2.43E-01	0.00E+00
Gd-153	—	1.17E-06	2.38E-05	4.33E-04
Ge-68+D	Ga-68	1.41E-06	5.19E-05	5.34E-03
H-3	—	6.40E-08	6.40E-08	3.86E-08
Hf-172+D	Lu-172	1.01E-05	3.23E-04	1.13E-02
Hf-175	—	1.82E-06	5.59E-06	1.97E-03
Hf-178m	—	2.10E-05	2.46E-03	1.31E-02
Hf-181	—	4.70E-06	1.54E-05	3.06E-03
Hf-182	—	1.59E-05	3.32E-03	1.33E-03
Hg-194+D	Au-194	2.90E-04	1.82E-04	6.17E-03
Hg-203	—	1.14E-05	7.33E-06	1.32E-03
Ho-166m	—	8.07E-06	7.73E-04	9.86E-03
I-125	—	3.85E-05	2.42E-05	6.09E-05
I-129	—	2.76E-04	1.74E-04	4.43E-05
In-114m+D	(In-114 0.957)	1.71E-05	8.88E-05	5.03E-04
In-115	—	1.58E-04	3.74E-03	5.25E-07
Ir-192	—	5.74E-06	2.82E-05	4.56E-03
Ir-192m	—	1.57E-06	3.85E-04	8.91E-04
Ir-194m	—	9.10E-06	6.84E-05	1.31E-02
K-40	—	1.86E-05	1.24E-05	9.39E-04
Kr-81	—	0.00E+00	0.00E+00	3.12E-05
Kr-85	—	0.00E+00	0.00E+00	1.39E-05
La-137	—	4.55E-07	8.77E-05	4.74E-05
La-138	—	5.88E-06	1.37E-03	7.24E-03

Table A-4 (Cont.)

Radionuclide[a]	Associated Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Lu-173	—	1.09E-06	2.25E-05	5.95E-04
Lu-174	—	1.11E-06	3.96E-05	6.37E-04
Lu-174m	—	2.13E-06	2.54E-05	2.54E-04
Lu-176	—	7.33E-06	6.62E-04	2.71E-03
Lu-177m+D	(Lu-177 0.21)	7.81E-06	7.38E-05	5.49E-03
Md-258		1.18E-04	1.65E-02	5.93E-06
Mn-53	—	1.08E-07	5.00E-07	0.00E+00
Mn-54	—	2.77E-06	6.70E-06	4.77E-03
Mo-93	—	1.35E-06	2.84E-05	2.94E-06
Na-22	—	1.15E-05	7.66E-06	1.26E-02
Nb-93m	—	5.22E-07	2.92E-05	5.18E-07
Nb-94	—	7.14E-06	4.14E-04	8.99E-03
Nb-95	—	2.57E-06	5.81E-06	4.36E-03
Ni-59	—	2.10E-07	2.70E-06	0.00E+00
Ni-63	—	5.77E-07	6.29E-06	0.00E+00
Np-235	—	2.43E-07	4.14E-06	5.95E-06
Np-236	—	8.66E-04	1.04E-01	6.25E-04
Np-237+D	Pa-233	4.44E-03	5.40E-01	1.21E-03
Os-185	—	2.26E-06	1.04E-05	4.00E-03
Os-194+D	Ir-194	1.62E-05	6.73E-04	5.33E-04
Pa-231	—	1.06E-02	1.28E+00	2.01E-04
Pb-202+D	Tl-202	4.04E-05	9.91E-05	2.54E-03
Pb-205	—	1.63E-06	3.92E-06	5.90E-08
Pb-210+D	Bi-210	5.38E-03	1.38E-02	1.04E-05
Pd-107	—	1.49E-07	1.28E-05	0.00E+00
Pm-143	—	1.03E-06	1.09E-05	1.70E-03
Pm-144	—	4.33E-06	5.37E-05	8.73E-03
Pm-145	—	4.74E-07	3.05E-05	8.27E-05
Pm-146	—	3.67E-06	1.47E-04	4.19E-03
Pm-147	—	1.05E-06	3.92E-05	8.09E-08
Pm-148m+D	(Pm-148 0.046)	8.16E-06	2.31E-05	1.15E-02
Po-209	—	0.00E+00	0.00E+00	0.00E+00
Po-210	—	1.90E-03	9.40E-03	4.85E-08
Pt-193	—	1.19E-07	2.27E-07	4.65E-08
Pu-236	—	1.17E-03	1.45E-01	7.41E-07
Pu-237	—	4.44E-07	1.97E-06	2.36E-04
Pu-238	—	3.20E-03	3.92E-01	5.70E-07
Pu-239	—	3.54E-03	4.29E-01	4.95E-07
Pu-240	—	3.54E-03	4.29E-01	5.54E-07
Pu-241+D	(U-237 0.0000245)	6.84E-05	8.25E-03	2.55E-08
Pu-242	—	3.36E-03	4.11E-01	4.68E-07
Pu-244+D	(U-240 0.9988), (Np-240m 0.9988)	3.32E-03	4.03E-01	1.89E-03
Ra-226+D	Rn-222,Po-218, (Pb-214 9.9980E-01), Bi-214, (Po-214 9.9980E-01), (Tl-210 2.0000E-04), (At-218 2.0000E-04)	1.32E-03	8.59E-03	1.03E-02
Ra-228+D	Ac-228	1.44E-03	5.08E-03	5.58E-03
Rb-83+D	(Kr-83m 0.76199)	7.70E-06	4.92E-06	2.79E-03
Rb-84	—	9.99E-06	6.51E-06	5.22E-03
Rb-87	—	4.92E-06	3.23E-06	2.12E-07

Table A-4 (Cont.)

Radionuclide[a]	Associated Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Re-184	—	2.19E-06	5.14E-06	5.01E-03
Re-184m	—	2.95E-06	1.47E-05	2.12E-03
Re-186m+D	Re-186	6.94E-06	3.93E-05	1.66E-04
Re-187	—	9.51E-09	5.44E-08	0.00E+00
Rh-101	—	2.32E-06	3.96E-05	1.41E-03
Rh-102	—	1.04E-05	1.20E-04	1.21E-02
Rh-102m	—	4.70E-06	4.77E-05	2.70E-03
Ru-103+D	(Rh-103m 0.997)	3.06E-06	8.96E-06	2.63E-03
Ru-106+D	Rh-106	2.74E-05	4.77E-04	1.21E-03
S-35	—	7.33E-07	2.48E-06	2.84E-08
Sb-124	—	1.01E-05	2.52E-05	1.07E-02
Sb-125	—	2.81E-06	1.22E-05	2.36E-03
Sc-46	—	6.40E-06	2.96E-05	1.16E-02
Se-75	—	9.62E-06	8.47E-06	2.16E-03
Se-79	—	8.69E-06	9.84E-06	3.54E-08
Si-32+D	P-32	1.09E-05	1.03E-03	1.16E-05
Sm-145	—	9.10E-07	1.10E-05	1.88E-04
Sm-146	—	2.04E-04	8.25E-02	0.00E+00
Sm-147	—	1.85E-04	7.47E-02	0.00E+00
Sm-151	—	3.89E-07	3.00E-05	4.21E-09
Sn-113+D	In-113m	3.18E-06	1.07E-05	1.46E-03
Sn-119m	—	1.39E-06	6.25E-06	1.18E-05
Sn-121m+D	(Sn-121 0.776)	2.25E-06	1.19E-05	7.24E-06
Sn-123	—	8.40E-06	3.25E-05	4.70E-05
Sn-126+D	Sb-126m, (Sb-126 0.14)	2.11E-05	1.01E-04	1.12E-02
Sr-85	—	1.98E-06	5.03E-06	2.82E-03
Sr-89	—	9.25E-06	4.14E-05	9.02E-06
Sr-90+D	Y-90	1.53E-04	1.31E-03	2.31E-05
Ta-179	—	2.73E-07	6.51E-06	1.27E-04
Ta-180	—	3.63E-06	2.45E-04	3.02E-03
Ta-182	—	6.51E-06	4.48E-05	7.47E-03
Tb-157	—	1.24E-07	9.21E-06	7.91E-06
Tb-158	—	4.40E-06	2.56E-04	4.48E-03
Tb-160	—	6.73E-06	2.50E-05	6.47E-03
Tc-95m+D	(Tc-95 0.04)	1.47E-06	3.89E-06	3.95E-03
Tc-97	—	1.71E-07	9.92E-07	3.89E-06
Tc-97m	—	1.24E-06	4.88E-06	5.42E-06
Tc-98	—	4.88E-06	2.29E-05	8.01E-03
Tc-99	—	1.46E-06	8.32E-06	1.89E-07
Te-121m+D	(Te-121 0.886)	9.19E-06	1.76E-05	3.95E-03
Te-123	—	4.18E-06	1.05E-05	2.51E-05
Te-123m	—	5.66E-06	1.06E-05	7.60E-04
Te-125m	—	3.67E-06	7.29E-06	5.29E-05
Te-127m+D	(Te-127 0.976)	8.92E-06	2.18E-05	4.47E-05
Te-129m+D	(Te-129 0.65)	1.08E-05	2.40E-05	3.89E-04
Th-228+D	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 0.6407), (Tl-208 0.3593)	8.09E-04	3.45E-01	9.37E-03

Table A-4 (Cont.)

Radionuclide[a]	Associated Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 0.9784), (Tl-209 0.0216), Pb-209	4.03E-03	2.17E+00	1.74E-03
Th-230	—	5.48E-04	3.26E-01	2.03E-06
Th-232	—	2.73E-03	1.64E+00	1.02E-06
Ti-44+D	Sc-44	2.45E-05	1.02E-03	1.29E-02
Tl-204	—	3.36E-06	2.41E-06	6.52E-06
Tm-170	—	5.29E-06	2.63E-05	2.60E-05
Tm-171	—	4.29E-07	9.14E-06	2.51E-06
U-232	—	1.31E-03	6.59E-01	1.66E-06
U-233	—	2.89E-04	1.35E-01	1.90E-06
U-234	—	2.83E-04	1.32E-01	8.91E-07
U-235+D	Th-231	2.67E-04	1.23E-01	9.01E-04
U-236	—	2.69E-04	1.25E-01	5.85E-07
U-238+D	Th-234, (Pa-234m 0.998), (Pa-234 0.0033)	2.69E-04	1.18E-01	1.60E-04
V-49	—	6.14E-08	3.45E-07	0.00E+00
W-181	—	3.44E-07	1.51E-07	1.63E-04
W-185	—	1.99E-06	7.51E-07	6.27E-07
W-188+D	Re-188	1.25E-05	6.12E-06	3.46E-04
Xe-127	—	0.00E+00	0.00E+00	1.46E-03
Y-88	—	5.99E-06	2.81E-05	1.60E-02
Y-91	—	9.51E-06	4.88E-05	3.03E-05
Yb-169	—	3.00E-06	8.07E-06	1.51E-03
Zn-65	—	1.44E-05	2.04E-05	3.38E-03
Zr-88	—	1.49E-06	2.43E-05	2.19E-03
Zr-93	—	1.66E-06	3.21E-04	0.00E+00
Zr-95+D	(Nb-95m 0.007)	3.79E-06	2.36E-05	4.20E-03

[a] Dose conversion factors for entries labeled with “+D” are aggregated dose conversion factors of the principal radionuclide together with the associated decay progenies.

[b] The associated decay progenies are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] Dash indicates there is no associated radionuclide.

A.2.2 ICRP-60 Based Dose Coefficient Libraries Developed with ICRP-38 Database

ICRP-72 lists inhalation and ingestion dose coefficients that were developed with the ICRP-38 radionuclide transformation database and the ICRP-60 dose estimation methodology (see Section A.3). Dose coefficients for six age groups—infant, 1, 5, 10, 15, and adult—are available and are stored in six separate base DCF libraries. In addition to using a newer biokinetic model than the ICRP-26/30 methodology, the ICRP-60 methodology also replaces the three inhalation classes D (days), W (week), and Y (year) used in the ICRP-26/30 methodology with the F (fast), M (medium), S (slow), and V (very fast) classes; the V class applies to radionuclides in a gas or vapor form. For a radionuclide that has multiple dose coefficients in a base library, the largest one is set as the default for use in dose calculations, unless the user chooses a different value and saves it to a user-created library for use by the code.

Table A-5 lists the default ingestion, inhalation, and air submersion dose coefficients for adult members of the general public that are used in the RESRAD-BUILD code for calculating the radiation dose associated with the exposure to each principal radionuclide with a cut-off half-life of at least 30 days. The listed values include the contributions from associated progenies, if applicable; in that case, the listed values are different from the default values stored in the ICRP-60/72 base library that can be displayed and viewed with the DCF Editor. The direct external exposure dose coefficients are provided in Appendix C.

Table A-5 Default Ingestion, Inhalation, and Air Submersion Dose Coefficients for at least 30 Day Half-life Radionuclides from ICRP-72 and FGR 13 in RESRAD-BUILD Code

Radionuclide[a]	Associated Progeny Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Ac-227+D	(Th-227 9.8620E-01), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (Tl-207 9.9720E-01), (Po-211 2.8000E-03), (Fr-223 1.3800E-02)	4.47E-03	2.10E+00	2.03E-03
Ag-105	—[c]	1.74E-06	3.00E-06	2.64E-03
Ag-108m+D	(Ag-108 8.9000E-02)	8.51E-06	1.37E-04	8.47E-03
Ag-110m+D	(Ag-110 1.3300E-02)	1.04E-05	4.44E-05	1.48E-02
Al-26	—	1.30E-05	7.40E-05	1.49E-02
Am-241	—	7.40E-04	3.55E-01	7.87E-05
Am-242m+D	(Am-242 0.9952), (Np-238 0.0048)	7.04E-04	3.40E-01	8.79E-05
Am-243+D	Np-239	7.43E-04	3.55E-01	1.03E-03
Ar-37	—	0.00E+00	0.00E+00	0.00E+00
Ar-39	—	0.00E+00	0.00E+00	1.34E-05
As-73	—	9.62E-07	3.70E-06	1.81E-05
Au-195	—	9.25E-07	6.29E-06	3.19E-04
Ba-133	—	5.55E-06	3.70E-05	1.89E-03
Be-10	—	4.07E-06	1.29E-04	1.61E-05
Be-7	—	1.04E-07	2.03E-07	2.56E-04
Bi-207	—	4.81E-06	2.07E-05	8.22E-03
Bi-210m+D	Tl-206	5.55E-05	1.26E-02	1.35E-03
Bk-247	—	1.29E-03	2.55E-01	4.90E-04
Bk-249+D	(Am-245 1.45E-5)	3.59E-06	5.92E-04	5.71E-08
C-14	—	2.15E-06	2.15E-05	3.04E-07
Ca-41	—	7.03E-07	6.66E-07	0.00E+00
Ca-45	—	2.63E-06	1.37E-05	1.79E-06
Cd-109	—	7.40E-06	3.00E-05	2.66E-05
Cd-113	—	9.25E-05	4.44E-04	2.95E-06
Cd-113m	—	8.51E-05	4.07E-04	1.06E-05
Cd-115m	—	1.22E-05	2.85E-05	1.73E-04
Ce-139	—	9.62E-07	7.03E-06	6.97E-04
Ce-141	—	2.63E-06	1.41E-05	3.62E-04
Ce-144+D	(Pr-144m 0.0178), Pr-144	1.94E-05	1.96E-04	3.99E-04
Cf-248	—	1.04E-04	3.26E-02	3.79E-07
Cf-249	—	1.29E-03	2.59E-01	1.69E-03

Table A-5 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Cf-250	—	5.92E-04	1.26E-01	3.61E-07
Cf-251	—	1.33E-03	2.63E-01	5.85E-04
Cf-252	—	3.33E-04	7.40E-02	2.70E-03
Cf-254	—	1.48E-03	1.52E-01	9.87E-02
Cl-36	—	3.44E-06	2.70E-05	1.94E-05
Cm-241	—	3.37E-06	1.37E-04	2.46E-03
Cm-242	—	4.44E-05	2.18E-02	4.69E-07
Cm-243	—	5.55E-04	2.55E-01	6.19E-04
Cm-244	—	4.44E-04	2.11E-01	3.97E-07
Cm-245	—	7.77E-04	3.66E-01	4.07E-04
Cm-246	—	7.77E-04	3.63E-01	3.62E-07
Cm-247+D	Pu-243	7.03E-04	3.33E-01	1.72E-03
Cm-248	—	2.85E-03	1.33E+00	7.74E-03
Cm-250	(Pu-246 0.25), (Am-246 0.25), (Bk-250 0.14)	1.63E-02	7.77E+00	5.93E-02
Co-56	—	9.25E-06	2.48E-05	2.02E-02
Co-57	—	7.77E-07	3.70E-06	5.80E-04
Co-58	—	2.74E-06	7.77E-06	5.18E-03
Co-60	—	1.26E-05	1.15E-04	1.39E-02
Cs-134	—	7.03E-05	7.40E-05	8.24E-03
Cs-135	—	7.40E-06	3.18E-05	1.11E-06
Cs-137+D	(Ba-137m 0.946)	4.81E-05	1.44E-04	2.98E-03
Dy-159	—	3.70E-07	1.37E-06	1.16E-04
Es-254+D	Bk250	1.04E-04	3.18E-02	4.83E-03
Eu-148	—	4.81E-06	9.62E-06	1.15E-02
Eu-149	—	3.70E-07	1.07E-06	2.28E-04
Eu-150	—	4.81E-06	1.96E-04	7.75E-03
Eu-152	—	5.18E-06	1.55E-04	6.17E-03
Eu-154	—	7.40E-06	1.96E-04	6.71E-03
Eu-155	—	1.18E-06	2.55E-05	2.50E-04
Fe-55	—	1.22E-06	2.85E-06	0.00E+00
Fe-59	—	6.66E-06	1.48E-05	6.56E-03
Fe-60+D	Co-60m	4.07E-04	1.04E-03	2.36E-05
Fm-257+D	Cf-253, (Es-253 9.9690E-01), (Cm-249 3.1000E-03)	8.32E-05	4.10E-02	4.89E-04
Gd-146	Eu-146	8.36E-06	2.66E-05	1.44E-02
Gd-148	—	2.07E-04	9.62E-02	0.00E+00
Gd-151	—	7.40E-07	3.18E-06	2.19E-04
Gd-152	—	1.52E-04	7.03E-02	0.00E+00
Gd-153	—	9.99E-07	7.77E-06	3.63E-04
Ge-68+D	Ga-68	5.18E-06	5.20E-05	5.01E-03
H-3	—	1.55E-07	9.62E-07	0.00E+00
Hf-172+D	Lu-172	8.51E-06	1.24E-04	1.05E-02
Hf-175	—	1.52E-06	4.44E-06	1.80E-03
Hf-178m	—	1.74E-05	9.62E-04	1.20E-02
Hf-181	—	4.07E-06	1.85E-05	2.83E-03
Hf-182	—	1.11E-05	1.15E-03	1.20E-03
Hg-194+D	Au-194	1.90E-04	1.49E-04	5.77E-03

Table A-5 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Hg-203	—	7.03E-06	2.59E-05	1.21E-03
Ho-166m	—	7.40E-06	4.44E-04	9.15E-03
I-125	—	5.55E-05	5.18E-05	4.36E-05
I-129	—	4.07E-04	3.55E-04	3.28E-05
In-114m+D	(In-114 0.957)	1.52E-05	3.44E-05	4.72E-04
In-115	—	1.18E-04	1.44E-03	7.65E-06
Ir-192	—	5.18E-06	2.44E-05	4.22E-03
Ir-192m	—	1.15E-06	1.44E-04	7.99E-04
Ir-194m	—	7.77E-06	4.81E-05	1.21E-02
K-40	—	2.29E-05	7.77E-06	9.25E-04
Kr-81	—	0.00E+00	0.00E+00	2.85E-05
Kr-85	—	0.00E+00	0.00E+00	2.80E-05
La-137	—	3.00E-07	3.22E-05	3.50E-05
La-138	—	4.07E-06	5.55E-04	6.82E-03
Lu-173	—	9.62E-07	8.88E-06	5.16E-04
Lu-174	—	9.99E-07	1.55E-05	5.77E-04
Lu-174m	—	1.96E-06	1.55E-05	2.15E-04
Lu-176	—	6.66E-06	2.59E-04	2.46E-03
Lu-177m+D	(Lu-177 0.21)	6.70E-06	6.01E-05	4.99E-03
Md-258		4.81E-05	2.18E-02	4.54E-06
Mn-53	—	1.11E-07	2.00E-07	0.00E+00
Mn-54	—	2.63E-06	5.55E-06	4.47E-03
Mo-93	—	1.15E-05	8.51E-06	2.02E-06
Na-22	—	1.18E-05	4.81E-06	1.19E-02
Nb-93m	—	4.44E-07	6.66E-06	3.56E-07
Nb-94	—	6.29E-06	1.81E-04	8.41E-03
Nb-95	—	2.15E-06	6.66E-06	4.08E-03
Ni-59	—	2.33E-07	3.07E-06	0.00E+00
Ni-63	—	5.55E-07	7.40E-06	0.00E+00
Np-235	—	1.96E-07	2.33E-06	4.89E-06
Np-236	—	6.29E-05	2.96E-02	5.54E-04
Np-237+D	Pa-233	4.10E-04	1.85E-01	1.10E-03
Os-185	—	1.89E-06	5.92E-06	3.71E-03
Os-194+D	Ir-194	1.37E-05	3.17E-04	5.55E-04
Pa-231	—	2.63E-03	5.18E-01	1.83E-04
Pb-202+D	Tl-202	3.42E-05	4.51E-05	2.34E-03
Pb-205	—	1.04E-06	3.14E-06	6.36E-08
Pb-210+D	Bi-210	2.56E-03	2.11E-02	3.53E-05
Pd-107	—	1.37E-07	2.18E-06	0.00E+00
Pm-143	—	8.51E-07	5.55E-06	1.58E-03
Pm-144	—	3.59E-06	3.03E-05	8.12E-03
Pm-145	—	4.07E-07	1.33E-05	6.41E-05
Pm-146	—	3.33E-06	7.77E-05	3.90E-03
Pm-147	—	9.62E-07	1.85E-05	1.01E-06
Pm-148m+D	(Pm-148 0.046)	6.75E-06	2.15E-05	1.07E-02
Po-209	—	0.00E+00	0.00E+00	0.00E+00
Po-210	—	4.44E-03	1.59E-02	4.54E-08

Table A-5 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Pt-193	—	1.15E-07	7.77E-08	4.75E-08
Pu-236	—	3.22E-04	1.48E-01	5.47E-07
Pu-237	—	3.70E-07	1.44E-06	2.05E-04
Pu-238	—	8.51E-04	4.07E-01	4.09E-07
Pu-239	—	9.25E-04	4.44E-01	4.06E-07
Pu-240	—	9.25E-04	4.44E-01	3.99E-07
Pu-241+D	(U-237 0.0000245)	1.78E-05	8.51E-03	2.25E-08
Pu-242	—	8.88E-04	4.07E-01	3.39E-07
Pu-244+D	(U-240 0.9988), (Np-240m 0.9988)	8.92E-04	4.07E-01	1.94E-03
Ra-226+D	Rn-222,Po-218, (Pb-214 9.9980E-01), Bi-214, (Po-214 9.9980E-01), (Tl-210 2.0000E-04), (At-218 2.0000E-04)	1.04E-03	3.53E-02	9.77E-03
Ra-228+D	Ac-228	2.55E-03	5.93E-02	5.24E-03
Rb-83+D	(Kr-83m 0.76199)	7.03E-06	2.55E-06	2.58E-03
Rb-84	—	1.04E-05	3.70E-06	4.88E-03
Rb-87	—	5.55E-06	1.85E-06	3.85E-06
Re-184	—	3.70E-06	7.03E-06	4.66E-03
Re-184m	—	5.55E-06	2.40E-05	1.95E-03
Re-186m+D	Re-186	1.37E-05	4.85E-05	1.65E-04
Re-187	—	1.89E-08	2.33E-08	0.00E+00
Rh-101	—	2.04E-06	2.00E-05	1.27E-03
Rh-102	—	9.62E-06	6.29E-05	1.13E-02
Rh-102m	—	4.44E-06	2.63E-05	2.51E-03
Ru-103+D	(Rh-103m 0.997)	2.71E-06	1.11E-05	2.43E-03
Ru-106+D	Rh-106	2.59E-05	2.44E-04	1.24E-03
S-35	—	2.85E-06	7.03E-06	3.63E-07
Sb-124	—	9.25E-06	3.18E-05	1.01E-02
Sb-125	—	4.07E-06	4.44E-05	2.18E-03
Sc-46	—	5.55E-06	2.52E-05	1.09E-02
Se-75	—	9.62E-06	4.81E-06	1.96E-03
Se-79	—	1.07E-05	2.52E-05	4.60E-07
Si-32+D	P-32	1.09E-05	4.20E-04	6.36E-05
Sm-145	—	7.77E-07	5.92E-06	1.47E-04
Sm-146	—	2.00E-04	4.07E-02	0.00E+00
Sm-147	—	1.81E-04	3.55E-02	0.00E+00
Sm-151	—	3.63E-07	1.48E-05	2.87E-09
Sn-113+D	In-113m	2.80E-06	1.01E-05	1.34E-03
Sn-119m	—	1.26E-06	8.14E-06	8.22E-06
Sn-121m+D	(Sn-121 0.776)	2.07E-06	1.73E-05	9.65E-06
Sn-123	—	7.77E-06	3.00E-05	8.15E-05
Sn-126+D	Sb-126m, (Sb-126 0.14)	1.88E-05	1.05E-04	1.05E-02
Sr-85	—	2.07E-06	3.00E-06	2.61E-03
Sr-89	—	9.62E-06	2.92E-05	5.10E-05
Sr-90+D	Y-90	1.14E-04	5.98E-04	1.04E-04
Ta-179	—	2.40E-07	2.07E-06	1.05E-04
Ta-180	—	3.11E-06	9.62E-05	2.74E-03
Ta-182	—	5.55E-06	3.70E-05	6.99E-03
Tb-157	—	1.26E-07	4.44E-06	6.24E-06

Table A-5 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Tb-158	—	4.07E-06	1.70E-04	4.18E-03
Tb-160	—	5.92E-06	2.59E-05	6.06E-03
Tc-95m+D	(Tc-95 0.04)	2.10E-06	4.46E-06	3.66E-03
Tc-97	—	2.52E-07	6.66E-06	2.64E-06
Tc-97m	—	2.04E-06	1.52E-05	4.34E-06
Tc-98	—	7.40E-06	1.67E-04	7.48E-03
Tc-99	—	2.37E-06	4.81E-05	3.35E-06
Te-121m+D	(Te-121 0.886)	9.92E-06	2.28E-05	3.64E-03
Te-123	—	1.63E-05	4.44E-05	1.76E-05
Te-123m	—	5.18E-06	1.89E-05	6.78E-04
Te-125m	—	3.22E-06	1.55E-05	3.91E-05
Te-127m+D	(Te-127 0.976)	9.12E-06	3.68E-05	5.11E-05
Te-129m+D	(Te-129 0.65)	1.13E-05	2.93E-05	3.99E-04
Th-228+D	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 0.6407), (Tl-208 0.3593)	5.30E-04	1.61E-01	8.92E-03
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 0.9784), (Tl-209 0.0216), Pb-209	2.27E-03	9.48E-01	1.63E-03
Th-230	—	7.77E-04	3.70E-01	1.73E-06
Th-232	—	8.51E-04	4.07E-01	8.45E-07
Ti-44+D	Sc-44	2.28E-05	4.45E-04	1.21E-02
Tl-204	—	4.44E-06	1.44E-06	2.00E-05
Tm-170	—	4.81E-06	2.59E-05	4.28E-05
Tm-171	—	4.07E-07	5.18E-06	2.07E-06
U-232	—	1.22E-03	1.37E-01	1.37E-06
U-233	—	1.89E-04	3.55E-02	1.66E-06
U-234	—	1.81E-04	3.48E-02	7.13E-07
U-235+D	Th-231	1.75E-04	3.14E-02	8.08E-04
U-236	—	1.74E-04	3.22E-02	4.51E-07
U-238+D	Th-234, (Pa-234m 0.998), (Pa-234 0.0033)	1.79E-04	2.96E-02	2.09E-04
V-49	—	6.66E-08	1.26E-07	0.00E+00
W-181	—	2.81E-07	9.99E-08	1.35E-04
W-185	—	1.63E-06	4.44E-07	5.80E-06
W-188+D	Re-188	1.30E-05	4.11E-06	3.78E-04
Xe-127	—	0.00E+00	0.00E+00	1.31E-03
Y-88	—	4.81E-06	1.63E-05	1.52E-02
Y-91	—	8.88E-06	3.29E-05	7.26E-05
Yb-169	—	2.63E-06	1.11E-05	1.32E-03
Zn-65	—	1.44E-05	8.14E-06	3.18E-03
Zr-88	—	1.67E-06	1.33E-05	2.02E-03
Zr-93	—	4.07E-06	9.25E-05	0.00E+00
Zr-95+D	(Nb-95m 0.007)	3.53E-06	2.19E-05	3.92E-03

[a] Dose conversion factors for entries labeled with "+D" are aggregated dose conversion factors of the principal radionuclide together with the associated decay progenies.

[b] The associated decay progenies are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] Dash indicates there is no associated radionuclide.

A.2.3 ICRP-60 Based Dose Coefficient Libraries Developed with ICRP-107 Radionuclide Transformation Database

Dose Coefficient File Package (DCFPAK) 3.02 contains direct external exposure, air submersion, inhalation, and ingestion dose coefficients that were developed with the ICRP-107 radionuclide transformation database and the ICRP-60 dose estimation methodology (see Section A.3). Dose coefficients for six age groups (infant, 1, 5, 10, 15, and adult) and for a reference person are available in separate base libraries. For a radionuclide that has multiple dose coefficients in a base library, the largest one is set as the default for use in dose calculations, unless the user chooses a different value and saves it to a user-created library for use by the code.

Table A-6 lists the default ingestion, inhalation, and air submersion dose coefficients for adult members of the general public that are used in the RESRAD-BUILD code for calculating the radiation dose associated with the exposure to each principal radionuclide with cut-off half-life of at least 30 days. The listed values include the contributions from associated progenies, if applicable; in that case, the listed values are different from the default values stored in the DCFPAK3.02 base library that can be displayed and viewed with the DCF Editor. The direct external exposure dose coefficients are provided in Appendix C.

Table A-6 Default Ingestion, Inhalation, and Air Submersion Dose Coefficients for at least 30 Day Half-life Radionuclides from DCFPAK3.02 in RESRAD-BUILD Code

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Ac-227+D	(Th-227 9.8620E-01), (Ra-223 1.0000E+00), (Rn-219 1.0000E+00), Po-215, Pb-211, Bi-211, (Tl-207 9.9724E-01), (Po-211 2.7600E-03), (Fr-223 1.3800E-02), (At-219 8.2800E-07), (Bi-215 8.2800E-07)	1.61E-03	6.46E-01	2.25E-03
Ag-105	—[c]	1.71E-06	3.02E-06	2.58E-03
Ag-108m+D	(Ag-108 8.7000E-02)	8.70E-06	1.42E-04	8.45E-03
Ag-110m+D	(Ag-110 1.3600E-02)	1.04E-05	4.62E-05	1.49E-02
Al-26	—	1.29E-05	4.03E-04	1.49E-02
Am-241	—	7.55E-04	3.57E-01	7.85E-05
Am-242m+D	(Am-242 0.9955) (Np-238 0.0045)	7.04E-04	3.39E-01	8.76E-05
Am-243+D	Np-239	7.54E-04	3.54E-01	1.08E-03
Ar-37	—	0.00E+00	0.00E+00	0.00E+00
Ar-39	—	0.00E+00	0.00E+00	1.34E-05
Ar-42	K-42	1.62E-06	1.32E-06	1.75E-03
As-73	—	9.58E-07	5.03E-06	1.80E-05
Au-195	—	9.80E-07	6.62E-06	3.15E-04
Ba-133	—	5.70E-06	3.85E-05	1.89E-03
Be-10	—	4.22E-06	1.28E-04	1.62E-05
Be-7	—	1.04E-07	2.06E-07	2.58E-04
Bi-207	—	4.74E-06	1.43E-04	8.21E-03
Bi-208	—	4.29E-06	1.36E-04	1.58E-02
Bi-210m+D	Tl-206	5.55E-05	3.66E-02	1.38E-03
Bk-247	—	1.29E-03	6.17E-01	6.99E-04
Bk-249+D	(Am-245 1.45E-05)	3.67E-06	1.55E-03	5.35E-08

Table A-6 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
C-14	—	2.15E-06	2.12E-05	3.04E-07
Ca-41	—	8.40E-07	7.86E-07	0.00E+00
Ca-45	—	2.62E-06	1.35E-05	1.77E-06
Cd-109	—	7.40E-06	3.01E-05	2.65E-05
Cd-113	—	9.06E-05	4.40E-04	2.91E-06
Cd-113m	—	8.66E-05	4.14E-04	1.08E-05
Cd-115m+D	(In-115m 1.06E-04)	1.22E-05	2.83E-05	2.32E-04
Ce-139	—	9.77E-07	7.15E-06	6.98E-04
Ce-141	—	2.64E-06	1.39E-05	3.65E-04
Ce-144+D	(Pr-144 9.9999E-01), (Pr-144m 9.7699E--03)	1.95E-05	1.95E-04	3.79E-04
Cf-248	—	1.05E-04	4.18E-02	2.34E-06
Cf-249	—	1.30E-03	6.20E-01	1.67E-03
Cf-250	—	5.96E-04	2.79E-01	5.63E-05
Cf-251	—	1.32E-03	6.32E-01	5.65E-04
Cf-252	—	3.35E-04	1.36E-01	2.60E-03
Cf-254	—	1.49E-03	1.60E-01	9.62E-02
Cl-36	—	3.43E-06	1.40E-04	1.94E-05
Cm-241	—	3.42E-06	1.38E-04	2.47E-03
Cm-242	—	4.33E-05	2.19E-02	4.55E-07
Cm-243	—	5.55E-04	2.59E-01	6.22E-04
Cm-244	—	4.55E-04	2.11E-01	4.67E-07
Cm-245	—	7.70E-04	3.64E-01	4.67E-04
Cm-246	—	7.66E-04	3.63E-01	2.09E-05
Cm-247+D	Pu-243	7.07E-04	3.33E-01	1.72E-03
Cm-248	—	2.87E-03	1.34E+00	7.48E-03
Cm-250+D	(Pu-246 0.18), (Am-246m 0.18), (Bk-250 0.08)	1.96E-02	9.11E+00	7.76E-02
Co-56	—	9.36E-06	2.46E-05	2.05E-02
Co-57	—	7.81E-07	3.71E-06	5.82E-04
Co-58	—	2.77E-06	7.80E-06	5.18E-03
Co-60	—	1.26E-05	1.14E-04	1.39E-02
Cs-134	—	7.14E-05	7.56E-05	8.26E-03
Cs-135	—	9.81E-06	4.33E-05	2.53E-06
Cs-137+D	(Ba-137m 9.4399E-01)	5.03E-05	1.46E-04	2.98E-03
Dy-154	—	2.06E-04	9.55E-02	0.00E+00
Dy-159	—	3.92E-07	1.69E-06	1.17E-04
Es-254+D	(Fm-254 1.7390E-06), (Bk-250 1.0000E+00)	1.05E-04	3.79E-02	4.90E-03
Es-255+D	(Fm-255 0.92), (Bk-251 0.08)	3.07E-05	1.79E-02	4.92E-05
Eu-148	—	4.81E-06	1.34E-05	1.18E-02
Eu-149	—	5.96E-07	1.97E-06	2.37E-04
Eu-150	—	4.63E-06	4.75E-04	8.08E-03
Eu-152	—	4.96E-06	3.45E-04	6.28E-03
Eu-154	—	7.29E-06	3.95E-04	6.75E-03
Eu-155	—	1.23E-06	4.60E-05	2.53E-04
Fe-55	—	1.23E-06	2.89E-06	7.81E-13
Fe-59	—	6.62E-06	1.49E-05	6.56E-03

Table A-6 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Fe-60+D	Co-60m	4.29E-04	1.07E-03	2.35E-05
Fm-257+D	(Cf-253 0.9979), (Es-253 0.9948), (Cm-249 0.0031)	8.81E-05	4.86E-02	7.09E-04
Gd-146+D	Eu-146	8.01E-06	2.91E-05	1.40E-02
Gd-148	—	2.02E-04	9.34E-02	0.00E+00
Gd-150	—	1.94E-04	8.96E-02	0.00E+00
Gd-151	—	8.40E-07	4.34E-06	2.51E-04
Gd-152	—	1.52E-04	7.04E-02	0.00E+00
Gd-153	—	1.03E-06	8.86E-06	3.63E-04
Ge-68+D	Ga-68	5.11E-06	1.14E-04	5.01E-03
H-3	—	1.55E-07	9.69E-07	0.00E+00
Hf-172+D	Lu-172m Lu-172	8.84E-06	1.29E-04	1.08E-02
Hf-174	—	9.44E-04	1.13E-01	0.00E+00
Hf-175	—	1.49E-06	5.16E-06	1.72E-03
Hf-178m	—	1.47E-05	8.20E-04	1.14E-02
Hf-181	—	4.11E-06	2.20E-05	2.71E-03
Hf-182	—	1.05E-05	1.09E-03	1.21E-03
Hg-194+D	Au-194	1.91E-04	1.51E-04	5.62E-03
Hg-203	—	7.07E-06	2.60E-05	1.21E-03
Ho-163	—	1.07E-08	9.80E-07	0.00E+00
Ho-166m	—	7.29E-06	1.04E-03	8.51E-03
I-125	—	5.74E-05	5.19E-05	4.41E-05
I-129	—	4.00E-04	3.63E-04	3.34E-05
In-114m+D	(In-114 0.9675)	1.53E-05	5.01E-05	4.63E-04
In-115	—	1.21E-04	1.45E-03	7.71E-06
Ir-192	—	5.07E-06	2.45E-05	4.22E-03
Ir-192n	—	3.39E-06	2.15E-04	7.77E-06
Ir-194m	—	7.62E-06	4.45E-05	1.21E-02
K-40	—	2.28E-05	3.13E-04	9.27E-04
Kr-81	—	0.00E+00	0.00E+00	4.46E-06
Kr-85	—	0.00E+00	0.00E+00	2.81E-05
La-137	—	3.11E-07	3.31E-05	3.59E-05
La-138	—	4.03E-06	5.76E-04	6.80E-03
Lu-173	—	1.35E-06	1.69E-05	7.55E-04
Lu-174	—	1.05E-06	2.67E-05	5.21E-04
Lu-174m	—	2.02E-06	1.63E-05	2.08E-04
Lu-176	—	6.70E-06	5.63E-04	2.42E-03
Lu-177m+D	(Lu-177 2.1700E-01)	6.75E-06	6.03E-05	4.98E-03
Mn-53	—	1.10E-07	1.25E-06	0.00E+00
Mn-54	—	2.67E-06	1.21E-05	4.47E-03
Mo-93	—	1.07E-05	8.24E-06	1.98E-06
Na-22	—	1.17E-05	1.07E-04	1.19E-02
Nb-91	—	1.62E-07	6.80E-06	9.87E-06
Nb-91m	—	1.52E-06	1.55E-05	1.40E-04
Nb-92	—	3.77E-06	1.00E-04	7.97E-03
Nb-93m	—	4.77E-07	7.05E-06	3.55E-07
Nb-94	—	6.40E-06	1.80E-04	8.33E-03
Nb-95	—	2.17E-06	6.46E-06	4.08E-03

Table A-6 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Nd-144	—	1.51E-04	7.04E-02	0.00E+00
Ni-59	—	2.31E-07	3.03E-06	8.08E-08
Ni-63	—	5.74E-07	7.39E-06	0.00E+00
Np-235+D	(U-235m 3.9934E-03)	2.09E-07	2.69E-06	3.32E-06
Np-236+D	(Pa-232 1.6E-3)	9.18E-05	4.25E-02	6.58E-04
Np-237+D	Pa-233	3.99E-04	1.84E-01	1.18E-03
Os-185	—	1.86E-06	5.75E-06	3.57E-03
Os-186	—	1.18E-04	1.54E-02	0.00E+00
Os-194+D	Ir-194	1.41E-05	3.18E-04	5.63E-04
Pa-231	—	1.77E-03	8.50E-01	1.69E-04
Pb-202+D	(Tl-202 9.9000E-01)	5.94E-05	1.84E-04	2.30E-03
Pb-205	—	1.00E-06	3.05E-06	5.74E-08
Pb-210+D	Bi-210, (Hg-206 1.9E-08), (Tl-206 1.339E-06)	2.58E-03	2.13E-02	3.56E-05
Pd-107	—	1.42E-07	2.25E-06	0.00E+00
Pm-143	—	8.70E-07	1.07E-05	1.58E-03
Pm-144	—	3.65E-06	6.33E-05	8.12E-03
Pm-145	—	4.11E-07	2.97E-05	6.42E-05
Pm-146	—	3.31E-06	1.63E-04	3.89E-03
Pm-147	—	9.66E-07	2.58E-05	1.01E-06
Pm-148m+D	(Pm-148 4.2000E-02)	6.93E-06	2.14E-05	1.06E-02
Po-208	—	5.62E-03	2.50E-02	1.09E-07
Po-209	—	5.59E-03	3.49E-02	3.22E-05
Po-210	—	4.48E-03	1.58E-02	5.20E-08
Pt-190	—	2.57E-05	1.91E-02	0.00E+00
Pt-193	—	1.32E-07	2.47E-06	3.30E-08
Pu-236	—	3.29E-04	1.51E-01	5.06E-07
Pu-237	—	4.14E-07	1.43E-06	2.09E-04
Pu-238	—	8.44E-04	4.00E-01	3.92E-07
Pu-239+D	(U-235m 9.9940E-01)	9.29E-04	4.41E-01	4.40E-07
Pu-240	—	9.29E-04	4.41E-01	3.84E-07
Pu-241+D	(U-237 2.45E-05)	1.75E-05	8.45E-03	2.23E-08
Pu-242	—	8.84E-04	4.19E-01	7.51E-07
Pu-244+D	U-240, Np-240m, (Np-240 1.1000E-03)	8.85E-04	4.13E-01	1.88E-03
Ra-226+D	Rn-222, Po-218, (Pb-214 9.9980E-01), (Bi-214 1.0E+00), (Po-214 9.9979E-01), (Tl-210 2.1E-04), (At-218 2.0E-04), (Rn-218 2.0E-07)	1.04E-03	3.53E-02	9.64E-03
Ra-228+D	Ac-228	2.58E-03	5.94E-02	4.68E-03
Rb-83+D	(Kr-83m 7.4292E-01)	6.55E-06	5.07E-06	2.52E-03
Rb-84	—	1.04E-05	1.06E-05	4.82E-03
Rb-87	—	5.66E-06	5.82E-05	4.17E-06
Re-183	—	3.57E-06	1.32E-05	6.46E-04
Re-184	—	3.74E-06	8.58E-06	4.66E-03
Re-184m	—	5.48E-06	3.76E-05	1.92E-03
Re-186m+D	Re-186	1.35E-05	2.29E-04	1.66E-04
Re-187	—	1.77E-08	1.45E-07	0.00E+00
Rh-101	—	2.04E-06	1.89E-05	1.37E-03
Rh-102	—	4.40E-06	2.69E-05	2.61E-03

Table A-6 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Rh-102m	—	1.02E-05	7.32E-05	1.14E-02
Ru-103+D	(Rh-103m 0.988)	2.66E-06	1.06E-05	2.58E-03
Ru-106+D	Rh-106	2.60E-05	2.46E-04	1.25E-03
S-35	—	2.86E-06	6.87E-06	3.58E-07
Sb-124	—	9.43E-06	3.17E-05	1.03E-02
Sb-125	—	4.26E-06	4.43E-05	2.22E-03
Sc-46	—	5.44E-06	2.50E-05	1.09E-02
Se-75	—	9.55E-06	4.86E-06	1.94E-03
Se-79	—	1.01E-05	2.33E-05	3.56E-07
Si-32+D	P-32	1.10E-05	4.27E-04	6.38E-05
Sm-145	—	7.84E-07	1.06E-05	1.44E-04
Sm-146	—	2.00E-04	9.35E-02	0.00E+00
Sm-147	—	1.83E-04	8.54E-02	0.00E+00
Sm-148	—	1.58E-04	7.34E-02	0.00E+00
Sm-151	—	3.66E-07	3.43E-05	3.09E-09
Sn-113+D	In-113m	2.88E-06	1.49E-05	1.36E-03
Sn-119m	—	1.31E-06	1.26E-05	1.08E-05
Sn-121m+D	(Sn-121 7.7600E-01)	2.09E-06	5.60E-05	9.81E-06
Sn-123	—	7.81E-06	4.78E-05	8.18E-05
Sn-126+D	Sb-126m, (Sb-126 1.4000E-01)	1.93E-05	5.89E-04	1.04E-02
Sr-85	—	2.04E-06	2.98E-06	2.56E-03
Sr-89	—	9.51E-06	2.95E-05	5.13E-05
Sr-90+D	Y-90	1.12E-04	5.84E-04	1.04E-04
Ta-179	—	2.22E-07	1.81E-06	8.13E-05
Ta-182	—	5.62E-06	3.82E-05	6.98E-03
Tb-157	—	1.44E-07	1.19E-05	1.15E-05
Tb-158	—	4.14E-06	3.90E-04	4.22E-03
Tb-160	—	5.99E-06	3.08E-05	6.07E-03
Tc-95m+D	(Tc-95 3.8800E-02)	2.13E-06	4.49E-06	3.74E-03
Tc-97	—	2.52E-07	6.60E-06	2.58E-06
Tc-97m	—	2.03E-06	1.54E-05	4.30E-06
Tc-98	—	6.88E-06	1.57E-04	7.48E-03
Tc-99	—	2.37E-06	4.94E-05	3.36E-06
Te-121m+D	(Te-121 8.8600E-01)	1.02E-05	2.32E-05	3.65E-03
Te-123	—	5.03E-06	1.39E-05	3.07E-08
Te-123m	—	5.07E-06	1.87E-05	6.78E-04
Te-125m	—	3.22E-06	1.53E-05	3.92E-05
Te-127m+D	(Te-127 9.7600E-01)	9.31E-06	3.68E-05	5.13E-05
Te-129m+D	(Te-129 6.3000E-01)	1.12E-05	2.92E-05	4.03E-04
Th-228+D	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 6.4060E-01), (Tl-208 3.5940E-01)	5.29E-04	1.60E-01	8.43E-03
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 9.7910E-01), Pb-209, (Tl-209 2.0900E-02)	2.36E-03	9.43E-01	1.58E-03
Th-230	—	7.92E-04	3.76E-01	1.77E-06
Th-232	—	8.55E-04	4.07E-01	9.22E-07
Ti-44+D	Sc-44	2.28E-05	4.69E-04	1.21E-02
Tl-204	—	4.40E-06	7.01E-05	2.04E-05

Table A-6 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	Ingestion (mrem/pCi)	Inhalation (mrem/pCi)	Air Submersion (mrem/yr per pCi/m^3)
Tm-168	—	3.85E-06	1.88E-05	6.43E-03
Tm-170	—	4.85E-06	3.38E-05	3.80E-05
Tm-171	—	3.92E-07	7.86E-06	1.98E-06
U-232	—	1.24E-03	1.37E-01	1.26E-06
U-233	—	1.89E-04	3.55E-02	1.24E-06
U-234	—	1.83E-04	3.48E-02	7.17E-07
U-235+D	Th-231	1.74E-04	3.13E-02	8.56E-04
U-236	—	1.72E-04	3.21E-02	4.41E-07
U-238+D	Th-234, Pa-234m, (Pa-234 1.6000E-03)	1.77E-04	2.98E-02	2.16E-04
V-49	—	6.81E-08	2.52E-07	0.00E+00
V-50	—	1.26E-05	2.40E-04	8.02E-03
W-181	—	3.20E-07	1.06E-06	1.34E-04
W-185	—	1.64E-06	1.43E-05	5.79E-06
W-188+D	Re-188	1.28E-05	5.97E-05	3.97E-04
Xe-127	—	0.00E+00	0.00E+00	1.32E-03
Y-88	—	4.81E-06	2.27E-05	1.52E-02
Y-91	—	8.77E-06	3.31E-05	7.02E-05
Yb-169	—	3.03E-06	1.26E-05	1.39E-03
Zn-65	—	1.45E-05	8.29E-06	3.18E-03
Zr-88	—	1.63E-06	1.34E-05	1.97E-03
Zr-93	—	3.96E-06	8.91E-05	7.53E-11

[a] Dose conversion factors for entries labeled with "+D" are aggregated dose conversion factors of the principal radionuclide together with the associated decay progenies.

[b] The associated decay progenies are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] Dash indicates there is no associated radionuclide.

A.3 DOSE ESTIMATION METHODOLOGY

The absorbed dose is a fundamental dosimetric quantity in radiological protection. It is a measure of the energy deposited per unit mass of a medium. To estimate the total dose, radiation doses from external and internal exposures are estimated separately and later added. For an external or internal exposure, the absorbed doses of different organs/tissues are estimated first. Because the same absorbed dose from different types of radiation of different energy have different biological effects, the absorbed dose is multiplied by the quality factor (the radiation weighting factor) to obtain the dose equivalent (equivalent dose) of each organ/tissue. The dose equivalent (equivalent dose) of each organ/tissue is multiplied by the organ/tissue weighting factor, and the weighted dose equivalents (equivalent doses) of different organs/tissue are added to obtain the effective dose equivalent (effective dose) for the whole body. For an internal exposure, the dose equivalent (equivalent dose) or effective dose equivalent (effective dose) is integrated over a period of time after the exposure to account for the retention of radionuclides in the body and the radiation continuously emitted by the radionuclides. The integrated dose equivalent (equivalent dose) and the effective dose equivalent (effective dose) are called the committed dose equivalent (committed equivalent dose) and the committed effective dose equivalent (committed effective dose), respectively. Finally, the effective dose equivalent (effective equivalent dose) associated with external exposure(s) and the committed effective dose equivalent (committed effective dose) associated with internal exposure(s) are added to obtain an estimate of the total dose (total effective dose equivalent or total effective dose) a receptor would incur.

Table A-7 and Table A-8 show the organ/tissue weighting factors and quality factors/radiation weighting factors used in the ICRP-26 (ICRP 1977) and ICRP-60 methodology. Table A-9 shows the different dose terms used in ICRP-26 and ICRP-60.

Table A-7 Tissue Weighting Factors in ICRP-26 and ICRP-60

	Weighting Factors	
Organ/Tissue	ICRP-26	ICRP-60
Gonads	0.25	0.20
Breast	0.15	0.05
Colon	-[a]	0.12
Red Marrow	0.12	0.12
Lungs	0.12	0.12
Stomach	-[a]	0.12
Urinary Bladder	-[a]	0.05
Liver	-[a]	0.05
Esophagus	-[a]	0.05
Thyroid	0.03	0.05
Bone Surface	0.03	0.01
Skin	-[a]	0.01
Remainder	0.30[b]	0.05[c,d]

[a] Weighting factor not assigned in ICRP-26.

[b] The value 0.30 is applied to the average dose among the five remaining organs or tissues receiving the highest dose, excluding the skin, lens of the eye, and the extremities.

[c] The remainder is composed of the following tissues and organs: adrenals, brain, small intestine, upper large intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

[d] The value 0.05 is applied to the average dose to the remainder tissue group. However, if a member of the remainder receives a dose in excess of the highest dose in any of the twelve organs for which weighting factors are specified, a weighting factor of 0.025 is applied to that organ and a weighting factor of 0.025 is applied to the average dose in the rest of the remainder.

Sources: ICRP (1977) and ICRP (1991).

Table A-8 Quality Factors in ICRP-26 and Radiation Weighting Factors in ICRP-60

Radiation Type and Energy Range	ICRP-26 Quality Factor	ICRP-60 Radiation Weighting Factor[a]
Photons, all energies	1	1
Electrons and muons, all energies[b]	1	1
Neutrons		
< 10 keV	–[c]	5
10 keV to 100 keV	–	10
> 100 Kev to 2 MeV	–	20
> 2 MeV to 20 MeV	–	10
> 20 MeV	–	5
Protons, other than recoil protons, energy > 2 MeV	1	5
Alpha particles, fission fragments, heavy nuclei	20	20

[a] All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

[b] Excluding Auger electrons emitted from nuclei bound to DNA.

[c] In ICRP-26, the quality factor for neutrons was recommended to be 10 for unknown energies, otherwise to be calculated, and a value of 2.3 for thermal neutrons.

Source: ICRP (1991).

Table A-9 Dose Terms Used in ICRP-26 and ICRP-60

Type of Dose	Dose Quantity: ICRP-26/ICRP-30	Dose Quantity: ICRP-60
Organ/tissue dose	Absorbed dose in tissue or organ, D_T	Absorbed dose in tissue or organ, D_T
Absorbed organ/tissue dose adjusted for radiation type	Dose equivalent in tissue or organ T, $H_T = D_T \times Q \times N$[a]	Equivalent dose in tissue or organ T, $H_T = \sum_R W_R \times D_{T,R}$ (average absorbed dose in tissue T from radiation type R)
Committed organ/tissue dose (over a period of time following intake)	Committed dose equivalent, $H_{T,50}$	Committed equivalent dose, $H_{T,50}$
Whole-body dose	Effective dose equivalent (EDE), $H_E = \sum_T W_T \times H_T$	Effective dose (E), $E = \sum_T W_T \times H_T$
Whole-body committed dose (internal only)	Committed effective dose equivalent (CEDE) = $\sum_T W_T \times H_{T,50}$	Committed effective dose (CED), $E_{50} = \sum_T W_T \times H_{T,50}$
Total committed whole-body dose	Total effective dose equivalent (TEDE) = EDE (ext.) + CEDE (int)	Total effective dose (TED) = E (ext) + CED (int)

[a] N is the product of all other modifying factors that might take account of, for example, absorbed dose rate and fractionation.

A.4 RISK COEFFICIENT LIBRARIES

There are two base risk coefficient, i.e., slope factor, libraries that were developed with each the ICRP-38 and ICRP-107 radionuclide transformation databases and that can be used in RESRAD-BUILD for risk calculations. One base library contains risk coefficients for latent cancer morbidity, and the other base library contains risk coefficients for latent cancer mortality. The risk coefficients in these two base libraries for ICRP-38 were obtained from FGR No. 13 (EPA 1999) and for ICRP-107 were obtained from DCFPAK3.02.

The risk coefficients from FGR 13 and DCFPAK 3.02 are for six different modes of exposure. They are inhalation of air, ingestion of food, ingestion of tap water, and external exposure from submersion in air, from a surface source of soil, and from an infinite volume source of soil. Risk coefficients for four of the exposure modes (inhalation, ingestion of soil, external exposure from submersion in air, and external exposure from an infinite source of soil) are used in RESRAD-BUILD for risk calculations.

Tables A-10 and A-11 list the default morbidity and mortality risk coefficients for ingestion, inhalation, and air submersion pathways used in the RESRAD-BUILD code for calculating the cancer risk associated with the exposure to at least 30 day cut-off half-life principal radionuclides from FGR 13 and DCFPAK 3.02, respectively. Note that FGR 13 and DCFPAK3.02 provide multiple risk coefficients for inhalation of particulate aerosols for classes of F, M, and S, which represent fast, medium, and slow absorption to blood, respectively. The largest risk coefficient is used as the default. The listed values in Table A-10 and A-11 include the contributions from associated progenies, if applicable; in that case, the listed values are different from the default values stored in the FGR 13 and DCFPAK 3.02 base libraries that can be displayed and viewed with the DCF Editor. Appendixes C, E, and H provide discussions on the calculation of cancer risks associated with the external exposure, inhalation, and ingestion pathways using the dose coefficients. Appendix C provides the risk coefficients for direct external exposure pathway.

A.5 RISK ESTIMATION METHODOLOGY

RESRAD-BUILD uses the risk coefficients developed by the U.S. Environmental Protection Agency (EPA) with the exposure rate (for the external radiation pathways) and the total intake of radionuclide (for internal exposure pathways) to estimate the cancer risk associated with radiation exposure. EPA calculates radionuclide risk coefficients using health effects data and dose and risk models from a number of national and international scientific advisory commissions and organizations. The risk coefficients are calculated for each radionuclide individually based on its unique chemical, metabolic, and radioactive properties.

Table A-10 FGR 13 Morbidity and Mortality Risk Coefficients for Different Modes of Exposure

Radionuclide[a]	Associated Progeny Radionuclides[b]	FGR 13 Morbidity Risk Coefficients			FGR 13 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m^3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m^3)
Ac-227+D	(Th-227 9.8620E-01), Ra-223, Rn-219, Po-215, Pb-211, Bi-211, (Tl-207 9.9720E-01), (Po-211 2.8000E-03), (Fr-223 1.3800E-02)	6.53E-10	2.13E-07	1.57E-09	4.45E-10	2.02E-07	1.06E-09
Ag-105	—[c]	2.49E-12	3.16E-12	2.11E-09	1.49E-12	2.63E-12	1.44E-09
Ag-108m+D	(Ag-108 8.9000E-02)	1.12E-11	1.04E-10	6.80E-09	7.10E-12	8.95E-11	4.63E-09
Ag-110m+D	(Ag-110 1.3300E-02)	1.37E-11	4.51E-11	1.20E-08	8.51E-12	3.81E-11	8.14E-09
Al-26	—	2.49E-11	2.90E-10	1.21E-08	1.42E-11	2.60E-10	8.24E-09
Am-241	—	1.34E-10	3.77E-08	5.84E-11	9.47E-11	3.34E-08	3.89E-11
Am-242m+D	(Am-242 0.9952), (Np-238 0.0048)	9.03E-11	3.45E-08	6.25E-11	6.81E-11	2.70E-08	4.23E-11
Am-243+D	Np-239	1.42E-10	3.70E-08	7.98E-10	9.82E-11	3.17E-08	5.39E-10
Ar-37	—	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]
Ar-39	—	-1[d]	-1[d]	1.94E-12	-1[d]	-1[d]	1.70E-12
As-73	—	2.28E-12	5.00E-12	1.33E-11	1.29E-12	4.55E-12	8.84E-12
Au-195	—	2.19E-12	6.48E-12	2.42E-10	1.22E-12	5.85E-12	1.62E-10
Ba-133	—	9.43E-12	3.25E-11	1.50E-09	6.40E-12	2.86E-11	1.02E-09
Be-10	—	1.02E-11	9.40E-11	2.36E-12	5.77E-12	8.81E-11	2.08E-12
Be-7	—	1.20E-13	2.13E-13	2.06E-10	7.07E-14	1.70E-13	1.39E-10
Bi-207	—	8.14E-12	1.10E-10	6.62E-09	4.63E-12	9.62E-11	4.49E-09
Bi-210m+D	Tl-206	7.77E-11	2.92E-08	1.05E-09	4.48E-11	2.78E-08	7.13E-10
Bk-247	—	1.60E-10	4.77E-08	3.83E-10	1.19E-10	3.96E-08	2.59E-10
Bk-249+D	(Am-245 1.45E-5)	1.57E-12	1.16E-10	1.17E-14	9.44E-13	9.55E-11	9.25E-15
C-14	—	2.00E-12	1.69E-11	4.27E-14	1.36E-12	1.59E-11	3.77E-14
Ca-41	—	4.37E-13	5.07E-13	0.00E+00	3.85E-13	4.70E-13	0.00E+00
Ca-45	—	3.37E-12	1.28E-11	2.30E-13	2.32E-12	1.19E-11	2.09E-13
Cd-109	—	6.70E-12	2.19E-11	1.86E-11	4.22E-12	2.01E-11	1.18E-11
Cd-113	—	2.90E-11	1.12E-10	3.84E-13	2.03E-11	8.07E-11	3.49E-13
Cd-113m	—	3.64E-11	1.30E-10	1.51E-12	2.49E-11	9.29E-11	1.33E-12
Cd-115m	—	2.46E-11	2.92E-11	1.08E-10	1.39E-11	2.56E-11	7.46E-11
Ce-139	—	1.95E-12	6.88E-12	5.44E-10	1.10E-12	6.18E-12	3.68E-10
Ce-141	—	6.77E-12	1.35E-11	2.79E-10	3.77E-12	1.22E-11	1.89E-10
Ce-144+D	(Pr-144m 0.0178), Pr-144	5.19E-11	1.80E-10	2.50E-10	2.87E-11	1.66E-10	1.73E-10
Cf-248	—	6.22E-11	2.56E-08	2.38E-13	3.81E-11	2.43E-08	1.35E-13
Cf-249	—	1.63E-10	4.85E-08	1.35E-09	1.21E-10	4.00E-08	9.19E-10
Cf-250	—	1.12E-10	3.68E-08	2.26E-13	7.95E-11	3.49E-08	1.30E-13
Cf-251	—	1.70E-10	4.92E-08	4.55E-10	1.26E-10	4.07E-08	3.08E-10
Cf-252	—	1.80E-10	2.60E-08	2.78E-13	5.40E-10	7.85E-08	1.65E-13
Cf-254	—	-1[d]	-1[d]	7.39E-16	-1[d]	-1[d]	4.20E-16
Cl-36	—	4.44E-12	1.01E-10	3.50E-12	2.93E-12	9.55E-11	2.92E-12
Cm-241	—	7.03E-12	1.22E-10	1.96E-09	3.92E-12	1.15E-10	1.33E-09
Cm-242	—	5.48E-11	2.01E-08	3.02E-13	3.20E-11	1.91E-08	1.75E-13
Cm-243	—	1.23E-10	3.67E-08	4.86E-10	8.51E-11	3.47E-08	3.28E-10
Cm-244	—	1.08E-10	3.56E-08	2.51E-13	7.47E-11	3.36E-08	1.42E-13
Cm-245	—	1.35E-10	3.81E-08	3.16E-10	9.51E-11	3.26E-08	2.14E-10
Cm-246	—	1.31E-10	3.77E-08	2.30E-13	9.29E-11	3.26E-08	1.31E-13

Table A-10 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	FGR 13 Morbidity Risk Coefficients Ingestion (risk/pCi)	FGR 13 Morbidity Risk Coefficients Inhalation (risk/pCi)	FGR 13 Morbidity Risk Coefficients Air Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Risk Coefficients Ingestion (risk/pCi)	FGR 13 Mortality Risk Coefficients Inhalation (risk/pCi)	FGR 13 Mortality Risk Coefficients Air Submersion (risk/yr per pCi/m^3)
Cm-247+D	Pu-243	1.31E-10	3.49E-08	1.38E-09	9.07E-11	2.91E-08	9.31E-10
Cm-248	—	1.30E-09	1.50E-07	1.74E-13	6.80E-09	8.25E-07	9.90E-14
Cm-250	(Pu-246 0.25), (Am-246 0.25), (Bk-250 0.14)	6.46E-12	5.00E-12	1.78E-09	3.61E-12	4.20E-12	1.21E-09
Co-56	—	1.43E-11	2.56E-11	1.64E-08	8.69E-12	2.12E-11	1.12E-08
Co-57	—	1.49E-12	3.74E-12	4.54E-10	8.99E-13	3.23E-12	3.07E-10
Co-58	—	4.18E-12	7.96E-12	4.18E-09	2.52E-12	6.70E-12	2.84E-09
Co-60	—	2.23E-11	1.01E-10	1.12E-08	1.44E-11	8.58E-11	7.65E-09
Cs-134	—	5.14E-11	6.99E-11	6.63E-09	3.54E-11	6.14E-11	4.51E-09
Cs-135	—	5.88E-12	2.49E-11	1.44E-13	3.96E-12	2.33E-11	1.31E-13
Cs-137+D	(Ba-137m 0.946)	3.74E-11	1.12E-10	2.39E-09	2.55E-11	1.02E-10	1.63E-09
Dy-159	—	7.70E-13	1.67E-12	8.34E-11	4.29E-13	1.46E-12	5.49E-11
Es-254+D	Bk250	7.89E-11	2.59E-08	3.89E-09	4.71E-11	2.46E-08	2.65E-09
Eu-148	—	6.03E-12	1.25E-11	9.25E-09	3.51E-12	9.29E-12	6.28E-09
Eu-149	—	7.40E-13	1.27E-12	1.75E-10	4.14E-13	1.08E-12	1.18E-10
Eu-150b	—	6.07E-12	2.64E-10	6.22E-09	3.61E-12	2.06E-10	4.23E-09
Eu-152	—	8.69E-12	1.90E-10	4.96E-09	5.00E-12	1.52E-10	3.37E-09
Eu-154	—	1.49E-11	2.11E-10	5.41E-09	8.47E-12	1.74E-10	3.68E-09
Eu-155	—	2.77E-12	1.91E-11	1.91E-10	1.55E-12	1.73E-11	1.28E-10
Fe-55	—	1.16E-12	1.48E-12	0.00E+00	8.84E-13	1.22E-12	0.00E+00
Fe-59	—	1.11E-11	1.47E-11	5.30E-09	7.07E-12	1.29E-11	3.61E-09
Fe-60+D	Co-60m	2.39E-10	3.70E-10	1.86E-11	1.83E-10	2.89E-10	1.26E-11
Fm-257+D	Cf-253, (Es-253 9.9690E-01), (Cm-249 3.1000E-03)	1.20E-10	4.37E-08	3.80E-10	6.85E-11	4.15E-08	2.57E-10
Gd-146	Eu-146	1.37E-11	2.92E-11	1.16E-08	7.77E-12	2.52E-11	7.87E-09
Gd-148	—	5.51E-11	1.53E-08	0.00E+00	4.00E-11	1.45E-08	0.00E+00
Gd-151	—	1.65E-12	3.69E-12	1.67E-10	9.21E-13	3.29E-12	1.12E-10
Gd-152	—	3.85E-11	9.10E-09	0.00E+00	2.83E-11	8.14E-09	0.00E+00
Gd-153	—	2.22E-12	8.58E-12	2.73E-10	1.24E-12	7.73E-12	1.83E-10
Ge-68+D	Ga-68	1.03E-11	1.08E-10	3.99E-09	5.86E-12	1.00E-10	2.71E-09
H-3	—	1.44E-13	8.51E-13	0.00E+00	9.84E-14	7.84E-13	0.00E+00
Hf-172+D	Lu-172	1.52E-11	9.04E-11	8.43E-09	8.66E-12	7.90E-11	5.72E-09
Hf-175	—	2.83E-12	5.37E-12	1.43E-09	1.59E-12	4.63E-12	9.66E-10
Hf-178m	—	2.13E-11	3.70E-10	9.58E-09	1.29E-11	3.00E-10	6.49E-09
Hf-181	—	9.25E-12	2.13E-11	2.25E-09	5.18E-12	1.92E-11	1.53E-09
Hf-182	—	7.25E-12	3.41E-10	9.60E-10	4.96E-12	2.86E-10	6.50E-10
Hg-194+D	Au-194	1.08E-10	7.63E-11	4.66E-09	7.47E-11	6.35E-11	3.16E-09
Hg-203	—	7.62E-12	2.45E-11	9.60E-10	5.07E-12	2.20E-11	6.50E-10
Ho-166m	—	1.14E-11	7.62E-10	7.36E-09	6.81E-12	5.77E-10	5.00E-09
I-125	—	6.29E-11	2.77E-11	2.81E-11	6.51E-12	2.87E-12	1.73E-11
I-129	—	3.22E-10	1.60E-10	2.16E-11	3.28E-11	2.21E-11	1.37E-11
In-114m+D	(In-114 0.957)	3.60E-11	3.27E-11	3.71E-10	2.05E-11	2.80E-11	2.51E-10
In-115	—	4.33E-11	4.03E-10	1.05E-12	3.68E-11	3.64E-10	9.42E-13
Ir-192	—	1.07E-11	2.41E-11	3.36E-09	5.99E-12	2.15E-11	2.29E-09
Ir-192m	—	1.32E-12	1.02E-10	6.29E-10	8.66E-13	9.21E-11	4.26E-10
Ir-194m	—	1.26E-11	4.59E-11	9.74E-09	7.29E-12	4.00E-11	6.62E-09
K-40	—	3.43E-11	2.22E-10	7.24E-10	2.18E-11	2.08E-10	4.94E-10

Table A-10 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	FGR 13 Morbidity Risk Coefficients: Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Risk Coefficients: Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m^3)
Kr-81	—	-1[d]	-1[d]	2.26E-11	-1[d]	-1[d]	1.54E-11
Kr-85	—	-1[d]	-1[d]	1.17E-11	-1[d]	-1[d]	8.44E-12
La-137	—	5.00E-13	1.39E-11	2.35E-11	2.88E-13	1.15E-11	1.48E-11
La-138	—	4.96E-12	3.05E-10	5.52E-09	2.98E-12	2.35E-10	3.76E-09
Lu-173	—	1.96E-12	8.69E-12	3.97E-10	1.10E-12	7.73E-12	2.67E-10
Lu-174	—	2.12E-12	1.42E-11	4.57E-10	1.19E-12	1.28E-11	3.08E-10
Lu-174m	—	4.96E-12	1.51E-11	1.62E-10	2.75E-12	1.38E-11	1.09E-10
Lu-176	—	1.35E-11	1.75E-10	1.95E-09	7.62E-12	1.52E-10	1.32E-09
Lu-177m+D	(Lu-177 0.21)	1.47E-11	5.80E-11	3.94E-09	8.19E-12	5.26E-11	2.67E-09
Md-258		6.25E-11	2.16E-08	3.14E-12	3.59E-11	2.05E-08	1.99E-12
Mn-53	—	2.25E-13	9.69E-13	0.00E+00	1.30E-13	8.99E-13	0.00E+00
Mn-54	—	3.11E-12	1.21E-11	3.60E-09	1.96E-12	9.88E-12	2.45E-09
Mo-93	—	4.18E-12	5.74E-12	1.27E-12	3.74E-12	5.37E-12	7.08E-13
Na-22	—	1.26E-11	9.73E-11	9.56E-09	8.66E-12	8.55E-11	6.50E-09
Nb-93m	—	1.17E-12	5.66E-12	2.24E-13	6.55E-13	5.25E-12	1.25E-13
Nb-94	—	1.11E-11	1.35E-10	6.76E-09	6.40E-12	1.18E-10	4.60E-09
Nb-95	—	3.50E-12	6.44E-12	3.28E-09	2.00E-12	5.55E-12	2.23E-09
Ni-59	—	3.89E-13	2.41E-12	0.00E+00	2.32E-13	1.69E-12	0.00E+00
Ni-63	—	9.51E-13	5.77E-12	0.00E+00	5.66E-13	4.03E-12	0.00E+00
Np-235	—	5.07E-13	1.94E-12	3.61E-12	2.81E-13	1.79E-12	2.35E-12
Np-236a	—	1.44E-11	2.34E-09	4.29E-10	8.95E-12	1.71E-09	2.90E-10
Np-237+D	Pa-233	9.10E-11	2.87E-08	8.68E-10	5.78E-11	2.71E-08	5.88E-10
Os-185	—	2.70E-12	6.14E-12	2.98E-09	1.58E-12	5.11E-12	2.02E-09
Os-194+D	Ir-194	3.49E-11	2.58E-10	4.01E-10	1.95E-11	2.41E-10	2.74E-10
Pa-231	—	2.26E-10	7.62E-08	1.45E-10	1.59E-10	5.62E-08	9.82E-11
Pb-202+D	Tl-202	3.13E-11	3.43E-11	1.87E-09	2.31E-11	2.96E-11	1.26E-09
Pb-205	—	8.25E-13	2.36E-12	3.47E-14	6.40E-13	2.21E-12	2.07E-14
Pb-210+D	Bi-210	1.19E-09	1.63E-08	9.04E-12	8.62E-10	1.54E-08	6.89E-12
Pd-107	—	3.67E-13	1.69E-12	0.00E+00	2.03E-13	1.56E-12	0.00E+00
Pm-143	—	1.24E-12	9.06E-12	1.26E-09	7.14E-13	6.88E-12	8.56E-10
Pm-144	—	4.66E-12	5.51E-11	6.52E-09	2.74E-12	4.18E-11	4.42E-09
Pm-145	—	8.07E-13	1.28E-11	4.51E-11	4.59E-13	1.10E-11	2.92E-11
Pm-146	—	5.99E-12	1.03E-10	3.13E-09	3.42E-12	8.25E-11	2.12E-09
Pm-147	—	2.48E-12	1.61E-11	1.44E-13	1.38E-12	1.50E-11	1.27E-13
Pm-148m+D	(Pm-148 0.046)	1.27E-11	2.17E-11	8.58E-09	7.15E-12	1.88E-11	5.84E-09
Po-209	—	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]
Po-210	—	2.25E-09	1.45E-08	3.66E-14	1.64E-09	1.37E-08	2.49E-14
Pt-193	—	3.09E-13	1.96E-12	2.69E-14	1.71E-13	1.83E-12	1.59E-14
Pu-236	—	9.92E-11	2.96E-08	3.66E-13	6.92E-11	2.80E-08	2.18E-13
Pu-237	—	8.40E-13	1.49E-12	1.59E-10	4.70E-13	1.32E-12	1.07E-10
Pu-238	—	1.69E-10	5.22E-08	2.66E-13	1.30E-10	4.40E-08	1.57E-13
Pu-239	—	1.74E-10	5.51E-08	2.99E-13	1.34E-10	4.66E-08	1.93E-13
Pu-240	—	1.74E-10	5.55E-08	2.61E-13	1.34E-10	4.66E-08	1.53E-13
Pu-241+D	(U-237 0.0000245)	2.28E-12	8.66E-10	1.75E-14	1.88E-12	7.33E-10	1.18E-14
Pu-242	—	1.65E-10	5.25E-08	2.23E-13	1.28E-10	4.40E-08	1.31E-13
Pu-244+D	(U-240 0.9988), (Np-240m 0.9988)	1.90E-10	5.00E-08	1.43E-09	1.40E-10	4.22E-08	9.67E-10

Table A-10 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	FGR 13 Morbidity Risk Coefficients: Ingestion (risk/pCi)	FGR 13 Morbidity Risk Coefficients: Inhalation (risk/pCi)	FGR 13 Morbidity Risk Coefficients: Air Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Risk Coefficients: Ingestion (risk/pCi)	FGR 13 Mortality Risk Coefficients: Inhalation (risk/pCi)	FGR 13 Mortality Risk Coefficients: Air Submersion (risk/yr per pCi/m^3)
Ra-226+D	Rn-222,Po-218, (Pb-214 9.9980E-01), Bi-214, (Po-214 9.9980E-01), (Tl-210 2.0000E-04), (At-218 2.0000E-04)	5.15E-10	2.83E-08	7.87E-09	3.55E-10	2.69E-08	5.35E-09
Ra-228+D	Ac-228	1.43E-09	4.37E-08	4.21E-09	1.01E-09	4.15E-08	2.86E-09
Rb-83+D	(Kr-83m 0.76199)	7.51E-12	5.48E-12	2.08E-09	5.14E-12	4.40E-12	1.41E-09
Rb-84	—	1.17E-11	9.29E-12	3.92E-09	7.96E-12	7.84E-12	2.66E-09
Rb-87	—	7.07E-12	4.33E-11	4.96E-13	4.74E-12	4.03E-11	4.52E-13
Re-184	—	4.40E-12	8.25E-12	3.74E-09	2.66E-12	7.18E-12	2.54E-09
Re-184m	—	6.96E-12	3.51E-11	1.55E-09	4.14E-12	3.17E-11	1.05E-09
Re-186m+D	Re-186	1.85E-11	1.71E-10	1.11E-10	1.08E-11	1.61E-10	7.54E-11
Re-187	—	2.56E-14	1.18E-13	0.00E+00	1.49E-14	1.10E-13	0.00E+00
Rh-101	—	3.01E-12	1.81E-11	1.00E-09	1.81E-12	1.61E-11	6.77E-10
Rh-102	—	1.04E-11	5.99E-11	9.10E-09	6.59E-12	4.96E-11	6.19E-09
Rh-102m	—	8.73E-12	2.56E-11	2.01E-09	5.00E-12	2.28E-11	1.37E-09
Ru-103+D	(Rh-103m 0.997)	5.56E-12	1.07E-11	1.95E-09	3.15E-12	9.59E-12	1.33E-09
Ru-106+D	Rh-106	6.10E-11	2.23E-10	9.17E-10	3.46E-11	2.06E-10	6.26E-10
S-35	—	3.70E-12	6.55E-12	4.99E-14	2.49E-12	6.03E-12	4.43E-14
Sb-124	—	1.85E-11	3.20E-11	8.14E-09	1.06E-11	2.79E-11	5.54E-09
Sb-125	—	6.14E-12	4.00E-11	1.75E-09	3.74E-12	3.60E-11	1.19E-09
Sc-46	—	8.88E-12	2.47E-11	8.83E-09	5.03E-12	2.14E-11	6.00E-09
Se-75	—	1.08E-11	5.00E-12	1.55E-09	7.55E-12	4.25E-12	1.05E-09
Se-79	—	9.69E-12	1.99E-11	6.29E-14	6.73E-12	1.87E-11	5.60E-14
Si-32+D	P-32	1.73E-11	3.07E-10	1.34E-11	1.12E-11	2.90E-10	1.08E-11
Sm-145	—	1.70E-12	5.96E-12	1.04E-10	9.51E-13	5.11E-12	6.78E-11
Sm-146	—	5.25E-11	1.39E-08	0.00E+00	4.03E-11	1.25E-08	0.00E+00
Sm-147	—	4.77E-11	1.26E-08	0.00E+00	3.66E-11	1.13E-08	0.00E+00
Sm-151	—	8.07E-13	9.18E-12	1.77E-15	4.55E-13	8.55E-12	1.01E-15
Sn-113+D	In-113m	6.46E-12	1.46E-11	1.07E-09	3.62E-12	1.31E-11	7.24E-10
Sn-119m	—	3.24E-12	1.19E-11	5.18E-12	1.80E-12	1.10E-11	3.08E-12
Sn-121m+D	(Sn-121 0.776)	5.12E-12	4.41E-11	3.88E-12	2.87E-12	4.14E-11	2.56E-12
Sn-123	—	2.05E-11	4.63E-11	3.90E-11	1.14E-11	4.22E-11	2.77E-11
Sn-126+D	Sb-126m, (Sb-126 0.14)	3.92E-11	4.13E-10	8.40E-09	2.25E-11	3.79E-10	5.70E-09
Sr-85	—	3.11E-12	3.23E-12	2.10E-09	2.06E-12	2.65E-12	1.43E-09
Sr-89	—	1.84E-11	3.02E-11	1.06E-11	1.10E-11	2.67E-11	8.52E-12
Sr-90+D	Y-90	9.53E-11	4.33E-10	2.45E-11	7.46E-11	4.06E-10	1.93E-11
Ta-179	—	5.00E-13	2.05E-12	7.81E-11	2.79E-13	1.79E-12	5.21E-11
Ta-180	—	6.44E-12	7.25E-11	2.17E-09	3.61E-12	6.51E-11	1.47E-09
Ta-182	—	1.15E-11	3.74E-11	5.64E-09	6.48E-12	3.35E-11	3.83E-09
Tb-157	—	2.70E-13	3.20E-12	4.45E-12	1.52E-13	2.89E-12	2.92E-12
Tb-158	—	6.99E-12	1.71E-10	3.36E-09	4.03E-12	1.39E-10	2.28E-09
Tb-160	—	1.27E-11	3.00E-11	4.87E-09	7.07E-12	2.68E-11	3.32E-09
Tc-95m+D	(Tc-95 0.04)	2.54E-12	4.60E-12	2.94E-09	1.53E-12	3.82E-12	1.99E-09
Tc-97	—	3.89E-13	4.81E-12	1.66E-12	2.25E-13	4.51E-12	9.21E-13
Tc-97m	—	3.44E-12	1.44E-11	2.73E-12	1.96E-12	1.33E-11	1.67E-12
Tc-98	—	1.01E-11	1.24E-10	6.01E-09	5.96E-12	1.10E-10	4.09E-09

Table A-10 (Cont.)

Radionuclide[a]	Associated Progeny Radionuclides[b]	FGR 13 Morbidity Risk Coefficients: Ingestion (risk/pCi)	FGR 13 Morbidity Risk Coefficients: Inhalation (risk/pCi)	FGR 13 Morbidity Risk Coefficients: Air Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Risk Coefficients: Ingestion (risk/pCi)	FGR 13 Mortality Risk Coefficients: Inhalation (risk/pCi)	FGR 13 Mortality Risk Coefficients: Air Submersion (risk/yr per pCi/m^3)
Tc-99	—	4.00E-12	3.81E-11	4.34E-13	2.28E-12	3.58E-11	3.95E-13
Te-121m+D	(Te-121 0.886)	1.03E-11	2.19E-11	2.91E-09	6.85E-12	1.93E-11	1.97E-09
Te-123	—	5.11E-12	1.19E-11	1.13E-11	4.37E-12	1.04E-11	6.82E-12
Te-123m	—	5.66E-12	1.78E-11	5.31E-10	3.60E-12	1.63E-11	3.60E-10
Te-125m	—	4.70E-12	1.45E-11	2.50E-11	2.78E-12	1.34E-11	1.54E-11
Te-127m+D	(Te-127 0.976)	1.34E-11	3.53E-11	2.99E-11	8.32E-12	3.23E-11	2.03E-11
Te-129m+D	(Te-129 0.65)	2.22E-11	3.01E-11	2.91E-10	1.26E-11	2.66E-11	1.98E-10
Th-228+D	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 0.6407), (Tl-208 0.3593)	4.22E-10	1.44E-07	7.19E-09	2.58E-10	1.37E-07	4.89E-09
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 0.9784), (Tl-209 0.0216), Pb-209	7.16E-10	2.30E-07	1.26E-09	4.73E-10	2.17E-07	8.53E-10
Th-230	—	1.19E-10	3.40E-08	1.31E-12	7.99E-11	2.68E-08	8.71E-13
Th-232	—	1.33E-10	4.33E-08	6.25E-13	9.07E-11	4.07E-08	4.10E-13
Ti-44+D	Sc-44	3.86E-11	3.42E-10	9.68E-09	2.27E-11	3.07E-10	6.57E-09
Tl-204	—	8.25E-12	6.07E-11	5.66E-12	4.96E-12	5.66E-11	4.27E-12
Tm-170	—	1.31E-11	3.33E-11	1.88E-11	7.25E-12	3.04E-11	1.32E-11
Tm-171	—	1.02E-12	4.37E-12	1.53E-12	5.70E-13	4.03E-12	1.02E-12
U-232	—	3.85E-10	9.25E-08	1.01E-12	2.67E-10	8.77E-08	6.61E-13
U-233	—	9.69E-11	2.83E-08	1.27E-12	6.25E-11	2.69E-08	8.45E-13
U-234	—	9.55E-11	2.78E-08	5.10E-13	6.14E-11	2.64E-08	3.26E-13
U-235+D	Th-231	9.76E-11	2.50E-08	6.33E-10	6.17E-11	2.38E-08	4.29E-10
U-236	—	9.03E-11	2.58E-08	3.12E-13	5.81E-11	2.45E-08	1.94E-13
U-238+D	Th-234, (Pa-234m 0.998), (Pa-234 0.0033)	1.21E-10	2.36E-08	1.22E-10	7.47E-11	2.25E-08	8.46E-11
V-49	—	1.79E-13	2.82E-13	0.00E+00	9.92E-14	2.51E-13	0.00E+00
W-181	—	5.70E-13	1.07E-12	1.01E-10	3.23E-13	9.14E-13	6.75E-11
W-185	—	4.29E-12	1.36E-11	9.29E-13	2.38E-12	1.26E-11	7.95E-13
W-188+D	Re-188	2.76E-11	5.78E-11	2.58E-10	1.50E-11	5.22E-11	1.77E-10
Xe-127	—	-1[d]	-1[d]	1.04E-09	-1[d]	-1[d]	7.02E-10
Y-88	—	5.85E-12	2.03E-11	1.23E-08	3.43E-12	1.48E-11	8.37E-09
Y-91	—	2.35E-11	3.36E-11	2.70E-11	1.30E-11	2.98E-11	1.97E-11
Yb-169	—	5.85E-12	1.08E-11	1.02E-09	3.25E-12	9.66E-12	6.87E-10
Zn-65	—	1.54E-11	7.59E-12	2.57E-09	1.04E-11	6.14E-12	1.75E-09
Zr-88	—	2.18E-12	1.35E-11	1.62E-09	1.32E-12	1.12E-11	1.10E-09
Zr-93	—	1.44E-12	1.52E-11	0.00E+00	1.05E-12	1.41E-11	0.00E+00
Zr-95+D	(Nb-95m 0.007)	6.63E-12	2.11E-11	3.17E-09	3.76E-12	1.87E-11	2.15E-09

[a] Risk coefficients for entries labeled by "+D" are aggregated risk coefficients of a principal radionuclide together with the associated decay chain progenies.

[b] The associated progenies are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] Indicates there is no associated radionuclide.

[d] "-1" indicates no value listed in FGR 13. For risk calculation, a value of 0 is used in the RESRAD family of codes.

Table A-11 Default Ingestion, Inhalation, and Air Submersion Slope Factors for at least 30 Day Half-life Radionuclides from DCFPAK3.02 in RESRAD-BUILD Code

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients			DCFPAK3.02 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
Ac-227+D	(Th-227 9.8620E-01), (Ra-223 1.0000E+00), (Rn-219 1.0000E+00), Po-215, Pb-211, Bi-211, (Tl-207 9.9724E-01), (Po-211 2.7600E-03), (Fr-223 1.3800E-02), (At-219 8.2800E-07), (Bi-215 8.2800E-07)	6.54E-10	2.13E-07	1.73E-09	4.45E-10	2.02E-07	1.17E-09
Ag-105	—[c]	2.46E-12	3.15E-12	2.07E-09	1.46E-12	2.62E-12	1.40E-09
Ag-108m+D	(Ag-108 8.7000E-02)	1.11E-11	1.05E-10	6.78E-09	7.07E-12	9.03E-11	4.60E-09
Ag-110m+D	(Ag-110 1.3600E-02)	1.39E-11	4.55E-11	1.20E-08	8.62E-12	3.85E-11	8.18E-09
Al-26	—	2.48E-11	2.90E-10	1.21E-08	1.42E-11	2.60E-10	8.24E-09
Am-241	—	1.34E-10	3.77E-08	5.80E-11	9.43E-11	3.34E-08	3.86E-11
Am-242m+D	(Am-242 0.9955) (Np-238 0.0045)	9.00E-11	3.43E-08	6.20E-11	6.81E-11	2.68E-08	4.21E-11
Am-243+D	Np-239	1.42E-10	3.70E-08	8.38E-10	9.86E-11	3.17E-08	5.67E-10
Ar-37	—	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]	-1[d]
Ar-39	—	-1[d]	-1[d]	1.94E-12	-1[d]	-1[d]	1.70E-12
Ar-42	K-42	1.74E-12	1.24E-12	1.33E-09	1.22E-12	1.09E-12	9.11E-10
As-73	—	2.29E-12	4.99E-12	1.32E-11	1.29E-12	4.55E-12	8.78E-12
Au-195	—	2.26E-12	6.62E-12	2.38E-10	1.26E-12	5.96E-12	1.60E-10
Ba-133	—	9.47E-12	3.29E-11	1.50E-09	6.44E-12	2.90E-11	1.02E-09
Be-10	—	1.03E-11	9.40E-11	2.37E-12	5.77E-12	8.80E-11	2.09E-12
Be-7	—	1.21E-13	2.15E-13	2.07E-10	7.14E-14	1.72E-13	1.40E-10
Bi-207	—	8.25E-12	1.10E-10	6.61E-09	4.70E-12	9.62E-11	4.49E-09
Bi-208	—	5.40E-12	9.95E-11	1.28E-08	3.17E-12	8.29E-11	8.77E-09
Bi-210m+D	Tl-206	7.77E-11	2.92E-08	1.07E-09	4.48E-11	2.77E-08	7.25E-10
Bk-247	—	1.61E-10	4.81E-08	5.47E-10	1.19E-10	3.96E-08	3.70E-10
Bk-249+D	(Am-245 1.45E-05)	1.56E-12	1.19E-10	1.31E-14	9.40E-13	9.80E-11	1.00E-14
C-14	—	2.00E-12	1.69E-11	4.29E-14	1.36E-12	1.59E-11	3.77E-14
Ca-41	—	5.11E-13	5.92E-13	0.00E+00	4.51E-13	5.51E-13	0.00E+00
Ca-45	—	3.36E-12	1.28E-11	2.29E-13	2.32E-12	1.19E-11	2.08E-13
Cd-109	—	6.70E-12	2.19E-11	1.85E-11	4.22E-12	2.02E-11	1.17E-11
Cd-113	—	2.88E-11	1.11E-10	3.78E-13	2.01E-11	7.99E-11	3.43E-13
Cd-113m	—	3.67E-11	1.32E-10	1.75E-12	2.51E-11	9.40E-11	1.49E-12
Cd-115m+D	(In-115m 1.06E-04)	2.45E-11	2.91E-11	1.55E-10	1.39E-11	2.56E-11	1.07E-10
Ce-139	—	1.97E-12	6.92E-12	5.43E-10	1.10E-12	6.21E-12	3.67E-10
Ce-141	—	6.81E-12	1.35E-11	2.80E-10	3.77E-12	1.22E-11	1.90E-10
Ce-144+D	(Pr-144 9.9999E-01), (Pr-144m 9.7699E-03)	5.19E-11	1.80E-10	2.33E-10	2.87E-11	1.66E-10	1.62E-10
Cf-248	—	6.25E-11	2.56E-08	1.81E-12	3.81E-11	2.43E-08	1.20E-12
Cf-249	—	1.63E-10	4.85E-08	1.33E-09	1.21E-10	4.00E-08	9.01E-10
Cf-250	—	1.15E-10	3.74E-08	4.53E-11	8.21E-11	3.54E-08	3.08E-11
Cf-251	—	1.69E-10	4.92E-08	4.39E-10	1.25E-10	4.07E-08	2.97E-10
Cf-252	—	1.82E-10	4.44E-08	2.09E-09	1.14E-10	4.22E-08	1.43E-09
Cf-254	—	3.06E-09	1.52E-07	7.74E-08	1.74E-09	1.44E-07	5.27E-08

Table A-11 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients			DCFPAK3.02 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
Cl-36	—	4.44E-12	1.01E-10	3.46E-12	2.93E-12	9.55E-11	2.88E-12
Cm-241	—	7.18E-12	1.22E-10	1.97E-09	4.03E-12	1.15E-10	1.33E-09
Cm-242	—	5.47E-11	2.01E-08	2.94E-13	3.20E-11	1.91E-08	1.70E-13
Cm-243	—	1.24E-10	3.68E-08	4.87E-10	8.55E-11	3.47E-08	3.29E-10
Cm-244	—	1.08E-10	3.55E-08	3.15E-13	7.47E-11	3.36E-08	1.89E-13
Cm-245	—	1.35E-10	3.81E-08	3.62E-10	9.55E-11	3.25E-08	2.45E-10
Cm-246	—	1.33E-10	3.81E-08	1.68E-11	9.40E-11	3.28E-08	1.14E-11
Cm-247+D	Pu-243	1.30E-10	3.49E-08	1.37E-09	9.07E-11	2.90E-08	9.31E-10
Cm-248	—	5.96E-10	1.44E-07	6.03E-09	4.07E-10	1.12E-07	4.10E-09
Cm-250+D	(Pu-246 0.18), (Am-246m 0.18), (Bk-250 0.08)	4.33E-09	9.88E-07	6.23E-08	2.94E-09	7.73E-07	4.25E-08
Co-56	—	1.42E-11	2.52E-11	1.67E-08	8.62E-12	2.09E-11	1.14E-08
Co-57	—	1.49E-12	3.74E-12	4.54E-10	8.99E-13	3.24E-12	3.07E-10
Co-58	—	4.14E-12	7.92E-12	4.17E-09	2.52E-12	6.66E-12	2.84E-09
Co-60	—	2.23E-11	1.01E-10	1.12E-08	1.44E-11	8.62E-11	7.65E-09
Cs-134	—	5.18E-11	6.99E-11	6.63E-09	3.54E-11	6.14E-11	4.51E-09
Cs-135	—	7.81E-12	3.36E-11	3.26E-13	5.25E-12	3.16E-11	2.98E-13
Cs-137+D	(Ba-137m 9.4399E-01)	3.74E-11	1.13E-10	2.38E-09	2.55E-11	1.03E-10	1.62E-09
Dy-154	—	4.22E-11	1.31E-08	0.00E+00	2.83E-11	1.24E-08	0.00E+00
Dy-159	—	7.92E-13	1.73E-12	8.39E-11	4.44E-13	1.51E-12	5.52E-11
Es-254+D	(Fm-254 1.7390E-06), (Bk-250 1.0000E+00)	7.93E-11	2.59E-08	3.94E-09	4.71E-11	2.46E-08	2.68E-09
Es-255+D	(Fm-255 0.92), (Bk-251 0.08)	6.37E-11	1.61E-08	3.55E-11	3.56E-11	1.53E-08	2.38E-11
Eu-148	—	6.14E-12	1.28E-11	9.46E-09	3.58E-12	9.47E-12	6.42E-09
Eu-149	—	1.28E-12	1.73E-12	1.82E-10	7.14E-13	1.47E-12	1.23E-10
Eu-150	—	5.62E-12	2.72E-10	6.48E-09	3.38E-12	2.11E-10	4.40E-09
Eu-152	—	8.32E-12	1.91E-10	5.06E-09	4.81E-12	1.52E-10	3.43E-09
Eu-154	—	1.42E-11	2.06E-10	5.44E-09	8.07E-12	1.69E-10	3.70E-09
Eu-155	—	2.83E-12	1.92E-11	1.93E-10	1.58E-12	1.76E-11	1.30E-10
Fe-55	—	1.16E-12	1.48E-12	6.11E-19	8.84E-13	1.22E-12	4.12E-19
Fe-59	—	1.11E-11	1.47E-11	5.30E-09	7.07E-12	1.29E-11	3.61E-09
Fe-60+D	Co-60m	2.49E-10	3.85E-10	1.81E-11	1.91E-10	3.02E-10	1.22E-11
Fm-257+D	(Cf-253 0.9979), (Es-253 0.9948), (Cm-249 0.0031)	1.27E-10	4.41E-08	5.55E-10	7.23E-11	4.19E-08	3.76E-10
Gd-146+D	Eu-146	1.33E-11	2.82E-11	1.12E-08	7.52E-12	2.45E-11	7.60E-09
Gd-148	—	5.44E-11	1.52E-08	0.00E+00	3.96E-11	1.44E-08	0.00E+00
Gd-150	—	4.88E-11	1.23E-08	0.00E+00	3.60E-11	1.16E-08	0.00E+00
Gd-151	—	1.91E-12	4.37E-12	1.91E-10	1.06E-12	3.88E-12	1.28E-10
Gd-152	—	3.85E-11	9.10E-09	0.00E+00	2.83E-11	8.14E-09	0.00E+00
Gd-153	—	2.22E-12	8.58E-12	2.72E-10	1.24E-12	7.73E-12	1.82E-10
Ge-68+D	Ga-68	1.02E-11	1.04E-10	3.98E-09	5.86E-12	9.63E-11	2.71E-09
H-3	—	1.44E-13	8.47E-13	0.00E+00	9.80E-14	7.81E-13	0.00E+00
Hf-172+D	Lu-172m Lu-172	1.54E-11	9.15E-11	8.70E-09	8.84E-12	8.01E-11	5.91E-09
Hf-174	—	7.99E-11	1.01E-08	0.00E+00	5.59E-11	9.55E-09	0.00E+00
Hf-175	—	2.77E-12	5.25E-12	1.35E-09	1.56E-12	4.51E-12	9.19E-10

Table A-11 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients			DCFPAK3.02 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
Hf-178m	—	1.72E-11	3.24E-10	9.10E-09	1.04E-11	2.59E-10	6.18E-09
Hf-181	—	9.32E-12	2.13E-11	2.15E-09	5.22E-12	1.92E-11	1.46E-09
Hf-182	—	6.36E-12	3.29E-10	9.60E-10	4.40E-12	2.74E-10	6.50E-10
Hg-194+D	Au-194	1.07E-10	7.51E-11	4.53E-09	7.38E-11	6.23E-11	3.07E-09
Hg-203	—	7.62E-12	2.45E-11	9.59E-10	5.07E-12	2.20E-11	6.50E-10
Ho-163	—	2.63E-14	1.20E-12	0.00E+00	1.52E-14	9.06E-13	0.00E+00
Ho-166m	—	1.18E-11	7.66E-10	6.83E-09	7.03E-12	5.81E-10	4.63E-09
I-125	—	3.45E-11	2.78E-11	2.84E-11	3.59E-12	2.88E-12	1.74E-11
I-129	—	1.97E-10	1.64E-10	2.20E-11	2.01E-11	2.27E-11	1.38E-11
In-114m+D	(In-114 0.9675)	3.64E-11	5.03E-11	3.24E-10	2.08E-11	4.48E-11	2.21E-10
In-115	—	4.33E-11	4.07E-10	1.06E-12	3.70E-11	3.66E-10	9.49E-13
Ir-192	—	1.07E-11	2.41E-11	3.36E-09	6.03E-12	2.15E-11	2.28E-09
Ir-192n	—	7.62E-12	1.57E-10	2.43E-12	4.37E-12	1.44E-10	1.80E-12
Ir-194m	—	1.20E-11	4.37E-11	9.74E-09	6.99E-12	3.81E-11	6.61E-09
K-40	—	3.42E-11	2.22E-10	7.25E-10	2.17E-11	2.07E-10	4.94E-10
Kr-81	—	-1[d]	-1[d]	3.50E-12	-1[d]	-1[d]	2.36E-12
Kr-85	—	-1[d]	-1[d]	1.18E-11	-1[d]	-1[d]	8.50E-12
La-137	—	5.07E-13	1.42E-11	2.38E-11	2.92E-13	1.17E-11	1.51E-11
La-138	—	4.96E-12	3.04E-10	5.50E-09	2.99E-12	2.34E-10	3.74E-09
Lu-173	—	2.80E-12	1.26E-11	5.83E-10	1.57E-12	1.12E-11	3.92E-10
Lu-174	—	2.27E-12	1.50E-11	4.10E-10	1.27E-12	1.36E-11	2.77E-10
Lu-174m	—	5.11E-12	1.57E-11	1.56E-10	2.82E-12	1.43E-11	1.04E-10
Lu-176	—	1.37E-11	1.77E-10	1.90E-09	7.73E-12	1.54E-10	1.28E-09
Lu-177m+D	(Lu-177 2.1700E-01)	1.46E-11	5.76E-11	3.94E-09	8.17E-12	5.23E-11	2.67E-09
Mn-53	—	2.22E-13	9.62E-13	0.00E+00	1.29E-13	8.88E-13	0.00E+00
Mn-54	—	3.10E-12	1.21E-11	3.60E-09	1.96E-12	9.88E-12	2.45E-09
Mo-93	—	3.88E-12	5.55E-12	1.25E-12	3.47E-12	5.22E-12	6.95E-13
Na-22	—	1.26E-11	9.73E-11	9.56E-09	8.66E-12	8.55E-11	6.50E-09
Nb-91	—	3.92E-13	4.99E-12	7.66E-12	2.19E-13	4.66E-12	5.08E-12
Nb-91m	—	3.92E-12	1.46E-11	1.12E-10	2.18E-12	1.35E-11	7.62E-11
Nb-92	—	4.59E-12	7.44E-11	6.42E-09	2.77E-12	6.22E-11	4.37E-09
Nb-93m	—	1.22E-12	6.03E-12	2.23E-13	6.77E-13	5.59E-12	1.24E-13
Nb-94	—	1.11E-11	1.34E-10	6.70E-09	6.40E-12	1.18E-10	4.55E-09
Nb-95	—	3.50E-12	6.40E-12	3.28E-09	2.00E-12	5.55E-12	2.23E-09
Nd-144	—	3.92E-11	1.04E-08	0.00E+00	3.02E-11	9.32E-09	0.00E+00
Ni-59	—	3.85E-13	2.39E-12	6.48E-14	2.29E-13	1.67E-12	4.40E-14
Ni-63	—	9.69E-13	5.88E-12	0.00E+00	5.73E-13	4.11E-12	0.00E+00
Np-235+D	(U-235m 3.9934E-03)	5.47E-13	2.05E-12	2.43E-12	3.03E-13	1.88E-12	1.58E-12
Np-236+D	(Pa-232 1.6E-3)	1.83E-11	3.36E-09	5.11E-10	1.15E-11	2.44E-09	3.45E-10
Np-237+D	Pa-233	9.18E-11	2.87E-08	9.30E-10	5.82E-11	2.71E-08	6.31E-10
Os-185	—	2.62E-12	5.92E-12	2.86E-09	1.53E-12	4.92E-12	1.94E-09
Os-186	—	1.05E-10	1.20E-08	0.00E+00	7.10E-11	1.14E-08	0.00E+00
Os-194+D	Ir-194	3.54E-11	2.59E-10	4.07E-10	1.98E-11	2.42E-10	2.78E-10
Pa-231	—	2.26E-10	7.62E-08	1.34E-10	1.59E-10	5.62E-08	9.05E-11
Pb-202+D	(Tl-202 9.9000E-01)	4.71E-11	1.39E-10	1.84E-09	3.44E-11	1.29E-10	1.25E-09
Pb-205	—	8.03E-13	2.28E-12	3.08E-14	6.25E-13	2.13E-12	1.85E-14
Pb-210+D	Bi-210, (Hg-206 1.9E-08), (Tl-206 1.339E-06)	1.19E-09	1.63E-08	9.22E-12	8.62E-10	1.55E-08	7.00E-12

Table A-11 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients			DCFPAK3.02 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
Pd-107	—	3.81E-13	1.75E-12	0.00E+00	2.10E-13	1.62E-12	0.00E+00
Pm-143	—	1.24E-12	9.06E-12	1.26E-09	7.14E-13	6.92E-12	8.56E-10
Pm-144	—	4.70E-12	5.51E-11	6.52E-09	2.74E-12	4.18E-11	4.42E-09
Pm-145	—	7.58E-13	1.24E-11	4.47E-11	4.33E-13	1.06E-11	2.90E-11
Pm-146	—	5.88E-12	1.03E-10	3.12E-09	3.37E-12	8.18E-11	2.11E-09
Pm-147	—	2.48E-12	1.61E-11	1.44E-13	1.38E-12	1.50E-11	1.27E-13
Pm-148m+D	(Pm-148 4.2000E-02)	1.25E-11	2.14E-11	8.54E-09	7.06E-12	1.86E-11	5.81E-09
Po-208	—	2.81E-09	2.26E-08	8.73E-14	2.05E-09	2.15E-08	5.93E-14
Po-209	—	2.79E-09	2.82E-08	2.58E-11	2.04E-09	2.67E-08	1.75E-11
Po-210	—	2.25E-09	1.45E-08	4.18E-14	1.65E-09	1.38E-08	2.84E-14
Pt-190	—	4.22E-11	1.50E-08	0.00E+00	2.57E-11	1.42E-08	0.00E+00
Pt-193	—	3.55E-13	1.97E-12	1.87E-14	1.96E-13	1.83E-12	1.10E-14
Pu-236	—	1.00E-10	2.96E-08	3.39E-13	7.03E-11	2.81E-08	2.03E-13
Pu-237	—	9.36E-13	1.49E-12	1.61E-10	5.22E-13	1.32E-12	1.09E-10
Pu-238	—	1.69E-10	5.22E-08	2.56E-13	1.29E-10	4.40E-08	1.50E-13
Pu-239+D	(U-235m 9.9940E-01)	1.74E-10	5.55E-08	3.22E-13	1.34E-10	4.66E-08	2.09E-13
Pu-240	—	1.74E-10	5.55E-08	2.52E-13	1.34E-10	4.66E-08	1.48E-13
Pu-241+D	(U-237 2.45E-05)	2.28E-12	8.66E-10	1.72E-14	1.87E-12	7.33E-10	1.16E-14
Pu-242	—	1.66E-10	5.25E-08	5.56E-13	1.28E-10	4.44E-08	3.59E-13
Pu-244+D	U-240, Np-240m, (Np-240 1.1000E-03)	1.98E-10	5.22E-08	1.48E-09	1.46E-10	4.40E-08	1.01E-09
Ra-226+D	Rn-222, Po-218, (Pb-214 9.9980E-01), (Bi-214 1.0E+00), (Po-214 9.9979E-01), (Tl-210 2.1E-04), (At-218 2.0E-04), (Rn-218 2.0E-07)	5.15E-10	2.82E-08	7.74E-09	3.54E-10	2.68E-08	5.27E-09
Ra-228+D	Ac-228	1.43E-09	4.37E-08	3.76E-09	1.01E-09	4.15E-08	2.56E-09
Rb-83+D	(Kr-83m 7.4292E-01)	7.07E-12	5.18E-12	2.02E-09	4.81E-12	4.14E-12	1.38E-09
Rb-84	—	1.19E-11	1.04E-11	3.88E-09	8.07E-12	8.92E-12	2.64E-09
Rb-87	—	7.32E-12	4.48E-11	5.39E-13	4.92E-12	4.18E-11	4.92E-13
Re-183	—	4.74E-12	1.24E-11	4.96E-10	2.77E-12	1.13E-11	3.34E-10
Re-184	—	4.40E-12	8.29E-12	3.74E-09	2.67E-12	7.21E-12	2.54E-09
Re-184m	—	6.99E-12	3.56E-11	1.52E-09	4.14E-12	3.21E-11	1.03E-09
Re-186m+D	Re-186	1.83E-11	1.68E-10	1.12E-10	1.07E-11	1.57E-10	7.60E-11
Re-187	—	2.39E-14	1.10E-13	0.00E+00	1.40E-14	1.02E-13	0.00E+00
Rh-101	—	2.86E-12	1.72E-11	1.08E-09	1.73E-12	1.51E-11	7.30E-10
Rh-102	—	8.92E-12	2.60E-11	2.09E-09	5.11E-12	2.32E-11	1.43E-09
Rh-102m	—	1.10E-11	6.66E-11	9.15E-09	6.99E-12	5.51E-11	6.22E-09
Ru-103+D	(Rh-103m 0.988)	5.27E-12	1.04E-11	2.07E-09	2.99E-12	9.26E-12	1.40E-09
Ru-106+D	Rh-106	6.10E-11	2.24E-10	9.20E-10	3.45E-11	2.07E-10	6.29E-10
S-35	—	3.70E-12	6.51E-12	4.94E-14	2.48E-12	6.03E-12	4.39E-14
Sb-124	—	1.85E-11	3.20E-11	8.30E-09	1.06E-11	2.79E-11	5.64E-09
Sb-125	—	6.21E-12	4.03E-11	1.78E-09	3.77E-12	3.64E-11	1.20E-09
Sc-46	—	8.84E-12	2.47E-11	8.83E-09	5.03E-12	2.14E-11	6.00E-09
Se-75	—	1.06E-11	4.92E-12	1.53E-09	7.44E-12	4.18E-12	1.04E-09
Se-79	—	9.18E-12	1.86E-11	5.00E-14	6.36E-12	1.74E-11	4.40E-14

Table A-11 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients			DCFPAK3.02 Mortality Risk Coefficients		
		Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
Si-32+D	P-32	1.75E-11	3.04E-10	1.35E-11	1.13E-11	2.87E-10	1.08E-11
Sm-145	—	1.66E-12	5.81E-12	1.01E-10	9.29E-13	4.99E-12	6.61E-11
Sm-146	—	5.22E-11	1.38E-08	0.00E+00	4.00E-11	1.24E-08	0.00E+00
Sm-147	—	4.77E-11	1.26E-08	0.00E+00	3.66E-11	1.13E-08	0.00E+00
Sm-148	—	4.11E-11	1.08E-08	0.00E+00	3.14E-11	9.73E-09	0.00E+00
Sm-151	—	8.14E-13	9.25E-12	1.90E-15	4.59E-13	8.62E-12	1.08E-15
Sn-113+D	In-113m	6.57E-12	1.48E-11	1.08E-09	3.67E-12	1.32E-11	7.33E-10
Sn-119m	—	3.30E-12	1.22E-11	6.75E-12	1.84E-12	1.13E-11	4.02E-12
Sn-121m+D	(Sn-121 7.7600E-01)	5.17E-12	4.41E-11	3.90E-12	2.89E-12	4.14E-11	2.58E-12
Sn-123	—	2.06E-11	4.66E-11	3.91E-11	1.14E-11	4.22E-11	2.78E-11
Sn-126+D	Sb-126m, (Sb-126 1.4000E-01)	4.00E-11	4.24E-10	8.35E-09	2.27E-11	3.86E-10	5.67E-09
Sr-85	—	3.05E-12	3.17E-12	2.05E-09	2.02E-12	2.60E-12	1.39E-09
Sr-89	—	1.84E-11	3.03E-11	1.06E-11	1.10E-11	2.67E-11	8.56E-12
Sr-90+D	Y-90	9.53E-11	4.34E-10	2.45E-11	7.42E-11	4.05E-10	1.93E-11
Ta-179	—	4.70E-13	1.78E-12	6.02E-11	2.63E-13	1.56E-12	4.02E-11
Ta-182	—	1.13E-11	3.70E-11	5.63E-09	6.33E-12	3.31E-11	3.82E-09
Tb-157	—	3.03E-13	3.70E-12	8.16E-12	1.71E-13	3.31E-12	5.35E-12
Tb-158	—	6.88E-12	1.72E-10	3.39E-09	3.96E-12	1.40E-10	2.30E-09
Tb-160	—	1.27E-11	3.02E-11	4.88E-09	7.14E-12	2.69E-11	3.32E-09
Tc-95m+D	(Tc-95 3.8800E-02)	2.57E-12	4.63E-12	2.99E-09	1.55E-12	3.86E-12	2.03E-09
Tc-97	—	3.92E-13	4.81E-12	1.62E-12	2.26E-13	4.48E-12	9.01E-13
Tc-97m	—	3.45E-12	1.45E-11	2.69E-12	1.96E-12	1.35E-11	1.65E-12
Tc-98	—	9.40E-12	1.18E-10	6.01E-09	5.55E-12	1.04E-10	4.09E-09
Tc-99	—	4.00E-12	3.81E-11	4.35E-13	2.28E-12	3.58E-11	3.97E-13
Te-121m+D	(Te-121 8.8600E-01)	1.04E-11	2.24E-11	2.91E-09	6.93E-12	1.96E-11	1.97E-09
Te-123	—	1.32E-12	3.08E-12	1.95E-14	1.18E-12	2.82E-12	1.18E-14
Te-123m	—	5.62E-12	1.77E-11	5.30E-10	3.58E-12	1.63E-11	3.59E-10
Te-125m	—	4.70E-12	1.45E-11	2.50E-11	2.78E-12	1.33E-11	1.54E-11
Te-127m+D	(Te-127 9.7600E-01)	1.34E-11	3.53E-11	2.98E-11	8.37E-12	3.24E-11	2.02E-11
Te-129m+D	(Te-129 6.3000E-01)	2.21E-11	2.99E-11	2.93E-10	1.26E-11	2.64E-11	2.01E-10
Th-228+D	Ra-224, Rn-220, Po-216, Pb-212, Bi-212, (Po-212 6.4060E-01), (Tl-208 3.5940E-01)	4.23E-10	1.44E-07	6.78E-09	2.58E-10	1.37E-07	4.62E-09
Th-229+D	Ra-225, Ac-225, Fr-221, At-217, Bi-213, (Po-213 9.7910E-01), Pb-209, (Tl-209 2.0900E-02)	7.17E-10	2.29E-07	1.22E-09	4.74E-10	2.18E-07	8.30E-10
Th-230	—	1.19E-10	3.41E-08	1.34E-12	8.03E-11	2.67E-08	8.92E-13
Th-232	—	1.33E-10	4.33E-08	6.81E-13	9.06E-11	4.07E-08	4.48E-13
Ti-44+D	Sc-44	3.86E-11	3.45E-10	9.69E-09	2.27E-11	3.10E-10	6.59E-09
Tl-204	—	8.21E-12	6.03E-11	6.06E-12	4.96E-12	5.66E-11	4.54E-12
Tm-168	—	6.44E-12	1.85E-11	5.16E-09	3.65E-12	1.61E-11	3.50E-09
Tm-170	—	1.29E-11	3.27E-11	1.51E-11	7.18E-12	2.99E-11	1.07E-11
Tm-171	—	1.02E-12	4.33E-12	1.46E-12	5.66E-13	4.03E-12	9.72E-13
U-232	—	3.85E-10	9.25E-08	9.25E-13	2.66E-10	8.77E-08	6.05E-13
U-233	—	9.69E-11	2.83E-08	9.38E-13	6.25E-11	2.69E-08	6.25E-13

Table A-11 (Cont.)

Principal Radionuclide[a]	Associated Decay Chain[b]	DCFPAK3.02 Morbidity Risk Coefficients Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)	DCFPAK3.02 Mortality Risk Coefficients Ingestion (risk/pCi)	Inhalation (risk/pCi)	Air Submersion (risk/yr per pCi/m3)
U-234	—	9.55E-11	2.78E-08	5.13E-13	6.14E-11	2.64E-08	3.28E-13
U-235+D	Th-231	9.76E-11	2.50E-08	6.71E-10	6.21E-11	2.37E-08	4.54E-10
U-236	—	8.99E-11	2.57E-08	3.06E-13	5.77E-11	2.44E-08	1.90E-13
U-238+D	Th-234, Pa-234m, (Pa-234 1.6000E-03)	1.20E-10	2.37E-08	1.28E-10	7.46E-11	2.25E-08	8.85E-11
V-49	—	1.77E-13	2.80E-13	0.00E+00	9.84E-14	2.49E-13	0.00E+00
V-50	—	7.95E-12	9.51E-11	6.52E-09	5.36E-12	7.14E-11	4.44E-09
W-181	—	6.51E-13	1.13E-12	9.99E-11	3.69E-13	9.73E-13	6.68E-11
W-185	—	4.29E-12	1.37E-11	9.14E-13	2.38E-12	1.26E-11	7.86E-13
W-188+D	Re-188	2.75E-11	5.81E-11	2.72E-10	1.49E-11	5.26E-11	1.86E-10
Xe-127	—	-1[d]	-1[d]	1.04E-09	-1[d]	-1[d]	7.02E-10
Y-88	—	5.88E-12	2.04E-11	1.24E-08	3.43E-12	1.48E-11	8.38E-09
Y-91	—	2.36E-11	3.36E-11	2.48E-11	1.30E-11	2.98E-11	1.82E-11
Yb-169	—	6.81E-12	1.24E-11	1.07E-09	3.81E-12	1.11E-11	7.18E-10
Zn-65	—	1.53E-11	7.55E-12	2.56E-09	1.04E-11	6.10E-12	1.74E-09
Zr-88	—	2.15E-12	1.34E-11	1.58E-09	1.30E-12	1.12E-11	1.07E-09
Zr-93	—	1.41E-12	1.46E-11	7.52E-18	1.02E-12	1.35E-11	7.52E-18

[a] Risk coefficients for entries labeled by "+D" are aggregated risk coefficients of a principal radionuclide together with the associated decay chain progenies.

[b] The associated progenies are listed. If a branching fraction is anything other than 1, it is listed along with the radionuclide in the bracket.

[c] Indicates there is no associated radionuclide.

[d] "-1" indicates no value listed in DCFPAK3.02. For risk calculation, a value of 0 is used in the RESRAD family of codes.

For the purpose of computing the risk coefficients, it is assumed the concentration of the radionuclide in the environmental medium remains constant and that all persons in the population are exposed to that environmental medium throughout their lifetimes. The risk coefficients are derived using the age and gender distributions of a hypothetical closed "stationary" population. The population is referred to as "stationary" because the gender-specific birth rates and survival functions are assumed to remain invariant over time. Risk coefficient estimates involve the use of (1) an age-dependent organ-specific cancer risk model (the age-at-exposure groups considered in the models are 0–9 years, 10–19 years, 20–29 years, 30–39 years, and 40+ years), which is an absolute risk model or a relative risk model for 14 cancer sites; (2) age-specific biokinetic and dosimetric models; (3) U.S. decennial life tables and the cancer mortality/morbidity data for the same period; and (4) age- and gender-dependent usage of contaminated media.

For each type of cancer, values for lifetime risk per unit of absorbed dose were used to convert the absorbed dose rates into the lifetime cancer risk as a function of age. This calculation involves the absorbed dose as a function of age, the time-dependent intake of radionuclides, and the population's survival function. The survival function is the age-dependent probability that a person will die at a particular age. It was assumed that the radiation dose to the population does not significantly alter the survival function.

Age- and gender-specific radiation risk models were taken from the EPA report, *Estimating Radiological Cancer Risks*, which was based on data from Japanese atomic bomb survivors as well as other study groups (EPA 1994). EPA also published an update on the dose to risk conversion coefficients in *Radiogenic Cancer Risk Models and Projections for the U.S. Population* (EPA 2011).

Figure A-1 shows the steps involved in estimating risk coefficients. A total risk coefficient is derived by first adding the risk estimates for the different cancer sites in each gender and then calculating a weighted mean of the coefficients for males and females.

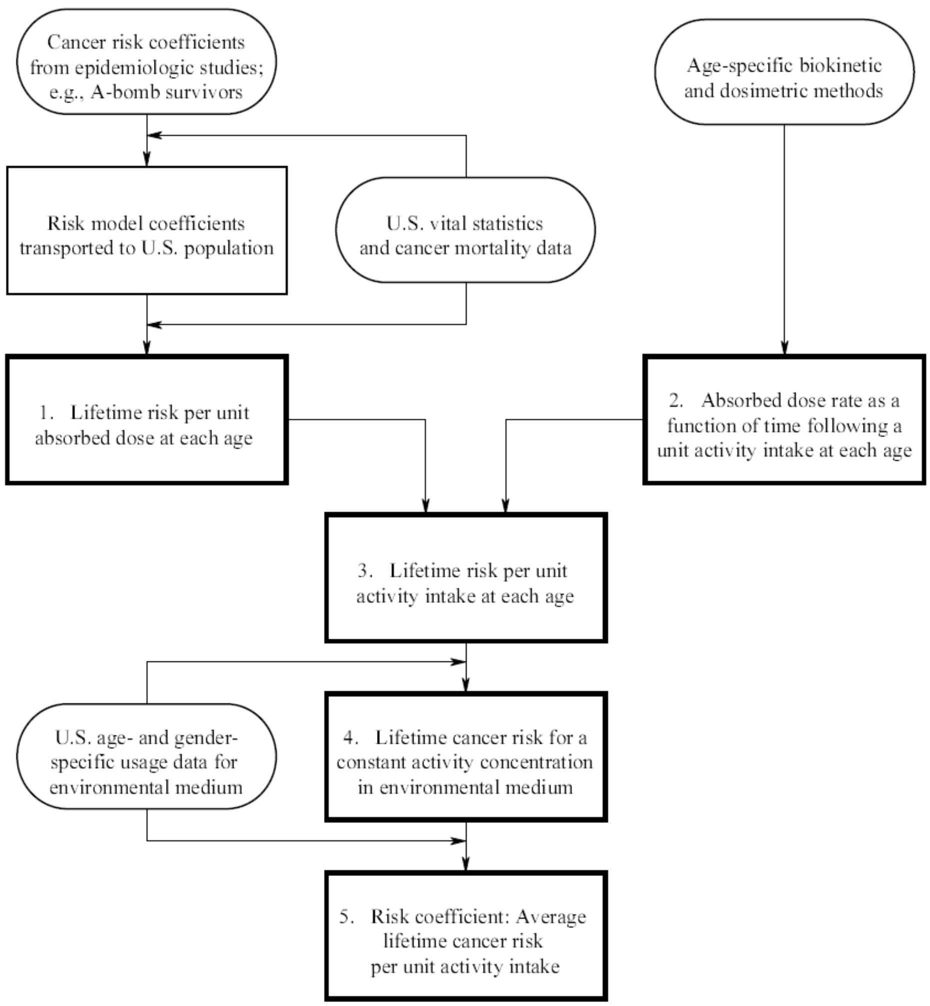

Figure A-1 Steps Involved in Computation of Risk Coefficients
Source: FGR 13 (EPA 1999).

The following are descriptions for each step shown in Figure A-1:

Step 1. Lifetime risk per unit absorbed dose at each age. For each of 14 cancer sites in the body, radiation risk models are used to calculate gender-specific values for the lifetime risk per unit absorbed dose received at each age. The cancer sites considered are the esophagus, stomach, colon, liver, lung, bone, skin, breast, ovary, bladder, kidney, thyroid, red marrow (leukemia), and residual (all remaining cancer sites combined). The computation involves an integration over age, beginning at the age at which the dose is received, of the product of the age-specific risk model coefficient and the survival function.

Step 2. Absorbed dose rate as a function of time post acute intake at each age. This step involves using the age-specific biokinetic models to calculate time-dependent inventories of Activity in various regions of the body following acute intake of a unit Activity of the radionuclide. For a given radionuclide and intake mode, this calculation is performed for each of six "basic" ages at intake: infancy (100 days); 1, 5, 10, and 15 years; and maturity (usually 20 years, but 25 years in the biokinetic models for some elements).

Age-specific dosimetric models are used to convert the calculated time-dependent regional activities in the body to absorbed dose rates (per unit intake) to radiosensitive tissues as a function of age at intake and time after intake. Absorbed dose rates for intake ages intermediate to the six basic ages at intake are determined by interpolation.

Step 3. Lifetime cancer risk per unit intake at each age. This step involves integration over age of the product of the absorbed dose rate at age *y* for a unit intake at age *yi*, the lifetime risk per unit absorbed dose received at age *y*, and the value of the survival function at age *y* divided by the value at age *yi*. The survival function is used to account for the probability that a person exposed at age *yi* is still alive at age *y* to receive the absorbed dose. It assumes the radiation dose received is low, and it does not change the survival function.

Step 4. Lifetime cancer risk for chronic intake. This step takes into account the variation in environmental media usage with age and gender. For each cancer site and each gender, the lifetime cancer risk for chronic exposure is obtained by integration over age *y* of the product of the lifetime cancer risk per unit intake at age *y* and the expected intake of the environmental medium at age *y*. The expected intake at a given age is the product of the usage rate of the medium and the value of the survival function at that age.

Step 5. Average lifetime cancer risk per unit activity intake. The average lifetime cancer risk is calculated by dividing the calculated lifetime cancer risk for chronic intake calculated in step 4 by the expected lifetime media usage.

The computation of risk coefficients for external exposure involves fewer steps because age-specific organ dose rates due to external exposure are not available.

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APPENDIX B:

MODELING THE FATE OF RADIOACTIVITY IN RESRAD-BUILD 4.0

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APPENDIX B:

MODELING THE FATE OF RADIOACTIVITY IN RESRAD-BUILD 4.0

This appendix describes the specification and modeling of the radioactivity in RESRAD-BUILD considering radiological transformations (both decay and ingrowth); removal of material from the source; release of removed source material to the air within the building and its subsequent fate, suspended in the air, deposited on the floor, or ventilated out of the building; and inadvertent ingestion of the removed source material. The code maintains mass balance of the source material and the nuclides in this modeling except for the release of radon. The effect of releasing the radon isotopes is not considered when computing the concentration of the next principal radionuclide progeny of the radon parent. All variables in this appendix are in the MKS system of units unless otherwise noted.

B.1 INITIAL RADIOACTIVITY OF RADIONUCLIDES IN EACH SOURCE TYPE

The initial radioactivity of the radionuclides is specified on a different basis in each of the four types of sources as shown in row 3 of Table B-1. These are multiplied in the computational code by the inputs that quantify the extent of the source (row 4) to obtain the initial quantity of radioactivity in the source (row 5).

Table B-1 Specification and Computation of Radioactivity in Source

Source Type	Volume		Area	Line	Point
Radionuclides	^3H	All but ^3H	All	All	All
Specification of initial radioactivity	C_{sV}^i Activity/g		C_{sA}^i Activity/m^2	C_{sL}^i Activity/m	C_{sP}^i Activity
Specification of extent of source	Area, A_s Wet Thickness, T_c Dry bulk density, ρ_b^s	Thickness, T_c	Area, A_s Or L_a, L_b $A_s = L_a L_b$	Length, L_s	–
Initial quantity of radioactivity	$Q_s^i = A_s T_c \rho_b^s C_{sV}^i$		$Q_s^i = A_s C_{sA}^i$	$Q_s^i = L_s C_{sL}^i$	$Q_s^i = C_{sP}^i$

B.2 REMOVAL AND DISPOSITION OF MATERIAL FROM SOURCE

The code models the removal and disposition of the material removed from the source. The removal of solid material from the source is modeled as occurring at a constant rate over one or more removal intervals; the number intervals depends on the source type. The removal of water associated with vaporizable tritium, ^3H, is modeled as described in Section B.3.3 with the rate of removal varying continuously over time. Part or all of the solid material that is removed can be modeled as becoming airborne. The transient model that is used to describe the fate of the material that is released to the air is developed later in this chapter. The material that is removed from the source, but does not become airborne, is assumed to be removed from the building continuously as it is generated, unless it is inadvertently ingested by receptors occupying the same room as the source. Figure B-1 depicts the disposition of source material over time. All the water that evaporates from a tritium source is modeled as being released to the air.

Radionuclide-specific inputs and modeling apply only to ^{3}H, ^{220}Rn, and ^{222}Rn. Thus, radiological transformations affect the concentration of the radionuclides in the same manner regardless of whether the source material is still intact in the source or whether it has been removed from the source and released to the air. The modeling of radiological transformations can therefore be independent of the modeling of the fate and disposition of the source material. This is reflected in Figure B-1 by the shading in the figure along the time axis; the shading at any time is the same across the four dispositions shown: released to air, inadvertently ingested, removed from building, and remains *in situ*.

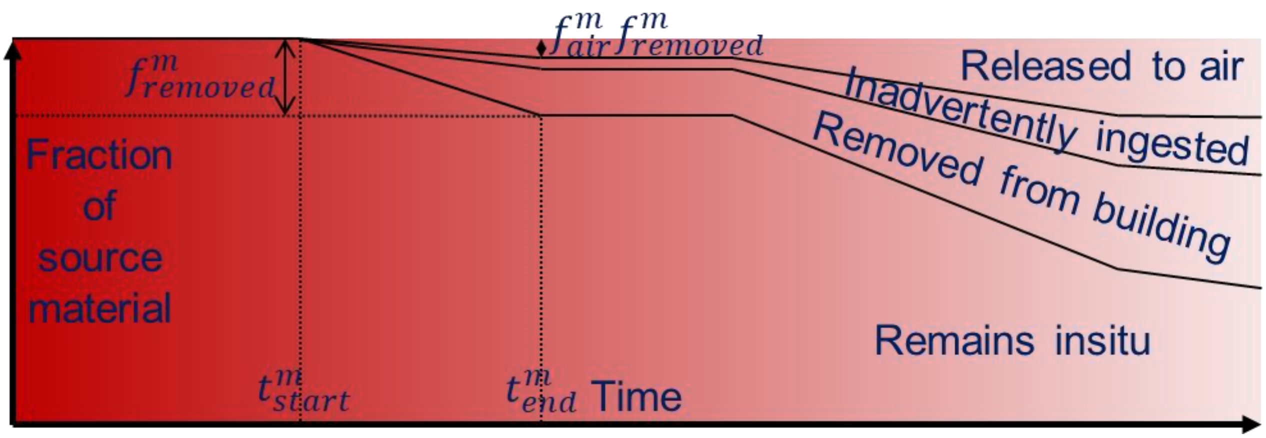


Figure B-1 Disposition of Source Material with Time

B.3 PHYSICAL REMOVAL OF THE SOURCE MATERIAL

The manner in which the physical removal of the source material is modeled depends on the source type and is summarized in Table B-2.

Table B-2 Characterizing the Removal of Source Material

Source Type	Volume		Area / Line / Point
Radionuclides	Vaporizable ^{3}H	All but vaporizable ^{3}H	All / All / All
Specification of removal	Erosion rate, ε_r Wet zone thickness, $T_c(0)$ Dry zone thickness, $T_d(0)$ Water content, θ Vaporizable water fraction, $f_{air}^{H_2O}$ Humidity, H Diffusion coefficient of water in the pore space, D_e	Erosion rate, ε_r Thickness, T_r for each region, r Index of region that is contaminated, c	Fraction removed, $f_{removed}^{m}$ Start time, t_{start}^{m} End time, t_{end}^{m} for each removal phase, m
Conditions			$t_{start}^{m} < t_{end}^{m} \leq t_{start}^{m+1}$ $0 < m \leq 10$ $\sum_m f_{removed}^{m} \leq 1$
Rate of removal	$r_{H_2O}(t) = \dfrac{D_e(c_g - H)}{\theta T_c(0)\sqrt{2D_e \dfrac{c_g - H}{f_{air}^{H_2O}\theta\rho_w} t + T_d{}^2(0)}}$	$r_s = \dfrac{\varepsilon_c}{T_c}$	$r_s^m = \dfrac{f_{removed}^{m}}{t_{end}^{m} - t_{start}^{m}}$
Time interval of removal, release to air and inadvertent ingestion	$t \leq \dfrac{f_{air}^{H_2O}\theta\rho_w[T_c(0) + 2T_d(0)]T_c(0)}{2D_e(c_g - H)}$	$\sum_r^{c-1} \dfrac{T_r}{\varepsilon_r} \leq t \leq \sum_r^{c} \dfrac{T_r}{\varepsilon_r}$	$t_{start}^{m} \leq t \leq t_{end}^{m}$
Rate of release to air	$r_{H_2O}(t)$	$f_{air} r_s$	$f_{air}^{m} r_s^{m}$

B.3.1 Physical Removal from Point, Line, and Area Sources

The physical removal of material from an area, line, or point source is modeled as occurring over up to ten distinct time intervals. The rate of removal is constant over each removal interval, but each interval can have its own removal rate. The start and end times of each removal interval and the fraction removed during that interval are specified by the user. The removal of source material over each time interval is modeled as being at a constant rate, r_s^m, given by the expression

$$r_s^m = \frac{f_{removed}^{m}}{t_{end}^{m} - t_{start}^{m}} \tag{B.1}$$

where:

r_s^m = rate of removal of the source material during the m^{th} removal interval,

$f_{removed}^{m}$ = fraction of source material removed during the m^{th} removal interval,

$t_{end}^{m} =$ time at which the m^{th} removal interval ends,

$t_{start}^{m} =$ time at which the m^{th} removal interval begins.

Each removal interval is of non-zero duration, $t_{start}^{m} < t_{end}^{m}$. There may be a period of no removal between two removal intervals, but removal intervals cannot overlap, $t_{end}^{m} \leq t_{start}^{m+1} \ \forall \ 0 < m < 10$.

B.3.2 Physical Removal from Volume Sources

Physical removal of material from a volume source is modeled as occurring at a constant rate over a single time interval. The volume source can have up to five regions or layers, but only one of them is modeled as being contaminated. The thicknesses and the erosion rates of each of the regions are specified. Region 1 is the outermost layer and it erodes first; the other layers erode sequentially after the outer layers have eroded away. Thus, the removal of the contaminated layer, region c, is modeled as occurring during the time interval given by the expression below, provided the erosion rates specified for all of the regions up to and including region c are non-zero.

$$\sum_{r}^{c-1} \frac{T_r}{\varepsilon_r} \leq t \leq \sum_{r}^{c} \frac{T_r}{\varepsilon_r} \tag{B.2}$$

where:

c = index of the contaminated region of the source,

r = an index of a region of the source,

T_r = thickness of region r of the source,

ε_r = rate of erosion of region r of the source,

t = range of times over which the contaminated region of the volume source erodes.

The erosion rate expresses the rate at which the source material is removed from a volume source, in dimensions of length per time. The removal of source material as a fraction of the initial quantity of source material per unit of time or in dimensions of mass per unit of time are given by the expressions

$$\begin{aligned} r_s &= \frac{\varepsilon_c}{T_c} \\ r_s^{mass} &= \varepsilon_c A_s \rho_b^s \end{aligned} \tag{B.3}$$

where:

r_s = rate of removal of the source material as a fraction of the initial quantity of source material,

r_s^{mass} = rate of removal of the source material in mass per unit time,

ε_c = rate of erosion of the contaminated region c of the source,

T_c = thickness of the contaminated region c of the source,

A_s = area of the volume source,

ρ_b^s = dry bulk density of the contaminated region of the volume source.

B.3.3 Physical Removal of Water from Tritium Volume Sources

The release and exposure to tritiated water vapor is detailed in Appendix F. This section summarizes the removal of tritium, ^3H, from a volume source. The removal of tritium, ^3H, from a volume source is modeled as having two components, removal of ^3H that is in the form of vaporizable ^3HHO and the removal of ^3H that is incorporated and fixed in the source material. A tritium source can initially have at most two layers, the contaminated layer, also called the wet layer, and possibly an uncontaminated outer layer, termed the initial dry layer. The modeling of the removal of ^3H that is incorporated or fixed in the source material is similar to that of the general volume source. The removal of ^3HHO is modeled assuming the following:

Textual Description	Mathematical Representation
Water vapor will vaporize into the air in the pore space of the wet layer and will be in equilibrium with the water in the wet layer. The temperature in the room is 21℃~70°F.	$c_g = \frac{P_{sat}^T MW}{RT} = \frac{0.0245 \times 18}{82 \times 294} \cong 1.8\ 10^{-5}\,\frac{g}{cc} \cong 0.018\ kg\ m^{-3}$
The water vapor in the pore space of the wet layer will diffuse through the dry layer into the room, provided the humidity in the room is less than the moisture content of the air in the pore space of the wet layer.	$c_g \leq H \Longrightarrow f_{air}^{H_2O} = 0$
The water content in the wet layer will remain constant at the specified value; the thickness of the wet layer will decrease as the water diffuses out of the wet layer.	$q_{water}(t) = \frac{dT_d(t)}{dt} f_{air}^{H_2O} \theta \rho_w A_s$
The concentration gradient of water vapor across the dry layer is constant over the thickness of the dry layer, but it varies with time, because the thickness of the wet layer decreases and the thickness of the dry layer increases correspondingly, as moisture is released from the wet layer and into the room.	$q_{water}(t) = D_e \frac{c_g - H}{T_d(t)} A_s$

where:

c_g = concentration of water vapor in the pores of the wet layer of the source (it is a hard coded value and not an input),

P_{sat}^{T} = partial pressure of the water vapor in equilibrium with moisture at room temperature (it is not an input),

MW = molecular weight of water (it is not an input),

R = ideal gas constant (it is not an input),

T = temperature in the room or building (it is not an input),

H = humidity in the room or building,

$f_{air}^{H_2O}$ = fraction of water in the tritium source that is vaporizable,

$q_{water}(t)$ = flux of water evaporating from the tritium source into the room,

$T_d(t)$ = thickness of the dry layer in the tritium source,

θ = volumetric water content in the wet layer of the tritium source,

ρ_w = density of water,

A_s = area of the tritium source,

D_e = effective diffusion coefficient of water in the pore space of the tritium source.

Equating the two expressions for the flux of water and integrating with respect to time yields the expression for the thickness of the dry layer as a function of time. Physical erosion of the dry layer is not included in this expression because vaporization is assumed to occur much faster than physical erosion. The expression for the flux of water as a function of time is then obtained using the expression for the thickness of the dry layer. Dividing the expression for the flux of water by the initial quantity of moisture gives the fractional release rate of moisture.

$$r_{H_2O}(t) = \frac{D_e}{\theta T_c(0)} \frac{c_g - H}{\sqrt{2D_e \dfrac{c_g - H}{f_{air}^{H_2O}\theta\rho_w} t + {T_d}^2(0)}} \tag{B.4}$$

where:

$r_{H_2O}(t)$ = fractional release rate of moisture from the tritium source,

$T_c(0)$ = initial thickness of the wet layer in the tritium source.

The release of vaporizable ^{3}HHO ceases when the wet zone disappears; at this time, the thickness of the dry zone equals the sum of the initial thicknesses of the wet and dry zones. The time over which release of vaporizable ^{3}HHO occurs is given by the expression

$$t \le \frac{f_{air}^{H_2O}\theta\rho_w[T_c(0)+2T_d(0)]T_c(0)}{2D_e(c_g - H)}$$

The fractional release rate of moisture per unit volume of the room into which the moisture is released is written to the temporary file "AH3RelRate#.out" where # is the identification number of the tritium source.

B.4 CHANGE IN THE QUANTITY OF RADIOACTIVITY IN THE SOURCE WITH TIME

The code models the change in the quantity of radioactivity with time due to radiological transformation and due to removal of the source. The effect of each process can be modeled independently because they do not affect each other.

$$Q_s^j(t) = Q_s^i(0) f_{RT}^{i,j}(t) f_{SR}(t) \tag{B.5}$$

where:

$Q_s^j(t)$ = quantity, at time t, of the activity of the jth radionuclide in the transformation chain of initially present radionuclide i in the source,

$Q_s^i(0)$ = initial quantity of activity of radionuclide i in the source,

$f_{RT}^{i,j}(t)$ = factor to account for the radiological transformations from radionuclide i to the jth radionuclide in the transformation chain,

$f_{SR}(t)$ = factor to account for the physical removal of source.

B.4.1 The Factor to Account for Radiological Transformations

RESRAD-BUILD Version 4.0 models all branches of the transformation chain of any radionuclide in ICRP-38 or in ICRP-107. A cut-off half-life is included in the formulations in case it is necessary to reduce the number of radionuclides for which the activity is to be explicitly computed in order to reduce the computation time. The activities of the radionuclides which have a half-life that is greater than the specified cut-off half-life are computed using the Bateman equation, or in the case of a transformation chain with branches, a modified Bateman equation. The activity of a radionuclide which has a half-life that is less than or equal to the cut-off half-life is modeled by multiplying the activity of its immediate parent radionuclide by the branching transformation fraction from the immediate parent radionuclide to it. When a cut-off half-life of 0 is specified, the activities of all the radionuclides in a transformation chain will be computed explicitly using the Bateman equation or a modified Bateman equation.

When the transformation chain has a single thread with no branching, for example ^{241}Am with a cut-off half-life of 1 day or ^{236}Pu with a cut-off half-life of 1 day, the factor for radiological transformation, $f_{RT}^{i,j}(t)$, for a radionuclide with a half-life greater than the cut-off half-life, is determined by computing the temporal activity of the j^{th} radionuclide in the transformation chain at time t resulting from an initial unit activity of radionuclide i in the source, using the Bateman equation.

$$f_{RT}^{i,j}(t) = \sum_{k=1}^{j} B_j^k e^{-\lambda_k t} \tag{B.6}$$

with:

$$B_1^1 = 1,$$

$$B_l^k = \frac{\lambda_l B_{l-1}^k}{\lambda_l - \lambda_k}, \quad \forall\ 0 < k < l \leq j$$

$$B_l^l = -\sum_{k=1}^{l-1} B_l^k, \quad \forall\ 1 < l \leq j$$

where:

$f_{RT}^{i,j}(t)$ = factor at time t, to account for the radiological transformations from radionuclide i to the j^{th} radionuclide in the transformation chain,

B_j^k = the k^{th} coefficient in the expression for the j^{th} radionuclide,

λ_k = transformation constant of the k^{th} radionuclide in the transformation chain.

The same expression is also used to compute the factor for radiological transformation, $f_{RT}^{i,j}(t)$, for radionuclides in a branching transformation chain, but the coefficients, B_j^k, are computed by summing over all immediate parents of the j^{th} radionuclide in the transformation chain, factoring the fraction of each immediate parent of the j^{th} radionuclide that transforms to the radionuclide in question. An immediate parent is one that that transforms directly to the progeny in question, not one that transforms through other intermediate progeny to the progeny in question.

$$B_1^1 = 1$$

$$B_l^k = \sum_{m=1}^{l-1} f_{br}^{m,l} \frac{\lambda_l B_m^k}{\lambda_l - \lambda_k}, \quad \forall\ 0 < k < l \leq j$$

$$B_l^l = -\sum_{k=1}^{l-1} B_l^k, \quad \forall\ 1 < l \leq j$$

where:

$f_{br}^{m,l}$ = fraction of the transformations of the m^{th} radionuclide in the transformation chain that result directly in the formation of the l^{th} radionuclide in the transformation chain,

B_j^k = the k th coefficient in the expression for the j th radionuclide,

λ_k = transformation constant of the k^{th} radionuclide in the transformation chain.

B.4.2 The Factor to Account for Physical Removal

The rates of removal of source material as a fraction of the initial source material from non-volume sources, Equation B.1; from volume sources that do not contain vaporizable ^{3}H, Equation B.3; and for vaporizable ^{3}H from volume sources, Equation B.4, were developed in the preceding sections. The effect of this physical removal of source material on the quantity of radioactivity in the source is characterized by the factor to account for physical removal

$$f_{SR}(t) = a + bt$$

$$a = 1 - \sum_{l=0}^{m-1} f_{removed}^{l}\,, b = 0 \text{ when } t_{end}^{m-1} < t < t_{start}^{m} \tag{B.7}$$

$$a = 1 - \sum_{l=0}^{m-1} f_{removed}^{l} + \frac{f_{removed}^{m} t_{start}^{m}}{t_{end}^{m} - t_{start}^{m}}\,, b = -\frac{f_{removed}^{m}}{t_{end}^{m} - t_{start}^{m}} \text{ when } t_{start}^{m} < t < t_{end}^{m}$$

B.4.3 Instantaneous Quantity of Radioactivity as a Function of Time

Combining Equations B.5, B.6, and B.7 gives the expression for the instantaneous activity in the source, which is in the form of a sum of exponentials of time and a sum of the product of time and the exponentials of time:

$$Q_s^j(t) = Q_s^i(0) \sum_{k=1}^{j} B_j^k e^{-\lambda_k t} (a + bt) \tag{B.8}$$

B.5 TIME-INTEGRATED QUANTITIES OF SOURCE REMAINING IN SITU AND SOURCE INGESTED

The doses and risks computed by RESRAD-BUILD are integrated over the exposure duration. The integration is preformed analytically, if possible. The time-integrated value of the source ingested over the exposure duration is used to compute the exposure from direct ingestion of the source. The time-integrated value of the source remaining *in situ* over the exposure duration is used in the calculation of external exposure from the source, when possible, to keep run time to a minimum.

B.5.1 Time Integration of Activity in Source for External Exposure Directly from the Source and for Exposure from Short-Lived Radon Progeny

The geometric factors for external exposure directly from the source do not change over time for a point, line, or area source. They may not change for a volume source depending on the locations of the receptor and the source, the number of layers in the source, and the erosion rates of the layers. The external exposure in these cases is proportional to the time-integrated activity in the source. The exposure from the three short-lived progeny of any radon released from the source is also proportional to the time-integrated activity of the immediate parent of the radon, Section B.7.1.

The expression for the instantaneous activity in the source, Equation B.8, can be integrated over the exposure duration by considering the integral of a single term in the sum

$$\int_{t_1}^{t_2} B_j^k (a + bt) e^{-\lambda_k t} dt = aB_j^k \int_{t_1}^{t_2} e^{-\lambda_k t} dt + bB_j^k \int_{t_1}^{t_2} t e^{-\lambda_k t} dt$$

The two definite integrals are evaluated using the indefinite integrals

$$\int e^{-\lambda_k t} dt = \frac{-e^{-\lambda_k t}}{\lambda_k}$$

and

$$\int t e^{-\lambda_k t} dt = t \frac{-e^{-\lambda_k t}}{\lambda_k} - \int 1 \frac{-e^{-\lambda_k t}}{\lambda_k} dt = t \frac{-e^{-\lambda_k t}}{\lambda_k} - \frac{e^{-\lambda_k t}}{{\lambda_k}^2} = \frac{-e^{-\lambda_k t}}{\lambda_k} \left(t + \frac{1}{\lambda_k} \right)$$

to get

$$\int_{t_1}^{t_2} B_j^k (a + bt) e^{-\lambda_k t} dt = aB_j^k \frac{e^{-\lambda_k t_1} - e^{-\lambda_k t_2}}{\lambda_k} + bB_j^k \frac{e^{-\lambda_k t_1}}{\lambda_k} \left(t_1 + \frac{1}{\lambda_k} \right) - bB_j^k \frac{e^{-\lambda_k t_2}}{\lambda_k} \left(t_2 + \frac{1}{\lambda_k} \right)$$

$$= \left(a + \frac{b}{\lambda_k} \right) B_j^k \frac{e^{-\lambda_k t_1} - e^{-\lambda_k t_2}}{\lambda_k} + bB_j^k \frac{t_1 e^{-\lambda_k t_1} - t_2 e^{-\lambda_k t_2}}{\lambda_k}$$

The time integrated value of the quantity of radioactivity in the source over the exposure duration is obtained by summing the above result over the radionuclides in the chain and over the parts of the release intervals that are within the period of time integration, after ensuring that each term is computed to the required precision.

B.5.2 Time Integration of Ingested Activity for Direct Ingestion of the Source

Direct ingestion of the source is possible while a portion of the source is being removed. The rate at which the source is ingested by a receptor is the product of the direct ingestion rate of the source and the fraction of time the receptor occupies the room where the source is located.

$$r_{di\,iRcp} = TF_{iRcp}^{SrcRm} r_{di}$$

where:

$r_{di\,iRcp}$ = rate of direct ingestion of the source by receptor $iRcp$,

TF_{iRcp}^{SrcRm} = fraction of time during which receptor $iRcp$ occupies the room where the source is located,

r_{di} = rate of direct ingestion of the source.

The airborne fraction of the removed material is not available for direct ingestion. The remainder is available for ingestion by each of the receptors who spend time in the same room as the source. The rate at which source material from a point, line, or area source is available for ingestion during a removal interval is given by the expression

$$r_s^m (1 - f_{air}^m)$$

where:

r_s^m = rate of removal of the source material during the m^{th} removal interval,

f_{air}^m = source material removed during the m^{th} removal interval that becomes airborne, expressed as a fraction of the source material that is removed during that interval.

The user-specified ingestion rate applies if there is sufficient material being removed to fulfill the ingestion by all receptors who occupy the room where the source is located. If not, the direct ingestion rate of the point, line, or area source will be limited by the rate of removal, yielding the expression,

$$r_{di} = minimum\left(r_{di}^{user}, \frac{r_s^m (1 - f_{air}^m)}{\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}} \right)$$

where:

r_{di} = rate of direct ingestion of the source,

r_{di}^{user} = value the user input for direct ingestion as a fraction of the initial source material per time,

r_s^m = rate of removal of the source material during the m^{th} removal interval,

f_{air}^m = source material removed during the m^{th} removal interval that becomes airborne, expressed as a fraction of the source material that is removed during that interval,

TF_{iRcp}^{SrcRm} = fraction of time during which receptor $iRcp$ occupies the room where the source is located,

$\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}$ = sum of the fractions of time each receptor spends in the room where the source is located.

The direct ingestion rate of a volume source is specified on a mass basis. This is divided by the initial mass of the contaminated layer and checked against the expression for the removal rate expressed as a fraction of the initial mass. The direct ingestion rate of a non-tritium volume source is given by the expression

$$r_{di} = minimum\left(\frac{r_{di}^{user}}{T_c A_s \rho_b^s}, \frac{r_s \ (1 - f_{air})}{\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}}\right)$$

where:

r_{di} = rate of direct ingestion of source,

r_{di}^{user} = user input value for direct ingestion on the basis of the mass of source material,

T_c = thickness of the contaminated region c of the source,

A_s = area of the volume source,

ρ_b^s = dry bulk density of the contaminated region of the volume source,

r_s = rate of removal of the source material expressed in terms of a fraction of the initial mass,

f_{air} = source material removed that becomes airborne, expressed as a fraction of the source material that is removed during that interval,

TF_{iRcp}^{SrcRm} = fraction of time during which receptor $iRcp$ occupies the room where the source is located,

$\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}$ = sum of the fractions of time each receptor spends in the room where the source is located.

Only the non-volatilizable ^3H is modeled as being ingestible. The direct ingestion rate of a tritium volume source is given by the expression

$$r_{di} = \left(1 - f_{air}^{H_2O}\right) minimum\left(\frac{r_{di}^{user}}{T_c A_s \rho_b^s}, \frac{r_s \ (1 - f_{air})}{\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}}\right)$$

where:

$f_{air}^{H_2O}$ = fraction of water in the tritium source that is vaporizable.

The instantaneous rate of ingestion of radioactivity is obtained by combining the initial activity of the initially present radionuclide, the factor for radiological transformations and the direction ingestion rate expressed in terms of the fraction of the source material

$$\dot{Q}^{j}_{ing,iRcp}(t) = TF^{SrcRm}_{iRcp} r_{di}\, Q^{i}_{s}(0) \sum_{k=1}^{j} B^{k}_{j} e^{-\lambda_k t}$$

where:

$\dot{Q}^{j}_{ing,iRcp}(t)$ = instantaneous rate of ingestion the jth radionuclide in the transformation chain of radionuclide i by receptor $iRcp$.

Consider the integral of a single term in the sum above

$$\int_{t_1}^{t_2} B^{k}_{j} e^{-\lambda_k t} dt = B^{k}_{j} \frac{e^{-\lambda_k t_1} - e^{-\lambda_k t_2}}{\lambda_k}$$

The quantity of radioactivity ingested by a receptor over the exposure duration is obtained by summing the following expression over the portions of the removal intervals that are within the exposure duration, after ensuring that each term is computed to the required precision:

$$Q^{j}_{ing,iRcp}(t) = TF^{SrcRm}_{iRcp} r_{di}\, Q^{i}_{s}(0) \sum_{k=1}^{j} B^{k}_{j} \frac{e^{-\lambda_k t_1} - e^{-\lambda_k t_2}}{\lambda_k} \quad \text{(B.9)}$$

where:

$Q^{j}_{ing,iRcp}(t)$ = quantity of the jth radionuclide in the transformation chain of radionuclide i that is ingested by receptor $iRcp$ over the exposure duration beginning at time t.

B.6 FATE OF SOLID SOURCE MATERIAL AND WATER VAPOR RELEASED TO AIR

The fate of the solid source material and water vapor released to air is computed using a transient model described in this section. The transient model is developed by representing the processes modeled by rate equations. The fate of the two radon isotopes, ^{220}Rn and ^{222}Rn, released to air and their three short-lived progeny produced after their release are modeled using the steady-state models described in Section B.7. Except for vaporizable tritiated water, ^{3}HHO, the properties used to model release and fate are independent of the radionuclide. Thus, for all the other cases, the effects of radiological transformation can be modeled independently of the modeling of the fate of the source material released to air. Buildings with up to 9 “rooms” or 9 fully mixed air spaces can be modeled using the transient model in RESRAD-BUILD Version 4.0. Both an analytical solution and a numerical solution to the transient model are included in the code. The analytical solution is limited to simulations that involve buildings with 3 or fewer rooms, releases that are constant over a time interval, and for cases where the system of equations described in B.6.2 have distinct eigen values and unique coefficients for the eigen vector terms, step 5 of Section B.6.4. The numerical solutions, which are potentially slower, model time-varying releases in buildings with up to 9 rooms, provided the time step selected is appropriate. The code uses the analytical solution when possible unless instructed otherwise.

B.6.1 Rate of Release to Air

The computation of the rate of release of source material to air depends on the type of source and, in the case of a volume source, on whether it contains vaporizable tritiated water.

The rate of release of solid source material from a point, line, or area source to air is constant over each release interval and is given by

$$rel_s^m = f_{air}^m r_s^m = f_{air}^m \frac{f_{removed}^m}{t_{end}^m - t_{start}^m}$$

where:

rel_s^m = rate of release of solid source material to air from source s during the m^{th} removal interval,

f_{air}^m = source material removed during the m^{th} removal interval that becomes airborne, expressed as a fraction of the source material that is removed during that interval,

r_s^m = rate of removal of the source material during the m^{th} removal interval,

$f_{removed}^m$ = fraction of source material removed during the m^{th} removal interval,

t_{end}^m = time at which the m^{th} removal interval ends,

t_{start}^m = time at which the m^{th} removal interval begins.

The rate of release of solid source material from a volume source to air is constant over time and is given by

$$rel_s = f_{air} r_s = f_{air} \frac{\varepsilon_c}{T_c}$$

where:

rel_s = rate of release of solid source material to air from source s,

f_{air} = eroded source material that becomes airborne, expressed as a fraction of the source material that is eroded,

r_s = rate of removal of the source material,

T_c = thickness of the contaminated region, c, of the source,

ε_c = rate of erosion of the contaminated region, c, of the source.

The rate of release of solid source material is written to the temporary file "AirRelRate#.out" where # is the identification number of the source.

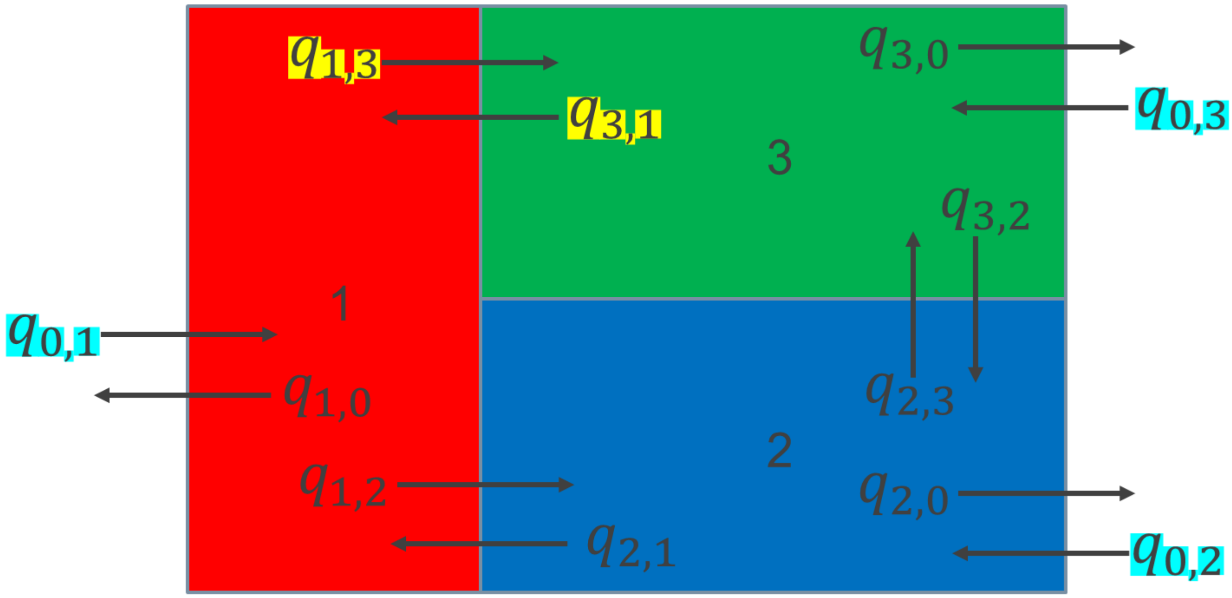
The rate of release of tritiated water from a volume source is equal to the rate of removal of tritiated water from the source. The rate of removal of tritiated water from a volume source is discussed in Section B.3.3 and is given by Equation B.4.

B.6.2 Description and Mathematical Representation of Process Considered in Transient Model of the Fate of Source Material

The transient model balances the air flows into and out of each room. It also maintains mass balance of the source material.

B.6.2.1 Air Flows

- The model considers air flows in both directions between every pair of rooms, not the net flow between rooms. This is illustrated for a three-roomed building in Figure B-2.
- The model considers air flows in both directions between each room and the outdoors.
- The model requires user input of air flows between rooms and from each room to the outdoors. These air flows must each be non-negative. The air flow from a room is assumed to have the same concentration of source material as the air in that room. These flows directly affect the source material balance.
- The model ensures flow balance for each room, i.e., sum of inflows = sum of outflows. Flow from the outdoors into each room is the sum of outflows from that room minus the sum of the inflows to the room from other rooms. Air flow from the outdoors is assumed not to contain any source material. Therefore, this flow does not directly affect the particulate balance. Hence, the choice to make it the variable that is determined by flow balance and not be a user input. These air flows must also be non-negative.



$$q_{0,i} = \sum_{j=0,j\neq i}^{j=n} q_{i,j} - \sum_{j=1,j\neq i}^{j=n} q_{j,i} = q_{i,0} + \sum_{j=1,j\neq i}^{j=n} \left(q_{i,j} - q_{j,i}\right) \geq 0 \;\forall\; 1 \leq i \leq n$$

Figure B-2 Airflows in a Three-Room Building

B.6.2.2 Movement of Source Material

The movement of source material for a three-room building is illustrated in Figure B-3.

- The model considers release of source material into the room where the source is located.
  - Particulates are modeled as being released at a constant rate over each release interval.
  - Vaporizable moisture is modeled as being released at a rate that varies continuously with time.
  - Radon is modeled as being released at a rate that depends on the quantity of the radon parent remaining in the source and the quantity of radon parent in the source particulates in the air and on the floor.
- The releases are modeled as being instantaneously fully mixed in the air in the room of release.
- The movement of source material with the air flow out of the rooms is modeled.
  - Air flow from a room is assumed to have the same concentration of source material as the air in that room.
  - Source material that flowed into an adjoining room can subsequently flow back into the room of release.

- The exchange of source material between the air in a room and the floor of the room is modeled.
  - Deposition of the material suspended in air is characterized by a single deposition velocity that applies to all the rooms in the building and for all the sources. The deposition velocity of zero is used for vaporizable tritiated water and for the radon isotopes.
  - Resuspension of material deposited on the floor is characterized by resuspension rates that are specific to each room. They apply to solid source material from all sources; they are not source-specific.

- The periodic removal of deposited source material due to vacuuming or sweeping is modeled.
  - Cleaning of the floors is quantified by the efficiency and by frequency.

- The model considers the balance of source material.
  - Both for the material suspended in air and for the material deposited on the floor.
  - The rate of change in the quantity of source material either in the air or on the floor is equal to the net flow of material to that location.

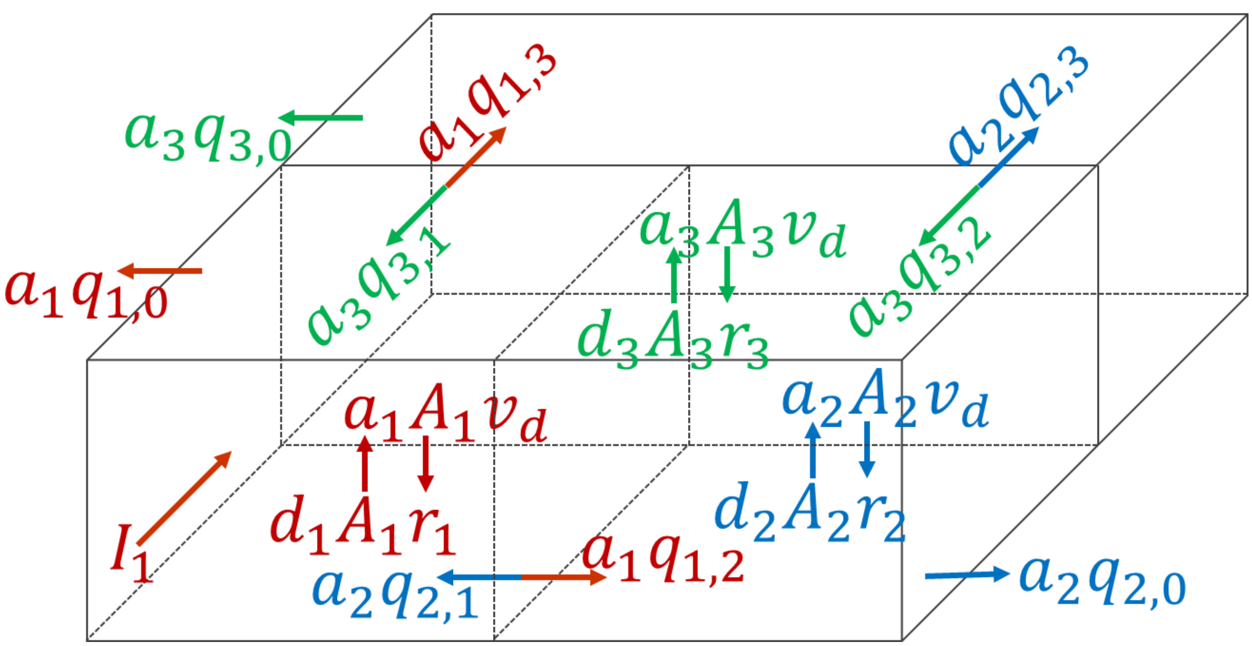


Figure B-3 Movement of Source Material in a Three-Room Building

B.6.2.3 Balance of Source Material

The rate of change of source material suspended in air is given by equating it to the net inflow of material to air in the room

$$V_i \frac{d}{dt} a_i = I_i + \sum_{j=0, j \neq i}^{j=n} a_j q_{j,i} - a_i \left(A_i v_d + \sum_{j=0, j \neq i}^{j=n} q_{i,j} \right) + d_i A_i r_i \tag{B.10}$$

where:

V_i = volume of the i^{th} room,

a_i = fraction of the source material in a unit volume of air in room i,

I_i = rate at which the source material is released into the air in room i,

$q_{i,j}$ = volumetric flow rate of air from room i to room j,

A_i = surface area of the i^{th} room,

v_d = representative deposition velocity of the particulates of source material,

d_i = fraction of the source material on a unit floor area of room i,

r_i = resuspension rate of particulates from the floor of room i.

This expression relates the rate of change of the concentration of source material suspended in air in the i^{th} room to the concentration of the source material suspended in the air in each of the rooms in the building, the concentration of source material deposited on the floor of the i^{th} room, and to any release of source material to the i^{th} room.

The rate of change of source material deposited on the floor is given by equating it to the net inflow of material to the floor in the room

$$A_i \frac{d}{dt} d_i = a_i A_i v_d - d_i A_i r_i \tag{B.11}$$

This expression relates the rate of change of the concentration of source material deposited on the floor of the i^{th} room to the concentration of the source material suspended in air in the i^{th} room in the building and the concentration of source material deposited on the floor of the i^{th} room.

B.6.2.4 Initial Conditions

The initial conditions to be satisfied by the solutions to the system of equations in Equations B.10 and B.11 are the concentrations of the source material suspended in the air and deposited on the floor of each of the rooms at a specific time, typically at time zero or at the time the floor is vacuumed.

B.6.3 Analytical Solution for the Transient Concentration of Solid Source Material Released at a Constant Rate for a One-Room Simulation

The steps involved in the analytical solution for the fate of the solid source material implemented in RESRAD-BUILD Version 4.0 for a one-room simulation are as follows:

Step 1. Determine the coefficients, $c_{1,1}, c_{1,2}, c_{2,1}, c_{2,2}$ and c_1, of the system of differential equations

$$\begin{bmatrix} \dot{a}_1 \\ \dot{d}_1 \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} \\ c_{2,1} & c_{2,2} \end{bmatrix} \begin{bmatrix} a_1 \\ d_1 \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \end{bmatrix}$$

$$c_{1,1} = -\frac{A_1 v_d + q_{1,0}}{V_1}$$

$$c_{1,2} = \frac{A_1 r_1}{V_1}$$

$$c_{2,1} = v_d$$

$$c_{2,2} = -r_1$$

$$c_1 = \frac{rel_s}{V_1}$$

The matrix of the coefficients of the system of equations is written to the temporary file "CoefSysEqn.out."

Step 2. Determine the eigen values, λ_1^{ev} and λ_2^{ev}, of the coefficient matrix $\begin{bmatrix} c_{1,1} & c_{1,2} \\ c_{2,1} & c_{2,2} \end{bmatrix}$

$$\begin{vmatrix} c_{1,1} - \lambda^{ev} & c_{1,2} \\ c_{2,1} & c_{2,2} - \lambda^{ev} \end{vmatrix} = 0$$

$$(c_{1,1} - \lambda^{ev})(c_{2,2} - \lambda^{ev}) - c_{1,2}c_{2,1} = 0$$

$$\lambda_1^{ev} = \frac{c_{1,1} + c_{2,2} + \sqrt{(c_{1,1} - c_{2,2})^2 + 4c_{1,2}c_{2,1}}}{2}$$

$$\lambda_2^{ev} = \frac{c_{1,1} + c_{2,2} - \sqrt{(c_{1,1} - c_{2,2})^2 + 4c_{1,2}c_{2,1}}}{2}$$

The code writes information about the eigen value calculations to the temporary file, "EigenValues.out." If the eigen vectors are identical, the code will set them to 0.999999 and 1.000001 times the identical value. This will allow the analytical solution to proceed while using eigen values that are practically the same. These adjusted values are also written to the temporary file “EigenValues.out.” The eigen values apply over the entire time horizon and need to be calculated only once for a one-room simulation.

Step 3. Determine the corresponding eigen vectors, $\widehat{ev}_i$.

$$\widehat{ev}_i = \begin{bmatrix} c_{2,2} - \lambda_i^{ev} \\ -c_{2,1} \end{bmatrix}$$

The eigen vectors apply over the entire time horizon and need to be calculated only once for a one-room simulation. The eigen vectors are written to the temporary file “EigenVectors.out.”

Step 4. Determine the particular solution, $\widehat{ps}$, for the constant release c_1

$$\widehat{ps} = \frac{c_1}{c_{1,1} - c_{2,1}\dfrac{c_{1,2}}{c_{2,2}}} \begin{bmatrix} -1 \\ \dfrac{c_{2,1}}{c_{2,2}} \end{bmatrix}$$

The particular solution is specific to each release interval of each source and depends on the value of c_1 for that interval; the other coefficients are constant over the time horizon. The value of c_1 is affected by the rate at which the source material is released to air. The rate of release of source material to air is discussed in Section B.6.1. The particular solution is written to the temporary file “EigenVectors.out.”

Step 5. Determine the coefficients, C_1 and C_2, of the complimentary solution that meet the initial condition

$$\begin{bmatrix} a_1(t_b) \\ d_1(t_b) \end{bmatrix} = \widehat{ps} + C_1\widehat{ev}_1 + C_2\widehat{ev}_2$$

These coefficients depend on the concentrations of the source material suspended in air and deposited on the floor at the beginning of the vacuuming interval or the release interval, including no release intervals. They need to be evaluated for each of these intervals using the initial condition for the first such interval and the concentration computed previously in step 6 for subsequent intervals.

Step 6. Evaluate the concentrations at the end of each release and or vacuuming interval using the expression for the concentrations

$$\begin{bmatrix} a_1(t) \\ d_1(t) \end{bmatrix} = \widehat{ps} + C_1\widehat{ev}_1 e^{\lambda_1^{ev}(t-t_b)} + C_2\widehat{ev}_2 e^{\lambda_2^{ev}(t-t_b)}$$

Factor the effect of cleaning the floor, if it is a vacuuming interval

$$d_1(t) = (1 - eff_{vac})\, d_1(t)$$

where:

eff_{vac} = efficiency of vacuuming or sweeping the floors.

The concentrations at the end of an interval are the concentrations at the beginning of the next release interval, there being no release interval or vacuuming interval. Progressively evaluate the coefficients of the complimentary solution and the concentrations at the end of successive intervals using steps 5 and 6. The concentrations are only evaluated at the end of each release or vacuuming interval and not at any intermediate times because the time-integrated or time-averaged concentration over the exposure duration is calculated analytically as described in Section B.6.6.

B.6.4 Analytical Solution for the Transient Concentration of Solid Source Material Released at a Constant Rate for a Three-Room Simulation

The steps involved in the analytical solution for the fate of the solid source material implemented in RESRAD-BUILD Version 4.0 for a three-room simulation are as follows:

Step 1. Determine the coefficients, $c_{\mathrm{i,j}}$, of the system of differential equations; the one- and two-room situations are subsets of this as shown by the green and blue overlays.

$$\begin{bmatrix} \dot{a}_1 \\ \dot{d}_1 \\ \dot{a}_2 \\ \dot{d}_2 \\ \dot{a}_3 \\ \dot{d}_3 \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & c_{1,5} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & c_{3,5} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & 0 & 0 \\ c_{5,1} & 0 & c_{5,3} & 0 & c_{5,5} & c_{5,6} \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6} \end{bmatrix} \begin{bmatrix} a_1 \\ d_1 \\ a_2 \\ d_2 \\ a_3 \\ d_3 \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$c_{1,1} = -\frac{A_1 v_d + q_{1,0} + q_{1,2} + q_{1,3}}{V_1}$$

$$c_{3,3,} = -\frac{A_2 v_d + q_{2,0} + q_{2,1} + q_{2,3}}{V_1}$$

$$c_{5,5} = -\frac{A_3 v_d + q_{3,0} + q_{3,1} + q_{3,2}}{V_1}$$

$$c_{1,2} = \frac{A_1 r_1}{V_1}, \qquad c_{3,4} = \frac{A_2 r_2}{V_2}, \qquad c_{5,6} = \frac{A_3 r_3}{V_3}$$

$$c_{1,3} = \frac{q_{2,1}}{V_1}, \qquad c_{1,5} = \frac{q_{3,1}}{V_1}, \qquad c_{3,1} = \frac{q_{1,2}}{V_2}, \qquad c_{3,5} = \frac{q_{3,2}}{V_2}, \qquad c_{5,1} = \frac{q_{1,3}}{V_3}, \qquad c_{3,5} = \frac{q_{2,3}}{V_3}$$

$$c_{2,1} = c_{4,3} = c_{6,5} = v_d$$

$$c_{2,2} = -r_1, \qquad c_{4,4} = -r_2, \qquad c_{6,6} = -r_3$$

$$c_1 = \frac{rel_s}{V_1}$$

The matrix of the coefficients of the system of equations is written to the temporary file "CoefSysEqn.out."

Preparatory steps 2, 3, and 4, prepare to determine the eigen values, λ, and the eigen vectors, $\widehat{ev}$, of the coefficient matrix and the particular solution for the constant rate release.

$$\begin{bmatrix} c_{1,1}-\lambda & c_{1,2} & c_{1,3} & 0 & c_{1,5} & 0 \\ c_{2,1} & c_{2,2}-\lambda & 0 & 0 & 0 & 0 \\ c_{3,1} & 0 & c_{3,3}-\lambda & c_{3,4} & c_{3,5} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4}-\lambda & 0 & 0 \\ c_{5,1} & 0 & c_{5,3} & 0 & c_{5,5}-\lambda & c_{5,6} \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6}-\lambda \end{bmatrix} \widehat{ev} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Perform elementary row operations to allow the components of the eigen vector to be specified in terms of the first component, the concentration in air in the source room.

a. Use the even rows to eliminate the off-diagonal components in the even columns.

$$\begin{bmatrix} c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda} & 0 & c_{1,3} & 0 & c_{1,5} & 0 \\ c_{2,1} & c_{2,2}-\lambda & 0 & 0 & 0 & 0 \\ c_{3,1} & 0 & c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda} & 0 & c_{3,5} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4}-\lambda & 0 & 0 \\ c_{5,1} & 0 & c_{5,3} & 0 & c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda} & 0 \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6}-\lambda \end{bmatrix} \widehat{ev} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

b. Use rows three and five to eliminate the off-diagonal components in the third and fifth columns of those rows.

$$\left[\begin{matrix} c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda} & 0 & c_{1,3} & 0 \\ c_{2,1} & c_{2,2}-\lambda & 0 & 0 \\ c_{3,1}-\frac{c_{5,1}c_{3,5}}{c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}} & 0 & c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}-\frac{c_{5,3}c_{3,5}}{c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4}-\lambda \\ c_{5,1}-\frac{c_{5,3}c_{3,1}}{c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{matrix}\right.$$

$$
\left.\begin{matrix}
c_{1,5} & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 \\
c_{6,5} & c_{6,6} - \lambda
\end{matrix}\right]
$$

c. Use the third and fifth rows to eliminate the off-diagonal components in the first row.

$$
\left[\begin{matrix}
c'_{1,1} & 0 & 0 & 0 \\
c_{2,1} & c_{2,2} - \lambda & 0 & 0 \\
c_{3,1} - \dfrac{c_{5,1}c_{3,5}}{c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}} & 0 & c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda} - \dfrac{c_{5,3}c_{3,5}}{c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}} & 0 \\
0 & 0 & c_{4,3} & c_{4,4} - \lambda \\
c_{5,1} - \dfrac{c_{5,3}c_{3,1}}{c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{matrix}\right.
$$

$$
\left.\begin{matrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 \\
c_{6,5} & c_{6,6} - \lambda
\end{matrix}\right] \widehat{ev} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
$$

The component in the first column of the first row is then,

$$c'_{1,1} = c_{1,1} - \lambda - \frac{c_{2,1}c_{1,2}}{c_{2,2} - \lambda} - c_{1,3}\frac{c_{3,1} - \cfrac{c_{5,1}c_{3,5}}{c_{5,5} - \lambda - \cfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}}}{c_{3,3} - \lambda - \cfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda} - \cfrac{c_{5,3}c_{3,5}}{c_{5,5} - \lambda - \cfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}}}$$

$$- c_{1,5}\frac{c_{5,1} - \cfrac{c_{5,3}c_{3,1}}{c_{3,3} - \lambda - \cfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}}}{c_{5,5} - \lambda - \cfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda} - \cfrac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda - \cfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}}}$$

Step 2. Determine the eigen values of the coefficient matrix $\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & c_{1,5} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & c_{3,5} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & 0 & 0 \\ c_{5,1} & 0 & c_{5,3} & 0 & c_{5,5} & c_{5,6} \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6} \end{bmatrix}$

The eigen values are the values of λ which satisfy the expression

$$\begin{vmatrix} c_{1,1} - \lambda & c_{1,2} & c_{1,3} & 0 & c_{1,5} & 0 \\ c_{2,1} & c_{2,2} - \lambda & 0 & 0 & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} - \lambda & c_{3,4} & c_{3,5} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} - \lambda & 0 & 0 \\ c_{5,1} & 0 & c_{5,3} & 0 & c_{5,5} - \lambda & c_{5,6} \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6} - \lambda \end{vmatrix} = 0$$

Writing out the determinant gives

$$\begin{aligned} \{(c_{1,1} - \lambda)(c_{2,2} - \lambda) - c_{1,2}c_{2,1}\} &\times \{(c_{3,3} - \lambda)(c_{4,4} - \lambda) - c_{4,3}c_{3,4}\} \\ &\times \{(c_{5,5} - \lambda)(c_{6,6} - \lambda) - c_{6,5}c_{5,6}\} \\ &- c_{5,3}c_{3,5}\{(c_{1,1} - \lambda)(c_{2,2} - \lambda) - c_{1,2}c_{2,1}\}(c_{4,4} - \lambda)(c_{6,6} - \lambda) \\ &- c_{1,3}c_{3,1}(c_{2,2} - \lambda)(c_{4,4} - \lambda)\{(c_{5,5} - \lambda)(c_{6,6} - \lambda) - c_{6,5}c_{5,6}\} \\ &- c_{1,5}c_{5,1}(c_{2,2} - \lambda)\{(c_{3,3} - \lambda)(c_{4,4} - \lambda) - c_{4,3}c_{3,4}\}(c_{6,6} - \lambda) \\ &+ (c_{1,3}c_{3,5}c_{5,1} + c_{1,5}c_{3,1}c_{5,3})(c_{2,2} - \lambda)(c_{4,4} - \lambda)(c_{6,6} - \lambda) = 0 \end{aligned}$$

Alternatively, the determinant can be written out using the transformed matrix that was developed in pre-steps 2, 3, and 4. This is done at the end of this discussion of step 2 to verify by an alternative means that the determinant listed above is correct.

The determinant can be expanded out in the form

$$\lambda^6 + c_{\lambda_6^5}\lambda^5 + c_{\lambda_6^4}\lambda^4 + c_{\lambda_6^3}\lambda^3 + c_{\lambda_6^2}\lambda^2 + c_{\lambda_6^1}\lambda^1 + c_{\lambda_6^0}\lambda^0 = 0$$

with:

$$c_{\lambda_6^5} = -c_{1,1} - c_{2,2} - c_{3,3} - c_{4,4} - c_{5,5} - c_{6,6}$$

$$\begin{aligned} c_{\lambda_6^4} = &\left(c_{1,1} + c_{2,2}\right)\left(c_{3,3} + c_{4,4}\right) + \left(c_{3,3} + c_{4,4}\right)\left(c_{5,5} + c_{6,6}\right) + \left(c_{5,5} + c_{6,6}\right)\left(c_{1,1} + c_{2,2}\right) \\ &+ \left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right) + \left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right) + \left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) - c_{1,3}c_{3,1} \\ &- c_{1,5}c_{5,1} - c_{3,5}c_{5,3} \end{aligned}$$

$$\begin{aligned} c_{\lambda_6^3} = &-\left(c_{1,1} + c_{2,2}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4} + c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- \left(c_{3,3} + c_{4,4}\right)\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1} + c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- \left(c_{5,5} + c_{6,6}\right)\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1} + c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right) \\ &- \left(c_{1,1} + c_{2,2}\right)\left(c_{3,3} + c_{4,4}\right)\left(c_{5,5} + c_{6,6}\right) + c_{1,3}c_{3,1}\left(c_{2,2} + c_{4,4} + c_{5,5} + c_{6,6}\right) \\ &+ c_{1,5}c_{5,1}\left(c_{2,2} + c_{3,3} + c_{4,4} + c_{6,6}\right) + c_{3,5}c_{5,3}\left(c_{1,1} + c_{2,2} + c_{4,4} + c_{6,6}\right) \\ &- c_{1,5}c_{3,1}c_{5,3} - c_{1,3}c_{3,5}c_{5,1} \end{aligned}$$

$$\begin{aligned} c_{\lambda_6^2} = &\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right) + \left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &+ \left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right)\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right) \\ &+ \left(c_{1,1} + c_{2,2}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)\left(c_{5,5} + c_{6,6}\right) \\ &+ \left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)\left(c_{3,3} + c_{4,4}\right)\left(c_{5,5} + c_{6,6}\right) \\ &+ \left(c_{1,1} + c_{2,2}\right)\left(c_{3,3} + c_{4,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- c_{1,3}c_{3,1}\left\{c_{2,2}c_{4,4} + \left(c_{2,2} + c_{4,4}\right)\left(c_{5,5} + c_{6,6}\right) + c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right\} \\ &- c_{1,5}c_{5,1}\left\{c_{2,2}c_{6,6} + \left(c_{2,2} + c_{6,6}\right)\left(c_{3,3} + c_{4,4}\right) + c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right\} \\ &- c_{3,5}c_{5,3}\left\{c_{4,4}c_{6,6} + \left(c_{4,4} + c_{6,6}\right)\left(c_{1,1} + c_{2,2}\right) + c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right\} \\ &+ \left(c_{2,2} + c_{4,4} + c_{6,6}\right)\left(c_{1,5}c_{3,1}c_{5,3} + c_{1,3}c_{3,5}c_{5,1}\right) \end{aligned}$$

$$\begin{aligned} c_{\lambda_6^1} = &-\left(c_{1,1} + c_{2,2}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- \left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)\left(c_{3,3} + c_{4,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- \left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)\left(c_{5,5} + c_{6,6}\right) \\ &+ c_{1,3}c_{3,1}\left\{\left(c_{2,2} + c_{4,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) + c_{2,2}c_{4,4}\left(c_{5,5} + c_{6,6}\right)\right\} \\ &+ c_{1,5}c_{5,1}\left\{\left(c_{2,2} + c_{6,6}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right) + c_{2,2}c_{6,6}\left(c_{3,3} + c_{4,4}\right)\right\} \\ &+ c_{3,5}c_{5,3}\left\{\left(c_{4,4} + c_{6,6}\right)\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right) + c_{4,4}c_{6,6}\left(c_{1,1} + c_{2,2}\right)\right\} \\ &- \left(c_{2,2}c_{4,4} + c_{2,2}c_{6,6} + c_{4,4}c_{6,6}\right)\left(c_{1,5}c_{3,1}c_{5,3} + c_{1,3}c_{3,5}c_{5,1}\right) \end{aligned}$$

$$\begin{aligned} c_{\lambda_6^0} = &\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) \\ &- c_{1,3}c_{3,1}c_{2,2}c_{4,4}\left(c_{5,5}c_{6,6} - c_{6,5}c_{5,6}\right) - c_{1,5}c_{5,1}\left(c_{3,3}c_{4,4} - c_{4,3}c_{3,4}\right)c_{2,2}c_{6,6} \\ &- c_{3,5}c_{5,3}\left(c_{1,1}c_{2,2} - c_{1,2}c_{2,1}\right)c_{4,4}c_{6,6} + c_{2,2}c_{4,4}c_{6,6}\left(c_{1,5}c_{3,1}c_{5,3} + c_{1,3}c_{3,5}c_{5,1}\right) \end{aligned}$$

The first two eigen values are obtained using the Newton-Raphson iterative method with initial estimates of 0 and $c_{1,1}$. The expression for the successive iterative estimate is then

$$\lambda = \frac{5\lambda^6 + 4c_{\lambda_6^5}\lambda^5 + 3c_{\lambda_6^4}\lambda^4 + 2c_{\lambda_6^3}\lambda^3 + 1c_{\lambda_6^2}\lambda^2 + 0c_{\lambda_6^1}\lambda^1 - 1c_{\lambda_6^0}\lambda^0}{6\lambda^5 + 5c_{\lambda_6^5}\lambda^4 + 4c_{\lambda_6^4}\lambda^3 + 3c_{\lambda_6^3}\lambda^2 + 2c_{\lambda_6^2}\lambda^1 + 1c_{\lambda_6^1}\lambda^0}$$

The code compares the absolute value of the difference between the last two estimates with the last estimate. It continues iterating until either the absolute value of the difference is less than one millionth (10^{-6}) of the last estimate or the number of iterations exceeds 50.

The code writes the coefficients of the polynomial of eigen values and the eigen values that were calculated using those coefficients to the temporary file “EigenValues.out.”

Factoring out these two eigen values gives the expression for the remaining four eigen values.

$$\left(\lambda^6 + c_{\lambda_6^5}\lambda^5 + c_{\lambda_6^4}\lambda^4 + c_{\lambda_6^3}\lambda^3 + c_{\lambda_6^2}\lambda^2 + c_{\lambda_6^1}\lambda^1 + c_{\lambda_6^0}\lambda^0\right)$$
$$= (\lambda - \lambda_1^{ev})(\lambda - \lambda_2^{ev})\left(\lambda^4 + c_{\lambda_4^3}\lambda^3 + c_{\lambda_4^2}\lambda^2 + c_{\lambda_4^1}\lambda^1 + c_{\lambda_4^0}\lambda^0\right)$$

$$\lambda^4 + c_{\lambda_4^3}\lambda^3 + c_{\lambda_4^2}\lambda^2 + c_{\lambda_4^1}\lambda^1 + c_{\lambda_4^0}\lambda^0 = 0$$

with:

$$c_{\lambda_4^3} = c_{\lambda_6^5} + \lambda_1^{ev} + \lambda_2^{ev}$$

$$c_{\lambda_4^2} = c_{\lambda_6^4} + (\lambda_1^{ev} + \lambda_2^{ev})c_{\lambda_4^3} - \lambda_1^{ev}\lambda_2^{ev}$$

$$c_{\lambda_4^1} = c_{\lambda_6^3} + (\lambda_1^{ev} + \lambda_2^{ev})c_{\lambda_4^2} - \lambda_1^{ev}\lambda_2^{ev}c_{\lambda_4^3}$$

$$c_{\lambda_4^0} = c_{\lambda_6^2} + (\lambda_1^{ev} + \lambda_2^{ev})c_{\lambda_4^1} - \lambda_1^{ev}\lambda_2^{ev}c_{\lambda_4^2}$$

$$c_{\lambda_4^0}^{check} = c_{\lambda_6^0} \div (\lambda_1^{ev}\lambda_2^{ev})$$

The code writes the coefficients of the polynomial of the four remaining eigen values, the product of the remaining eigen values, $c_{\lambda_4^0}^{check}$, and the next two eigen values that are calculated using those coefficients to the temporary file “EigenValues.out.” These two eigen values are obtained using the Newton-Raphson iterative method, again with initial estimates of 0 and $c_{1,1}$. The expression for the successive iterative estimate is then

$$\lambda = \frac{3\lambda^4 + 2c_{\lambda_4^3}\lambda^3 + 1c_{\lambda_4^2}\lambda^2 + 0c_{\lambda_4^1}\lambda^1 - 1c_{\lambda_4^0}\lambda^0}{4\lambda^3 + 3c_{\lambda_4^3}\lambda^2 + 2c_{\lambda_4^2}\lambda^1 + 1c_{\lambda_4^1}\lambda^0}$$

Factoring out these two eigen values gives the expression for the remaining two eigen values

$$\left(\lambda^4 + c_{\lambda_4^3}\lambda^3 + c_{\lambda_4^2}\lambda^2 + c_{\lambda_4^1}\lambda^1 + c_{\lambda_4^0}\lambda^0\right) = (\lambda - \lambda_3^{ev})(\lambda - \lambda_4^{ev})\left(\lambda^2 + c_{\lambda_2^1}\lambda^1 + c_{\lambda_2^0}\lambda^0\right)$$

$$\lambda^2 + c_{\lambda_2^1}\lambda^1 + c_{\lambda_2^0}\lambda^0 = 0$$

with:

$$c_{\lambda_2^1} = c_{\lambda_4^3} + \lambda_3^{ev} + \lambda_4^{ev}$$

$$c_{\lambda_2^0} = c_{\lambda_4^2} + (\lambda_3^{ev} + \lambda_4^{ev})c_{\lambda_2^1} - \lambda_3^{ev}\lambda_4^{ev}$$

$$c_{\lambda_2^0}^{check} = c_{\lambda_4^0} \div (\lambda_3^{ev}\lambda_4^{ev})$$

The code writes the coefficients of the polynomial of the two remaining eigen values, the product of the remaining eigen values, $c_{\lambda_2^0}^{check}$, and the last two eigen values that are calculated using those coefficients to the temporary file, "EigenValues.out."

The last two eigen values are determined directly

$$\lambda_5^{ev} = \frac{-c_{\lambda_2^1} + \sqrt{\left(c_{\lambda_2^1}\right)^2 + 4c_{\lambda_2^0}}}{2}$$

$$\lambda_6^{ev} = \frac{-c_{\lambda_2^1} - \sqrt{\left(c_{\lambda_2^1}\right)^2 + 4c_{\lambda_2^0}}}{2}$$

If the eigen vectors are identical, the code will set them each apart by no more than 0.000002 times the identical value. This will allow the analytical solution to proceed while using eigen values that are practically the same. These adjusted values are also written to the temporary file "EigenValues.out."

The eigen values apply over the entire time horizon and need to be calculated only once for a simulation.

Check of eigen value polynomial:

The determinant of the transformed matrix developed in the pre-steps 2, 3, and 4 is the product of its diagonal components. This is also the determinant of the coefficient matrix, as elementary row operations do not affect the determinant.

$$\left(c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}-c_{1,3}\frac{c_{3,1}-\dfrac{c_{5,1}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}-\dfrac{c_{5,3}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}}}\right.$$
$$\left.-c_{1,5}\frac{c_{5,1}-\dfrac{c_{5,3}c_{3,1}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}-\dfrac{c_{5,3}c_{3,5}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}}}\right)$$
$$\times\left(c_{2,2}-\lambda\right)\left(c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}-\frac{c_{5,3}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}}\right)$$
$$\times\left(c_{4,4}-\lambda\right)\left(c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}-\frac{c_{5,3}c_{3,5}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}}\right)\left(c_{6,6}-\lambda\right)$$

The determinant will be zero when the first diagonal component is zero. It will not be zero when any of the other diagonal components are zero.

$$c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}-c_{1,3}\frac{c_{3,1}-\dfrac{c_{5,1}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}-\dfrac{c_{5,3}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}}}$$
$$-c_{1,5}\frac{c_{5,1}-\dfrac{c_{5,3}c_{3,1}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}-\dfrac{c_{5,3}c_{3,5}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}}}=0$$

$$c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}-c_{1,3}\frac{c_{3,1}\left(c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)-c_{5,1}c_{3,5}}{\left(c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)\left(c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)-c_{5,3}c_{3,5}}$$
$$-c_{1,5}\frac{c_{5,1}\left(c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)-c_{5,3}c_{3,1}}{\left(c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)\left(c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)-c_{5,3}c_{3,5}}=0$$

$$\begin{aligned}&\left(c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}\right)\left\{\left(c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)\left(c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)-c_{5,3}c_{3,5}\right\}\\ &\qquad -c_{1,5}c_{5,1}\left(c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)+c_{1,5}c_{5,3}c_{3,1}-c_{1,3}c_{3,1}\left(c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)\\ &\qquad +c_{1,3}c_{5,1}c_{3,5}=0\end{aligned}$$

$$\begin{aligned}&\left(c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}\right)\left(c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)\left(c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)\\ &\qquad -c_{5,3}c_{3,5}\left(c_{1,1}-\lambda-\frac{c_{2,1}c_{1,2}}{c_{2,2}-\lambda}\right)-c_{1,5}c_{5,1}\left(c_{3,3}-\lambda-\frac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}\right)\\ &\qquad -c_{1,3}c_{3,1}\left(c_{5,5}-\lambda-\frac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}\right)+c_{1,5}c_{5,3}c_{3,1}+c_{1,3}c_{5,1}c_{3,5}=0\end{aligned}$$

$$\begin{aligned}&\{(c_{1,1}-\lambda)(c_{2,2}-\lambda)-c_{1,2}c_{2,1}\}\times\{(c_{3,3}-\lambda)(c_{4,4}-\lambda)-c_{4,3}c_{3,4}\}\\ &\qquad \times\{(c_{5,5}-\lambda)(c_{6,6}-\lambda)-c_{6,5}c_{5,6}\}\\ &\qquad -c_{5,3}c_{3,5}\{(c_{1,1}-\lambda)(c_{2,2}-\lambda)-c_{1,2}c_{2,1}\}(c_{4,4}-\lambda)(c_{6,6}-\lambda)\\ &\qquad -c_{1,3}c_{3,1}(c_{2,2}-\lambda)(c_{4,4}-\lambda)\{(c_{5,5}-\lambda)(c_{6,6}-\lambda)-c_{6,5}c_{5,6}\}\\ &\qquad -c_{1,5}c_{5,1}(c_{2,2}-\lambda)\{(c_{3,3}-\lambda)(c_{4,4}-\lambda)-c_{4,3}c_{3,4}\}(c_{6,6}-\lambda)\\ &\qquad +(c_{1,3}c_{3,5}c_{5,1}+c_{1,5}c_{3,1}c_{5,3})(c_{2,2}-\lambda)(c_{4,4}-\lambda)(c_{6,6}-\lambda)=0\end{aligned}$$

This is the expression used in the beginning of this step for the determinant.

Step 3. Determine the corresponding eigen vectors.

The eigen values and the eigen vectors are related by the matrix obtained by performing the elementary row operations in preparatory steps 2, 3, and 4. Rows 2 through 6 can be used to express the second through sixth components of the eigen vector $\widehat{ev}_i$, corresponding to the eigen value λ_i^{ev}, in terms of the first component which represents the concentration of source material in air in the room of release.

$$\left[\begin{matrix} c'_{1,1} & 0 & 0 & 0 \\ c_{2,1} & c_{2,2}-\lambda & 0 & 0 \\ c_{3,1}-\dfrac{c_{5,1}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}} & 0 & c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}-\dfrac{c_{5,3}c_{3,5}}{c_{5,5}-\lambda-\dfrac{c_{6,5}c_{5,6}}{c_{6,6}-\lambda}} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4}-\lambda \\ c_{5,1}-\dfrac{c_{5,3}c_{3,1}}{c_{3,3}-\lambda-\dfrac{c_{4,3}c_{3,4}}{c_{4,4}-\lambda}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{matrix}\right.$$

$$
\begin{matrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
c_{5,5} - \lambda - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda} - \frac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 \\
c_{6,5} & c_{6,6} - \lambda
\end{matrix}\Bigg] \widehat{ev} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
$$

$$
\widehat{ev}_i = \begin{bmatrix}
1 \\
-\frac{c_{2,1}}{c_{2,2} - \lambda_i^{ev}} \\
-\frac{c_{3,1} - \frac{c_{5,1}c_{3,5}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}}}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}} - \frac{c_{5,3}c_{3,5}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}}}} \\
\frac{c_{4,3}}{c_{4,4} - \lambda_i^{ev}} \frac{c_{3,1} - \frac{c_{5,1}c_{3,5}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}}}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}} - \frac{c_{5,3}c_{3,5}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}}}} \\
-\frac{c_{5,1} - \frac{c_{5,3}c_{3,1}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}}}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}} - \frac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}}}} \\
\frac{c_{6,5}}{c_{6,6} - \lambda_i^{ev}} \frac{c_{5,1} - \frac{c_{5,3}c_{3,1}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}}}}{c_{5,5} - \lambda_i^{ev} - \frac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda_i^{ev}} - \frac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda_i^{ev} - \frac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda_i^{ev}}}}
\end{bmatrix}, \qquad \forall\, 0 < i \le 6
$$

The eigen vectors apply over the entire time horizon and need to be calculated only once in a simulation where all the rooms are connected by air flows. The eigen vectors are written to the temporary file “EigenVectors.out.”

Step 4. Determine the particular solution for the constant release c_1.

The particular solution, $\widehat{ps}$, is related to the constant rate release per volume of the room of release, c_1, by the matrix obtained by performing the elementary row operations in preparatory steps 2, 3, and 4 with $\lambda = 0$.

$$\begin{bmatrix} c'_{1,1} & 0 & 0 & 0 & 0 & 0 \\ c_{2,1} & c_{2,2} - \lambda & 0 & 0 & 0 & 0 \\ c_{3,1} - \dfrac{c_{5,1}c_{3,5}}{c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}} & 0 & c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda} - \dfrac{c_{5,3}c_{3,5}}{c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda}} & 0 & 0 & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} - \lambda & 0 & 0 \\ c_{5,1} - \dfrac{c_{5,3}c_{3,1}}{c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 & 0 & 0 & c_{5,5} - \lambda - \dfrac{c_{6,5}c_{5,6}}{c_{6,6} - \lambda} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \lambda - \dfrac{c_{4,3}c_{3,4}}{c_{4,4} - \lambda}} & 0 \\ 0 & 0 & 0 & 0 & c_{6,5} & c_{6,6} - \lambda \end{bmatrix} \widehat{ps} = - \begin{bmatrix} c_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$
\widehat{ps} = \frac{-c_1}{c'_{1,1}}
\begin{bmatrix}
1 \\
-\dfrac{c_{2,1}}{c_{2,2}} \\
-\dfrac{c_{3,1} - \dfrac{c_{5,1}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}} - \dfrac{c_{5,3}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}} \\
\dfrac{c_{4,3}}{c_{4,4}}\dfrac{c_{3,1} - \dfrac{c_{5,1}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}} - \dfrac{c_{5,3}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}} \\
-\dfrac{c_{5,1} - \dfrac{c_{5,3}c_{3,1}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}} \\
\dfrac{c_{6,5}}{c_{6,6}}\dfrac{c_{5,1} - \dfrac{c_{5,3}c_{3,1}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}}
\end{bmatrix}
$$

with:

$$
c'_{1,1} = c_{1,1} - \frac{c_{2,1}c_{1,2}}{c_{2,2}} - c_{1,3}\frac{c_{3,1} - \dfrac{c_{5,1}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}} - \dfrac{c_{5,3}c_{3,5}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}}}} - c_{1,5}\frac{c_{5,1} - \dfrac{c_{5,3}c_{3,1}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}}{c_{5,5} - \dfrac{c_{6,5}c_{5,6}}{c_{6,6}} - \dfrac{c_{5,3}c_{3,5}}{c_{3,3} - \dfrac{c_{4,3}c_{3,4}}{c_{4,4}}}}
$$

The particular solution is specific to each release interval of each source and depends on the value of c_1 for that interval and source; the other coefficients are constant over the time horizon. The value of c_1 is affected by the rate at which the source material is released to air. The rate of release of source material to air is discussed in Section B.6.1. The particular solution is written to the temporary file “EigenVectors.out.”

Step 5. Determine the coefficients of the complimentary solution that meet the initial condition

$$\begin{bmatrix} a_1(t_b) \\ d_1(t_b) \\ a_2(t_b) \\ d_2(t_b) \\ a_3(t_b) \\ d_3(t_b) \end{bmatrix} = \widehat{ps} + C_1\widehat{ev}_1 + C_2\widehat{ev}_2 + C_3\widehat{ev}_3 + C_4\widehat{ev}_4 + C_5\widehat{ev}_5 + C_6\widehat{ev}_6$$

Writing a matrix with the six eigen vectors as the columns and the six coefficients as a vector gives

$$[\widehat{ev}_1 \quad \widehat{ev}_2 \quad \widehat{ev}_3 \quad \widehat{ev}_4 \quad \widehat{ev}_5 \quad \widehat{ev}_6]\begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \end{bmatrix} = \begin{bmatrix} a_1(t_b) \\ d_1(t_b) \\ a_2(t_b) \\ d_2(t_b) \\ a_3(t_b) \\ d_3(t_b) \end{bmatrix} - \widehat{ps}$$

The matrix of eigen vectors is written to the temporary file "EVCoefMatrix.out." The code performs elementary row operations to eliminate the off-diagonal components of the matrix of eigen vectors. This is possible if the rows of the matrix of eigen vectors are independent; that is, if the matrix is not singular. They will not be independent if the two rooms that do not contain the source have identical coefficients in the coefficient matrix. The code will use the numerical solution if the matrix of eigen vectors is singular.

The code performs elementary row operations to zero the off-diagonal components of the matrix starting with the diagonal component on row one to eliminate the components below it in the first column. Then it starts at the diagonal component on row two to eliminate the components below it in the second column and so on. Once the diagonal component in the last row is reached, the code uses it to eliminate the components above it. The code moves back up the rows to the diagonal components and eliminates the components above them.

The code performs the same elementary row operations on a 6×6 identity matrix and obtains the six coefficients. These coefficients depend on the concentrations of the source material suspended in air and deposited on the floor at the beginning of the vacuuming interval or the release interval, including no release intervals. They need to be evaluated for each of these intervals using the initial condition for the first such interval and the concentration computed in step 6 for subsequent intervals.

Step 6. Evaluate the expression for the concentrations at the end of each release and or vacuuming interval

$$\begin{bmatrix} a_1(t) \\ d_1(t) \\ a_2(t) \\ d_2(t) \\ a_3(t) \\ d_3(t) \end{bmatrix} = \widehat{ps} + \sum_{l=1}^{6} C_l \widehat{ev}_l e^{\lambda_l^{ev}(t-t_b)} \tag{B.12}$$

Factor the effect of cleaning the floor, if it is a vacuuming interval

$$d_i(t) = (1 - eff_{vac})\, d_i(t) \tag{B.13}$$

These concentrations at the end of an interval are the concentrations at the beginning of the next release interval, there being no release interval or vacuuming interval. Progressively evaluate the coefficients of the complimentary solution and the concentrations at the end of successive intervals using steps 5 and 6. The concentrations are only evaluated at the end of each release or vacuuming interval and not at any intermediate times because the time-integrated or time-averaged concentration over the exposure duration is calculated analytically as described in Section B.6.6.

B.6.5 Analytical Expressions for Instantaneous Concentrations of Radionuclides Suspended in Air and Deposited on the Floor

The instantaneous concentrations of radionuclides suspended in air and deposited on the floor are obtained by combining the factor for radiological transformations, $f_{RT}^{i,j}(t)$, developed in Section B.4.1 with the concentrations of source material.

$$\begin{bmatrix} c_1^{i\to j}(t) \\ c_2^{i\to j}(t) \\ c_3^{i\to j}(t) \\ c_4^{i\to j}(t) \\ c_5^{i\to j}(t) \\ c_6^{i\to j}(t) \end{bmatrix} = Q_s^i(0) \sum_{k=1}^{j} B_j^k e^{-\lambda_k t} \begin{bmatrix} a_1(t) \\ d_1(t) \\ a_2(t) \\ d_2(t) \\ a_3(t) \\ d_3(t) \end{bmatrix}$$

Using the expressions developed in Sections B.6.3 and B.6.4 for the concentrations of the source material gives the general expression

$$\begin{bmatrix} c_1^{i\to j}(t) \\ \dots \\ c_{2n}^{i\to j}(t) \end{bmatrix} = Q_s^i(0) \sum_{k=1}^{j} B_j^k e^{-\lambda_k t}\, \widehat{ps} + Q_s^i(0) \sum_{k=1}^{j} B_j^k e^{-\lambda_k t} \sum_{l=1}^{2n} C_l \widehat{ev}_l e^{\lambda_l^{ev}(t-t_b)} \tag{B.14}$$

where:

$c_{2m-1}^{i \to j}(t)$ = concentration at time t of the j^{th} member of the transformation chain of the i^{th} radionuclide in source s, suspended in air in room m of a n-room building,

$c_{2m}^{i \to j}(t)$ = concentration at time t of the j^{th} member of the transformation chain of the i^{th} radionuclide in source s, deposited on the floor in room m of a n-room building.

This consists of exponentials of time, summed over the radionuclides in a transformation chain and exponentials of time, summed over both the radionuclides in a transformation chain and the rooms.

B.6.6 Analytical Expressions for Time-Averaged Concentrations of Radionuclides Suspended in Air and Deposited on the Floor

The expression for the instantaneous concentrations of each radionuclide in air or on the floor, Equation B.14, can be integrated over the exposure duration by considering the integral of a single term from each of the sums over each release or vacuuming interval. The particular solution, $\widehat{ps}$, the eigen vector $\widehat{ev}_l$ and its coefficient, C_l, are constant over each release or vacuuming interval. The integrals can be evaluated using the expressions

$$\int_{t_1}^{t_2} B_j^k e^{-\lambda_k t} dt = B_j^k \frac{e^{-\lambda_k t_1} - e^{-\lambda_k t_2}}{\lambda_k}$$

and

$$\int_{t_1}^{t_2} B_j^k e^{-\lambda_k t} C_l \widehat{ev}_l e^{\lambda_l^{ev}(t-t_b)} dt = e^{-t_b \lambda_l^{ev}} B_j^k C_l \widehat{ev}_l \int_{t_1}^{t_2} e^{-(\lambda_k - \lambda_l^{ev})t} dt$$

$$= e^{-t_b \lambda_l^{ev}} B_j^k C_l \widehat{ev}_l \frac{e^{-(\lambda_k - \lambda_l^{ev})t_1} - e^{-(\lambda_k - \lambda_l^{ev})t_2}}{\lambda_k - \lambda_l^{ev}}$$

The time-integrated values of the concentrations of each radionuclide in air or on the floor over the exposure duration is obtained by summing the above result over the radionuclides in the chain, over the eigen values/eigen vectors, and over the parts of the release and vacuuming intervals that are within the period of time integration, after ensuring that each term is computed to the required precision. The time-averaged concentration, obtained by dividing the time-integrated concentration by the exposure duration, is written to temporary file "AirRelTimeIntegratedConcSource#.out," where # is the identification number of the source.

B.6.7 Numerical Solution for the Transient Concentration of Solid Source Material for an n-Room Simulation

The steps involved in the numerical solution implemented in RESRAD-BUILD Version 4.0 for solid source material in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of differential equations.

$$\begin{bmatrix} \dot{a}_1 \\ \dot{d}_1 \\ \dot{a}_2 \\ \dot{d}_2 \\ \cdots \\ \cdots \\ \dot{a}_n \\ \dot{d}_n \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & . & . & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & . & . & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1 \\ d_1 \\ a_2 \\ d_2 \\ . \\ . \\ a_n \\ d_n \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ 0 \\ 0 \\ \cdots \\ \cdots \\ 0 \\ 0 \end{bmatrix}$$

The odd diagonal coefficients are the proportionality factors for the rates of change of airborne particulates in air due to outflows from the room and to settling

$$c_{2i-1,2i-1} = -\frac{A_i v_d}{V_i} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

The other coefficients on the odd columns of the odd rows are the proportionality factors for the rates of change of particulates in air due to inflows from other rooms

$$c_{2i-1,2j-1} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

The coefficient to the right of an odd diagonal is the proportionality factor for the rate of change of particulates in air due to resuspension from the floor

$$c_{2i-1,2i} = \frac{A_i r_i}{V_i}$$

$$c_{2i-1,2j} = 0 \quad \forall\, j \neq i$$

The coefficient to the left of an even diagonal is the proportionality factor for the rate of change of particulates on the floor due to deposition

$$c_{2i,2i-1} = v_d$$

$$c_{2i,2j-1} = 0 \quad \forall\, j \neq i$$

The even diagonal coefficients are the proportionality factors for the rates of change of the particulates on the floor due to resuspension

$$c_{2i,2i} = -r_1$$

$$c_{2i,2j} = 0 \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "CoefSysEqn.out."

The non-zero term in the vector is

$$c_1 = \frac{rel_s}{V_1}$$

Step 2. Determine the diagonal components of the two matrices after expressing in difference form and rearranging for the concentrations at the end time in terms of the concentration at the beginning.

$$\begin{bmatrix} \dot{a}_1 \\ \dot{d}_1 \\ \dot{a}_2 \\ \dot{d}_2 \\ \cdots \\ \cdots \\ \dot{a}_n \\ \dot{d}_n \end{bmatrix} = \frac{1}{t^e - t^s} \begin{bmatrix} a_1^e \\ d_1^e \\ a_2^e \\ d_2^e \\ . \\ . \\ a_n^e \\ d_n^e \end{bmatrix} - \frac{1}{t^e - t^s} \begin{bmatrix} a_1^s \\ d_1^s \\ a_2^s \\ d_2^s \\ . \\ . \\ a_n^s \\ d_n^s \end{bmatrix}$$

$$= \frac{1}{2} \begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & . & . & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & . & . & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1^e \\ d_1^e \\ a_2^e \\ d_2^e \\ . \\ . \\ a_n^e \\ d_n^e \end{bmatrix}$$

$$+ \frac{1}{2} \begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & . & . & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & . & . & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1^s \\ d_1^s \\ a_2^s \\ d_2^s \\ . \\ . \\ a_n^s \\ d_n^s \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ 0 \\ 0 \\ \cdots \\ \cdots \\ 0 \\ 0 \end{bmatrix}$$

$$
-\begin{bmatrix}
c_{1,1}-\nabla & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\
c_{2,1} & c_{2,2}-\nabla & 0 & 0 & . & . & 0 & 0 \\
c_{3,1} & 0 & c_{3,3}-\nabla & c_{3,4} & . & . & c_{3,2n-1} & 0 \\
0 & 0 & c_{4,3} & c_{4,4}-\nabla & . & . & 0 & 0 \\
. & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . \\
c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1}-\nabla & c_{2n-1,2n} \\
0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n}-\nabla
\end{bmatrix}
\begin{bmatrix} a_1^e \\ d_1^e \\ a_2^e \\ d_2^e \\ . \\ . \\ a_n^e \\ d_n^e \end{bmatrix}
$$

$$
=\begin{bmatrix}
c_{1,1}+\nabla & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\
c_{2,1} & c_{2,2}+\nabla & 0 & 0 & . & . & 0 & 0 \\
c_{3,1} & 0 & c_{3,3}+\nabla & c_{3,4} & . & . & c_{3,2n-1} & 0 \\
0 & 0 & c_{4,3} & c_{4,4}+\nabla & . & . & 0 & 0 \\
. & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . \\
c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1}+\nabla & c_{2n-1,2n} \\
0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n}+\nabla
\end{bmatrix}
\begin{bmatrix} a_1^s \\ d_1^s \\ a_2^s \\ d_2^s \\ . \\ . \\ a_n^s \\ d_n^s \end{bmatrix}
$$

$$
+\begin{bmatrix} c_1 \\ 0 \\ 0 \\ 0 \\ \cdots \\ \cdots \\ 0 \\ 0 \end{bmatrix}
$$

where:

$\nabla = \frac{2}{t^e - t^s}$,

t^e = time at which the concentrations are being computed,

t^s = time at which the concentrations are known, having been previously computed or initialized.

Step 3a. Perform elementary row operations to zero the off-diagonal components of the matrix.

$$
\begin{bmatrix}
c_{1,1}-\nabla & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\
c_{2,1} & c_{2,2}-\nabla & 0 & 0 & . & . & 0 & 0 \\
c_{3,1} & 0 & c_{3,3}-\nabla & c_{3,4} & . & . & c_{3,2n-1} & 0 \\
0 & 0 & c_{4,3} & c_{4,4}-\nabla & . & . & 0 & 0 \\
. & . & . & . & . & . & . & . \\
. & . & . & . & . & . & . & . \\
c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1}-\nabla & c_{2n-1,2n} \\
0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n}-\nabla
\end{bmatrix}
$$

The general procedure for eliminating the off-diagonal components described in step 5 of Section B.6.4 is as follows:

a. Use the diagonal component to eliminate the components below it, starting with the left-most diagonal component and then moving right along the diagonals,

b. Then use the diagonal component to eliminate the components above it, starting with the right-most diagonal component and then moving left along the diagonals.

This algorithm is not computationally efficient for this sparce matrix.

Only two components in each of the even rows and in each of the even columns of this matrix are non-zero: the even diagonal component, the component to the left of the even diagonal, and the component above the even diagonal. It is more efficient to eliminate the off-diagonal components following the procedure in preparatory steps 2, 3, and 4 of Section B.6.4.

a. Use the even rows to eliminate the off-diagonal components in the even columns,

b. Use the odd-diagonal component to eliminate the components in the odd rows below it, starting with the left-most diagonal component and then moving right along the diagonals,

c. Use the odd-diagonal component to eliminate the components above it, starting with the right-most diagonal component,

d. Eliminate the off-diagonal components in the even rows using the row immediately above them.

Step 3b. Perform the same row operations on the matrix

$$\begin{bmatrix} c_{1,1}+\nabla & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2}+\nabla & 0 & 0 & . & . & 0 & 0 \\ c_{3,1} & 0 & c_{3,3}+\nabla & c_{3,4} & . & . & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4}+\nabla & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1}+\nabla & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n}+\nabla \end{bmatrix}$$

and on the vector

$$\begin{bmatrix} 2 \\ 0 \\ 0 \\ 0 \\ \cdots \\ \cdots \\ 0 \\ 0 \end{bmatrix}$$

Step 4. Use the transformed matrix and vector from step 3b, the concentrations of source material at time t^s, and the rate of release per unit volume of the room of release, c_1, to compute the concentrations at time t^e.

Step 5. Compute the concentrations at any of the integration times that fall within the current time step. This is described in Section B.6.8.

Step 6. Repeat steps 4 and 5 over the time horizon of the analysis.

Time step considerations:

This numerical solution computes the concentration over time in steps of $t^e - t^s$. In step 2 above, it uses the concentration at the end of the time step t^e and the concentration at the beginning of the time step t^s to estimate and represent the rate of change of concentration over that time step. The error due to this representation will be negligible as long as the time step is not too large. The code chooses the time step based on three criteria.

1. It cannot exceed the maximum value, $t_{step}^{maximum}$, specified in the room airflow and particulates form.

$$t_{step} \leq t_{step}^{maximum}$$

2. It cannot exceed the quotient of the exposure duration, t_{ed}, and the maximum number of time integration points, $n_{TI}^{maximum}$, specified in the evaluation times form. The code imposes this constraint to avoid interpolating for more than one integration time within each time step.

$$t_{step} \leq \frac{t_{ed}}{n_{TI}^{maximum}}$$

3. It cannot exceed the value given by the expression

$$t_{step} \leq V_s \Bigg/ \left(A_s v_d + \sum_{j=0, j \neq i}^{n} q_{i,j} \right)$$

where:

V_s = volume of the room in which the source is located,

A_s = area of the room in which the source is located,

v_d = representative deposition velocity of particulates containing the radionuclides,

$\sum_{j=0,j\neq i}^{n} q_{i,j}$ = sum of the air flows out of the room in which the source is located.

The code imposes this last constraint to ensure that the computed value of the quantity of particulates transferring from the air of the room during the time step does not exceed the product of the change in the release rate and the time step.

B.6.8 Numerical Evaluation of Instantaneous Concentrations of Source Material Suspended in Air and Deposited on Floor

The exposure, both dose and risk, computed at time 0 and at up to 9 user-specified times are time-integrated quantities. These are integrated over the exposure duration. The instantaneous values are computed at a number of integration times and summed numerically to obtain the time-integrated value. The times for the numerical integration over the exposure duration are determined by the expression

$$t_{k,l}^{TI} = t_k^{ER} + t_{ed} \frac{l-1}{n_{TI}^{maximum} - 1}$$

where:

$t_{k,l}^{TI}$ = l^{th} integration time of the k^{th} exposure reporting time,

t_k^{ER} = k^{th} exposure reporting time,

t_{ed} = exposure duration,

l = index of the integration time,

$n_{TI}^{maximum}$ = maximum number of times to be used for the numerical integration over time.

In step 5 of Section B.6.7, the code checks whether any of the integration times fall within the time step. If any do, the concentration of source material suspended in air or deposited on the floor is calculated by interpolation.

$$\begin{aligned} a_i\left(t_{k,l}^{TI}\right) &= a_i^s + \frac{t_{k,l}^{TI} - t^s}{t^e - t^s}\left(a_i^e - a_i^s\right) \ \forall \ t^s \le t_{k,l}^{TI} \le t^e \\ d_i\left(t_{k,l}^{TI}\right) &= d_i^s + \frac{t_{k,l}^{TI} - t^s}{t^e - t^s}\left(d_i^e - d_i^s\right) \ \forall \ t^s \le t_{k,l}^{TI} \le t^e \end{aligned} \tag{B.15}$$

B.6.9 Numerical Evaluation of the Instantaneous Concentrations of Radionuclides Suspended in Air and Deposited on the Floor

The concentrations of the radionuclides suspend in air and deposited on the floor are computed using the concentrations of the source material suspended in air and deposited on the floor, Equation B.15, and the factor for radiological transformations, Equation B.6

$$\begin{aligned} c_{2m-1}^{i\to j}\left(t_{k,l}^{TI}\right) &= a_i\left(t_{k,l}^{TI}\right) f_{RT}^{i,j}\left(t_{k,l}^{TI}\right) \\ c_{2m}^{i\to j}\left(t_{k,l}^{TI}\right) &= d_i\left(t_{k,l}^{TI}\right) f_{RT}^{i,j}\left(t_{k,l}^{TI}\right) \end{aligned} \tag{B.16}$$

where:

$c_{2m-1}^{i \to j}(t)$ = concentration at time t of the j^{th} member of the transformation chain of the i^{th} radionuclide in source s, suspended in air in room m of a n-room building,

$c_{2m}^{i \to j}(t)$ = concentration at time t of the j^{th} member of the transformation chain of the i^{th} radionuclide in source s, deposited on the floor in room m of a n room building,

$f_{RT}^{i,j}(t)$ = factor at time t, to account for the radiological transformations from radionuclide i to the jth radionuclide in the transformation chain,

$t_{k,l}^{TI}$ = l^{th} integration time of the k^{th} exposure reporting time.

B.6.10 Numerical Evaluation of the Time-Averaged Concentrations of Radionuclides Suspended in Air and Deposited on the Floor

The concentrations of radionuclides in air and on the floor are used to compute the exposure, both dose and risk, from the following pathways: inhalation of particulates, direct exposure from deposition, direct exposure from immersion, and ingestion of deposited particulates. The exposures computed by the code are time-integrated quantities. The concentrations are the only time-varying factors in the expressions for the exposure from these pathways. The code estimates the time-averaged concentrations using the Simpson's rule. It computes this estimate using the concentrations at progressively increasing numbers of times until either a desired convergence is achieved or the number of estimates reaches the specified limit. The iterative procedure is described below.

Step 1. Compute the first trapezoidal estimate using the concentrations at the beginning and end of the exposure duration

$$T_0 = \frac{c_m^{i \to j}\left(t_{k,1}^{TI}\right) + c_m^{i \to j}\left(t_{k,n_{TI}^{maximum}}^{TI}\right)}{2}$$

Step 2. Compute the second trapezoidal estimate using the concentrations at the beginning, midpoint, and end of the exposure duration

$$T_1 = \frac{c_m^{i \to j}\left(t_{k,1}^{TI}\right) + 2c_m^{i \to j}\left(t_{k,\frac{1}{2}n_{TI}^{maximum}+\frac{1}{2}}^{TI}\right) + c_m^{i \to j}\left(t_{k,n_{TI}^{maximum}}^{TI}\right)}{4}$$

$$T_1 = \frac{T_0 + c_m^{i \to j}\left(t_{k,\frac{1}{2}n_{TI}^{maximum}+\frac{1}{2}}^{TI}\right)}{2}$$

Step 3. Compute the first parabolic estimate, S_1, using the previous two trapezoidal estimates.

$$S_1 = \frac{c_m^{i\to j}\left(t_{k,1}^{TI}\right) + 4c_m^{i\to j}\left(t_{k,\frac{1}{2}n_{TI}^{maximum}+\frac{1}{2}}^{TI}\right) + c_m^{i\to j}\left(t_{k,n_{TI}^{maximum}}^{TI}\right)}{6}$$

$$S_1 = \frac{4}{3}\frac{c_m^{i\to j}\left(t_{k,1}^{TI}\right) + 2c_m^{i\to j}\left(t_{k,\frac{1}{2}n_{TI}^{maximum}+\frac{1}{2}}^{TI}\right) + c_m^{i\to j}\left(t_{k,n_{TI}^{maximum}}^{TI}\right)}{4} - \frac{1}{3}\frac{c_m^{i\to j}\left(t_{k,1}^{TI}\right) + c_m^{i\to j}\left(t_{k,n_{TI}^{maximum}}^{TI}\right)}{2}$$

$$S_1 = \frac{4T_1 - T_0}{3}$$

Step 4. Check for convergence with the second trapezoidal estimate. Use S_1 as the time-averaged concentration, if the convergence criterion, below, is satisfied.

$$\frac{|S_1 - T_1|}{S_1} \le \varepsilon$$

where:

ε is the user-specified convergence criterion.

Step 5. If the convergence criterion is not met, compute the next trapezoidal estimate.

$$T_l = \frac{T_{l-1}}{2} + \frac{1}{2^l}\sum_{n=0}^{2^{l-1}-1} c_m^{i\to j}\left(t_{k,\frac{1}{2^l}\left\{n_{TI}^{maximum}-1\right\}+1+\frac{n}{2^{l-1}}\left\{n_{TI}^{maximum}-1\right\}}^{TI}\right)$$

Step 6. Compute the next parabolic estimate.

$$S_l = \frac{4T_l - T_{l-1}}{3}$$

Step 7. Check for convergence with the previous parabolic estimate. Use S_l as the time-averaged concentration, if the convergence criterion, below, is satisfied.

$$\frac{|S_l - T_l|}{S_l} \le \varepsilon$$

Step 8. Repeat steps 5 through 7, if the convergence criterion is not met and if the maximum number of integration times have not been used.

$$2^l + 1 < n_{TI}^{maximum}$$

Step 9. Use S_l as the time-averaged concentration, if the maximum number of integration times have been used.

The code uses the algorithm above to estimate the concentrations of radionuclides suspended in air and of radionuclides deposited on the floor in each room of the building, averaged over the exposure duration beginning at each of k exposure reporting time, t_k^{ER}. The time-averaged concentration is written to temporary file "AirRelTimeIntegratedConcSource#.out," where # is the identification number of the source.

B.6.11 Numerical Solution for the Transient Concentration of Vaporizable Water for an n-Room Simulation

This model differs from the model for solid source material in two ways:

1. There is no suspended phase nor deposited phase, only a gaseous phase, water vapor, in each room.

2. The release of water vapor is not constant over the release duration; it varies continuously over time and is computed by the code at each time step.

The steps involved in the numerical solution implemented in RESRAD-BUILD Version 4.0 for tritiated water vapor in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of differential equations

$$\begin{bmatrix} \dot{a}_1 \\ \dot{a}_2 \\ \cdots \\ \dot{a}_n \end{bmatrix} = \begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ . \\ a_n \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

$$c_{i,i} = -\frac{1}{V_i} \sum_{j=0, j\neq i}^{n} q_{i,j}$$

$$c_{i,j} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "CoefSysEqnH3vapour.out."

Step 2. Determine the diagonal components of the two matrices after expressing in difference form and rearranging for the concentrations at the end time in terms of the concentration at the beginning.

$$\begin{bmatrix} \dot{a}_1 \\ \dot{a}_2 \\ \cdots \\ \dot{a}_n \end{bmatrix} = \frac{1}{t^e - t^s} \begin{bmatrix} a_1^e \\ a_2^e \\ . \\ a_n^e \end{bmatrix} - \frac{1}{t^e - t^s} \begin{bmatrix} a_1^s \\ a_2^s \\ . \\ a_n^s \end{bmatrix}$$

$$= \frac{1}{2} \begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} a_1^e \\ a_2^e \\ . \\ a_n^e \end{bmatrix} + \frac{1}{2} \begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} a_1^s \\ a_2^s \\ . \\ a_n^s \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

$$- \begin{bmatrix} c_{1,1} - \nabla & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} - \nabla & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} - \nabla \end{bmatrix} \begin{bmatrix} a_1^e \\ a_2^e \\ . \\ a_n^e \end{bmatrix} = \begin{bmatrix} c_{1,1} + \nabla & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} + \nabla & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} + \nabla \end{bmatrix} \begin{bmatrix} a_1^s \\ a_2^s \\ . \\ a_n^s \end{bmatrix} + \begin{bmatrix} c_1 \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

where:

$\nabla = \frac{2}{t^e - t^s}$,

t^e = time at which the concentrations are being computed,

t^s = time at which the concentrations are known, having been previously computed or initialized.

Step 3a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} - \nabla & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} - \nabla & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} - \nabla \end{bmatrix}$$

Step 3b. Perform the same row operations on the matrix

$$\begin{bmatrix} c_{1,1} + \nabla & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} + \nabla & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} + \nabla \end{bmatrix}$$

and on the vector

$$\begin{bmatrix} 2 \\ 0 \\ \cdots \\ 0 \end{bmatrix}$$

Step 4. Compute the rate of release of water vapor per unit volume of the room of release, c_1.

$$c_1 = \frac{r_{H_2O}(t)}{V_1}$$

Step 5. Use the transformed matrix and vector from step 3b, the concentrations of water vapor from the source at time t^s, and the rate of release of water vapor per unit volume of the room of release, c_1, to compute the concentrations at time t^e.

Step 6. Compute the concentrations at any of the integration times that fall within the current time step in a manner similar to that described in Section B.6.8. The concentration of water vapor from the source at the time-integration times is written to the temporary file "AH3RelConcSource#.out," where # is the identification number of the tritium source.

Step 7. Repeat steps 4, 5, and 6 over the time horizon of the analysis.

Time step considerations:

This numerical solution computes the concentration over time in steps of $t^e - t^s$. In step 2 above, it uses the concentration at the end of the time step t^e and the concentration at the beginning of the time step t^s to estimate and represent the rate of change of concentration over that time step. The error due to this representation will be negligible as long as the time step is not too large. The code chooses the time step based on three criteria.

1. It cannot exceed the maximum value, $t_{step}^{maximum}$, specified in the room airflow and particulates form.

$$t_{step} \leq t_{step}^{maximum}$$

2 It cannot exceed the quotient of the exposure duration, $t_{exposure\ duration}$, and the maximum number of time integration points, $n_{time\ integration\ points}^{maximum}$, specified in the evaluation times form. The code imposes this constraint to avoid interpolating for more than one time-integration time within each time step.

$$t_{step} \leq \frac{t_{exposure\ duration}}{n_{time\ integration\ points}^{maximum}}$$

3 It cannot exceed the value given by the expression

$$t_{step} \leq V_s \Big/ \sum_{j=0, j \neq i}^{n} q_{i,j}$$

where:

V_s = volume of the room in which the source is located,

$q_{i,j}$ = rate of flow from room i to room j.

B.6.12 Numerical Evaluation of the Concentrations of Tritiated Water Vapor in Air

The instantaneous concentrations of the tritiated water vapor in air are computed using the concentrations of the water vapor from the source in air and the factor for radiological transformation of tritium

$$c_m^{i\to j}\left(t_{k,l}^{TI}\right) = a_i\left(t_{k,l}^{TI}\right)e^{-\lambda_{^3H} t_{k,l}^{TI}} \tag{B.17}$$

where:

$c_m^{i\to i}(t)$ = concentration at time t of tritium in source s in water vapor in room m of an n-room building,

$\lambda_{^3H}$ = transformation rate of ^{3}H,

$t_{k,l}^{TI}$ = l^{th} integration time of the k^{th} exposure reporting time.

The instantaneous concentrations are averaged over the exposure duration in a manner similar to that described in Section B.6.10. These time-averaged concentrations at the time-integration times are written to the temporary file "AH3RelTimeIntegratedConcSource#.out," where # is the identification number of the tritium source.

B.7 FATE OF RADON RELEASED TO AIR AND ITS FIRST THREE SHORT-LIVED PROGENY

The general principles of computing the dose from the inhalation of the first three short-lived progeny of the two radon isotopes, ^{220}Rn and ^{222}Rn, are given in Appendix E. The general model for computing the steady-state release of radon gas from multilayered volume sources containing radon precursors is discussed in detail in Appendix E, Section E.1.1. Analytic expressions used by the code for the release of radon from a single-layered volume source and a two-layered volume source derived using the general steady-state model are discussed in Sections B.7.2 and B.7.3, respectively. The steady-state releases computed by the code are written to the intermediate output file "RadonAndProgeny.out."

The fate of the two radon isotopes, ^{220}Rn and ^{222}Rn, released to air and their three short-lived progeny produced after their release are modeled using the steady-state model described in Sections B.7.4 through B.7.11. The steady-state models in this section for radon and its first three short-lived progeny differ from the transient models in Section B.6.

The transient model computes the temporal concentrations of the material released from the source to the air. Initially, the concentrations of material suspended in air and deposited on floors change with time, even under a constant-rate release, because the rate of introduction of the material is different from the rate at which the material removed. The rate at which material is removed is proportional to its concentration. The concentration changes with time toward a value that will make the rate of removal equal to the rate of introduction of material. A steady state is reached when the concentration attains a value where the rate of removal equals the rate of introduction. The time required to reach steady state depends on the rates of removal of the material suspended in air and deposited on the floors. The transient model computes the concentration as it changes from the initial value to the steady-state value over time.

The radon models in this section compute the steady-state concentrations of radon and its first three short-lived progeny corresponding to the rate of release of radon at any time. These concentrations, computed assuming a steady state between the concentration and the release, will vary with time in step with any variation in the rate of release of radon.

The ratio of the concentration to the release does not change with time. Thus, the value of the concentration integrated over the exposure duration is simply the product of this ratio and the time-integrated value of release over the exposure duration. The steady-state concentrations of radon and the three short-lived progeny are written to the intermediate output file "RadonAndProgeny.out."

B.7.1 Time-Integrated Release of Radon from Point, Line, and Area Sources

The rate of release of radon from a point, line, or area source is given by Equation E.1 of Appendix E. The quantity of radon precursor, ^{226}Ra or ^{228}Th, varies with time while the other two factors in the expression do not. Thus, the time-integrated release of radon from a point, line, or area source is computed using the expression

$$TIrel_s^{i\to Rn}(t_k^{ER}) = f_{air}^{Rn}\lambda_{Rn}\int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} Q_s^{i\to RnP}(t)dt \tag{B.18}$$

where:

$TIrel_s^{i\to Rn}(t_k^{ER})$ = release of the radon, derived from the transformation of initially present radionuclide i in source s,

s = index of the source,

i = index of the initially present radionuclide,

Rn = isotope of radon, either ^{220}Rn or ^{222}Rn,

t_k^{ER} = k^{th} exposure reporting time,

f_{air}^{Rn} = fraction of radon generated within the source that is released to the air in the room,

λ_{Rn} = transformation rate coefficient of the radon isotope,

t_{ed} = exposure duration,

$Q_s^{i\to RnP}(t)$ = quantity at time t of parent of the radon isotope, currently either ^{228}Th or ^{226}Ra, respectively, derived from the transformation of initially present radionuclide i in source s,

t = variable representing time in the integral.

The integral is evaluated as described in Section B.5.1.

B.7.2 Steady-State Release of Radon from a Single-Layered Volume Source

The general model for computing the steady-state release of radon gas from multilayered volume sources containing radon precursors is discussed in detail in Appendix E, Section E.1.1. The code also contains the analytic expressions for the release of radon from a single-layered volume source, developed using the general model. The development of this expression is outlined below.

1. Write the mass balance expression for radon in the volume source:

$$n\frac{\partial c}{\partial t} = -\frac{\partial}{\partial x}\left(-nD\frac{\partial c}{\partial x}\right) - \lambda_{Rn}nc + \varepsilon_s\lambda_{Rn}\rho_b^s c_s^{i\to RnP}(t)$$

$$n\frac{\partial c}{\partial t} = nD\frac{\partial^2 c}{\partial x^2} - \lambda_{Rn}nc + r_{Rn}^V, \qquad r_{Rn}^V = \varepsilon_s\lambda_{Rn}\rho_b^s c_s^{i\to RnP}$$

where:

n = porosity of the volume source,

D = effective diffusion coefficient in the porous volume source,

λ_{Rn} = transformation rate coefficient of the radon isotope,

c = concentration of the radon isotope in the pores of the volume source,

ε_s = radon emanation coefficient of source s,

ρ_b^s = dry bulk density of the volume source,

$c_s^{i\to RnP}(t)$ = activity concentration at time t of the parent of the radon isotope derived from the transformation of initially present radionuclide i in source s,

r_{Rn}^V = rate of emanation of radon from the solid phase of the volume source into the pores of the volume source.

2. Consider steady state, to simplify the mass balance:

$$\frac{\partial c}{\partial t} = 0 \;\; \Longrightarrow \frac{\partial^2 c}{\partial x^2} - \frac{\lambda_{Rn}}{D}c + \frac{r_{Rn}^V}{nD} = 0$$

$$\frac{\partial^2 c}{\partial x^2} - \alpha^2 c = -\frac{r_{Rn}^V}{nD}, \qquad \alpha = \sqrt{\frac{\lambda_{Rn}}{D}}$$

3. Solve by combining the complementary function and the particular integral of the steady-state mass balance:

   Complementary function:

$$c(x) = K_1 e^{\alpha x} + K_2 e^{-\alpha x}$$

   Particular integral:

$$c(x) = \frac{r_{Rn}^{V}}{n\lambda_{Rn}}$$

   General solution:

$$c(x) = K_1 e^{\alpha x} + K_2 e^{-\alpha x} + \frac{r_{Rn}^{V}}{n\lambda_{Rn}}$$

4. Compute the two coefficients of the general solution that satisfy the assumed boundary conditions, zero concentrations of radon in pores at the two external faces of the volume source:

   Boundary conditions:

$$c(0) = K_1 + K_2 + \frac{r_{Rn}^{V}}{n\lambda_{Rn}} = 0$$

$$c(T_c) = K_1 e^{\alpha T_c} + K_2 e^{-\alpha T_c} + \frac{r_{Rn}^{V}}{n\lambda_{Rn}} = 0$$

   Solved in matrix form by performing elementary row operations (ERO):

$$\begin{bmatrix} 1 & 1 \\ e^{\alpha T_c} & e^{-\alpha T_c} \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = -\frac{r_{Rn}^{V}}{n\lambda_{Rn}} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

   ERO $(2 - e^{\alpha T_c} \times 1)$ then ERO $\left(\frac{1}{e^{-\alpha T_c} - e^{\alpha T_c}} \times 2\right)$ yields,

$$\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = -\frac{r_{Rn}^{V}}{n\lambda_{Rn}} \begin{bmatrix} 1 \\ \dfrac{1 - e^{\alpha T_c}}{e^{-\alpha T_c} - e^{\alpha T_c}} \end{bmatrix}$$

   ERO $(1 - 2)$ yields,

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = -\frac{r_{Rn}^{V}}{n\lambda_{Rn}} \begin{bmatrix} \dfrac{e^{-\alpha T_c} - 1}{e^{-\alpha T_c} - e^{\alpha T_c}} \\ \dfrac{1 - e^{\alpha T_c}}{e^{-\alpha T_c} - e^{\alpha T_c}} \end{bmatrix}$$

Simplify

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = -\frac{r_{Rn}^V}{n\lambda_{Rn}}\frac{e^{-\alpha T_c}-1}{e^{-\alpha T_c}-e^{\alpha T_c}}\begin{bmatrix} 1 \\ e^{\alpha T_c} \end{bmatrix} = -\frac{r_{Rn}^V}{n\lambda_{Rn}}\frac{1-e^{\alpha T_c}}{1-e^{2\alpha T_c}}\begin{bmatrix} 1 \\ e^{\alpha T_c} \end{bmatrix} = -\frac{r_{Rn}^V}{n\lambda_{Rn}}\frac{1}{1+e^{\alpha T_c}}\begin{bmatrix} 1 \\ e^{\alpha T_c} \end{bmatrix}$$

5. Write the expression for flux

$$F(x) = -nD\frac{\partial c}{\partial x} = -nD(\alpha K_1 e^{\alpha x} - \alpha K_2 e^{-\alpha x})$$

$$F(x) = -nD\alpha\left(-\frac{r_{Rn}^V}{n\lambda_{Rn}}\right)\frac{e^{\alpha x} - e^{\alpha T_c}e^{-\alpha x}}{1+e^{\alpha T_c}}$$

$$F(x) = \frac{D\alpha}{\lambda_{Rn}} r_{Rn}^V \frac{e^{\alpha x} - e^{\alpha(T_c - x)}}{1+e^{\alpha T_c}}$$

$$F(x) = \frac{1}{\alpha} r_{Rn}^V \frac{e^{\alpha x} - e^{\alpha(T_c - x)}}{1+e^{\alpha T_c}}$$

6. Compute the rate of release of radon from the two external faces of the volume source:

   Release out of the face at $x = 0$

$$Rel(0) = -A_s F(0) = -\frac{A_s r_{Rn}^V}{\alpha}\frac{1-e^{\alpha T_c}}{1+e^{\alpha T_c}}$$

   Release out of the face at $x = T_c$

$$Rel(T_c) = A_s F(T_c) = \frac{A_s r_{Rn}^V}{\alpha}\frac{e^{\alpha T_c} - e^{\alpha(T_c - T_c)}}{1+e^{\alpha T_c}} = Rel(0)$$

7. Sum them to obtain the instantaneous rate of release of radon from the volume source:

$$rel_{Vs}^{i\to Rn}(t) = Rel(0,t) + Rel(T_c,t) = 2\frac{A_s r_{Rn}^V}{\alpha}\frac{e^{\alpha T_c}-1}{1+e^{\alpha T_c}}$$

$$rel_{Vs}^{i\to Rn}(t) = 2A_s\varepsilon_s\lambda_{Rn}\rho_b^s c_s^{i\to RnP}\frac{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c}-1}{\sqrt{\frac{\lambda_{Rn}}{D}}\left(e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c}+1\right)}$$

Note the code uses a less simplified form of this equation:

$$rel_{Vs}^{i\to Rn}(t) = 2A_s nD\sqrt{\frac{\lambda_{Rn}}{D}}\frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n}\frac{1}{\lambda_{Rn}}\frac{1-2e^{-\sqrt{\frac{\lambda_{Rn}}{D}}T_c}+e^{-2\sqrt{\frac{\lambda_{Rn}}{D}}T_c}}{1-e^{-2\sqrt{\frac{\lambda_{Rn}}{D}}T_c}}$$

Rearrange the expression to identify the time-dependent factors:

$$rel_{Vs}^{i\rightarrow Rn}(t) = 2\varepsilon_s \lambda_{Rn} A_s T_c(t) \rho_b^s c_s^{i\rightarrow RnP}(t) \frac{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} - 1}{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)\left(e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} + 1\right)}$$

$$rel_{Vs}^{i\rightarrow Rn}(t) = 2\varepsilon_s \lambda_{Rn} Q_s^{i\rightarrow RnP}(t) \frac{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} - 1}{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)\left(e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} + 1\right)}$$

Rearrange to compare with the release from a point, line, or area source with the same inventory of radon parent:

$$rel_{Vs}^{i\rightarrow Rn}(t) = \varepsilon_s \lambda_{Rn} Q_s^{i\rightarrow RnP}(t) \frac{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} - 1}{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} \frac{2}{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} + 1}$$

$$f_{RT}^{Rn_{diffusion}}(t) = \frac{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} - 1}{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} \frac{2}{e^{\sqrt{\frac{\lambda_{Rn}}{D}}T_c(t)} + 1} \tag{B.19}$$

$$rel_{Vs}^{i\rightarrow Rn}(t) = \varepsilon_s \lambda_{Rn} Q_s^{i\rightarrow RnP}(t) f_{RT}^{Rn_{diffusion}}(t) \tag{B.20}$$

The release from a single-layered volume source, Equation B.20, differs from the release from a point, line, or area source with the same inventory, Equation B.18, by the factor that accounts for radiological decay of radon while diffusing through the pores of the volume source, $f_{RT}^{Rn_{diffusion}}(t)$. The expression for the factor is given in Equation B.19. The factor that accounts for radiological decay of radon while diffusing through the pores of a single-layered volume source depends on the effective diffusion coefficient and the thickness of the layer. Plots of the variation of this factor against the effective diffusion coefficient for the two radon isotopes in sources of different thicknesses are shown in Figure B-4.

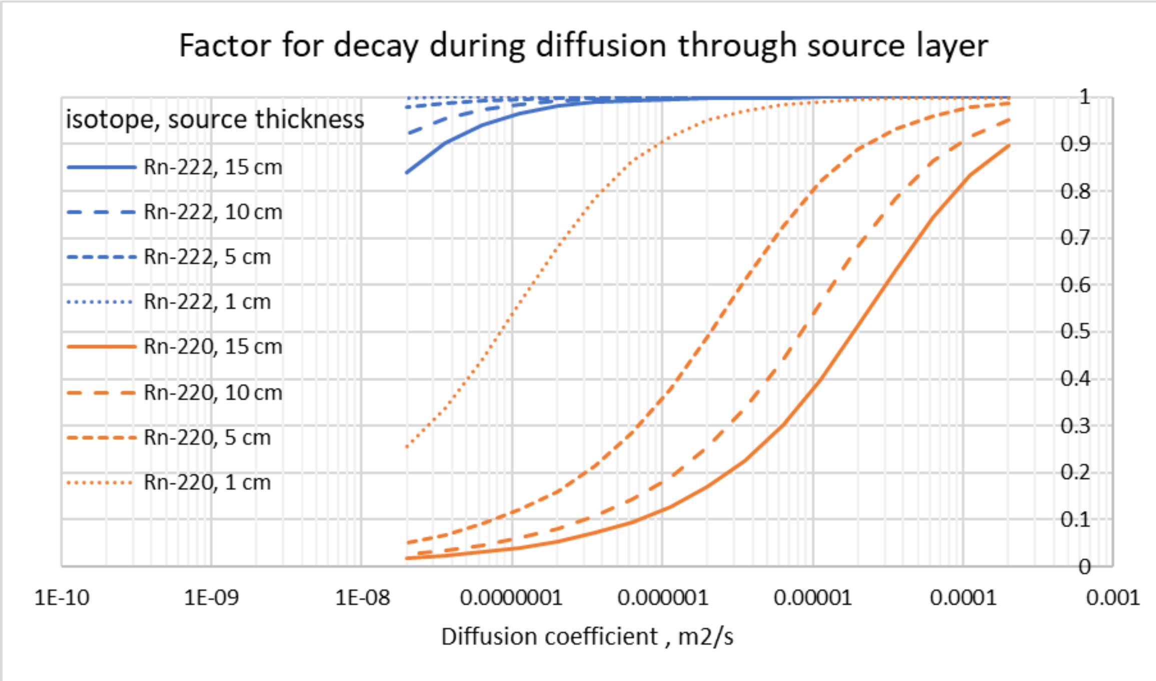


Figure B-4 Variation of the Factor that Accounts for Radiological Decay of Radon while Diffusing through the Pores of the Volume Source against the Effective Diffusion Coefficient for the Two Radon Isotopes in Sources of Different Thicknesses

8. Integrate over time to obtain the time-integrated rate of release of radon from the volume source:

$$TIrel_{Vs}^{i\to Rn}(t_k^{ER}) = \varepsilon_s \lambda_{Rn} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} Q_s^{i\to RnP}(t) f_{RT}^{Rn_{diffusion}}(t)dt \tag{B.21}$$

The time-integrated activity of the radon parent in the source $Q_s^{i\to RnP}(t)$, obtained analytically as outlined in Sections B.5.1 and B.4.3, is already available in the code. It is used directly with an average value of $f_{RT}^{Rn_{diffusion}}(t)$ if the variation in the latter over the exposure duration is less than the convergence criteria. If not, the expression in Equation B.21 is evaluated numerically using the procedure outlined in Section B.6.10.

B.7.3 Steady-State Release of Radon from a Two-Layered Volume Source

The general model for computing the steady-state release of radon gas from multilayered volume sources containing radon precursors is discussed in detail in Appendix E, Section E.1.1. The code also contains the analytic expressions for the release of radon from a single-layered volume source and for a two-layered volume source, developed using the general model. The development of the single-layered volume source is in Section B.7.2. The expressions for the two-layered volume source with one layer being contaminated are given at the end of this section after a brief outline of its development.

Steps 1 and 2 are the same as for the single layered volume source.

3. Write the general solution for a layer using the general solution for the single-layered volume source. Both layers are assumed to be contaminated, but to a different extent in the general solution. The formulations in the code assume that one layer is contaminated and the other is not.

$$c_l(x) = K_{l1}e^{\alpha_l x} + K_{l2}e^{-\alpha_l x} + \frac{\varepsilon\rho_b^s {c^P}_l}{n_l}$$

where:

l = index of the layer.

4. Write the expression for flux

$$F_l(x) = -n_l D_l \frac{\partial c_l}{\partial x} = -n_l D_l \alpha_l (K_{l1}e^{\alpha_l x} - K_{l2}e^{-\alpha_l x})$$

5. Compute the four coefficients of the general solution that satisfy the assumed boundary conditions, zero concentrations of radon in pores at the two external faces of the volume source and continuity of the concentration and the flux at the boundary between the two layers:

Boundary conditions:

$$c_1(0) = 0 \Longrightarrow K_{11} + K_{12} = -\frac{\varepsilon\rho_b^s {c^P}_1}{n_1}$$

$$c_1(T_1) = c_2(T_1) \Longrightarrow K_{11}e^{\alpha_1 T_1} + K_{12}e^{-\alpha_1 T_1} - K_{21}e^{\alpha_2 T_1} - K_{22}e^{-\alpha_2 T_1} = -\frac{\varepsilon\rho_b^s {c^P}_1}{n_1} + \frac{\varepsilon\rho_b^s {c^P}_2}{n_2}$$

$$F_1(T_1) = F_2(T_1) \Longrightarrow -n_1 D_1 \alpha_1 (K_{11}e^{\alpha_1 T_1} - K_{12}e^{-\alpha_1 T_1}) + n_2 D_2 \alpha_2 (K_{21}e^{\alpha_2 T_1} - K_{22}e^{-\alpha_2 T_1}) = 0$$

$$c_2(0) = 0 \Longrightarrow K_{21}e^{\alpha_2 (T_1+T_2)} + K_{22}e^{-\alpha_2 (T_1+T_2)} = -\frac{\varepsilon\rho_b^s {c^P}_2}{n_2}$$

Boundary conditions in matrix form:

$$\begin{bmatrix} 1 & 1 & 0 & 0 \\ e^{\alpha_1 T_1} & e^{-\alpha_1 T_1} & -e^{\alpha_2 T_1} & -e^{-\alpha_2 T_1} \\ -n_1 D_1 \alpha_1 e^{\alpha_1 T_1} & n_1 D_1 \alpha_1 e^{-\alpha_1 T_1} & n_2 D_2 \alpha_2 e^{\alpha_2 T_1} & -n_2 D_2 \alpha_2 e^{-\alpha_2 T_1} \\ 0 & 0 & e^{\alpha_2 (T_1+T_2)} & e^{-\alpha_2 (T_1+T_2)} \end{bmatrix} K = \begin{bmatrix} -1 & 0 \\ -1 & +1 \\ 0 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \frac{\varepsilon\rho_b^s {c^P}_1}{n_1} \\ \frac{\varepsilon\rho_b^s {c^P}_2}{n_2} \end{bmatrix}$$

Sequence of elementary row operations to determine the coefficients:

a. ERO $(2 - e^{\alpha_1 T_1} \times 1)$ then ERO $\left(\frac{1}{e^{-\alpha_1 T_1} - e^{\alpha_1 T_1}} \times 2\right)$, i.e., add $-e^{\alpha_1 T_1}$ times row 1 to row 2 and replace row 2 with the result; then scale the row 2 to make the diagonal component in row unity.

b. ERO $(3 + n_1 D_1 \alpha_1 e^{\alpha_1 T_1} \times 1)$ then ERO $\left(\frac{1}{n_1 D_1 \alpha_1 (e^{-\alpha_1 T_1} + e^{\alpha_1 T_1})} \times 3\right)$,

c. ERO $(3 - 2)$,

d. ERO $\left(e^{\alpha_2 (T_1 + T_2)} \times 4\right)$,

e. ERO $\left(2 + \frac{e^{-\alpha_2 T_1}}{e^{-\alpha_1 T_1} - e^{\alpha_1 T_1}} \times 4\right)$,

f. ERO $\left(3 - \left(\frac{-n_2 D_2 \alpha_2 e^{-\alpha_2 T_1}}{n_1 D_1 \alpha_1 (e^{-\alpha_1 T_1} + e^{\alpha_1 T_1})} + \frac{e^{-\alpha_2 T_1}}{e^{-\alpha_1 T_1} - e^{\alpha_1 T_1}}\right) \times 4\right)$

Simplify to get (highlighting signifies rows that should be aligned)

$$\begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & \dfrac{-e^{\alpha_2 T_1}(1 - e^{2\alpha_2 T_2})}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} & 0 \\ 0 & 0 & \dfrac{n_2 D_2 \alpha_2 e^{\alpha_2 T_1}(1 + e^{2\alpha_2 T_2})}{n_1 D_1 \alpha_1 (1 + 2e^{\alpha_1 T_1})} + \dfrac{e^{\alpha_2 T_1}(1 - e^{2\alpha_2 T_2})}{(1 - e^{2\alpha_1 T_1})} & 0 \\ 0 & 0 & e^{2\alpha_2 (T_1 + T_2)} & 1 \end{bmatrix} \begin{bmatrix} K_{11} \\ K_{12} \\ K_{21} \\ K_{22} \end{bmatrix}$$

$$= \begin{bmatrix} -1 & 0 \\ \dfrac{-1 + e^{\alpha_1 T_1}}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} & \dfrac{1 - e^{\alpha_2 T_2}}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} \\ \dfrac{1 - e^{\alpha_1 T_1}}{(1 + 2e^{\alpha_1 T_1})(1 + e^{\alpha_1 T_1})} & \dfrac{-1 + e^{\alpha_2 T_2}}{(1 - e^{2\alpha_1 T_1})} - \dfrac{n_2 D_2 \alpha_2 e^{\alpha_2 T_2}}{n_1 D_1 \alpha_1 (1 + e^{2\alpha_1 T_1})} \\ 0 & -e^{\alpha_2 (T_1 + T_2)} \end{bmatrix} \begin{bmatrix} \dfrac{\varepsilon \rho_b^s c^P{}_1}{n_1} \\ \dfrac{\varepsilon \rho_b^s c^P{}_2}{n_2} \end{bmatrix}$$

Row 3 gives

$$K_{21} = \frac{\dfrac{1 - e^{\alpha_1 T_1}}{(1 + e^{2\alpha_1 T_1})(1 + e^{\alpha_1 T_1})} \dfrac{\varepsilon \rho_b^s c^P{}_1}{n_1} + \left(\dfrac{-1 + e^{\alpha_2 T_2}}{1 - e^{2\alpha_1 T_1}} - \dfrac{n_2 D_2 \alpha_2 e^{\alpha_2 T_2}}{n_1 D_1 \alpha_1 (1 + e^{2\alpha_1 T_1})}\right) \dfrac{\varepsilon \rho_b^s c^P{}_2}{n_2}}{\dfrac{n_2 D_2 \alpha_2 e^{\alpha_2 T_1}(1 + e^{2\alpha_2 T_2})}{n_1 D_1 \alpha_1 (1 + e^{2\alpha_1 T_1})} + \dfrac{e^{\alpha_2 T_1}(1 - e^{2\alpha_2 T_2})}{(1 - e^{2\alpha_1 T_1})}}$$

Substituting for K_{21} in row 4 gives

$$K_{22} = -e^{\alpha_2 (T_1 + T_2)} \frac{\varepsilon \rho_b^s c^P{}_2}{n_2} - e^{2\alpha_2 (T_1 + T_2)} K_{21}$$

Substituting for K_{21} in row 2 gives

$$K_{12} = \frac{-1 + e^{\alpha_1 T_1}}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} \frac{\varepsilon \rho_b^s c^P{}_1}{n_1} + \frac{1 - e^{\alpha_2 T_2}}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} \frac{\varepsilon \rho_b^s c^P{}_2}{n_2} + \frac{e^{\alpha_2 T_1}(1 - e^{2\alpha_2 T_2})}{e^{-\alpha_1 T_1}(1 - e^{2\alpha_1 T_1})} K_{21}$$

Substituting for K_{12} in row 1 gives

$$K_{11} = -\frac{\varepsilon\rho_b^s {c^P}_1}{n_1} - K_{12}$$

6. Compute the rate of release of radon from the two external faces of the volume source:

Release out of the face at $x = 0$

$$Rel(0) = -A_s F(0) = A_s n_1 D_1 \alpha_1 (K_{11} - K_{12}) = A_s n_1 D_1 \alpha_1 \left(-\frac{\varepsilon\rho_b^s {c^P}_1}{n_1} - 2K_{12}\right)$$

Release out of the face at $x = T_1 + T_2$:

$$\begin{aligned} Rel(T_1+T_2) = A_s F(T_1+T_2) &= -A_s n_2 D_2 \alpha_2 \left(K_{21} e^{\alpha_2(T_1+T_2)} - K_{22} e^{-\alpha_2(T_1+T_2)}\right) \\ &= -A_s n_2 D_2 \alpha_2 \left(\frac{\varepsilon\rho_b^s {c^P}_2}{n_2} + 2K_{21} e^{\alpha_2(T_1+T_2)}\right) \end{aligned}$$

7. Sum them to obtain the instantaneous rate of release of radon from the two-layered volume source:

$$\begin{aligned} rel_{Vs}^{i\to Rn}(t) &= Rel(0,t) + Rel(T_1+T_2,t) \\ &= A_s n_1 D_1 \alpha_1 \left(-\frac{\varepsilon\rho_b^s {c^P}_1}{n_1} - 2K_{12}\right) - A_s n_2 D_2 \alpha_2 \left(\frac{\varepsilon\rho_b^s {c^P}_2}{n_2} + 2K_{21} e^{\alpha_2(T_1+T_2)}\right) \end{aligned}$$

The code uses the following equivalent equations for the coefficients to compute the releases from the two faces.

$$K_{22} = \frac{-\frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n_c\lambda_{Rn}} e^{-\alpha_c(T_o+T_c)} \left(\frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} + e^{-\alpha_0 T_0}} \frac{n_c D_c \alpha_c}{n_0 D_0 \alpha_0} - \frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}}\right) - \frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n_c\lambda_{Rn}(e^{\alpha_0 T_0} - e^{-\alpha_0 T_0})}}{e^{-2\alpha_c(T_o+T_c)} \left(\frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} + e^{-\alpha_0 T_0}} \frac{n_c D_c \alpha_c}{n_0 D_0 \alpha_0} - \frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}}\right) + \frac{e^{-\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}} + \frac{e^{-\alpha_c T_0}}{e^{\alpha_0 T_0} + e^{-\alpha_0 T_0}} \frac{n_c D_c \alpha_c}{n_0 D_0 \alpha_0}}$$

$$K_{21} = -e^{-2\alpha_c(T_o+T_c)} K_{22} - \frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n_c\lambda_{Rn}} e^{-\alpha_c(T_o+T_c)}$$

$$\begin{aligned} K_{11} = -K_{12} = &\left(-e^{-2\alpha_c(T_o+T_c)} \frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}} + \frac{e^{-\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}}\right) K_{22} \\ &- \frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n_c\lambda_{Rn}} e^{-\alpha_c(T_o+T_c)} \frac{e^{\alpha_c T_0}}{e^{\alpha_0 T_0} - e^{-\alpha_0 T_0}} + \frac{\varepsilon_s\rho_b^s c_s^{i\to RnP}\lambda_{Rn}}{n_c\lambda_{Rn}(e^{\alpha_0 T_0} - e^{-\alpha_0 T_0})} \end{aligned}$$

$$Rel(0) = A_s n_o D_o \alpha_o (K_{11} - K_{12})$$

$$Rel(T_1+T_2) = -A_s n_c D_c \alpha_c \left(K_{21} e^{\alpha_c(T_o+T_c)} - K_{22} e^{-\alpha_c(T_o+T_c)}\right)$$

$$rel_{Vs}^{i\to Rn}(t) = Rel(0,t) + Rel(T_1+T_2,t)$$

8. Time integration is performed in the same manner as for the single-layered volume source, Section B.7.2.

B.7.4 Time-Integrated Steady-State Concentration of Radon for an n-Room Simulation

This model computes the concentration of radon (^{222}Rn or ^{220}Rn) in the rooms of the building, a_i^{Rn}. It differs from the model for solid source material in following ways:

a. There is no suspended phase nor deposited phase, only a gaseous phase, the radon isotope, in each room.

b. The release of radon has three components: the release of radon from the radon parent *in situ* in the source, release of radon from the radon parents in source particulates suspended in air in each room, and release of radon from radon parents deposited on the floor of each room. It is not constant over the release duration; it varies continuously over time and its time-integrated value is computed by the code for each exposure duration.

c. It is a steady-state model that relates the steady-state concentrations of radon to a constant release rate of radon. The concentrations of the source material are computed using a transient model which tracks the changes in the concentration over time even under a constant rate of release. The time-integrated concentration of radon in air is computed assuming that the steady-state concentration of radon is achieved instantaneously as the release changes over the exposure duration.

d. The radiological transformation of radon cannot be calculated independently of the calculations of the distribution of radon between the rooms.

This model differs from the model for water vapor in three ways:

1. The release of radon has three components described previously. The water vapor is released only from the source that is *in situ*. While the releases of both radon and water vapor vary continuously over time, a time-integrated value of radon release is computed by the code for each exposure duration.

2. The time-integrated concentration of radon in air is computed assuming that the steady-state concentration of radon is achieved instantaneously as the release changes over the exposure duration.

3. The radiological transformation of radon cannot be calculated independently of the calculations of the distribution of radon between the rooms.

The steps involved in the solution for radon gas in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} a_1^{Rn} \\ a_2^{Rn} \\ . \\ a_n^{Rn} \end{bmatrix} = - \begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix}$$

$$c_{i,i} = -\lambda_{Rn} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{i,j} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file “RadonAndProgeny.out.”

Step 2a. Perform row operations to zero the off-diagonal components of the matrix and to normalize the diagonal components to 1.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. *Compute the time-integrated rates of release of radon from the source material in situ*, suspended in the air in each room and deposited on the floor in each room at an exposure reporting time. Sum them to compute the corresponding time-integrated rates of release of radon per unit volume in each room

$$c_i = \frac{1}{V_i} \int_{t_k^{ER}}^{t_k^{ER} + t_{ed}} r_{Rn}^{i}(t)\,dt$$

Step 4. Use the transformed matrices from step 2b and the rates of release of radon per unit volume in each room, c_i, to compute the time-integrated concentration of radon for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 to compute the time-integrated concentration of radon for each exposure reporting time.

B.7.5 Time-Integrated Steady-State Concentration of the Free RnA, the First Radon Progeny, for an n-Room Simulation

This model computes the concentration of the first progeny of radon (^{218}Po or ^{216}Po) in the free form in the air in the rooms of the building. It differs from the model for solid source material in four ways:

1. There is no suspended phase, deposited phase, nor a gaseous phase, only the free phase of the first progeny of the radon isotope, RnA, in each room.
2. The production of the first progeny of radon is from the radon in the rooms and is not a release from the source.
3. The instantaneous concentration of the free first radon progeny is computed assuming that the steady-state concentration is achieved instantaneously as the concentration of radon changes over the exposure duration.
4. The time-integrated concentration of the free first radon progeny is computed by multiplying the time-integrated production of the first progeny and the steady-state concentration per unit production.

The steps involved in the solution for the first progeny of radon in the free state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} f_1^{RnA} \\ f_2^{RnA} \\ . \\ f_n^{RnA} \end{bmatrix} = - \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix}$$

$$c_{i,i} = -\lambda_{RnA} - \lambda_{po} - \lambda_{at} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{i,j} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file “RadonAndProgeny.out.”

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Compute the time-integrated rate of production of the first progeny of radon using the time-integrated concentration of radon in air in each room for the reporting time t_k^{ER}.

$$c_i = \lambda_{RnA} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_i^{Rn} dt$$

Step 4. Use the transformed matrices from step 2b and the time-integrated rates of production of the first progeny of radon per unit volume in each room, c_i, to compute the time-integrated concentration of first progeny of radon in the free state for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 to compute the time-integrated concentration of the first progeny of radon in the free state for each exposure reporting time.

B.7.6 Time-Integrated Steady-State Concentration of the Attached RnA, the First Radon Progeny, for an n-Room Simulation

This model computes the concentration of the first progeny of radon (^{218}Po or ^{216}Po) in the attached form suspended in air and deposited on the floors of the rooms of the building. It differs from the model for solid source material in two ways:

1. Radiological transformation of radon produces the first progeny of radon in the free form. Some of the free progeny attach to particulates in the air to produce the attached form. These two processes lead to the production of the attached form in all the rooms.

2. The time-integrated concentrations of the first radon progeny in the attached forms are computed assuming that the steady-state concentrations are achieved instantaneously as the concentrations of radon and its first progeny in the free form change over the exposure duration.

The steps involved in the solution for the first progeny of radon in the attached state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & \cdot & \cdot & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & \cdot & \cdot & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & \cdot & \cdot & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & \cdot & \cdot & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & \cdot & \cdot & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1^{RnA} \\ d_1^{RnA} \\ a_2^{RnA} \\ d_2^{RnA} \\ \cdot \\ \cdot \\ a_n^{RnA} \\ d_n^{RnA} \end{bmatrix} = - \begin{bmatrix} c_1 \\ 0 \\ c_3 \\ 0 \\ \cdots \\ \cdots \\ c_{2n-1} \\ 0 \end{bmatrix}$$

$$c_{2i-1,2i-1} = -\lambda_{RnA} - \frac{A_i v_d}{V_i} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{2i-1,2j-1} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

$$c_{2i-1,2i} = \frac{A_i r_i}{V_i}$$

$$c_{2i-1,2j} = 0 \quad \forall\, j \neq i$$

$$c_{2i,2i-1} = v_d$$

$$c_{2i,2j-1} = 0 \quad \forall\, j \neq i$$

$$c_{2i,2i} = -\lambda_{RnA} - r_i$$

$$c_{2i,2j} = 0 \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "RadonAndProgeny.out."

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & \cdot & \cdot & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & \cdot & \cdot & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & \cdot & \cdot & c_{2n-1,3} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & \cdot & \cdot & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & \cdot & \cdot & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the $2n \times 2n$ identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Use the time-integrated concentration of first progeny of radon in the free state to compute the time-integrated rate of production of the attached form of the first progeny of radon in the air in each room for an exposure reporting time.

$$c_{2i-1} = \lambda_{at} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnA} dt$$

Step 4. Use the transformed matrices from step 2b and the rates of production of the attached form of the first progeny of radon per unit volume in each room, c_i, to compute the two components of the time-integrated concentrations of first progeny of radon in the attached state, suspended in air and deposited on the floor, for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 for each exposure reporting time.

B.7.7 Time-Integrated Steady-State Concentration of the Plated-out RnA, the First Radon Progeny, for an n-Room Simulation

There is no transfer of the plated-out material from room to room because the radionuclides are plated out on fixed surfaces in the room. For the purpose of this analysis, the concentration of the nuclides that are plated on the fixed surfaces is expressed in terms of the volume of the room. At steady state, the rate of production of the plated-out form is equal to the rate of decay of the plated-out form.

$$\lambda_{RnA} p_i^{RnA} = \lambda_{po} f_i^{RnA}$$

$$\int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} p_i^{RnA} dt = \frac{\lambda_{po}}{\lambda_{RnA}} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnA} dt$$

B.7.8 Time-Integrated Steady-State Concentration of the Free RnB, the Second Radon Progeny, for an n-Room Simulation

This model computes the concentration of the second progeny of radon (^{214}Pb or ^{212}Pb) in the free form in the air in the rooms of the building. These calculations are similar to the calculations of the free form of the first progeny except for the production term of the second progeny in step 3.

The steps involved in the solution for the second progeny of radon in the free state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} f_1^{RnB} \\ f_2^{RnB} \\ . \\ f_n^{RnB} \end{bmatrix} = - \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix}$$

$$c_{i,i} = -\lambda_{RnB} - \lambda_{po} - \lambda_{at} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{i,j} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "RadonAndProgeny.out."

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Compute the time-integrated rate of production of the free RnB from of the second progeny of radon using the time-integrated concentrations of the free, attached, and plated-out forms of the first progeny of radon in each room for the reporting time t_k^{ER}.

$$c_i = \lambda_{RnB} \left(\int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnA} dt + P_{at} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_i^{RnA} dt + P_{at} \frac{A_i}{V_i} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} d_i^{RnA} dt + P_{po} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} p_i^{RnA} dt \right)$$

$$c_i = \lambda_{RnB} \left(\left(1 + P_{po} \frac{\lambda_{po}}{\lambda_{RnA}} \right) \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnA} dt + P_{at} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_i^{RnA} dt + P_{at} \frac{A_i}{V_i} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} d_i^{RnA} dt \right)$$

Step 4. Use the transformed matrices from step 2b and the time-integrated rates of production of the second progeny of radon per unit volume in each room, c_i, to compute the time-integrated concentration of second progeny of radon in the free state for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 to compute the time-integrated concentration of second progeny of radon in the free state for each exposure reporting time.

B.7.9 Time-Integrated Steady-State Concentration of the Attached RnB, the Second Radon Progeny, for an n-Room Simulation

This model computes the concentration of the second progeny of radon (^{214}Pb or ^{212}Pb) in the attached form suspended in air and deposited on the floors of the rooms of the building. These calculations are similar to the calculations of the attached form of the first progeny except for the production term of the second progeny in step 3.

The steps involved in the solution for the second progeny of radon in the attached state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & \cdot & \cdot & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & \cdot & \cdot & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & \cdot & \cdot & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & \cdot & \cdot & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & \cdot & \cdot & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1^{RnB} \\ d_1^{RnB} \\ a_2^{RnB} \\ d_2^{RnB} \\ \cdot \\ \cdot \\ a_n^{RnB} \\ d_n^{RnB} \end{bmatrix} = - \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ \cdots \\ \cdots \\ c_{2n-1} \\ c_{2n} \end{bmatrix}$$

$$c_{2i-1,2i-1} = -\lambda_{RnB} - \frac{A_i v_d}{V_i} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{2i-1,2j-1} = \frac{q_{j,i}}{V_i} \quad \forall\, j \neq i$$

$$c_{2i-1,2i} = \frac{A_i r_i}{V_i}$$

$$c_{2i-1,2j} = 0 \quad \forall\, j \neq i$$

$$c_{2i,2i-1} = v_d$$

$$c_{2i,2j-1} = 0 \quad \forall\, j \neq i$$

$$c_{2i,2i} = -\lambda_{RnB} - r_i$$

$$c_{2i,2j} = 0 \quad \forall\, j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "RadonAndProgeny.out."

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & \cdot & \cdot & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & \cdot & \cdot & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & \cdot & \cdot & c_{2n-1,3} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & \cdot & \cdot & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & \cdot & \cdot & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the $2n \times 2n$ identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Use the time-integrated concentrations of second progeny of radon in the free state and of the first progeny of radon in the attached states to compute the time-integrated rates of production of the attached forms of the second progeny of radon in each room for an exposure reporting time.

$$c_{2i-1} = \lambda_{at} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnB} dt + \lambda_{RnB}(1 - P_{at}) \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_i^{RnA} dt$$

$$c_{2i} = \lambda_{RnB}(1 - P_{at}) \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} d_i^{RnA} dt$$

Step 4. Use the transformed matrices from step 2b and the rates of production of the attached form of the second progeny of radon per unit volume in each room, c_i, to compute the two components of the time-integrated concentrations of second progeny of radon in the attached state, suspended in air and deposited on the floor, for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 for each exposure reporting time.

B.7.10 Time-Integrated Steady-State Concentration of the Free RnC, the Third Radon Progeny, for an n-Room Simulation

This model computes the concentration of the third progeny of radon (^{210}Bi or ^{208}Bi) in the free form in air in the rooms of the building. These calculations are similar to the calculations of the free form of the second progeny except for the production term of the third progeny in step 3.

The steps involved in the solution for the third progeny of radon in the free state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix} \begin{bmatrix} f_1^{RnC} \\ f_2^{RnC} \\ . \\ f_n^{RnC} \end{bmatrix} = - \begin{bmatrix} c_1 \\ c_2 \\ \cdots \\ c_n \end{bmatrix}$$

$$c_{i,i} = -\lambda_{RnC} - \lambda_{po} - \lambda_{at} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{i,j} = \frac{q_{j,i}}{V_i} \quad \forall j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file "RadonAndProgeny.out."

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & . & c_{1,n} \\ c_{2,1} & c_{2,2} & . & c_{2,n} \\ . & . & . & . \\ c_{n,1} & c_{n,2} & . & c_{n,n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Compute the time-integrated rate of production of the free RnC from of the third progeny of radon using the time-integrated concentration of the free form of the second progeny of radon in each room for the reporting time t_k^{ER}.

$$c_i = \lambda_{RnC} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnB} dt$$

Step 4. Use the transformed matrices from step 2b and the time-integrated rates of production of the third progeny of radon per unit volume in each room, c_i, to compute the time-integrated concentration of third progeny of radon in the free state for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 to compute the time-integrated concentration of third progeny of radon in the free state for each exposure reporting time.

B.7.11 Time-Integrated Steady-State Concentration of the Attached RnC, the Third Radon Progeny, for an n-Room Simulation

This model computes the concentration of the third progeny of radon (^{210}Bi or ^{208}Bi) in the attached form suspended in air and deposited on the floors of the rooms of the building. These calculations are similar to the calculations of the attached form of the second progeny except for the production term of the third progeny in step 3.

The steps involved in the solution for the third progeny of radon in the attached state in an n-room simulation are as follows:

Step 1. Determine the coefficients of the system of equations at steady state.

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & \cdot & \cdot & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & \cdot & \cdot & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & \cdot & \cdot & c_{3,2n-1} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & \cdot & \cdot & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & \cdot & \cdot & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & \cdot & \cdot & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix} \begin{bmatrix} a_1^{RnC} \\ d_1^{RnC} \\ a_2^{RnC} \\ d_2^{RnC} \\ \cdot \\ \cdot \\ a_n^{RnC} \\ d_n^{RnC} \end{bmatrix} = - \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ \cdots \\ \cdots \\ c_{2n-1} \\ c_{2n} \end{bmatrix}$$

$$c_{2i-1,2i-1} = -\lambda_{RnC} - \frac{A_i v_d}{V_i} - \frac{1}{V_i} \sum_{j=0, j \neq i}^{n} q_{i,j}$$

$$c_{2i-1,2j-1} = \frac{q_{j,i}}{V_i} \quad \forall j \neq i$$

$$c_{2i-1,2i} = \frac{A_i r_i}{V_i}$$

$$c_{2i-1,2j} = 0 \quad \forall j \neq i$$

$$c_{2i,2i-1} = v_d$$

$$c_{2i,2j-1} = 0 \quad \forall j \neq i$$

$$c_{2i,2i} = -\lambda_{RnC} - r_i$$

$$c_{2i,2j} = 0 \quad \forall j \neq i$$

The matrix of the coefficients of the system of equations is written to the temporary file “RadonAndProgeny.out.”

Step 2a. Perform row operations to zero the off-diagonal components of the matrix

$$\begin{bmatrix} c_{1,1} & c_{1,2} & c_{1,3} & 0 & . & . & c_{1,2n-1} & 0 \\ c_{2,1} & c_{2,2} & 0 & 0 & . & . & 0 & 0 \\ c_{3,1} & 0 & c_{3,3} & c_{3,4} & . & . & c_{2n-1,3} & 0 \\ 0 & 0 & c_{4,3} & c_{4,4} & . & . & 0 & 0 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ c_{2n-1,1} & 0 & c_{2n-1,3} & 0 & . & . & c_{2n-1,2n-1} & c_{2n-1,2n} \\ 0 & 0 & 0 & 0 & . & . & c_{2n,2n-1} & c_{2n,2n} \end{bmatrix}$$

Step 2b. Perform the same row operations on the $2n \times 2n$ identity matrix

$$\begin{bmatrix} 1 & 0 & . & 0 \\ 0 & 1 & . & 0 \\ . & . & . & . \\ 0 & 0 & . & 1 \end{bmatrix}$$

Step 3. Use the time-integrated concentrations of third progeny of radon in the free state and the second progeny of radon in the attached states to compute the time-integrated rates of production of the attached forms of the third progeny of radon in each room for an exposure reporting time.

$$c_{2i-1} = \lambda_{at} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} f_i^{RnC} dt + \lambda_{RnC} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_i^{RnB} dt$$

$$c_{2i} = \lambda_{RnC} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} d_i^{RnB} dt$$

Step 4. Use the transformed matrices from step 2b and the rates of production of the attached form of the third progeny of radon per unit volume in each room, c_i, to compute the two components of the time-integrated concentrations of third progeny of radon in the attached state, suspended in air and deposited on the floor, for the reporting time t_k^{ER}.

Step 5. Repeat steps 3 and 4 for each exposure reporting time.

APPENDIX C:

EXTERNAL RADIATION EXPOSURE

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APPENDIX C:

EXTERNAL RADIATION EXPOSURE

The external radiation exposure model is used to calculate the dose and risk incurred by a receptor from (1) direct external exposure to a radiation source, (2) external exposure to deposited radioactive material (modeled as an area source), and (3) external exposure to radioactive dust particles in the indoor air (air submersion). For the deposition and air submersion pathways (2 and 3), the exposure is considered to result only from the deposited and airborne radionuclides, respectively, in the room occupied by the receptor.

Two direct external exposure models based on the geometrical type of sources are used in RESRAD-BUILD. The model for point and line sources is a simple dose integral model. The model for area and volume sources is based on an infinite slab source, with correction factors to account for the geometry and finite dimensions of actual sources. The correction factors are derived using the methodology described in Kamboj et al. (1998, 2002), with extension to consider differences due to the source material. An area source is treated as a volume source with a small thickness (0.001 cm) and unit density. The external exposure from radioactive material deposited on the floor is estimated by treating the contaminated floor as a circular area source, with the receptor located at 1 m above the center of the floor.

The external radiation exposure model employs dose and risk coefficients to calculate dose and risk incurred by the receptor. Three sets of base dose coefficient libraries can be used in RESRAD-BUILD Version 4.0; two sets of libraries are based on the ICRP-38 (ICRP 1983) radionuclide transformation database, and one library is based on the ICRP-107 radionuclide transformation database. Two base (cancer) risk coefficient libraries developed based on the ICRP-38 transformation database from FGR 13 Eckerman et al. 1999) can be used in RESRAD-BUILD, one for estimating morbidity risk and the other for estimating mortality risk. Two base risk coefficient libraries developed based on the ICRP-107 transformation database from DCFPAK3.02 can be used in RESRAD-BUILD, one for estimating morbidity risk and the other for estimating mortality risk (see Appendix A for more information on dose/risk coefficients).

C.1 EXTERNAL DOSE AND RISK FROM A CONTAMINATED VOLUME SOURCE

The total time-integrated external dose at time *t* over the exposure duration *ED* from exposure to a volume source containing radionuclide *n* in compartment *i*, $D_{iV}^{n}(t)$, is expressed as:

$$D_{iV}^{n}(t) = \left(\frac{1}{365}\right) F_{in} F_i DCF_v^n \int_t^{t+ED} C_{sV}^n(t) F_G^n(t) dt \qquad \text{(C.1)}$$

where:

365 = time conversion factor (d/yr);

F_{in} = fraction of time spent indoors;

F_i = fraction of time spent in compartment *i*;

DCF_v^n = external dose coefficient for an infinite volume source [(mrem/yr)/(pCi/g)];

$F_n^G(t)$ = geometrical factor for radionuclide *n* in the source at time *t*, to correct DCF_v^n for finite area and thickness of the source, shielding between the source and the receptor, source material, and position of receptor relative to the source;

$C_{sV}^n(t)$ = concentration of radionuclide *n* in the volume source at time *t* (pCi/g); and

ED = exposure duration (d).

The instantaneous concentration of radionuclide *n* at time *t*, $C_{sV}^n(t)$, is related to its instantaneous quantity of radioactivity at that time, $Q_s^n(t)$, as shown in the expression below

$$Q_s^n(t) = A_s \rho_s t_s(t) C_{sV}^n(t) \tag{C.2}$$

where:

$Q_s^n(t)$ = quantity of radionuclide *n* in the source at time *t* (pCi),

A_s = area of the volume source (cm^2),

$t_s(t)$ = thickness of the volume source at time *t* (cm), and

ρ_s = source density (g/cm^3).

The calculation of the instantaneous quantity of a radionuclide in the source is discussed in Section B.4.3 of Appendix B. The calculation of the geometrical factor, $F_G^n(t)$, is discussed later in this section.

In cases when the value of the geometrical factor is time-dependent (e.g., in cases when erosion changes the distance between the source and the receptor over time), the radiation dose incurred by the receptor over the entire exposure duration starting at time *t* is calculated by the RESRAD-BUILD code numerically with Simpson's formula. For this evaluation, time-integration points and convergence criteria are used. The integration points are used to divide the exposure duration (from *t* to *t* + *ED*) into smaller intervals and to obtain additional time points in addition to *t* and *t* + *ED*. Radiation dose is calculated at times *t*, *t* + *ED*, and at additional time points in between using the values of C_{sV}^n and F_n^G at each time point. The dose at each time point is multiplied by a certain weighting factor according to Simpson's formula. The sum of the weighting factors of all the time points is 1. The sum of the weighted dose of all the time points is then an estimate of the integrated dose over the exposure duration starting at time *t*. Time integration is performed repeatedly by increasing the number of time points until either the number of time-integration points equals the maximum value or the fractional difference between the two successive estimates of time-integrated dose is less than the convergence criteria. See Section B.6.10 for more detailed information on numerical time integration.

In cases when the value of the geometrical factor is constant over the exposure duration, to reduce run time instead of performing the integral on both the time-dependent concentration and geometrical factor, the average concentration of radionuclide *n*, $\overline{C_{sV}^n(t)}$ from Section B.5.1 and the constant F_G^n is used.

For calculating the total cancer risk from exposure to radionuclide *n* in a volume source, the dose calculated by Equation C.1 is multiplied by the ratio of slope factor to the dose coefficient of radionuclide *n*, both for an infinitely large volume source.

The geometrical factor, F_G, is the ratio of the dose (effective dose equivalent in ICRP-26/30 methodology or effective dose in ICRP-60 methodology) for the actual source to the dose for the standard source. The standard source is a source of contaminated soil that has an infinite depth and infinite lateral extent with no cover. The geometrical factor is expressed as the product of the depth-and-cover factor, F_{CD}, the area and material factor, F_{AM}, and the off-set factor, $F_{OFF\text{-}SET}$.

C.1.1 Depth-and-Cover Factor

The external dose coefficients in three sets of dose coefficient libraries, are given for a surface source and four volume sources, each with a specific thickness (1, 5, 15 cm, and effectively infinite). The assumptions are that all the sources are infinite in lateral extent, are uniformly distributed with radionuclides, and are without any cover. The depth-and-cover factor function, F_{CD}, was developed by performing data fitting regression analysis on its mathematical expression that describes the attenuation by source material to the radiation emitted by radionuclides. Four radionuclide-specific parameters (three are independent) are included in the mathematical expression, Equation C.3, and their values were determined by fitting the expression using the dose coefficients for different depths. Kamboj et al. (1998) describes the data fitting using the effective dose equivalent values of FGR 12 (Eckerman and Ryman 1993).

$$F_{CD} = \frac{D(T_c=t_c, T_S=t_s)}{D(T_c=0, T_S=\infty)} = Ae^{-K_A\rho_c t_c}(1-e^{-K_A\rho_S t_S}) + Be^{-K_B\rho_c t_c}(1-e^{-K_B\rho_S t_S}) \; , \quad \text{(C.3)}$$

where:

D = direct external dose from a source with a thickness of T_s and a cover thickness of T_c (mrem/yr);

A, B = fit parameters (dimensionless);

K_A, K_B = fit parameters (cm^2/g);

t_c = shielding (cover) thickness (cm) (it is the sum of all shielding thicknesses between the source and the receptor and include all uncontaminated regions in a volume source; the shielding is placed immediately adjacent to the source as shown in Figure C-1);

ρ_c = shielding density (g/cm^3) (it is the thickness averaged density between the source and receptor);

t_s = source thickness (cm);

ρ_s = source density (g/cm^3);

T_c = shielding parameter; and

T_s = source depth parameter.

The following three constraints were put on the four fitting parameters:

1. All the parameters are forced to be positive.
2. A + B = 1.
3. In the limit for zero cover depth and source depth, $t_s = 0$, the value of F_{CD} should match the ratio of dose coefficient for a surface source to dose coefficient for a volume source with an infinite thickness.

Figure C-1 shows the source and shielding geometry modeled in RESRAD-BUILD code.

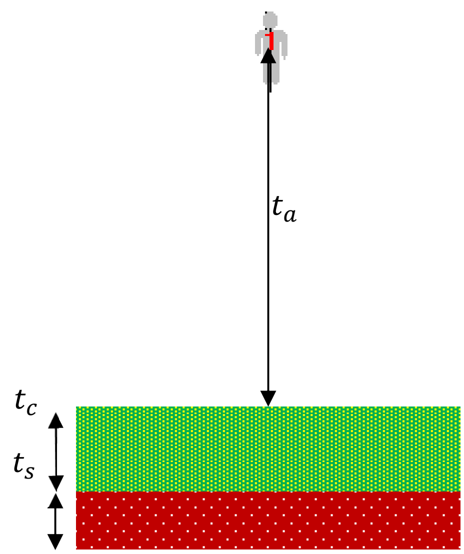

Figure C-1 Source and Shielding Modeled in RESRAD-BUILD

Fitted values for all the four parameters (A, B, K_A, K_B) were determined through regression analysis for all radionuclides and saved in the RESRAD-BUILD database for each of the three external dose factor libraries. Parameters A, B, K_A, and K_B for the three databases for principal radionuclides were based on a 30-day half-life cut-off, and their decay progeny radionuclides are listed in Tables C-1, C-2, and C-3. Table C-1 lists the fitted parameters determined using the dose coefficients from FGR 12 based on ICRP-26/30 methodology, Table C-2 lists the fitted parameters determined using the dose coefficients from FGR 13 based on the ICRP-60 methodology, and Table C-3 lists the fitted parameters determined using the dose coefficients from DCFPAK 3.02.

Table C-1 Fitted Parameters *A, B, K_A,* and *K_B* for at least 30 Day Cut-off Half-life Radionuclides and Their Associated Progeny Determined with the Dose Coefficients from FGR 12

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Ac-225	9.08E-01	9.20E-02	1.51E-01	1.66E+00
Ac-227	9.13E-01	8.70E-02	1.60E-01	2.58E+00
Ac-228	9.00E-02	9.10E-01	1.18E+00	8.30E-02
Ag-105	9.19E-01	8.10E-02	9.90E-02	1.41E+00
Ag-108	9.06E-01	9.40E-02	9.20E-02	1.28E+00
Ag-108m	9.28E-01	7.20E-02	9.70E-02	1.44E+00
Ag-110	9.19E-01	8.10E-02	9.60E-02	1.36E+00
Ag-110m	9.00E-02	9.10E-01	1.17E+00	8.30E-02
Al-26	9.14E-01	8.60E-02	7.50E-02	1.15E+00
Am-241	8.36E-01	1.64E-01	3.13E-01	2.88E+00
Am-242	8.00E-02	9.20E-01	2.56E+00	1.78E-01
Am-242m	7.04E-01	2.96E-01	1.83E-01	6.62E+00
Am-243	8.84E-01	1.16E-01	2.38E-01	1.98E+00
Am-245	9.26E-01	7.40E-02	1.37E-01	1.68E+00
Am-246m	7.30E-02	9.27E-01	1.36E+00	8.60E-02
Ar-37	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ar-39	8.48E-01	1.52E-01	1.63E-01	2.10E+00
As-73	8.12E-01	1.88E-01	3.66E-01	2.35E+00
At-217	9.22E-01	7.80E-02	1.00E-01	1.36E+00
At-218	8.14E-01	1.86E-01	3.71E-01	2.88E+00
Au-194	7.90E-02	9.21E-01	1.29E+00	8.40E-02
Au-195	8.77E-01	1.23E-01	2.38E-01	1.89E+00
Ba-133	8.00E-02	9.21E-01	1.64E+00	1.13E-01
Ba-137m	9.28E-01	7.20E-02	9.50E-02	1.41E+00
Be-10	8.55E-01	1.45E-01	1.64E-01	2.12E+00
Be-7	9.22E-01	7.80E-02	1.00E-01	1.37E+00
Bi-207	8.00E-02	9.20E-01	1.31E+00	8.70E-02
Bi-210	8.68E-01	1.32E-01	1.33E-01	1.71E+00
Bi-210m	9.19E-01	8.10E-02	1.14E-01	1.33E+00
Bi-211	6.60E-02	9.34E-01	1.58E+00	1.13E-01
Bi-212	7.30E-02	9.27E-01	1.36E+00	8.60E-02
Bi-213	9.16E-01	8.40E-02	9.90E-02	1.32E+00
Bi-214	8.70E-02	9.13E-01	1.15E+00	7.50E-02
Bk-247	8.96E-01	1.04E-01	1.37E-01	1.43E+00
Bk-249	5.55E-01	4.45E-01	2.60E-01	3.54E+00
Bk-250	7.40E-02	9.26E-01	1.35E+00	8.60E-02
C-14	6.42E-01	3.58E-01	2.94E-01	3.39E+00
Ca-41	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ca-45	2.52E-01	7.48E-01	2.74E+00	2.26E-01
Cd-109	6.53E-01	3.47E-01	2.05E-01	4.77E+00
Cd-113	7.90E-01	2.10E-01	2.10E-01	2.65E+00
Cd-113m	8.48E-01	1.52E-01	1.68E-01	2.18E+00
Cd-115m	8.70E-02	9.13E-01	1.24E+00	8.40E-02
Ce-139	9.18E-01	8.20E-02	1.42E-01	1.90E+00
Ce-141	9.30E-01	7.00E-02	1.56E-01	1.81E+00
Ce-144	9.01E-01	9.90E-02	1.62E-01	1.87E+00
Cf-248	8.20E-01	1.80E-01	8.60E+00	1.20E+00

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Cf-249	9.20E-01	8.00E-02	1.06E-01	1.37E+00
Cf-250	8.20E-01	1.80E-01	8.60E+00	1.20E+00
Cf-251	9.17E-01	8.30E-02	1.41E-01	1.70E+00
Cf-252	6.50E-01	3.50E-01	7.26E+00	1.82E-01
Cf-253	7.49E-01	2.51E-01	2.20E-01	3.25E+00
Cf-254	8.20E-01	1.80E-01	8.60E+00	1.20E+00
Cl-36	8.89E-01	1.11E-01	1.33E-01	1.90E+00
Cm-241	9.06E-01	9.40E-02	1.03E-01	1.30E+00
Cm-242	2.24E-01	7.76E-01	1.70E-01	8.40E+00
Cm-243	9.25E-01	7.50E-02	1.35E-01	1.68E+00
Cm-244	7.00E-03	9.93E-01	8.46E+02	2.19E+00
Cm-245	7.90E-02	9.21E-01	1.86E+00	1.65E-01
Cm-246	8.70E-02	9.13E-01	4.58E-01	8.60E+00
Cm-247	9.22E-01	7.80E-02	1.05E-01	1.37E+00
Cm-248	7.33E-01	2.67E-01	1.04E+01	1.22E+00
Cm-249	9.16E-01	8.40E-02	9.70E-02	1.30E+00
Cm-250	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Co-56	9.60E-02	9.04E-01	1.01E+00	7.10E-02
Co-57	9.29E-01	7.10E-02	1.60E-01	1.69E+00
Co-58	9.23E-01	7.70E-02	9.00E-02	1.34E+00
Co-60	7.60E-02	9.24E-01	1.28E+00	7.80E-02
Co-60m	1.20E-01	8.80E-01	1.17E+00	7.90E-02
Cs-134	9.27E-01	7.30E-02	9.30E-02	1.38E+00
Cs-135	7.25E-01	2.75E-01	2.51E-01	3.03E+00
Cs-137	8.48E-01	1.52E-01	1.57E-01	2.05E+00
Dy-159	8.00E-01	2.00E-01	4.80E-01	3.01E+00
Es-253	1.22E-01	8.78E-01	3.65E+00	1.11E-01
Es-254	7.73E-01	2.27E-01	1.42E-01	4.60E+00
Eu-146	7.80E-02	9.22E-01	1.33E+00	8.70E-02
Eu-148	9.19E-01	8.10E-02	9.00E-02	1.31E+00
Eu-149	8.40E-01	1.60E-01	1.16E-01	1.72E+00
Eu-150b	9.25E-01	7.50E-02	9.70E-02	1.42E+00
Eu-152	9.00E-02	9.10E-01	1.19E+00	8.40E-02
Eu-154	9.00E-02	9.10E-01	1.17E+00	8.30E-02
Eu-155	8.62E-01	1.38E-01	1.91E-01	1.55E+00
Fe-55	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Fe-59	7.20E-02	9.28E-01	1.32E+00	8.20E-02
Fe-60	6.10E-01	3.90E-01	3.12E-01	3.48E+00
Fm-257	9.22E-01	7.80E-02	1.49E-01	1.84E+00
Fr-221	9.39E-01	6.10E-02	1.32E-01	1.69E+00
Fr-223	8.60E-01	1.40E-01	1.33E-01	1.57E+00
Ga-68	9.27E-01	7.30E-02	9.90E-02	1.42E+00
Gd-146	8.82E-01	1.18E-01	1.64E-01	1.82E+00
Gd-148	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Gd-151	8.22E-01	1.78E-01	1.37E-01	1.78E+00
Gd-152	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Gd-153	8.23E-01	1.77E-01	1.99E-01	1.94E+00
Ge-68	9.90E-01	1.00E-02	3.20E+01	1.20E+00
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Hf-172	8.23E-01	1.77E-01	2.37E-01	1.90E+00
Hf-175	8.30E-02	9.17E-01	1.50E+00	1.13E-01
Hf-178m	9.15E-01	8.50E-02	1.03E-01	1.34E+00
Hf-181	9.12E-01	8.80E-02	1.02E-01	1.33E+00
Hf-182	9.30E-01	7.00E-02	1.21E-01	1.51E+00
Hg-194	9.90E-01	1.00E-02	2.20E+01	1.20E+00
Hg-203	9.30E-01	7.00E-02	1.18E-01	1.50E+00
Ho-166m	8.10E-02	9.19E-01	1.33E+00	9.30E-02
I-125	8.54E-01	1.46E-01	3.45E+00	4.42E-01
I-129	4.35E-01	5.65E-01	7.14E-01	3.58E+00
In-113m	9.27E-01	7.30E-02	1.07E-01	1.47E+00
In-114	7.70E-02	9.23E-01	1.37E+00	7.90E-02
In-114m	9.10E-01	9.00E-02	9.90E-02	1.46E+00
In-115	8.28E-01	1.72E-01	1.70E-01	2.25E+00
Ir-192	9.31E-01	6.90E-02	1.08E-01	1.49E+00
Ir-192m	9.32E-01	6.80E-02	1.41E-01	1.61E+00
Ir-194	9.18E-01	8.20E-02	9.70E-02	1.30E+00
Ir-194m	9.22E-01	7.80E-02	1.00E-01	1.35E+00
K-40	8.40E-02	9.16E-01	1.17E+00	7.20E-02
Kr-81	9.46E-01	5.40E-02	1.21E-01	2.33E+00
Kr-83m	1.30E-02	9.87E-01	9.85E+02	1.90E+00
Kr-85	9.05E-01	9.50E-02	9.90E-02	1.33E+00
La-137	4.00E-01	6.00E-01	6.10E-01	3.15E+00
La-138	9.00E-02	9.10E-01	1.13E+00	7.60E-02
Lu-172	9.00E-02	9.10E-01	1.21E+00	8.30E-02
Lu-173	8.25E-01	1.75E-01	1.33E-01	1.43E+00
Lu-174	1.57E-01	8.43E-01	1.10E+00	8.25E-02
Lu-174m	7.10E-01	2.90E-01	1.40E-01	1.32E+00
Lu-176	9.30E-01	7.00E-02	1.20E-01	1.58E+00
Lu-177	9.24E-01	7.60E-02	1.38E-01	1.62E+00
Lu-177m	9.16E-01	8.40E-02	1.18E-01	1.43E+00
Md-258	6.10E-01	3.90E-01	2.40E-01	5.55E+00
Mn-53	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Mn-54	8.50E-02	9.15E-01	1.22E+00	8.80E-02
Mo-93	9.99E-01	1.00E-03	1.06E+01	9.19E-01
Na-22	7.40E-02	9.26E-01	1.34E+00	8.70E-02
Nb-93m	9.99E-01	1.00E-03	1.06E+01	9.19E-01
Nb-94	9.28E-01	7.20E-02	9.10E-02	1.39E+00
Nb-95	7.50E-02	9.25E-01	1.36E+00	9.10E-02
Nb-95m	9.45E-01	5.50E-02	1.27E-01	1.99E+00
Ni-59	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Np-235	8.28E-01	1.72E-01	1.90E-01	6.75E+00
Np-236a	6.50E-02	9.35E-01	2.20E+00	1.72E-01
Np-237	8.97E-01	1.03E-01	1.85E-01	2.58E+00
Np-238	8.30E-02	9.17E-01	1.24E+00	8.40E-02
Np-239	9.25E-01	7.50E-02	1.39E-01	1.64E+00
Np-240m	9.21E-01	7.90E-02	9.00E-02	1.35E+00
Os-185	8.30E-02	9.17E-01	1.36E+00	9.30E-02

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Os-194	7.80E-01	2.20E-01	5.20E-01	3.36E+00
P-32	9.00E-01	1.00E-01	1.28E-01	1.74E+00
Pa-231	9.30E-01	7.00E-02	1.16E-01	2.02E+00
Pa-233	9.25E-01	7.50E-02	1.18E-01	1.52E+00
Pa-234	8.50E-02	9.15E-01	1.24E+00	8.80E-02
Pa-234m	9.16E-01	8.40E-02	9.10E-02	1.39E+00
Pb-202	9.90E-01	1.00E-02	2.57E+01	1.20E+00
Pb-205	9.90E-01	1.00E-02	2.51E+01	1.20E+00
Pb-209	8.52E-01	1.48E-01	1.63E-01	2.14E+00
Pb-210	8.04E-01	1.96E-01	4.93E-01	4.04E+00
Pb-211	9.26E-01	7.40E-02	9.60E-02	1.42E+00
Pb-212	9.27E-01	7.30E-02	1.31E-01	1.59E+00
Pb-214	8.00E-02	9.21E-01	1.39E+00	1.11E-01
Pd-107	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Pm-143	9.20E-01	8.00E-02	9.30E-02	1.49E+00
Pm-144	9.27E-01	7.30E-02	9.60E-02	1.45E+00
Pm-145	5.90E-01	4.10E-01	4.00E-01	2.60E+00
Pm-146	9.28E-01	7.20E-02	9.70E-02	1.48E+00
Pm-147	7.73E-01	2.27E-01	2.09E-01	2.80E+00
Pm-148	7.50E-02	9.25E-01	1.31E+00	8.20E-02
Pm-148m	7.90E-02	9.21E-01	1.33E+00	9.30E-02
Po-209	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Po-210	9.27E-01	7.30E-02	9.00E-02	1.38E+00
Po-211	9.22E-01	7.80E-02	9.00E-02	1.33E+00
Po-212	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Po-213	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Po-214	8.40E-02	9.16E-01	1.23E+00	8.80E-02
Po-215	9.15E-01	8.50E-02	1.00E-01	1.28E+00
Po-216	8.40E-02	9.16E-01	1.24E+00	8.80E-02
Po-218	8.20E-02	9.18E-01	1.25E+00	8.80E-02
Pr-144	8.20E-02	9.18E-01	1.26E+00	7.90E-02
Pr-144m	5.32E-01	4.68E-01	1.29E-01	2.11E+00
Pt-193	9.90E-01	1.00E-02	2.49E+01	1.20E+00
Pu-236	4.05E-01	5.95E-01	1.57E-01	8.36E+00
Pu-237	7.60E-02	9.24E-01	2.20E+00	1.84E-01
Pu-238	2.97E-01	7.03E-01	1.96E-01	9.12E+00
Pu-239	8.00E-01	2.00E-01	1.35E-01	6.75E+00
Pu-240	2.98E-01	7.02E-01	2.18E-01	9.00E+00
Pu-241	7.90E-02	9.21E-01	2.80E+00	1.76E-01
Pu-242	3.31E-01	6.69E-01	2.11E-01	8.98E+00
Pu-243	8.81E-01	1.19E-01	1.73E-01	1.70E+00
Pu-244	8.00E-03	9.92E-01	8.46E+02	1.90E+00
Pu-246	9.22E-01	7.80E-02	1.45E-01	1.81E+00
Ra-223	9.05E-01	9.50E-02	1.30E-01	1.38E+00
Ra-224	9.43E-01	5.70E-02	1.27E-01	1.74E+00
Ra-225	7.08E-01	2.92E-01	5.80E-01	3.44E+00
Ra-226	9.32E-01	6.80E-02	1.35E-01	1.64E+00
Ra-228	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Rb-83	9.16E-01	8.40E-02	9.60E-02	1.29E+00

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Rb-84	8.50E-02	9.15E-01	1.24E+00	8.80E-02
Rb-87	7.87E-01	2.13E-01	2.15E-01	2.63E+00
Re-184	9.18E-01	8.20E-02	9.00E-02	1.35E+00
Re-184m	9.08E-01	9.20E-02	1.01E-01	1.35E+00
Re-186	9.06E-01	9.40E-02	1.64E-01	1.68E+00
Re-186m	7.96E-01	2.04E-01	2.75E-01	1.96E+00
Re-187	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Re-188	8.97E-01	1.03E-01	9.90E-02	1.23E+00
Rh-101	9.32E-01	6.80E-02	1.34E-01	1.73E+00
Rh-102	9.19E-01	8.10E-02	9.00E-02	1.29E+00
Rh-102m	9.25E-01	7.50E-02	9.80E-02	1.35E+00
Rh-103m	7.90E-01	2.10E-01	7.30E+00	1.22E+00
Rh-106	9.27E-01	7.30E-02	9.60E-02	1.41E+00
Rn-219	8.00E-02	9.21E-01	1.34E+00	1.11E-01
Rn-220	9.26E-01	7.40E-02	9.70E-02	1.41E+00
Rn-222	9.22E-01	7.80E-02	9.80E-02	1.34E+00
Ru-103	9.22E-01	7.80E-02	1.00E-01	1.35E+00
Ru-106	0.00E+00	1.00E+00	0.00E+00	0.00E+00
S-35	3.40E-01	6.60E-01	3.31E+00	2.90E-01
Sb-124	7.70E-02	9.23E-01	1.28E+00	7.90E-02
Sb-125	9.22E-01	7.80E-02	9.80E-02	1.44E+00
Sb-126	7.50E-02	9.25E-01	1.38E+00	9.30E-02
Sb-126m	9.27E-01	7.30E-02	9.60E-02	1.40E+00
Sc-44	7.90E-02	9.21E-01	1.31E+00	8.70E-02
Sc-46	7.30E-02	9.27E-01	1.35E+00	8.60E-02
Se-75	6.90E-02	9.31E-01	1.55E+00	1.24E-01
Se-79	6.62E-01	3.38E-01	2.86E-01	3.29E+00
Si-32	7.22E-01	2.78E-01	2.52E-01	3.02E+00
Sm-145	6.66E-01	3.34E-01	4.30E-01	2.66E+00
Sm-146	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Sm-151	3.30E-02	9.67E-01	8.27E-01	6.15E+00
Sn-113	8.07E-01	1.93E-01	1.25E-01	3.82E+00
Sn-119m	7.33E-01	2.67E-01	5.09E+00	1.22E+00
Sn-121	8.00E-01	2.00E-01	1.87E-01	2.39E+00
Sn-121m	8.00E-01	2.00E-01	3.53E+00	4.42E-01
Sn-123	8.30E-02	9.17E-01	1.37E+00	8.70E-02
Sn-126	8.90E-01	1.10E-01	2.12E-01	2.23E+00
Sr-85	9.20E-01	8.00E-02	9.70E-02	1.34E+00
Sr-89	9.00E-01	1.00E-01	1.28E-01	1.77E+00
Sr-90	8.48E-01	1.52E-01	1.70E-01	2.15E+00
Ta-179	8.24E-01	1.76E-01	3.24E-01	2.12E+00
Ta-180	9.20E-01	8.00E-02	1.18E-01	1.49E+00
Ta-182	7.90E-02	9.21E-01	1.32E+00	8.40E-02
Tb-157	7.92E-01	2.08E-01	5.20E-01	3.20E+00
Tb-158	8.30E-02	9.17E-01	1.34E+00	8.70E-02
Tb-160	7.70E-02	9.23E-01	1.33E+00	8.70E-02
Tc-95	9.25E-01	7.50E-02	9.00E-02	1.39E+00
Tc-95m	9.25E-01	7.50E-02	9.60E-02	1.41E+00

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Tc-97	9.99E-01	1.00E-03	9.40E+00	9.19E-01
Tc-97m	5.20E-01	4.80E-01	1.89E-01	7.70E+00
Tc-98	9.26E-01	7.40E-02	9.30E-02	1.38E+00
Tc-99	7.87E-01	2.13E-01	2.11E-01	2.63E+00
Te-121	9.24E-01	7.60E-02	9.70E-02	1.46E+00
Te-121m	9.30E-01	7.00E-02	1.18E-01	1.70E+00
Te-123	1.30E-02	9.87E-01	1.24E+02	1.90E+00
Te-123m	9.34E-01	6.60E-02	1.45E-01	1.98E+00
Te-125m	7.76E-01	2.24E-01	3.48E+00	3.70E-01
Te-127	9.13E-01	8.70E-02	1.03E-01	1.36E+00
Te-127m	2.78E-01	7.22E-01	1.60E-01	3.30E+00
Te-129	9.22E-01	7.80E-02	1.00E-01	1.54E+00
Te-129m	9.10E-01	9.00E-02	9.30E-02	1.70E+00
Th-227	9.17E-01	8.30E-02	1.21E-01	1.47E+00
Th-228	9.12E-01	8.80E-02	1.56E-01	2.31E+00
Th-229	9.12E-01	8.80E-02	1.66E-01	1.82E+00
Th-230	8.63E-01	1.37E-01	1.87E-01	4.11E+00
Th-231	8.70E-01	1.30E-01	1.95E-01	3.26E+00
Th-232	8.15E-01	1.85E-01	2.08E-01	5.76E+00
Th-234	8.96E-01	1.04E-01	2.09E-01	2.08E+00
Ti-44	8.82E-01	1.18E-01	2.39E-01	1.86E+00
Tl-202	9.07E-01	9.30E-02	1.02E-01	1.31E+00
Tl-204	8.68E-01	1.32E-01	2.07E-01	1.88E+00
Tl-206	9.00E-01	1.00E-01	1.33E-01	1.83E+00
Tl-207	9.08E-01	9.20E-02	9.70E-02	1.46E+00
Tl-208	9.60E-02	9.04E-01	9.60E-01	6.30E-02
Tl-209	7.90E-02	9.21E-01	1.26E+00	7.90E-02
Tl-210	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Tm-170	8.48E-01	1.52E-01	2.20E-01	1.82E+00
Tm-171	8.15E-01	1.85E-01	3.32E-01	2.16E+00
U-232	8.09E-01	1.91E-01	1.75E-01	6.12E+00
U-233	8.89E-01	1.11E-01	1.39E-01	4.28E+00
U-234	7.23E-01	2.77E-01	1.94E-01	7.34E+00
U-235	9.33E-01	6.70E-02	1.38E-01	1.65E+00
U-236	5.93E-01	4.07E-01	1.98E-01	8.40E+00
U-237	9.04E-01	9.60E-02	1.49E-01	1.65E+00
U-238	3.97E-01	6.03E-01	4.30E-01	1.01E+01
U-240	4.90E-01	5.10E-01	3.90E-01	6.46E+00
V-49	0.00E+00	1.00E+00	0.00E+00	0.00E+00
W-181	8.30E-01	1.70E-01	3.08E-01	2.04E+00
W-185	8.48E-01	1.52E-01	1.88E-01	2.22E+00
W-188	9.17E-01	8.30E-02	1.21E-01	1.46E+00
Xe-127	9.30E-01	7.00E-02	1.27E-01	1.78E+00
Y-88	9.60E-02	9.04E-01	9.90E-01	7.10E-02
Y-90	9.07E-01	9.30E-02	1.18E-01	1.65E+00
Y-91	9.70E-02	9.03E-01	1.31E+00	8.80E-02
Yb-169	8.72E-01	1.28E-01	1.44E-01	1.54E+00
Zn-65	7.30E-02	9.27E-01	1.33E+00	8.40E-02
Zr-88	9.27E-01	7.30E-02	1.05E-01	1.47E+00

Table C-1 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Zr-93	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Zr-95	9.30E-01	7.00E-02	9.30E-02	1.44E+00

[a] Fitting parameters are used in depth and cover factor calculations.

Table C-2 Fitted Parameters *A, B, K_A,* and *K_B* for at least 30 Day Cut-off Half-life Radionuclides and Their Associated Progeny Determined with the Dose Coefficients from FGR 13

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Ac-225	9.14E-01	8.60E-02	1.59E-01	1.77E+00
Ac-227	9.13E-01	8.70E-02	1.61E-01	2.56E+00
Ac-228	9.15E-01	8.50E-02	8.44E-02	1.36E+00
Ag-105	9.06E-01	9.40E-02	9.95E-02	1.27E+00
Ag-108	8.70E-01	1.31E-01	1.01E-01	6.35E+00
Ag-108m	9.15E-01	8.50E-02	9.43E-02	1.33E+00
Ag-110	8.25E-01	1.75E-01	9.69E-02	4.13E+00
Ag-110m	9.18E-01	8.20E-02	8.56E-02	1.31E+00
Al-26	9.13E-01	8.70E-02	7.63E-02	1.20E+00
Am-241	8.36E-01	1.64E-01	3.14E-01	2.88E+00
Am-242	9.08E-01	9.20E-02	1.75E-01	2.80E+00
Am-242m	7.45E-01	2.55E-01	1.88E-01	6.65E+00
Am-243	8.80E-01	1.20E-01	2.38E-01	2.01E+00
Am-245	9.24E-01	7.60E-02	1.38E-01	3.08E+00
Am-246m	9.13E-01	8.70E-02	8.31E-02	1.34E+00
Ar-37	9.15E-01	8.50E-02	7.19E-02	1.13E+00
Ar-39	8.30E-01	1.70E-01	1.69E-01	2.06E+01
As-73	7.80E-01	2.20E-01	3.56E-01	2.25E+00
At-217	9.26E-01	7.40E-02	1.03E-01	1.53E+00
At-218	8.21E-01	1.79E-01	3.81E-01	3.19E+00
Au-194	9.11E-01	9.00E-02	8.13E-02	1.24E+00
Au-195	8.70E-01	1.30E-01	2.38E-01	1.90E+00
Ba-133	9.11E-01	8.90E-02	1.13E-01	1.53E+00
Ba-137m	9.16E-01	8.40E-02	9.38E-02	1.34E+00
Be-10	8.30E-01	1.70E-01	1.69E-01	2.23E+01
Be-7	9.15E-01	8.50E-02	9.97E-02	1.33E+00
Bi-207	9.10E-01	9.00E-02	8.63E-02	1.26E+00
Bi-210	5.30E-01	4.70E-01	1.36E-01	1.58E+01
Bi-210m	9.19E-01	8.10E-02	1.14E-01	1.41E+00
Bi-211	9.23E-01	7.70E-02	1.11E-01	1.49E+00
Bi-212	9.19E-01	8.10E-02	8.44E-02	1.96E+00
Bi-213	9.19E-01	8.10E-02	1.03E-01	2.19E+00
Bi-214	9.16E-01	8.40E-02	7.69E-02	1.31E+00
Bk-247	9.14E-01	8.60E-02	1.46E-01	1.69E+00
Bk-249	5.50E-01	4.50E-01	2.39E-01	3.39E+00
Bk-250	9.09E-01	9.10E-02	8.24E-02	1.22E+00
C-14	6.55E-01	3.45E-01	2.88E-01	3.38E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Ca-41	9.18E-01	8.20E-02	6.77E-02	1.13E+00
Ca-45	7.70E-01	2.30E-01	2.31E-01	2.81E+00
Cd-109	7.00E-01	3.00E-01	2.12E-01	4.78E+00
Cd-113	7.90E-01	2.10E-01	2.06E-01	2.53E+00
Cd-113m	8.20E-01	1.80E-01	1.69E-01	1.83E+01
Cd-115m	8.84E-01	1.16E-01	8.63E-02	5.64E+00
Ce-139	9.26E-01	7.40E-02	1.46E-01	2.06E+00
Ce-141	9.34E-01	6.60E-02	1.55E-01	2.06E+00
Ce-144	9.10E-01	9.00E-02	1.67E-01	2.01E+00
Cf-248	5.00E-02	9.50E-01	6.25E-01	7.83E+00
Cf-249	9.21E-01	7.90E-02	1.08E-01	1.46E+00
Cf-250	5.00E-02	9.50E-01	6.25E-01	7.84E+00
Cf-251	9.20E-01	8.00E-02	1.45E-01	1.78E+00
Cf-252	9.17E-01	8.30E-02	7.44E-02	1.21E+00
Cf-253	7.70E-01	2.30E-01	2.25E-01	3.25E+00
Cf-254	9.07E-01	9.30E-02	7.25E-02	1.09E+00
Cl-36	7.78E-01	2.22E-01	1.28E-01	2.31E+01
Cm-241	9.12E-01	8.80E-02	1.08E-01	1.41E+00
Cm-242	2.70E-01	7.30E-01	1.63E-01	8.68E+00
Cm-243	9.23E-01	7.70E-02	1.37E-01	1.71E+00
Cm-244	5.00E-02	9.50E-01	3.13E-01	8.75E+00
Cm-245	9.20E-01	8.00E-02	1.70E-01	1.88E+00
Cm-246	1.30E-01	8.70E-01	6.25E-01	9.19E+00
Cm-247	9.16E-01	8.40E-02	1.06E-01	1.35E+00
Cm-248	9.16E-01	8.40E-02	7.38E-02	1.19E+00
Cm-249	9.20E-01	8.00E-02	9.81E-02	3.34E+00
Cm-250	9.09E-01	9.10E-02	7.26E-02	1.12E+00
Co-56	9.12E-01	8.80E-02	7.25E-02	1.15E+00
Co-57	9.20E-01	8.00E-02	1.59E-01	1.68E+00
Co-58	9.03E-01	9.70E-02	8.69E-02	1.17E+00
Co-60	9.14E-01	8.60E-02	7.69E-02	1.21E+00
Co-60m	8.87E-01	1.13E-01	8.07E-02	1.32E+00
Cs-134	9.11E-01	8.90E-02	9.00E-02	1.26E+00
Cs-135	7.50E-01	2.50E-01	2.63E-01	3.13E+00
Cs-137	7.00E-01	3.00E-01	1.63E-01	1.36E+01
Dy-159	6.90E-01	3.10E-01	4.13E-01	2.36E+00
Es-253	8.86E-01	1.14E-01	1.13E-01	3.35E+00
Es-254	7.90E-01	2.10E-01	1.41E-01	4.25E+00
Eu-146	9.16E-01	8.40E-02	8.62E-02	1.31E+00
Eu-148	9.04E-01	9.60E-02	8.81E-02	1.18E+00
Eu-149	8.62E-01	1.38E-01	1.21E-01	1.86E+00
Eu-150b	9.16E-01	8.40E-02	9.58E-02	1.36E+00
Eu-152	9.04E-01	9.60E-02	8.29E-02	1.19E+00
Eu-154	9.15E-01	8.50E-02	8.31E-02	1.32E+00
Eu-155	8.80E-01	1.20E-01	1.94E-01	1.81E+00
Fe-55	9.25E-01	7.50E-02	1.01E-01	1.40E+00
Fe-59	9.05E-01	9.50E-02	7.75E-02	1.12E+00
Fe-60	6.10E-01	3.90E-01	2.96E-01	3.39E+00
Fm-257	9.30E-01	7.00E-02	1.55E-01	2.01E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Fr-221	9.37E-01	6.30E-02	1.31E-01	1.75E+00
Fr-223	8.67E-01	1.33E-01	1.35E-01	2.88E+00
Ga-68	9.16E-01	8.40E-02	9.81E-02	1.55E+00
Gd-146	8.97E-01	1.03E-01	1.69E-01	2.03E+00
Gd-148	8.22E-01	1.78E-01	1.99E-01	1.93E+00
Gd-151	8.50E-01	1.50E-01	1.46E-01	1.98E+00
Gd-152	9.18E-01	8.20E-02	8.36E-02	1.27E+00
Gd-153	8.30E-01	1.70E-01	2.06E-01	1.97E+00
Ge-68	2.00E-03	9.98E-01	9.38E-01	3.71E+01
H-3	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-172	7.80E-01	2.20E-01	2.13E-01	1.68E+00
Hf-175	9.11E-01	8.90E-02	1.13E-01	1.48E+00
Hf-178m	9.21E-01	7.90E-02	1.08E-01	1.46E+00
Hf-181	9.17E-01	8.30E-02	1.08E-01	1.41E+00
Hf-182	9.14E-01	8.60E-02	1.17E-01	1.36E+00
Hg-194	2.00E-03	9.98E-01	4.75E-01	2.46E+01
Hg-203	9.14E-01	8.60E-02	1.14E-01	1.36E+00
Ho-166m	9.15E-01	8.50E-02	9.43E-02	1.33E+00
I-125	2.00E-01	8.00E-01	6.25E-01	3.69E+00
I-129	4.02E-01	5.98E-01	6.35E-01	3.56E+00
In-113m	9.24E-01	7.60E-02	1.08E-01	1.49E+00
In-114	9.12E-01	8.80E-02	7.72E-02	1.33E+00
In-114m	9.13E-01	8.70E-02	1.03E-01	1.48E+00
In-115	8.46E-01	1.54E-01	1.81E-01	6.56E+00
Ir-192	9.28E-01	7.20E-02	1.11E-01	1.49E+00
Ir-192m	9.29E-01	7.10E-02	1.43E-01	1.65E+00
Ir-194	9.00E-01	1.00E-01	9.81E-02	3.13E+00
Ir-194m	9.15E-01	8.50E-02	9.88E-02	1.33E+00
K-40	9.24E-01	7.60E-02	7.56E-02	2.22E+00
Kr-81	9.30E-01	7.00E-02	1.18E-01	2.03E+00
Kr-83m	5.20E-02	9.48E-01	3.63E-01	1.74E+01
Kr-85	9.07E-01	9.30E-02	1.03E-01	8.71E+00
La-137	4.07E-01	5.93E-01	6.35E-01	3.25E+00
La-138	9.07E-01	9.30E-02	7.55E-02	1.14E+00
Lu-172	9.04E-01	9.60E-02	8.28E-02	1.18E+00
Lu-173	8.44E-01	1.56E-01	1.39E-01	1.56E+00
Lu-174	8.64E-01	1.36E-01	8.44E-02	1.25E+00
Lu-174m	7.09E-01	2.91E-01	1.37E-01	1.31E+00
Lu-176	9.18E-01	8.20E-02	1.18E-01	1.46E+00
Lu-177	9.19E-01	8.10E-02	1.37E-01	1.66E+00
Lu-177m	9.15E-01	8.50E-02	1.19E-01	1.49E+00
Md-258	6.44E-01	3.56E-01	2.39E-01	5.43E+00
Mn-53	9.19E-01	8.10E-02	8.18E-02	1.24E+00
Mn-54	9.09E-01	9.10E-02	8.60E-02	1.23E+00
Mo-93	2.00E-03	9.98E-01	3.13E-01	1.09E+01
Na-22	9.19E-01	8.10E-02	8.54E-02	1.32E+00
Nb-93m	2.00E-03	9.98E-01	3.13E-01	1.09E+01
Nb-94	9.13E-01	8.70E-02	8.75E-02	1.28E+00
Nb-95	9.10E-01	9.00E-02	8.81E-02	1.23E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Nb-95m	9.37E-01	6.30E-02	1.27E-01	1.83E+00
Ni-59	8.44E-01	1.56E-01	1.20E-01	1.30E+00
Ni-63	9.25E-01	7.50E-02	9.77E-02	1.39E+00
Np-235	8.43E-01	1.57E-01	1.94E-01	6.50E+00
Np-236a	9.16E-01	8.40E-02	1.67E-01	1.88E+00
Np-237	9.00E-01	1.00E-01	1.88E-01	2.55E+00
Np-238	9.11E-01	8.90E-02	8.31E-02	1.29E+00
Np-239	9.18E-01	8.20E-02	1.37E-01	1.65E+00
Np-240m	9.16E-01	8.40E-02	9.00E-02	1.81E+00
Os-185	9.08E-01	9.20E-02	9.25E-02	1.29E+00
Os-194	6.40E-01	3.60E-01	4.19E-01	2.57E+00
P-32	4.75E-01	5.25E-01	1.25E-01	9.19E+00
Pa-231	9.30E-01	7.00E-02	1.18E-01	2.03E+00
Pa-233	9.23E-01	7.70E-02	1.20E-01	1.57E+00
Pa-234	9.14E-01	8.60E-02	8.81E-02	1.31E+00
Pa-234m	7.80E-01	2.20E-01	8.94E-02	5.50E+00
Pb-202	2.00E-03	9.98E-01	7.50E-01	3.04E+01
Pb-205	2.00E-03	9.98E-01	5.63E-01	2.97E+01
Pb-209	8.02E-01	1.98E-01	1.69E-01	2.43E+01
Pb-210	8.90E-01	1.10E-01	5.72E-01	6.88E+00
Pb-211	9.21E-01	7.90E-02	9.56E-02	3.74E+00
Pb-212	9.37E-01	6.30E-02	1.34E-01	1.91E+00
Pb-214	9.17E-01	8.30E-02	1.11E-01	1.49E+00
Pd-107	9.32E-01	6.80E-02	1.13E-01	1.51E+00
Pm-143	9.04E-01	9.60E-02	8.94E-02	1.33E+00
Pm-144	9.11E-01	8.90E-02	9.31E-02	1.30E+00
Pm-145	5.70E-01	4.30E-01	3.91E-01	2.56E+00
Pm-146	9.14E-01	8.60E-02	9.44E-02	1.36E+00
Pm-147	7.90E-01	2.10E-01	2.13E-01	2.81E+00
Pm-148	9.17E-01	8.30E-02	8.13E-02	1.56E+00
Pm-148m	9.08E-01	9.20E-02	9.13E-02	1.24E+00
Po-209	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	9.12E-01	8.80E-02	8.75E-02	1.26E+00
Po-211	9.16E-01	8.40E-02	9.00E-02	1.33E+00
Po-212	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-214	9.14E-01	8.60E-02	8.88E-02	1.28E+00
Po-215	9.19E-01	8.10E-02	1.03E-01	1.38E+00
Po-216	9.16E-01	8.40E-02	8.88E-02	1.33E+00
Po-218	9.16E-01	8.40E-02	8.75E-02	1.31E+00
Pr-144	8.32E-01	1.68E-01	7.94E-02	3.84E+00
Pr-144m	5.60E-01	4.40E-01	1.21E-01	2.16E+00
Pt-193	2.00E-03	9.98E-01	5.63E-01	2.85E+01
Pu-236	4.56E-01	5.44E-01	1.75E-01	8.56E+00
Pu-237	9.28E-01	7.20E-02	1.89E-01	2.31E+00
Pu-238	3.30E-01	6.70E-01	1.96E-01	9.19E+00
Pu-239	8.24E-01	1.76E-01	1.33E-01	6.56E+00
Pu-240	3.30E-01	6.70E-01	1.96E-01	9.19E+00
Pu-241	9.22E-01	7.80E-02	1.78E-01	2.75E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Pu-242	3.60E-01	6.40E-01	1.94E-01	9.03E+00
Pu-243	8.94E-01	1.06E-01	1.81E-01	1.98E+00
Pu-244	9.15E-01	8.50E-02	7.38E-02	1.22E+00
Pu-246	9.20E-01	8.00E-02	1.45E-01	1.78E+00
Ra-223	9.16E-01	8.40E-02	1.33E-01	1.61E+00
Ra-224	9.37E-01	6.30E-02	1.28E-01	1.66E+00
Ra-225	6.66E-01	3.34E-01	5.72E-01	3.19E+00
Ra-226	9.27E-01	7.30E-02	1.36E-01	1.64E+00
Ra-228	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Rb-83	9.25E-01	7.50E-02	9.88E-02	1.49E+00
Rb-84	9.14E-01	8.60E-02	8.87E-02	1.31E+00
Rb-87	8.00E-01	2.00E-01	2.13E-01	2.66E+00
Re-184	9.08E-01	9.20E-02	8.88E-02	1.28E+00
Re-184m	8.97E-01	1.03E-01	9.88E-02	1.28E+00
Re-186	8.87E-01	1.13E-01	1.63E-01	5.06E+00
Re-186m	8.56E-01	1.44E-01	3.13E-01	2.55E+00
Re-187	9.04E-01	9.60E-02	1.26E-01	1.49E+00
Re-188	8.80E-01	1.20E-01	1.05E-01	3.75E+00
Rh-101	9.27E-01	7.30E-02	1.36E-01	1.69E+00
Rh-102	9.15E-01	8.50E-02	9.00E-02	1.31E+00
Rh-102m	9.06E-01	9.40E-02	9.38E-02	1.33E+00
Rh-103m	1.10E-01	8.90E-01	6.25E-01	6.78E+00
Rh-106	8.98E-01	1.02E-01	9.50E-02	2.33E+00
Rn-219	9.25E-01	7.50E-02	1.11E-01	1.49E+00
Rn-220	9.25E-01	7.50E-02	9.88E-02	1.49E+00
Rn-222	9.26E-01	7.40E-02	1.01E-01	1.49E+00
Ru-103	9.15E-01	8.50E-02	9.94E-02	1.33E+00
Ru-106	9.25E-01	7.50E-02	9.56E-02	1.52E+00
S-35	6.70E-01	3.30E-01	2.81E-01	3.29E+00
Sb-124	9.07E-01	9.30E-02	7.75E-02	1.16E+00
Sb-125	9.19E-01	8.10E-02	1.00E-01	1.44E+00
Sb-126	9.09E-01	9.10E-02	9.00E-02	1.26E+00
Sb-126m	9.14E-01	8.60E-02	9.38E-02	1.40E+00
Sc-44	9.09E-01	9.10E-02	8.56E-02	1.29E+00
Sc-46	9.15E-01	8.50E-02	8.24E-02	1.27E+00
Se-75	9.32E-01	6.80E-02	1.26E-01	1.67E+00
Se-79	6.80E-01	3.20E-01	2.88E-01	3.31E+00
Si-32	7.33E-01	2.67E-01	2.56E-01	2.98E+00
Sm-145	6.00E-01	4.00E-01	3.69E-01	2.42E+00
Sm-146	9.25E-01	7.50E-02	1.01E-01	1.40E+00
Sm-147	9.19E-01	8.10E-02	8.72E-02	1.30E+00
Sm-151	4.00E-02	9.60E-01	6.25E-01	6.38E+00
Sn-113	8.25E-01	1.75E-01	1.20E-01	3.56E+00
Sn-119m	1.00E-01	9.00E-01	6.25E-01	4.54E+00
Sn-121	8.20E-01	1.80E-01	1.96E-01	2.46E+00
Sn-121m	3.00E-01	7.00E-01	6.25E-01	3.94E+00
Sn-123	8.30E-01	1.70E-01	8.50E-02	8.00E+00
Sn-126	8.80E-01	1.20E-01	2.10E-01	2.06E+00
Sr-85	9.18E-01	8.20E-02	9.88E-02	1.38E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Sr-89	4.90E-01	5.10E-01	1.25E-01	1.03E+01
Sr-90	8.58E-01	1.42E-01	1.88E-01	1.97E+01
Ta-179	8.20E-01	1.80E-01	3.25E-01	2.18E+00
Ta-180	9.17E-01	8.30E-02	1.19E-01	1.52E+00
Ta-182	9.06E-01	9.40E-02	8.06E-02	1.19E+00
Tb-157	7.00E-01	3.00E-01	4.69E-01	2.61E+00
Tb-158	9.08E-01	9.20E-02	8.63E-02	1.28E+00
Tb-160	9.07E-01	9.30E-02	8.40E-02	1.20E+00
Tc-95	9.16E-01	8.40E-02	8.94E-02	1.31E+00
Tc-95m	9.11E-01	8.90E-02	9.38E-02	1.28E+00
Tc-97	2.00E-03	9.98E-01	3.13E-01	9.62E+00
Tc-97m	5.82E-01	4.18E-01	1.98E-01	7.81E+00
Tc-98	9.04E-01	9.60E-02	8.94E-02	1.17E+00
Tc-99	8.00E-01	2.00E-01	2.13E-01	2.63E+00
Te-121	9.21E-01	7.90E-02	9.81E-02	1.46E+00
Te-121m	9.23E-01	7.70E-02	1.19E-01	1.59E+00
Te-123	1.30E-01	8.70E-01	6.25E-01	4.04E+00
Te-123m	9.24E-01	7.60E-02	1.45E-01	1.78E+00
Te-125m	2.50E-01	7.50E-01	3.88E-01	3.63E+00
Te-127	9.22E-01	7.80E-02	1.08E-01	4.50E+00
Te-127m	3.40E-01	6.60E-01	1.86E-01	3.54E+00
Te-129	9.07E-01	9.30E-02	9.88E-02	3.59E+00
Te-129m	9.00E-01	1.00E-01	9.25E-02	2.93E+00
Th-227	9.27E-01	7.30E-02	1.24E-01	1.72E+00
Th-228	9.13E-01	8.70E-02	1.59E-01	2.31E+00
Th-229	9.10E-01	9.00E-02	1.67E-01	1.86E+00
Th-230	8.62E-01	1.38E-01	1.87E-01	3.88E+00
Th-231	8.72E-01	1.28E-01	1.96E-01	3.09E+00
Th-232	8.15E-01	1.85E-01	2.06E-01	5.38E+00
Th-234	8.91E-01	1.09E-01	2.09E-01	2.07E+00
Ti-44	8.63E-01	1.37E-01	2.38E-01	1.74E+00
Tl-202	9.12E-01	8.80E-02	1.08E-01	1.41E+00
Tl-204	8.10E-01	1.90E-01	2.13E-01	1.63E+01
Tl-206	5.00E-01	5.00E-01	1.31E-01	1.11E+01
Tl-207	7.35E-01	2.65E-01	9.88E-02	1.04E+01
Tl-208	9.11E-01	8.90E-02	6.63E-02	1.10E+00
Tl-209	9.10E-01	9.00E-02	7.75E-02	1.24E+00
Tl-210	9.13E-01	8.70E-02	7.88E-02	1.29E+00
Tm-170	7.85E-01	2.15E-01	2.13E-01	9.36E+00
Tm-171	8.00E-01	2.00E-01	3.25E-01	2.15E+00
U-232	8.20E-01	1.80E-01	1.75E-01	5.81E+00
U-233	8.89E-01	1.11E-01	1.39E-01	3.88E+00
U-234	7.50E-01	2.50E-01	1.97E-01	7.38E+00
U-235	9.28E-01	7.20E-02	1.38E-01	1.68E+00
U-236	6.20E-01	3.80E-01	2.00E-01	8.39E+00
U-237	9.14E-01	8.60E-02	1.54E-01	1.88E+00
U-238	4.60E-01	5.40E-01	5.00E-01	1.11E+01
U-240	5.10E-01	4.90E-01	3.88E-01	6.39E+00
V-49	9.21E-01	7.90E-02	1.02E-01	1.37E+00

Table C-2 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
W-181	7.90E-01	2.10E-01	2.88E-01	1.86E+00
W-185	8.60E-01	1.40E-01	1.94E-01	2.53E+00
W-188	9.32E-01	6.80E-02	1.26E-01	1.79E+00
Xe-127	9.26E-01	7.40E-02	1.27E-01	1.74E+00
Y-88	9.12E-01	8.80E-02	7.25E-02	1.14E+00
Y-90	5.20E-01	4.80E-01	1.25E-01	6.56E+00
Y-91	7.35E-01	2.65E-01	8.88E-02	8.44E+00
Yb-169	8.87E-01	1.13E-01	1.49E-01	1.71E+00
Zn-65	9.09E-01	9.10E-02	7.88E-02	1.18E+00
Zr-88	9.20E-01	8.00E-02	1.08E-01	1.38E+00
Zr-93	9.18E-01	8.20E-02	7.53E-02	1.19E+00
Zr-95	9.08E-01	9.20E-02	8.94E-02	1.21E+00

[a] Fitting parameters are used in depth and cover factor calculations.

Table C-3 Fitted Parameters *A, B, K_A,* and *K_B* for at least 30 Day Cut-off Half-life Radionuclides and Their Associated Progeny Determined with the Dose Coefficients from DCFPAK3.02

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Ac-225	9.10E-02	9.09E-01	1.73E+00	1.47E-01
Ac-227	1.65E-01	8.35E-01	5.57E+00	1.66E-01
Ac-228	1.19E-01	8.81E-01	1.01E+00	8.05E-02
Ag-105	9.70E-02	9.03E-01	1.24E+00	9.95E-02
Ag-108	1.35E-01	8.65E-01	5.94E+00	9.82E-02
Ag-108m	9.80E-02	9.02E-01	1.18E+00	9.31E-02
Ag-110	1.84E-01	8.16E-01	3.94E+00	9.52E-02
Ag-110m	1.20E-01	8.80E-01	9.30E-01	8.03E-02
Al-26	1.34E-01	8.66E-01	8.14E-01	6.97E-02
Am-241	1.75E-01	8.25E-01	2.46E+00	3.08E-01
Am-242	8.00E-02	9.20E-01	3.15E+00	1.80E-01
Am-242m	3.17E-01	6.83E-01	6.80E+00	1.75E-01
Am-243	1.23E-01	8.77E-01	1.97E+00	2.38E-01
Am-245	7.30E-02	9.27E-01	3.17E+00	1.39E-01
Am-246m	1.09E-01	8.91E-01	1.09E+00	8.04E-02
Ar-37	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ar-39	1.71E-01	8.29E-01	2.06E+01	1.68E-01
Ar-42	1.95E-01	8.05E-01	2.46E+01	1.65E-01
As-73	1.88E-01	8.12E-01	2.47E+00	3.74E-01
At-217	8.60E-02	9.14E-01	1.39E+00	1.13E-01
At-218	4.82E-01	5.18E-01	5.31E+00	1.14E-01
At-219	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Au-194	1.39E-01	8.61E-01	8.27E-01	7.55E-02
Au-195	1.33E-01	8.67E-01	1.86E+00	2.36E-01
Ba-133	8.50E-02	9.15E-01	1.59E+00	1.14E-01
Ba-137m	9.70E-02	9.03E-01	1.20E+00	9.05E-02
Be-10	1.69E-01	8.31E-01	2.26E+01	1.68E-01

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Be-7	9.10E-02	9.09E-01	1.25E+00	9.96E-02
Bi-207	1.19E-01	8.81E-01	9.84E-01	8.19E-02
Bi-208	1.48E-01	8.52E-01	6.31E-01	5.47E-02
Bi-210	4.65E-01	5.35E-01	1.59E+01	1.42E-01
Bi-210m	7.80E-02	9.22E-01	1.46E+00	1.15E-01
Bi-211	8.30E-02	9.17E-01	1.38E+00	1.10E-01
Bi-212	9.70E-02	9.03E-01	2.18E+00	8.31E-02
Bi-213	8.00E-02	9.20E-01	2.30E+00	1.04E-01
Bi-214	1.25E-01	8.75E-01	9.15E-01	7.13E-02
Bi-215	9.00E-02	9.10E-01	1.92E+00	9.75E-02
Bk-247	8.60E-02	9.14E-01	1.56E+00	1.38E-01
Bk-249	2.92E-01	7.08E-01	3.19E+00	1.58E-01
Bk-250	1.18E-01	8.82E-01	9.64E-01	7.90E-02
Bk-251	7.50E-02	9.25E-01	2.74E+00	1.60E-01
C-14	3.44E-01	6.56E-01	3.38E+00	2.91E-01
Ca-41	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ca-45	2.31E-01	7.69E-01	2.82E+00	2.30E-01
Cd-109	3.02E-01	6.98E-01	4.76E+00	2.07E-01
Cd-113	2.05E-01	7.95E-01	2.59E+00	2.08E-01
Cd-113m	1.43E-01	8.57E-01	1.53E+01	1.49E-01
Cd-115m	1.13E-01	8.87E-01	4.31E+00	8.29E-02
Ce-139	8.00E-02	9.20E-01	1.95E+00	1.44E-01
Ce-141	7.10E-02	9.29E-01	1.92E+00	1.53E-01
Ce-144	9.00E-02	9.10E-01	1.92E+00	1.62E-01
Cf-248	1.28E-01	8.72E-01	3.51E+00	7.41E-02
Cf-249	7.90E-02	9.21E-01	1.42E+00	1.09E-01
Cf-250	1.30E-01	8.70E-01	9.40E-01	6.83E-02
Cf-251	7.40E-02	9.26E-01	1.80E+00	1.49E-01
Cf-252	1.37E-01	8.63E-01	8.30E-01	6.74E-02
Cf-253	3.53E-01	6.47E-01	3.96E-01	5.88E+00
Cf-254	1.40E-01	8.60E-01	8.20E-01	6.71E-02
Cl-36	2.19E-01	7.81E-01	2.38E+01	1.33E-01
Cm-241	9.20E-02	9.08E-01	1.34E+00	1.07E-01
Cm-242	2.87E-01	7.13E-01	1.46E-01	8.44E+00
Cm-243	7.70E-02	9.23E-01	1.70E+00	1.37E-01
Cm-244	4.34E-01	5.66E-01	7.77E+00	8.27E-02
Cm-245	8.00E-02	9.20E-01	1.85E+00	1.67E-01
Cm-246	1.18E-01	8.82E-01	1.15E+00	6.89E-02
Cm-247	8.10E-02	9.19E-01	1.39E+00	1.07E-01
Cm-248	1.38E-01	8.62E-01	8.36E-01	6.72E-02
Cm-249	8.10E-02	9.19E-01	3.33E+00	9.76E-02
Cm-250	1.40E-01	8.60E-01	8.25E-01	6.72E-02
Co-56	1.47E-01	8.53E-01	7.19E-01	6.56E-02
Co-57	7.20E-02	9.28E-01	1.78E+00	1.63E-01
Co-58	1.07E-01	8.93E-01	1.05E+00	8.63E-02
Co-60	1.31E-01	8.69E-01	8.17E-01	7.17E-02
Co-60m	1.81E-01	8.19E-01	8.59E-01	7.11E-02
Cs-134	1.05E-01	8.95E-01	1.09E+00	8.82E-02
Cs-135	2.19E-01	7.81E-01	2.67E+00	2.19E-01

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Cs-137	3.07E-01	6.93E-01	1.34E+01	1.59E-01
Dy-154	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Dy-159	2.54E-01	7.46E-01	2.66E+00	4.48E-01
Es-253	9.50E-02	9.05E-01	2.78E+00	1.13E-01
Es-254	2.00E-01	8.00E-01	4.21E+00	1.40E-01
Es-255	1.52E-01	8.48E-01	8.05E-01	6.67E-02
Eu-146	1.23E-01	8.77E-01	9.19E-01	7.92E-02
Eu-148	1.10E-01	8.90E-01	1.04E+00	8.64E-02
Eu-149	1.48E-01	8.52E-01	1.73E+00	1.16E-01
Eu-150	9.90E-02	9.01E-01	1.18E+00	9.35E-02
Eu-152	1.28E-01	8.72E-01	9.03E-01	7.90E-02
Eu-154	1.23E-01	8.77E-01	9.28E-01	7.92E-02
Eu-155	1.14E-01	8.86E-01	1.84E+00	1.98E-01
Fe-55	7.00E-02	9.30E-01	1.77E+00	1.63E-01
Fe-59	1.29E-01	8.71E-01	8.47E-01	7.36E-02
Fe-60	2.94E-01	7.06E-01	3.11E+00	2.65E-01
Fm-254	1.28E-01	8.72E-01	1.01E+00	6.83E-02
Fm-255	2.69E-01	7.31E-01	5.25E+00	1.96E-01
Fm-257	1.01E-01	8.99E-01	1.40E+00	1.17E-01
Fr-221	6.90E-02	9.31E-01	1.67E+00	1.30E-01
Fr-223	1.38E-01	8.62E-01	2.90E+00	1.33E-01
Ga-68	8.40E-02	9.16E-01	1.56E+00	9.83E-02
Gd-146	1.17E-01	8.83E-01	1.83E+00	1.64E-01
Gd-148	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Gd-150	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Gd-151	1.50E-01	8.50E-01	1.83E+00	1.39E-01
Gd-152	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Gd-153	1.73E-01	8.27E-01	1.96E+00	2.01E-01
Ge-68	0.00E+00	1.00E+00	0.00E+00	3.73E+01
H-3	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Hf-172	1.85E-01	8.15E-01	1.84E+00	2.20E-01
Hf-174	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Hf-175	9.20E-02	9.08E-01	1.44E+00	1.14E-01
Hf-178m	8.80E-02	9.12E-01	1.33E+00	1.06E-01
Hf-181	8.80E-02	9.12E-01	1.35E+00	1.06E-01
Hf-182	7.10E-02	9.29E-01	1.59E+00	1.22E-01
Hg-194	0.00E+00	1.00E+00	1.10E-02	2.46E+01
Hg-203	7.30E-02	9.27E-01	1.54E+00	1.19E-01
Hg-206	7.40E-02	9.26E-01	2.40E+00	1.14E-01
Ho-163	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ho-166m	1.07E-01	8.93E-01	1.08E+00	9.12E-02
I-125	2.85E-01	7.15E-01	8.47E-01	4.01E+00
I-129	4.68E-01	5.32E-01	7.65E-01	3.83E+00
In-113m	8.10E-02	9.19E-01	1.43E+00	1.07E-01
In-114	3.74E-01	6.26E-01	7.26E+00	9.77E-02
In-114m	8.80E-02	9.12E-01	1.50E+00	1.05E-01
In-115	1.57E-01	8.43E-01	6.74E+00	1.79E-01
In-115m	7.30E-02	9.27E-01	1.62E+00	1.13E-01
Ir-192	8.10E-02	9.19E-01	1.40E+00	1.07E-01

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Ir-192n	1.33E-01	8.67E-01	3.57E+00	1.98E-01
Ir-194	1.00E-01	9.00E-01	3.11E+00	9.82E-02
Ir-194m	9.10E-02	9.09E-01	1.25E+00	9.84E-02
K-40	9.50E-02	9.05E-01	1.81E+00	7.18E-02
K-42	1.11E-01	8.89E-01	1.69E+00	7.13E-02
Kr-81	6.90E-02	9.31E-01	4.80E+00	1.20E-01
Kr-83m	2.03E-01	7.97E-01	9.00E-01	2.02E+01
Kr-85	9.30E-02	9.07E-01	8.65E+00	1.03E-01
La-137	4.47E-01	5.53E-01	6.70E-01	3.42E+00
La-138	1.42E-01	8.58E-01	7.64E-01	6.98E-02
Lu-172	1.26E-01	8.74E-01	9.22E-01	7.92E-02
Lu-172m	1.96E-01	8.04E-01	1.68E+01	6.62E-01
Lu-173	1.49E-01	8.51E-01	1.47E+00	1.34E-01
Lu-174	2.03E-01	7.97E-01	9.21E-01	7.79E-02
Lu-174m	2.60E-01	7.40E-01	1.48E+00	1.59E-01
Lu-176	7.30E-02	9.27E-01	1.60E+00	1.21E-01
Lu-177	7.70E-02	9.23E-01	1.69E+00	1.38E-01
Lu-177m	8.30E-02	9.17E-01	1.50E+00	1.21E-01
Mn-53	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Mn-54	1.14E-01	8.86E-01	9.90E-01	8.35E-02
Mo-93	0.00E+00	1.00E+00	1.01E-03	1.09E+01
Na-22	1.19E-01	8.81E-01	9.38E-01	8.04E-02
Nb-91	1.04E-01	8.96E-01	4.99E+00	9.98E-02
Nb-91m	1.08E-01	8.92E-01	1.22E+00	7.58E-02
Nb-92	1.07E-01	8.93E-01	1.06E+00	8.59E-02
Nb-93m	0.00E+00	1.00E+00	1.01E-03	1.09E+01
Nb-94	1.07E-01	8.93E-01	1.06E+00	8.55E-02
Nb-95	1.04E-01	8.96E-01	1.09E+00	8.68E-02
Nb-95m	6.40E-02	9.36E-01	1.94E+00	1.25E-01
Nd-144	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Ni-59	9.30E-02	9.07E-01	1.22E+00	9.73E-02
Ni-63	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Np-235	1.68E-01	8.32E-01	7.02E+00	1.88E-01
Np-236	7.60E-02	9.24E-01	1.95E+00	1.63E-01
Np-237	1.06E-01	8.94E-01	2.44E+00	1.86E-01
Np-238	1.16E-01	8.84E-01	1.01E+00	7.92E-02
Np-239	7.80E-02	9.22E-01	1.70E+00	1.40E-01
Np-240	1.09E-01	8.91E-01	1.10E+00	8.74E-02
Np-240m	9.10E-02	9.09E-01	1.72E+00	8.93E-02
Os-185	1.09E-01	8.91E-01	1.11E+00	9.08E-02
Os-186	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Os-194	2.89E-01	7.11E-01	2.91E+00	4.67E-01
P-32	4.79E-01	5.21E-01	1.28E-01	9.25E+00
Pa-231	7.80E-02	9.22E-01	1.83E+00	1.18E-01
Pa-232	1.16E-01	8.84E-01	9.86E-01	8.41E-02
Pa-233	8.00E-02	9.20E-01	1.52E+00	1.20E-01
Pa-234	1.15E-01	8.85E-01	1.02E+00	8.48E-02
Pa-234m	1.87E-01	8.13E-01	5.17E+00	8.75E-02
Pb-202	0.00E+00	1.00E+00	1.10E-02	3.08E+01

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Pb-205	0.00E+00	1.00E+00	1.10E-02	3.08E+01
Pb-209	2.06E-01	7.94E-01	2.34E+01	1.67E-01
Pb-210	2.28E-01	7.72E-01	3.72E+00	4.71E-01
Pb-211	8.80E-02	9.12E-01	2.93E+00	9.40E-02
Pb-212	8.10E-02	9.19E-01	1.54E+00	1.30E-01
Pb-214	7.90E-02	9.21E-01	1.55E+00	1.13E-01
Pd-107	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Pm-143	1.08E-01	8.92E-01	1.19E+00	8.79E-02
Pm-144	1.01E-01	8.99E-01	1.16E+00	9.16E-02
Pm-145	3.75E-01	6.25E-01	2.85E+00	4.55E-01
Pm-146	9.90E-02	9.01E-01	1.21E+00	9.28E-02
Pm-147	2.18E-01	7.82E-01	2.74E+00	2.09E-01
Pm-148	1.05E-01	8.95E-01	1.26E+00	7.76E-02
Pm-148m	1.01E-01	8.99E-01	1.14E+00	9.08E-02
Po-208	1.06E-01	8.94E-01	1.15E+00	9.58E-02
Po-209	1.22E-01	8.78E-01	9.94E-01	8.91E-02
Po-210	1.16E-01	8.84E-01	9.85E-01	8.39E-02
Po-211	1.13E-01	8.87E-01	1.01E+00	8.51E-02
Po-212	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Po-213	1.05E-01	8.95E-01	1.08E+00	8.61E-02
Po-214	1.04E-01	8.96E-01	1.08E+00	8.59E-02
Po-215	8.60E-02	9.14E-01	1.31E+00	1.03E-01
Po-216	1.10E-01	8.90E-01	1.02E+00	8.46E-02
Po-218	2.38E-01	7.62E-01	2.80E+00	2.30E-01
Pr-144	1.91E-01	8.09E-01	3.67E+00	7.71E-02
Pr-144m	3.49E-01	6.51E-01	2.03E+00	9.58E-02
Pt-190	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Pt-193	0.00E+00	1.00E+00	1.10E-02	2.86E+01
Pu-236	4.85E-01	5.15E-01	1.79E-01	8.65E+00
Pu-237	8.40E-02	9.16E-01	2.03E+00	1.84E-01
Pu-238	3.40E-01	6.60E-01	2.00E-01	9.43E+00
Pu-239	1.91E-01	8.09E-01	6.19E+00	1.37E-01
Pu-240	3.66E-01	6.34E-01	1.87E-01	9.14E+00
Pu-241	8.20E-02	9.18E-01	1.93E+00	1.75E-01
Pu-242	1.83E-01	8.17E-01	5.96E+00	7.50E-02
Pu-243	1.16E-01	8.84E-01	1.84E+00	1.78E-01
Pu-244	1.33E-01	8.67E-01	8.89E-01	6.79E-02
Pu-246	8.40E-02	9.16E-01	1.77E+00	1.43E-01
Ra-223	9.20E-02	9.08E-01	1.49E+00	1.31E-01
Ra-224	6.50E-02	9.35E-01	1.67E+00	1.26E-01
Ra-225	2.31E-01	7.69E-01	4.10E+00	6.44E-01
Ra-226	6.60E-02	9.34E-01	1.77E+00	1.39E-01
Ra-228	0.00E+00	1.00E+00	0.00E+00	1.30E+01
Rb-83	9.60E-02	9.04E-01	1.20E+00	9.60E-02
Rb-84	1.02E-01	8.98E-01	1.13E+00	8.72E-02
Rb-87	2.00E-01	8.00E-01	2.57E+00	2.10E-01
Re-183	1.32E-01	8.68E-01	1.60E+00	1.60E-01
Re-184	1.19E-01	8.81E-01	1.02E+00	8.53E-02
Re-184m	1.25E-01	8.75E-01	1.07E+00	9.58E-02

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Re-186	1.07E-01	8.93E-01	5.24E+00	1.63E-01
Re-186m	1.91E-01	8.09E-01	2.10E+00	2.82E-01
Re-187	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Re-188	1.16E-01	8.84E-01	3.72E+00	1.07E-01
Rh-101	6.90E-02	9.31E-01	1.77E+00	1.36E-01
Rh-102	9.20E-02	9.08E-01	1.32E+00	9.50E-02
Rh-102m	1.06E-01	8.94E-01	1.07E+00	8.73E-02
Rh-103m	1.27E-01	8.73E-01	7.76E-01	6.87E+00
Rh-106	1.06E-01	8.94E-01	2.25E+00	9.39E-02
Rn-218	9.70E-02	9.03E-01	1.18E+00	9.23E-02
Rn-219	7.70E-02	9.23E-01	1.46E+00	1.13E-01
Rn-220	9.40E-02	9.06E-01	1.21E+00	9.62E-02
Rn-222	8.40E-02	9.16E-01	1.34E+00	9.97E-02
Ru-103	8.80E-02	9.12E-01	1.29E+00	9.94E-02
Ru-106	0.00E+00	1.00E+00	0.00E+00	0.00E+00
S-35	3.30E-01	6.70E-01	3.29E+00	2.82E-01
Sb-124	1.30E-01	8.70E-01	8.53E-01	7.27E-02
Sb-125	9.70E-02	9.03E-01	1.25E+00	9.66E-02
Sb-126	1.00E-01	9.00E-01	1.15E+00	9.05E-02
Sb-126m	9.60E-02	9.04E-01	1.28E+00	9.25E-02
Sc-44	1.05E-01	8.95E-01	1.12E+00	8.42E-02
Sc-46	1.26E-01	8.74E-01	8.84E-01	7.73E-02
Se-75	7.20E-02	9.28E-01	1.59E+00	1.25E-01
Se-79	3.38E-01	6.62E-01	3.35E+00	2.94E-01
Si-32	2.54E-01	7.46E-01	2.95E+00	2.46E-01
Sm-145	3.66E-01	6.34E-01	2.57E+00	4.06E-01
Sm-146	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Sm-148	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Sm-151	3.60E-02	9.64E-01	9.74E-01	6.33E+00
Sn-113	1.55E-01	8.45E-01	3.62E+00	1.24E-01
Sn-119m	1.07E-01	8.93E-01	7.29E-01	4.58E+00
Sn-121	1.82E-01	8.18E-01	2.43E+00	1.94E-01
Sn-121m	2.54E-01	7.46E-01	5.20E-01	3.77E+00
Sn-123	1.77E-01	8.23E-01	7.75E+00	8.58E-02
Sn-126	1.15E-01	8.85E-01	2.15E+00	2.11E-01
Sr-85	9.50E-02	9.05E-01	1.21E+00	9.66E-02
Sr-89	4.97E-01	5.03E-01	1.28E-01	1.04E+01
Sr-90	1.64E-01	8.36E-01	1.72E+01	1.71E-01
Ta-179	1.68E-01	8.32E-01	2.27E+00	3.30E-01
Ta-182	1.35E-01	8.65E-01	8.58E-01	7.57E-02
Tb-157	2.47E-01	7.53E-01	2.95E+00	5.06E-01
Tb-158	1.18E-01	8.82E-01	1.02E+00	8.28E-02
Tb-160	1.21E-01	8.79E-01	9.51E-01	8.09E-02
Tc-95	1.13E-01	8.87E-01	1.01E+00	8.51E-02
Tc-95m	9.80E-02	9.02E-01	1.17E+00	9.28E-02
Tc-97	0.00E+00	1.00E+00	1.01E-03	9.66E+00
Tc-97m	4.18E-01	5.82E-01	7.77E+00	1.92E-01
Tc-98	1.03E-01	8.97E-01	1.09E+00	8.90E-02

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Tc-99	2.05E-01	7.95E-01	2.57E+00	2.10E-01
Te-121	9.00E-02	9.10E-01	1.31E+00	9.61E-02
Te-121m	7.70E-02	9.23E-01	1.61E+00	1.18E-01
Te-123	4.19E-01	5.81E-01	1.18E+00	5.33E+00
Te-123m	6.90E-02	9.31E-01	1.94E+00	1.45E-01
Te-125m	2.14E-01	7.86E-01	2.95E-01	3.50E+00
Te-127	7.80E-02	9.22E-01	4.61E+00	1.08E-01
Te-127m	3.26E-01	6.74E-01	1.84E-01	3.51E+00
Te-129	9.00E-02	9.10E-01	3.55E+00	9.99E-02
Te-129m	1.01E-01	8.99E-01	3.00E+00	9.19E-02
Th-227	7.60E-02	9.24E-01	1.61E+00	1.25E-01
Th-228	9.00E-02	9.10E-01	2.24E+00	1.60E-01
Th-229	8.90E-02	9.11E-01	1.83E+00	1.67E-01
Th-230	1.37E-01	8.63E-01	3.79E+00	1.84E-01
Th-231	1.19E-01	8.81E-01	3.10E+00	2.01E-01
Th-232	1.79E-01	8.21E-01	5.13E+00	2.28E-01
Th-234	1.19E-01	8.81E-01	1.94E+00	2.07E-01
Ti-44	1.21E-01	8.79E-01	1.90E+00	2.43E-01
Tl-202	1.01E-01	8.99E-01	1.24E+00	1.04E-01
Tl-204	1.89E-01	8.11E-01	1.52E+01	2.13E-01
Tl-206	4.98E-01	5.02E-01	1.11E+01	1.32E-01
Tl-207	2.62E-01	7.38E-01	1.02E+01	9.64E-02
Tl-208	1.44E-01	8.56E-01	7.06E-01	6.05E-02
Tl-209	1.39E-01	8.61E-01	8.35E-01	7.21E-02
Tl-210	1.28E-01	8.72E-01	9.04E-01	7.34E-02
Tm-168	1.09E-01	8.91E-01	1.11E+00	9.08E-02
Tm-170	2.17E-01	7.83E-01	1.10E+01	2.14E-01
Tm-171	1.87E-01	8.13E-01	2.23E+00	3.34E-01
U-232	1.83E-01	8.17E-01	5.66E+00	1.75E-01
U-233	1.18E-01	8.82E-01	4.08E+00	1.40E-01
U-234	2.53E-01	7.47E-01	7.17E+00	1.95E-01
U-235	6.70E-02	9.33E-01	1.77E+00	1.40E-01
U-235m	0.00E+00	1.00E+00	0.00E+00	0.00E+00
U-236	3.62E-01	6.38E-01	8.47E+00	2.07E-01
U-237	9.40E-02	9.06E-01	1.73E+00	1.52E-01
U-238	3.46E-01	6.54E-01	7.47E+00	1.30E-01
U-240	1.00E-01	9.00E-01	2.86E+00	1.69E-01
V-49	0.00E+00	1.00E+00	0.00E+00	0.00E+00
V-50	1.41E-01	8.59E-01	7.38E-01	6.68E-02
W-181	1.71E-01	8.29E-01	2.10E+00	3.14E-01
W-185	1.53E-01	8.47E-01	2.42E+00	1.86E-01
W-188	8.00E-02	9.20E-01	1.56E+00	1.23E-01
Xe-127	7.50E-02	9.25E-01	1.75E+00	1.26E-01
Y-88	1.42E-01	8.58E-01	7.29E-01	6.61E-02
Y-90	4.98E-01	5.02E-01	1.17E-01	6.25E+00
Y-91	2.84E-01	7.16E-01	8.52E+00	9.01E-02
Yb-169	1.29E-01	8.71E-01	1.59E+00	1.48E-01
Zn-65	1.27E-01	8.73E-01	8.64E-01	7.53E-02
Zr-88	7.90E-02	9.21E-01	1.42E+00	1.07E-01

Table C-3 (Cont.)

Radionuclide	Fitted Parameters[a]			
	A	B	K_A (cm^2/g)	K_B (cm^2/g)
Zr-93	0.00E+00	1.00E+00	0.00E+00	0.00E+00
Zr-95	1.03E-01	8.97E-01	1.09E+00	8.82E-02

[a] Fitted parameters are used in depth and cover factor calculations.

C.1.2 Area and Material Factor

For actual radiation sources with a finite area and of different materials than soil, the area and material factor F_{AM} was derived by using the point-kernel method. This factor depends not only on the lateral extent of the source but also on source thickness, shielding thickness between the source and the receptor, gamma energies emitted by radionuclides, and source material through its radiation attenuation and buildup properties (Equation C.4).

The photon energies and yields of different radionuclides were obtained by condensing the ICRP-38 and ICRP-107 (ICRP 2008) photon spectra in four or fewer collapsed photons.

For ICRP-38 radionuclides, the algorithm was chosen to analyze the full spectra and repeatedly combine the photons with the smallest relative ratio in their energies. The yield of the resultant photon is the sum of the two photons, and the energy is the yield weighted energy of the two photons. This combining of pairs of photons was repeated until the closest pair had an energy ratio larger than 3. This resulted in four or fewer collapsed photons for all radionuclides processed. More information on the collapsed photons and their photon fraction is available in the external exposure model used in the RESRAD code for various geometries of contaminated soil (Kamboj et al. 1998). Table C-4 shows the collapsed photon energies and yields for ICRP-38 radionuclides with half-life of at least 30 days and their shorter-lived progeny.

A somewhat different approach is used to collapse the photon spectra from ICRP-107. The Oak Ridge National Laboratory (ORNL) file ICRP-07.RAD contains energy and yield data for all radiations emitted for each nuclear transformation of the ICRP-107 set of radionuclides. There are 11 possible radiation types (ICODE 1 to 11) in this file. The external exposure pathway uses 1 through 5: gammas, x rays, annihilation photons, β+, β-. For β emissions, the bremsstrahlung energy yield, y’, is taken to be: y’ = (y)(MeV)(0.0175) where y is the β yield per decay and MeV is the energy.

For the ICRP-107 radionuclide transformation database, all nuclides with total ICODE 1-5 photons greater than four are condensed to four photons. Nuclides with ICODE 1-5 that have total four or less photons are not condensed. Each nuclide’s full spectra (ICODE 1-5) is sorted by increasing energy. The two photons with the closest energy ratio are condensed into a single photon with a yield-weighted energy and sum of the two yields. This conserves energy. The process is repeated until four condensed photons represent the original spectra. Table C-5 shows the collapsed photon energies and yields for ICRP-107 radionuclides with half-lives of at least 30 days, as well as their shorter-lived progeny.

The energy-dependent coefficient *K* that converts energy flux to dose is also used.

$$F_{AM} = \frac{\sum_{Energies:j} y_j K_j \int_{V'} \frac{B(x')e^{-\mu x'}}{(x')^2} dV'}{\sum_{Energies:j} y_j K_j \int_{V} \frac{B(x)e^{-\mu x}}{(x)^2} dV} \quad \text{(C.4)}$$

At source thickness t and radius r,

$$(x')^2 = r^2 + (t_a + t_c + t)^2 \quad \text{(C.5)}$$

$$(x)^2 = r^2 + (100 + t)^2 \quad \text{(C.6)}$$

$$\mu = \frac{(t_a\mu_a + t_c\mu_c + t\mu_s)}{(t_a + t_c + t)} \quad \text{(C.7)}$$

$$B(x) = B_a\left(\frac{t_a}{t_a + t_c + t} x\right) B_c\left(\frac{t_c}{t_a + t_c + t} x\right) B_s\left(\frac{t}{t_a + t_c + t} x\right) \quad \text{(C.8)}$$

where B and μ are the buildup factor and the attenuation factor, respectively, for the appropriate material (a for air, c for shield material, and s for source material or soil reference). The buildup factors and attenuation coefficients are taken from the Trubey (1991) report. The values of K for the ICRP-26/30 methodology are taken from ICRP Publication 51 (ICRP 1987), and the values of K for the ICRP-60 methodology are taken from ICRP-74 (ICRP 1996) and are listed in Table C-6. The integration volume V' is the source geometry of specified material with radius R; for the integration, the shielding thickness is t_c, and the air thickness is t_a. The integration volume V is the reference geometry of soil extending infinitely in the lateral direction; for the integration, there is no shielding and the air thickness is 1 m, the distance from the receptor midpoint to the exposed surface of the reference volume.

Table C-4 Collapsed Photon Energies (EPT) (MeV) and Yield Fractions (FPT) for ICRP-38 Radionuclides with Half-life of at least 30 Days and Their Associated Progeny

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Ac-225	4.55E-01	1.12E-01	1.40E-02	0.00E+00	2.10E-03	1.32E-01	1.64E-01	0.00E+00
Ac-227	1.47E-02	4.65E-02	1.12E-01	3.53E-01	7.40E-03	1.38E-05	1.08E-03	7.87E-06
Ac-228	1.53E-02	1.06E-01	3.50E-01	1.01E+00	4.20E-01	1.51E-01	3.70E-01	8.15E-01
Ag-105	4.11E-01	6.40E-02	2.16E-02	1.62E-01	1.22E+00	1.05E-01	8.19E-01	2.28E-08
Ag-108	1.08E+00	5.79E-01	2.16E-02	6.26E-01	2.35E-04	2.98E-02	1.51E-02	1.07E-02
Ag-108m	5.91E-01	7.92E-02	2.16E-02	0.00E+00	2.72E+00	6.78E-02	6.56E-01	0.00E+00
Ag-110	6.67E-01	2.17E-02	1.19E+00	0.00E+00	4.59E-02	2.22E-03	2.07E-02	0.00E+00
Ag-110m	8.57E-01	1.33E-01	0.00E+00	0.00E+00	3.21E+00	1.15E-03	0.00E+00	0.00E+00
Al-26	2.94E+00	1.79E+00	5.11E-01	5.44E-01	2.40E-03	1.02E+00	1.64E+00	7.78E-03
Am-241	5.96E-02	1.68E-02	0.00E+00	0.00E+00	3.59E-01	6.65E-01	0.00E+00	0.00E+00
Am-242	1.75E-02	4.28E-02	1.06E-01	1.91E-01	3.12E-01	5.24E-04	1.22E-01	2.77E-03
Am-242m	1.51E-01	1.01E-01	5.22E-02	1.74E-02	5.19E-04	2.06E-03	2.31E-03	2.71E-01
Am-243	7.52E-02	4.34E-02	1.64E-02	0.00E+00	6.70E-01	5.69E-02	1.92E-01	0.00E+00
Am-245	1.75E-02	4.56E-02	1.11E-01	2.54E-01	1.02E-01	9.91E-04	1.24E-01	7.05E-02
Am-246m	1.80E-02	1.11E-01	3.28E-01	9.92E-01	3.33E-01	5.95E-02	5.01E-02	1.00E+00
Ar-37	2.82E-03	2.62E-03	2.62E-03	0.00E+00	6.44E-03	5.29E-02	2.66E-02	0.00E+00
Ar-39	2.19E-01	0.00E+00	0.00E+00	0.00E+00	3.83E-03	0.00E+00	0.00E+00	0.00E+00
As-73	5.34E-02	1.00E-02	1.19E-03	0.00E+00	1.05E-01	1.04E+00	2.11E-02	0.00E+00
At-217	5.94E-01	2.59E-01	7.88E-02	1.21E-02	4.00E-04	2.30E-04	1.38E-04	5.42E-05

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
At-218	5.32E-02	1.55E-02	1.30E-02	1.08E-02	6.59E-02	2.93E-02	1.23E-01	1.07E-01
Au-194	1.04E-02	6.84E-02	3.60E-01	1.50E+00	2.78E-01	7.93E-01	9.15E-01	4.55E-01
Au-195	7.18E-02	3.09E-02	1.05E-02	0.00E+00	1.10E+00	7.52E-03	5.34E-01	0.00E+00
Ba-133	3.41E-01	7.93E-02	3.17E-02	4.54E-03	9.76E-01	3.85E-01	1.20E+00	1.45E-01
Ba-137m	6.62E-01	3.29E-02	0.00E+00	0.00E+00	8.98E-01	7.49E-02	0.00E+00	0.00E+00
Be-10	2.52E-01	0.00E+00	0.00E+00	0.00E+00	4.41E-03	0.00E+00	0.00E+00	0.00E+00
Be-7	4.78E-01	0.00E+00	0.00E+00	0.00E+00	1.03E-01	0.00E+00	0.00E+00	0.00E+00
Bi-207	1.18E-02	7.67E-02	5.70E-01	1.12E+00	3.30E-01	7.47E-01	9.78E-01	8.21E-01
Bi-210	3.89E-01	0.00E+00	0.00E+00	0.00E+00	6.81E-03	0.00E+00	0.00E+00	0.00E+00
Bi-210m	6.40E-01	2.81E-01	7.45E-02	1.15E-02	3.12E-02	8.05E-01	1.33E-01	5.79E-02
Bi-211	1.14E-02	7.45E-02	1.75E-01	3.51E-01	9.46E-03	2.54E-02	8.55E-06	1.27E-01
Bi-212	1.16E-02	5.23E-02	7.48E-01	1.62E+00	7.99E-02	1.58E-02	1.75E-01	3.66E-02
Bi-213	1.25E-02	8.10E-02	4.37E-01	9.42E-01	1.66E-02	4.10E-02	2.87E-01	7.94E-03
Bi-214	1.54E+00	6.43E-01	8.11E-02	7.75E-01	7.16E-01	6.25E-01	1.94E-02	1.12E-02
Bk-247	2.65E-01	9.33E-02	1.91E-02	1.45E-02	1.60E-01	6.43E-01	9.60E-02	8.09E-02
Bk-249	1.69E-02	3.30E-02	1.09E-01	3.24E-01	8.30E-08	5.76E-04	1.45E-07	2.06E-07
Bk-250	1.01E+00	1.16E-01	1.89E-02	3.07E-01	8.76E-01	1.16E-02	2.46E-01	4.52E-03
C-14	4.95E-02	0.00E+00	0.00E+00	0.00E+00	8.65E-04	0.00E+00	0.00E+00	0.00E+00
Ca-41	3.59E-03	3.31E-03	3.31E-03	0.00E+00	1.30E-02	7.47E-02	3.75E-02	0.00E+00
Ca-45	1.25E-02	4.46E-03	4.09E-03	7.72E-02	2.66E-06	2.81E-07	2.21E-06	1.35E-03
Cd-109	8.80E-02	2.26E-02	3.09E-03	0.00E+00	3.61E-02	1.01E+00	8.62E-02	0.00E+00
Cd-113	9.33E-02	0.00E+00	0.00E+00	0.00E+00	1.63E-03	0.00E+00	0.00E+00	0.00E+00
Cd-113m	1.85E-01	0.00E+00	0.00E+00	0.00E+00	3.24E-03	0.00E+00	0.00E+00	0.00E+00
Cd-115m	9.95E-01	1.48E-01	6.13E-01	0.00E+00	2.21E-02	1.65E-04	1.06E-02	0.00E+00
Ce-139	1.66E-01	3.42E-02	4.88E-03	0.00E+00	7.91E-01	8.13E-01	1.04E-01	0.00E+00
Ce-141	1.45E-01	3.69E-02	5.28E-03	1.49E-01	4.80E-01	1.70E-01	2.15E-02	2.54E-03
Ce-144	5.38E-03	3.70E-02	8.14E-02	1.34E-01	1.70E-02	1.12E-01	2.69E-02	1.08E-01
Cf-248	4.30E-02	2.30E-02	1.92E-02	1.48E-02	1.58E-04	8.27E-03	3.62E-02	2.77E-02
Cf-249	3.73E-01	1.11E-01	1.77E-02	0.00E+00	8.60E-01	8.10E-02	2.93E-01	0.00E+00
Cf-250	4.29E-02	2.30E-02	1.92E-02	1.48E-02	1.48E-04	7.87E-03	3.45E-02	2.63E-02
Cf-251	1.96E-01	1.11E-01	6.74E-02	1.78E-02	3.07E-01	5.13E-01	1.16E-02	7.61E-01
Cf-252	1.60E-01	1.00E-01	4.34E-02	1.80E-02	1.94E-05	1.29E-04	1.48E-04	6.57E-02
Cf-253	1.48E-02	1.99E-02	5.00E-02	7.94E-02	4.71E-04	7.76E-04	5.67E-06	1.39E-03
Cf-254	4.30E-02	2.30E-02	1.92E-02	1.48E-02	4.90E-07	2.56E-05	1.12E-04	8.57E-05
Cl-36	5.11E-01	2.47E-03	2.31E-03	2.79E-01	2.97E-04	7.64E-05	1.23E-03	4.79E-03
Cm-241	4.74E-01	1.16E-01	1.72E-02	0.00E+00	8.05E-01	8.82E-01	1.01E+00	0.00E+00
Cm-242	1.21E-01	4.41E-02	1.69E-02	0.00E+00	4.27E-05	3.21E-04	1.07E-01	0.00E+00
Cm-243	2.52E-01	1.05E-01	1.67E-02	0.00E+00	2.88E-01	4.94E-01	5.76E-01	0.00E+00
Cm-244	4.28E-02	2.16E-02	1.80E-02	1.42E-02	2.60E-04	1.09E-02	4.93E-02	3.96E-02
Cm-245	1.74E-01	1.08E-01	1.67E-02	0.00E+00	6.60E-02	6.81E-01	6.16E-01	0.00E+00
Cm-246	4.45E-02	2.16E-02	1.80E-02	1.42E-02	2.80E-04	9.73E-03	4.40E-02	3.51E-02
Cm-247	3.93E-01	1.06E-01	5.91E-02	1.69E-02	7.87E-01	3.64E-02	6.98E-03	1.12E-01
Cm-248	4.40E-02	2.16E-02	1.80E-02	1.42E-02	2.02E-04	7.44E-03	3.36E-02	2.69E-02
Cm-249	5.80E-01	1.19E-01	1.79E-02	2.77E-01	3.17E-02	6.12E-03	3.27E-03	4.76E-03
Cm-250	1.13E-02	0.00E+00	0.00E+00	0.00E+00	2.76E-05	0.00E+00	0.00E+00	0.00E+00
Co-56	2.41E+00	1.02E+00	5.11E-01	6.25E-01	5.97E-01	1.90E+00	3.98E-01	2.11E-03
Co-57	6.68E-01	1.24E-01	1.44E-02	6.48E-03	1.89E-03	9.62E-01	9.19E-02	5.72E-01
Co-58	6.48E-03	2.01E-01	7.42E-01	1.67E+00	2.66E-01	5.28E-04	1.30E+00	5.17E-03
Co-60	1.25E+00	9.85E-02	0.00E+00	0.00E+00	2.00E+00	1.68E-03	0.00E+00	0.00E+00
Co-60m	7.01E-03	5.86E-02	6.02E-01	1.32E+00	3.23E-01	2.07E-02	2.60E-05	2.59E-03

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Cs-134	6.98E-01	2.01E-01	0.00E+00	0.00E+00	2.23E+00	2.74E-03	0.00E+00	0.00E+00
Cs-135	6.73E-02	0.00E+00	0.00E+00	0.00E+00	1.18E-03	0.00E+00	0.00E+00	0.00E+00
Cs-137	4.25E-01	1.73E-01	0.00E+00	0.00E+00	4.02E-04	2.87E-03	0.00E+00	0.00E+00
Dy-159	4.58E-02	6.75E-03	0.00E+00	0.00E+00	9.58E-01	1.80E-01	0.00E+00	0.00E+00
Es-253	3.96E-01	1.10E-01	4.19E-02	1.84E-02	6.43E-04	4.55E-04	7.27E-04	4.28E-02
Es-254	3.10E-01	5.81E-02	1.81E-02	1.10E-03	4.24E-03	3.49E-02	8.55E-01	3.00E-01
Eu-146	8.00E-01	4.11E-02	6.35E-01	0.00E+00	3.09E+00	7.36E-01	5.38E-04	0.00E+00
Eu-148	6.74E-01	4.11E-02	4.05E-01	0.00E+00	3.18E+00	7.90E-01	1.06E-05	0.00E+00
Eu-149	3.30E-01	4.11E-02	2.25E-02	6.05E-03	9.27E-02	7.74E-01	4.42E-03	1.37E-01
Eu-150b	9.71E-01	4.31E-01	4.11E-02	0.00E+00	4.55E-01	2.37E+00	8.18E-01	0.00E+00
Eu-152	1.09E+00	2.55E-01	4.11E-02	3.85E-01	8.63E-01	7.13E-01	7.56E-01	1.46E-03
Eu-154	1.00E+00	1.42E-01	4.40E-02	3.73E-01	1.16E+00	4.77E-01	2.75E-01	3.96E-03
Eu-155	6.51E-03	2.55E-02	4.48E-02	9.41E-02	6.96E-02	3.77E-03	2.56E-01	5.17E-01
Fe-55	6.49E-03	5.89E-03	0.00E+00	0.00E+00	3.35E-02	2.49E-01	0.00E+00	0.00E+00
Fe-59	1.18E+00	1.80E-01	1.32E-01	0.00E+00	9.98E-01	4.00E-02	2.05E-03	0.00E+00
Fe-60	4.91E-02	0.00E+00	0.00E+00	0.00E+00	8.60E-04	0.00E+00	0.00E+00	0.00E+00
Fm-257	2.13E-01	1.18E-01	6.36E-02	1.87E-02	1.38E-01	5.77E-01	1.88E-02	6.45E-01
Fr-221	3.82E-01	2.17E-01	8.46E-02	1.31E-02	2.35E-03	1.26E-01	2.85E-02	2.13E-02
Fr-223	1.45E-02	6.20E-02	2.53E-01	7.92E-01	3.59E-01	5.19E-01	6.77E-02	8.89E-03
Ga-68	1.11E+00	5.11E-01	8.33E-01	0.00E+00	3.65E-02	1.78E+00	1.29E-02	0.00E+00
Gd-146	1.28E-01	4.25E-02	6.26E-03	0.00E+00	1.32E+00	1.85E+00	3.11E-01	0.00E+00
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-151	2.02E-01	4.25E-02	2.15E-02	6.35E-03	1.35E-01	8.17E-01	2.32E-02	2.30E-01
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	9.84E-02	4.25E-02	6.26E-03	0.00E+00	5.34E-01	1.22E+00	2.09E-01	0.00E+00
Ge-68	1.03E-02	9.24E-03	1.11E-03	0.00E+00	5.42E-02	3.86E-01	6.29E-03	0.00E+00
H-3	5.68E-03	0.00E+00	0.00E+00	0.00E+00	9.94E-05	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.24E-01	5.69E-02	2.40E-02	8.32E-03	1.61E-01	1.54E+00	2.00E-01	6.82E-01
Hf-175	3.46E-01	9.22E-02	5.53E-02	8.35E-03	9.12E-01	2.66E-02	8.95E-01	2.34E-01
Hf-178m	4.96E-01	2.59E-01	7.21E-02	8.64E-03	3.01E+00	2.83E+00	1.78E+00	5.56E-01
Hf-181	4.63E-01	1.04E-01	8.93E-03	1.19E-01	1.01E+00	8.40E-01	1.48E-01	2.08E-03
Hf-182	8.92E-03	5.88E-02	1.45E-01	2.70E-01	4.69E-02	1.44E-01	9.88E-02	8.00E-01
Hg-194	1.36E-02	1.15E-02	9.71E-03	8.49E-03	2.74E-02	1.20E-01	9.55E-02	3.65E-03
Hg-203	1.15E-02	5.77E-02	7.45E-02	2.79E-01	5.44E-02	1.01E-03	1.34E-01	8.15E-01
Ho-166m	7.22E-01	2.15E-01	5.77E-02	1.82E-02	2.03E+00	1.14E+00	5.25E-01	3.01E-04
I-125	3.55E-02	2.81E-02	3.92E-03	0.00E+00	6.67E-02	1.40E+00	1.24E-01	0.00E+00
I-129	3.96E-02	3.04E-02	4.28E-03	4.89E-02	7.51E-02	7.00E-01	6.76E-02	8.55E-04
In-113m	3.92E-01	2.47E-02	0.00E+00	0.00E+00	6.42E-01	2.45E-01	0.00E+00	0.00E+00
In-114	1.30E+00	5.51E-01	2.37E-02	7.77E-01	2.01E-03	1.46E-04	3.88E-03	1.35E-02
In-114m	6.41E-01	1.90E-01	2.46E-02	3.41E-03	8.72E-02	1.54E-01	3.69E-01	4.46E-02
In-115	1.52E-01	0.00E+00	0.00E+00	0.00E+00	2.66E-03	0.00E+00	0.00E+00	0.00E+00
Ir-192	9.14E-01	3.71E-01	6.83E-02	1.84E-01	3.60E-03	2.17E+00	1.39E-01	3.00E-03
Ir-192m	1.61E-01	0.00E+00	0.00E+00	0.00E+00	1.00E+00	0.00E+00	0.00E+00	0.00E+00
Ir-194	9.36E-01	3.22E-01	6.84E-02	8.23E-01	4.10E-02	1.59E-01	8.60E-03	1.41E-02
Ir-194m	1.01E+00	4.81E-01	8.35E-02	6.98E-02	3.60E-02	4.73E+00	2.53E-01	1.22E-03
K-40	1.46E+00	5.85E-01	0.00E+00	0.00E+00	1.07E-01	9.14E-03	0.00E+00	0.00E+00
Kr-81	2.76E-01	1.21E-02	1.49E-03	0.00E+00	2.00E-02	5.15E-01	1.37E-02	0.00E+00
Kr-83m	3.22E-02	1.28E-02	9.40E-03	1.61E-03	5.09E-04	1.63E-01	5.64E-02	2.58E-02
Kr-85	5.14E-01	2.51E-01	0.00E+00	0.00E+00	4.30E-03	4.38E-03	0.00E+00	0.00E+00
La-137	3.29E-02	5.63E-03	4.68E-03	0.00E+00	7.24E-01	5.37E-03	8.02E-02	0.00E+00

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
La-138	1.44E+00	7.88E-01	3.29E-02	9.49E-02	6.71E-01	3.29E-01	4.10E-01	5.47E-04
Lu-172	8.07E-03	5.79E-02	1.86E-01	9.32E-01	4.09E-01	1.28E+00	2.49E-01	1.89E+00
Lu-173	6.06E-01	2.57E-01	5.61E-02	8.06E-03	1.26E-02	1.67E-01	1.37E+00	3.04E-01
Lu-174	8.07E-03	5.50E-02	1.74E-01	1.24E+00	2.69E-01	8.70E-01	5.10E-07	6.11E-02
Lu-174m	9.92E-01	2.31E-01	5.51E-02	8.39E-03	6.98E-03	1.13E-02	9.01E-01	4.92E-01
Lu-176	8.65E-03	5.71E-02	8.83E-02	2.58E-01	2.10E-01	3.29E-01	1.31E-01	1.79E+00
Lu-177	8.64E-03	5.74E-02	1.14E-01	2.11E-01	3.03E-02	5.89E-02	6.68E-02	1.14E-01
Lu-177m	8.58E-03	5.69E-02	1.83E-01	3.58E-01	4.50E-01	1.39E+00	2.39E+00	1.35E+00
Md-258	7.50E-02	2.52E-02	2.09E-02	1.59E-02	7.43E-03	3.64E-02	1.50E-01	1.02E-01
Mn-53	5.95E-03	5.41E-03	0.00E+00	0.00E+00	2.91E-02	2.25E-01	0.00E+00	0.00E+00
Mn-54	8.35E-01	5.41E-03	0.00E+00	0.00E+00	1.00E+00	2.26E-01	0.00E+00	0.00E+00
Mo-93	1.69E-02	2.21E-03	0.00E+00	0.00E+00	6.28E-01	2.60E-02	0.00E+00	0.00E+00
Na-22	1.27E+00	5.11E-01	2.17E-01	0.00E+00	9.99E-01	1.80E+00	3.40E-03	0.00E+00
Nb-93m	1.69E-02	2.18E-03	0.00E+00	0.00E+00	1.10E-01	2.09E-02	0.00E+00	0.00E+00
Nb-94	8.71E-01	7.03E-01	1.66E-01	0.00E+00	1.00E+00	1.00E+00	2.90E-03	0.00E+00
Nb-95	7.66E-01	4.33E-02	0.00E+00	0.00E+00	1.00E+00	7.58E-04	0.00E+00	0.00E+00
Nb-95m	2.35E-01	1.69E-02	0.00E+00	0.00E+00	2.59E-01	4.46E-01	0.00E+00	0.00E+00
Ni-59	7.65E-03	6.93E-03	0.00E+00	0.00E+00	4.09E-02	3.02E-01	0.00E+00	0.00E+00
Ni-63	1.71E-02	0.00E+00	0.00E+00	0.00E+00	3.00E-04	0.00E+00	0.00E+00	0.00E+00
Np-235	1.00E-01	5.08E-02	1.61E-02	0.00E+00	7.57E-03	1.44E-03	3.90E-01	0.00E+00
Np-236a	1.60E-01	1.01E-01	1.61E-02	1.13E-01	2.39E-01	7.65E-01	1.30E+00	1.76E-04
Np-237	1.71E-01	8.96E-02	2.94E-02	1.56E-02	1.81E-02	2.05E-01	1.40E-01	5.81E-01
Np-238	9.95E-01	1.08E-01	1.69E-02	3.53E-01	5.48E-01	9.79E-03	3.56E-01	3.90E-03
Np-239	2.60E-01	1.05E-01	1.67E-02	1.25E-01	3.31E-01	7.37E-01	5.81E-01	2.06E-03
Np-240m	1.69E-02	9.28E-02	5.95E-01	1.52E+00	4.60E-01	1.31E-02	4.84E-01	3.15E-02
Os-185	6.77E-01	1.75E-01	6.26E-02	9.53E-03	9.87E-01	1.54E-02	7.28E-01	2.36E-01
Os-194	1.04E-02	2.28E-02	4.31E-02	6.80E-02	7.33E-02	3.75E-04	2.32E-02	4.10E-04
P-32	6.95E-01	0.00E+00	0.00E+00	0.00E+00	1.22E-02	0.00E+00	0.00E+00	0.00E+00
Pa-231	3.04E-01	9.26E-02	2.88E-02	1.48E-02	1.10E-01	1.73E-02	1.02E-01	7.02E-01
Pa-233	3.19E-01	9.91E-02	1.59E-02	7.53E-02	5.01E-01	3.79E-01	4.40E-01	1.11E-03
Pa-234	1.61E-02	1.11E-01	2.64E-01	8.70E-01	1.14E+00	9.30E-01	3.45E-01	1.96E+00
Pa-234m	1.59E-02	9.97E-02	3.01E-01	8.93E-01	5.59E-03	5.03E-03	7.97E-04	2.52E-02
Pb-202	1.46E-02	1.23E-02	1.03E-02	8.95E-03	9.16E-04	4.31E-02	1.53E-01	6.04E-03
Pb-205	1.46E-02	1.23E-02	1.03E-02	8.95E-03	2.08E-03	4.84E-02	1.58E-01	6.25E-03
Pb-209	1.98E-01	0.00E+00	0.00E+00	0.00E+00	3.46E-03	0.00E+00	0.00E+00	0.00E+00
Pb-210	1.08E-02	1.30E-02	1.55E-02	4.65E-02	9.81E-02	1.12E-01	2.68E-02	4.05E-02
Pb-211	8.20E-01	4.09E-01	7.85E-02	4.65E-01	3.83E-02	4.53E-02	7.26E-03	7.92E-03
Pb-212	2.43E-01	7.94E-02	1.21E-02	1.07E-01	4.81E-01	3.74E-01	1.44E-01	1.74E-03
Pb-214	1.22E-02	7.79E-02	3.20E-01	6.66E-01	1.30E-01	2.33E-01	6.52E-01	3.32E-02
Pd-107	9.26E-03	0.00E+00	0.00E+00	0.00E+00	1.62E-04	0.00E+00	0.00E+00	0.00E+00
Pm-143	7.42E-01	3.82E-02	5.50E-03	0.00E+00	3.85E-01	7.62E-01	1.04E-01	0.00E+00
Pm-144	6.27E-01	3.82E-02	0.00E+00	0.00E+00	2.44E+00	7.80E-01	0.00E+00	0.00E+00
Pm-145	7.12E-02	3.82E-02	6.73E-03	5.51E-03	2.83E-02	7.42E-01	9.12E-03	1.18E-01
Pm-146	5.95E-01	3.82E-02	2.52E-01	0.00E+00	1.23E+00	4.89E-01	1.51E-03	0.00E+00
Pm-147	1.21E-01	4.11E-02	6.02E-03	6.20E-02	2.85E-05	2.18E-05	3.56E-06	1.08E-03
Pm-148	1.27E+00	5.53E-01	8.42E-01	0.00E+00	3.47E-01	2.44E-01	1.26E-02	0.00E+00
Pm-148m	6.20E-01	1.13E-01	4.07E-02	1.66E-01	3.21E+00	6.08E-02	1.11E-01	2.54E-03
Po-209	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	8.02E-01	0.00E+00	0.00E+00	0.00E+00	1.06E-05	0.00E+00	0.00E+00	0.00E+00
Po-211	7.31E-01	3.28E-01	7.67E-02	0.00E+00	1.06E-02	3.24E-05	1.93E-04	0.00E+00

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-214	8.00E-01	2.98E-01	0.00E+00	0.00E+00	1.04E-04	5.00E-07	0.00E+00	0.00E+00
Po-215	4.39E-01	7.67E-02	0.00E+00	0.00E+00	4.00E-04	1.07E-05	0.00E+00	0.00E+00
Po-216	8.06E-01	0.00E+00	0.00E+00	0.00E+00	2.10E-05	0.00E+00	0.00E+00	0.00E+00
Po-218	8.37E-01	7.05E-02	0.00E+00	0.00E+00	1.09E-05	2.47E-07	0.00E+00	0.00E+00
Pr-144	1.99E+00	6.97E-01	1.22E+00	0.00E+00	1.08E-02	1.49E-02	2.11E-02	0.00E+00
Pr-144m	5.33E-03	3.69E-02	5.90E-02	7.54E-01	9.55E-02	3.04E-01	7.90E-04	1.21E-03
Pt-193	1.28E-02	1.07E-02	9.17E-03	8.04E-03	2.58E-02	1.10E-01	7.23E-02	2.63E-03
Pu-236	5.86E-01	1.12E-01	4.76E-02	1.61E-02	5.10E-06	1.30E-04	6.90E-04	1.27E-01
Pu-237	1.03E-01	5.95E-02	1.64E-02	0.00E+00	4.11E-01	3.25E-02	4.93E-01	0.00E+00
Pu-238	5.50E-02	1.61E-02	0.00E+00	0.00E+00	4.77E-04	1.11E-01	0.00E+00	0.00E+00
Pu-239	7.30E-05	1.65E-02	1.33E-01	3.85E-01	9.99E-01	4.20E-02	1.15E-04	6.61E-05
Pu-240	1.08E-01	4.52E-02	1.61E-02	0.00E+00	7.54E-05	4.50E-04	1.06E-01	0.00E+00
Pu-241	5.24E-03	1.60E-02	4.36E-02	1.07E-01	9.16E-05	6.25E-05	1.83E-07	1.44E-05
Pu-242	1.03E-01	4.49E-02	1.61E-02	0.00E+00	7.94E-05	3.60E-04	8.79E-02	0.00E+00
Pu-243	1.73E-02	4.17E-02	8.53E-02	3.76E-01	1.37E-01	8.56E-03	2.41E-01	7.30E-03
Pu-244	4.30E-02	2.03E-02	1.70E-02	1.35E-02	2.50E-04	8.63E-03	3.83E-02	2.82E-02
Pu-246	1.70E-02	4.19E-02	1.08E-01	2.11E-01	4.48E-01	2.86E-01	4.57E-01	3.38E-01
Ra-223	3.04E-01	9.67E-02	1.33E-02	0.00E+00	2.33E-01	6.23E-01	2.25E-01	0.00E+00
Ra-224	5.63E-01	2.41E-01	8.56E-02	1.36E-02	1.10E-04	3.91E-02	4.24E-03	3.70E-03
Ra-225	1.26E-02	1.61E-02	4.00E-02	9.46E-02	5.76E-02	8.49E-02	2.90E-01	1.65E-03
Ra-226	1.86E-01	8.56E-02	1.37E-02	0.00E+00	3.29E-02	6.17E-03	7.67E-03	0.00E+00
Ra-228	6.67E-03	9.86E-03	0.00E+00	0.00E+00	6.21E-07	1.73E-04	0.00E+00	0.00E+00
Rb-83	5.32E-01	1.25E-02	0.00E+00	0.00E+00	9.34E-01	6.25E-01	0.00E+00	0.00E+00
Rb-84	1.90E+00	7.25E-01	1.28E-02	5.88E-01	7.80E-03	1.24E+00	3.97E-01	2.64E-03
Rb-87	1.11E-01	0.00E+00	0.00E+00	0.00E+00	1.95E-03	0.00E+00	0.00E+00	0.00E+00
Re-184	8.52E-01	2.53E-01	6.89E-02	9.22E-03	9.48E-01	3.09E-02	1.05E+00	3.18E-01
Re-184m	8.56E-01	2.46E-01	7.04E-02	9.32E-03	2.50E-01	4.08E-01	1.01E+00	4.42E-01
Re-186	7.03E-01	1.01E-01	9.60E-03	3.51E-01	5.08E-04	1.96E-01	4.65E-02	5.75E-03
Re-186m	9.93E-02	5.91E-02	4.03E-02	9.76E-03	1.06E-02	1.87E-01	5.00E-02	5.31E-01
Re-187	6.60E-04	0.00E+00	0.00E+00	0.00E+00	1.16E-05	0.00E+00	0.00E+00	0.00E+00
Re-188	9.89E-03	1.33E-01	7.10E-01	1.69E+00	2.92E-02	1.96E-01	5.33E-02	2.18E-03
Rh-101	3.27E-01	1.62E-01	1.97E-02	0.00E+00	1.33E-01	1.29E+00	8.09E-01	0.00E+00
Rh-102	6.81E-01	1.97E-02	1.02E-01	0.00E+00	3.12E+00	6.64E-01	1.69E-09	0.00E+00
Rh-102m	5.36E-01	1.97E-02	5.13E-01	0.00E+00	8.92E-01	4.26E-01	2.85E-03	0.00E+00
Rh-103m	3.98E-02	2.06E-02	2.78E-03	2.45E-03	6.99E-04	7.87E-02	3.54E-02	1.10E-03
Rh-106	1.16E+00	5.48E-01	1.42E+00	0.00E+00	2.82E-02	3.14E-01	2.47E-02	0.00E+00
Rn-219	3.25E-01	8.44E-02	1.26E-02	0.00E+00	1.68E-01	1.90E-02	9.65E-03	0.00E+00
Rn-220	5.50E-01	8.11E-02	0.00E+00	0.00E+00	7.00E-04	1.25E-05	0.00E+00	0.00E+00
Rn-222	5.10E-01	8.11E-02	0.00E+00	0.00E+00	7.80E-04	1.62E-05	0.00E+00	0.00E+00
Ru-103	5.03E-01	9.99E-02	0.00E+00	0.00E+00	9.30E-01	1.26E-03	0.00E+00	0.00E+00
Ru-106	1.00E-02	0.00E+00	0.00E+00	0.00E+00	1.76E-04	0.00E+00	0.00E+00	0.00E+00
S-35	4.88E-02	0.00E+00	0.00E+00	0.00E+00	8.55E-04	0.00E+00	0.00E+00	0.00E+00
Sb-124	9.81E-01	6.24E-01	0.00E+00	0.00E+00	1.85E+00	6.70E-03	0.00E+00	0.00E+00
Sb-125	5.17E-01	1.76E-01	2.87E-02	1.28E-01	7.77E-01	7.89E-02	5.14E-01	1.52E-03
Sb-126	6.40E-01	4.25E-01	0.00E+00	0.00E+00	4.43E+00	4.71E-03	0.00E+00	0.00E+00
Sb-126m	1.48E+00	5.96E-01	6.84E-01	0.00E+00	3.43E-03	2.59E+00	1.02E-02	0.00E+00
Sc-44	2.65E+00	1.16E+00	5.11E-01	6.32E-01	1.16E-03	1.01E+00	1.89E+00	1.04E-02
Sc-46	1.12E+00	8.89E-01	1.12E-01	0.00E+00	1.00E+00	1.00E+00	1.96E-03	0.00E+00

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Se-75	2.14E-01	1.07E-02	0.00E+00	0.00E+00	1.82E+00	5.55E-01	0.00E+00	0.00E+00
Se-79	5.58E-02	0.00E+00	0.00E+00	0.00E+00	9.77E-04	0.00E+00	0.00E+00	0.00E+00
Si-32	6.47E-02	0.00E+00	0.00E+00	0.00E+00	1.13E-03	0.00E+00	0.00E+00	0.00E+00
Sm-145	4.14E-02	5.80E-03	0.00E+00	0.00E+00	1.54E+00	2.15E-01	0.00E+00	0.00E+00
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	5.18E-03	6.32E-03	7.71E-03	2.05E-02	8.59E-06	9.44E-04	1.43E-04	6.36E-04
Sn-113	2.55E-01	2.47E-02	3.42E-03	0.00E+00	1.85E-02	7.25E-01	5.56E-02	0.00E+00
Sn-119m	6.57E-02	2.51E-02	4.31E-03	3.57E-03	1.94E-04	4.40E-01	7.36E-03	1.08E-01
Sn-121	1.14E-01	0.00E+00	0.00E+00	0.00E+00	2.00E-03	0.00E+00	0.00E+00	0.00E+00
Sn-121m	3.72E-02	2.69E-02	3.58E-03	1.21E-01	1.85E-02	1.53E-01	4.17E-02	4.73E-04
Sn-123	1.09E+00	5.22E-01	0.00E+00	0.00E+00	6.34E-03	9.10E-03	0.00E+00	0.00E+00
Sn-126	3.83E-03	2.61E-02	4.26E-02	8.36E-02	9.52E-02	3.70E-01	5.00E-03	5.57E-01
Sr-85	5.14E-01	1.36E-02	0.00E+00	0.00E+00	9.80E-01	5.87E-01	0.00E+00	0.00E+00
Sr-89	9.09E-01	5.83E-01	0.00E+00	0.00E+00	9.30E-05	1.02E-02	0.00E+00	0.00E+00
Sr-90	1.96E-01	0.00E+00	0.00E+00	0.00E+00	3.43E-03	0.00E+00	0.00E+00	0.00E+00
Ta-179	5.71E-02	1.07E-02	9.09E-03	7.87E-03	5.39E-01	1.79E-02	9.38E-02	8.12E-02
Ta-180	2.78E-01	9.30E-02	5.71E-02	8.64E-03	1.76E+00	1.73E-01	9.08E-01	4.02E-01
Ta-182	9.27E-03	7.09E-02	1.99E-01	1.18E+00	2.31E-01	1.01E+00	2.96E-01	9.88E-01
Tb-157	4.40E-02	8.03E-03	6.56E-03	5.36E-03	5.69E-02	1.78E-02	1.12E-01	1.02E-03
Tb-158	6.56E-03	5.08E-02	1.86E-01	9.38E-01	2.26E-01	1.00E+00	1.04E-01	7.74E-01
Tb-160	1.01E+00	2.81E-01	6.23E-02	2.24E-01	9.84E-01	3.88E-01	3.45E-01	3.62E-03
Tc-95	7.81E-01	1.78E-02	0.00E+00	0.00E+00	1.00E+00	6.63E-01	0.00E+00	0.00E+00
Tc-95m	7.27E-01	2.05E-01	1.78E-02	3.01E-01	7.36E-01	6.26E-01	6.61E-01	2.61E-05
Tc-97	1.78E-02	2.34E-03	0.00E+00	0.00E+00	6.35E-01	2.87E-02	0.00E+00	0.00E+00
Tc-97m	9.65E-02	1.87E-02	2.46E-03	0.00E+00	3.14E-03	4.92E-01	3.14E-02	0.00E+00
Tc-98	6.99E-01	1.56E-01	0.00E+00	0.00E+00	2.02E+00	2.73E-03	0.00E+00	0.00E+00
Tc-99	1.01E-01	0.00E+00	0.00E+00	0.00E+00	1.77E-03	0.00E+00	0.00E+00	0.00E+00
Te-121	5.60E-01	2.69E-02	0.00E+00	0.00E+00	9.94E-01	7.53E-01	0.00E+00	0.00E+00
Te-121m	1.09E+00	2.12E-01	2.79E-02	3.91E-03	2.66E-02	8.15E-01	5.26E-01	7.31E-02
Te-123	2.69E-02	3.74E-03	0.00E+00	0.00E+00	7.26E-01	5.90E-02	0.00E+00	0.00E+00
Te-123m	1.59E-01	2.81E-02	3.94E-03	0.00E+00	8.42E-01	4.93E-01	7.28E-02	0.00E+00
Te-125m	1.09E-01	3.55E-02	2.81E-02	3.95E-03	2.74E-03	6.63E-02	1.16E+00	1.27E-01
Te-127	4.11E-01	2.06E-01	3.69E-02	2.24E-01	1.13E-02	1.00E-03	1.11E-03	3.90E-03
Te-127m	3.95E-03	2.86E-02	2.53E-01	6.49E-01	6.19E-02	3.80E-01	1.06E-04	1.56E-04
Te-129	4.26E-03	2.78E-02	4.46E-01	9.77E-01	5.85E-02	1.57E-01	1.10E-01	1.07E-02
Te-129m	3.95E-03	2.81E-02	1.05E-01	6.96E-01	4.12E-02	2.87E-01	1.48E-03	4.51E-02
Th-227	7.54E-01	2.65E-01	7.23E-02	1.44E-02	2.29E-04	3.36E-01	2.07E-01	4.22E-01
Th-228	2.15E-01	1.46E-01	8.47E-02	1.45E-02	3.01E-03	1.93E-03	1.25E-02	9.04E-02
Th-229	1.73E-01	9.02E-02	3.35E-02	1.43E-02	1.64E-01	6.12E-01	4.61E-02	7.61E-01
Th-230	2.53E-01	1.51E-01	6.85E-02	1.45E-02	1.12E-04	5.37E-04	3.89E-03	8.10E-02
Th-231	1.59E-01	8.53E-02	1.72E-02	7.87E-02	4.93E-03	1.15E-01	8.78E-01	1.35E-03
Th-232	1.26E-01	9.04E-02	5.90E-02	1.45E-02	4.30E-04	1.31E-04	1.91E-03	7.99E-02
Th-234	9.34E-02	6.33E-02	1.56E-02	4.65E-02	5.82E-02	3.83E-02	9.83E-02	7.59E-04
Ti-44	1.47E-01	7.84E-02	6.78E-02	4.13E-03	1.00E-03	9.47E-01	8.77E-01	1.96E-01
Tl-202	1.11E-02	7.24E-02	1.85E-01	4.41E-01	2.90E-01	7.85E-01	2.92E-09	9.24E-01
Tl-204	9.94E-03	1.22E-02	7.24E-02	2.44E-01	3.52E-03	3.55E-03	1.45E-02	4.16E-03
Tl-206	1.17E-02	7.67E-02	5.36E-01	8.03E-01	2.69E-04	7.17E-04	9.39E-03	5.50E-05
Tl-207	8.98E-01	5.70E-01	7.67E-02	4.94E-01	2.40E-03	1.00E-04	4.85E-05	8.62E-03
Tl-208	2.61E+00	5.83E-01	7.67E-02	5.76E-01	9.98E-01	1.30E+00	7.23E-02	9.80E-03

Table C-4 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Tl-209	1.57E+00	4.67E-01	1.09E-01	6.59E-01	9.84E-01	8.11E-01	1.02E+00	1.15E-02
Tl-210	2.24E-01	7.80E-01	1.19E+00	2.18E+00	1.18E+00	1.06E+00	7.33E-01	3.56E-01
Tm-170	8.07E-03	5.35E-02	8.43E-02	3.17E-01	3.67E-02	4.55E-02	3.26E-02	5.54E-03
Tm-171	7.92E-03	9.84E-03	2.51E-02	5.53E-02	3.24E-03	2.54E-04	4.35E-04	1.12E-02
U-232	2.98E-01	1.22E-01	5.77E-02	1.53E-02	7.22E-05	9.49E-04	2.10E-03	1.26E-01
U-233	2.76E-01	1.09E-01	4.22E-02	1.53E-02	4.99E-04	1.32E-03	1.26E-03	6.53E-02
U-234	1.16E-01	5.32E-02	1.53E-02	0.00E+00	4.99E-04	1.18E-03	1.05E-01	0.00E+00
U-235	3.83E-01	1.68E-01	1.52E-02	0.00E+00	1.37E-03	9.02E-01	2.71E-01	0.00E+00
U-236	1.10E-01	4.94E-02	1.66E-02	1.29E-02	2.33E-04	7.74E-04	6.34E-02	3.52E-02
U-237	1.66E-02	5.97E-02	1.03E-01	2.14E-01	6.77E-01	3.50E-01	5.42E-01	2.57E-01
U-238	4.96E-02	1.91E-02	1.61E-02	1.29E-02	6.97E-04	1.02E-02	4.56E-02	3.10E-02
U-240	1.38E-02	1.82E-02	4.40E-02	1.02E-01	1.59E-01	2.56E-01	1.69E-02	1.78E-03
V-49	4.93E-03	4.51E-03	0.00E+00	0.00E+00	2.29E-02	1.76E-01	0.00E+00	0.00E+00
W-181	1.48E-01	5.88E-02	8.96E-03	6.21E-03	1.38E-03	6.51E-01	2.06E-01	9.75E-03
W-185	9.31E-03	1.18E-02	6.25E-02	1.27E-01	1.25E-04	1.00E-05	4.60E-04	2.43E-03
W-188	9.71E-03	6.32E-02	1.01E-01	2.67E-01	1.39E-03	3.08E-03	1.80E-03	6.30E-03
Xe-127	2.20E-01	5.76E-02	2.92E-02	4.14E-03	1.15E+00	1.33E-02	8.80E-01	8.66E-02
Y-88	1.84E+00	8.96E-01	1.44E-02	3.55E-01	1.00E+00	9.39E-01	6.01E-01	1.36E-05
Y-90	1.61E-02	2.08E-03	9.35E-01	0.00E+00	1.05E-04	3.90E-06	1.64E-02	0.00E+00
Y-91	1.20E+00	6.04E-01	0.00E+00	0.00E+00	3.00E-03	1.05E-02	0.00E+00	0.00E+00
Yb-169	1.79E-01	5.39E-02	7.80E-03	0.00E+00	1.03E+00	2.25E+00	4.54E-01	0.00E+00
Zn-65	1.12E+00	5.11E-01	8.14E-03	1.43E-01	5.08E-01	2.92E-02	3.86E-01	3.65E-05
Zr-88	3.93E-01	1.52E-02	0.00E+00	0.00E+00	1.00E+00	6.29E-01	0.00E+00	0.00E+00
Zr-93	1.96E-02	0.00E+00	0.00E+00	0.00E+00	3.44E-04	0.00E+00	0.00E+00	0.00E+00
Zr-95	7.42E-01	1.18E-01	0.00E+00	0.00E+00	9.96E-01	2.02E-03	0.00E+00	0.00E+00

Table C-5 Collapsed Photon Energies (EPT) (MeV) and Yield Fractions (FPT) for ICRP-107 Radionuclides with Half-life of at least 30 Days and Their Associated Progeny

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Ac-225	6.06E-05	4.23E-04	1.22E-02	1.25E-01	7.33E+00	8.28E-04	2.32E-01	1.10E-01
Ac-227	8.17E-05	4.79E-04	1.10E-02	1.14E-01	4.26E+00	5.95E-04	5.80E-02	5.70E-04
Ac-228	8.24E-05	1.35E-02	1.06E-01	7.96E-01	1.02E+01	4.11E-01	1.19E-01	1.07E+00
Ag-105	7.86E-06	2.80E-03	2.64E-02	4.09E-01	9.36E+00	6.32E-02	9.28E-01	1.20E+00
Ag-108	7.88E-06	3.37E-04	2.03E-02	5.92E-01	2.06E-01	4.11E-05	1.96E-02	4.19E-02
Ag-108m	8.23E-06	2.81E-03	2.68E-02	5.90E-01	8.16E+00	5.52E-02	7.25E-01	2.71E+00
Ag-110	8.26E-06	3.41E-04	2.03E-02	8.27E-01	2.52E-02	5.11E-06	2.39E-03	6.68E-02
Ag-110m	1.35E-05	3.76E-04	2.13E-02	8.59E-01	1.99E-01	5.07E-05	1.37E-02	3.21E+00
Al-26	3.10E-07	6.89E-06	1.24E-03	1.00E+00	6.16E-17	7.67E-01	4.61E-03	2.67E+00
Am-241	7.44E-05	3.34E-03	3.71E-02	3.42E-01	1.12E+01	7.46E-02	7.62E-01	3.87E-05
Am-242	7.54E-05	5.63E-04	1.54E-02	1.08E-01	7.37E+00	1.29E-03	3.48E-01	1.24E-01
Am-242m	7.23E-05	5.56E-04	3.56E-03	1.83E-02	8.67E+00	1.52E-03	5.88E-02	2.62E-01
Am-243	7.44E-05	3.35E-03	6.09E-02	6.55E-01	6.02E+00	4.03E-02	9.51E-01	1.50E-05
Am-245	7.76E-05	5.81E-04	1.53E-02	1.64E-01	2.62E+00	4.72E-04	1.17E-01	1.93E-01
Am-246m	7.76E-05	5.79E-04	2.85E-02	9.62E-01	6.90E+00	1.26E-03	3.80E-01	1.01E+00
Ar-37	1.78E-06	1.49E-05	1.60E-04	2.61E-03	4.02E-13	3.89E+00	8.35E-04	8.54E-02
Ar-39	2.19E-01	0.00E+00	0.00E+00	0.00E+00	3.83E-03	0.00E+00	0.00E+00	0.00E+00
Ar-42	2.33E-01	0.00E+00	0.00E+00	0.00E+00	4.07E-03	0.00E+00	0.00E+00	0.00E+00
As-73	1.21E-05	1.05E-04	1.16E-03	1.41E-02	2.21E+01	2.92E-04	4.55E-02	1.11E+00

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
At-217	3.25E-05	3.56E-04	1.08E-02	2.40E-01	5.08E-03	4.37E-07	1.55E-04	1.01E-03
At-218	1.10E+00	0.00E+00	0.00E+00	0.00E+00	1.92E-05	0.00E+00	0.00E+00	0.00E+00
At-219	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Au-194	1.01E-05	2.88E-04	5.11E-02	7.38E-01	1.44E+01	8.81E-04	1.11E+00	1.33E+00
Au-195	1.01E-05	2.90E-04	9.21E-03	7.18E-02	3.06E+01	1.87E-03	6.30E-01	1.08E+00
Ba-133	2.19E-05	4.27E-03	4.32E-02	3.41E-01	2.09E+01	1.72E-01	1.60E+00	9.76E-01
Ba-137m	1.86E-05	4.44E-03	3.29E-02	6.62E-01	1.37E+00	1.06E-02	7.53E-02	8.97E-01
Be-10	2.52E-01	0.00E+00	0.00E+00	0.00E+00	4.42E-03	0.00E+00	0.00E+00	0.00E+00
Be-7	4.78E-01	0.00E+00	0.00E+00	0.00E+00	1.04E-01	0.00E+00	0.00E+00	0.00E+00
Bi-207	2.66E-05	3.42E-04	5.39E-02	8.22E-01	1.41E+01	1.14E-03	1.13E+00	1.80E+00
Bi-208	2.66E-05	3.43E-04	4.72E-02	2.61E+00	1.29E+01	1.03E-03	7.55E-01	1.00E+00
Bi-210	2.07E-05	3.27E-04	1.02E-02	3.89E-01	3.76E-06	2.81E-10	1.04E-07	6.81E-03
Bi-210m	2.07E-05	3.27E-04	1.03E-02	2.68E-01	2.47E+00	1.85E-04	6.84E-02	9.69E-01
Bi-211	2.07E-05	3.27E-04	1.02E-02	3.05E-01	4.17E-01	3.11E-05	1.15E-02	1.55E-01
Bi-212	2.08E-05	2.27E-03	1.74E-02	8.74E-01	4.05E+00	1.48E-02	8.80E-02	1.25E-01
Bi-213	3.84E-05	3.70E-04	1.11E-02	4.04E-01	6.26E-01	5.74E-05	2.00E-02	3.24E-01
Bi-214	3.84E-05	3.70E-04	5.79E-02	1.11E+00	3.14E-01	2.89E-05	3.01E-02	1.33E+00
Bi-215	3.84E-05	3.70E-04	1.11E-02	3.63E-01	2.67E+00	2.45E-04	8.54E-02	7.15E-01
Bk-247	7.22E-05	5.57E-04	1.49E-02	1.47E-01	4.83E+00	8.20E-04	2.19E-01	9.76E-01
Bk-249	7.22E-05	3.52E-03	3.24E-02	2.38E-01	1.57E-05	1.13E-07	5.68E-04	2.77E-06
Bk-250	7.46E-05	6.20E-04	1.67E-02	9.92E-01	5.07E+00	1.04E-03	2.62E-01	9.03E-01
Bk-251	7.45E-05	6.28E-04	1.55E-02	1.26E-01	1.43E+01	2.92E-03	6.06E-01	6.56E-01
C-14	4.95E-02	0.00E+00	0.00E+00	0.00E+00	8.65E-04	0.00E+00	0.00E+00	0.00E+00
Ca-41	3.01E-06	2.62E-05	2.69E-04	3.31E-03	2.19E-12	3.73E+00	1.45E-03	1.22E-01
Ca-45	6.75E-06	3.51E-04	4.17E-03	7.72E-02	1.42E-04	5.32E-08	3.10E-06	1.35E-03
Cd-109	1.21E-05	3.68E-04	3.04E-03	2.48E-02	1.45E+01	3.52E-03	1.06E-01	1.05E+00
Cd-113	9.26E-02	0.00E+00	0.00E+00	0.00E+00	1.62E-03	0.00E+00	0.00E+00	0.00E+00
Cd-113m	1.72E-05	3.99E-04	2.12E-02	1.90E-01	8.18E-03	2.42E-06	5.78E-04	3.46E-03
Cd-115m	8.13E-06	4.32E-04	2.38E-02	9.00E-01	2.06E-03	3.63E-07	1.16E-04	4.38E-02
Ce-139	2.11E-05	7.29E-04	4.90E-03	9.87E-02	1.50E+01	8.26E-03	1.22E-01	1.61E+00
Ce-141	1.56E-05	7.99E-04	5.30E-03	1.17E-01	2.46E+00	1.95E-03	2.56E-02	6.59E-01
Ce-144	1.56E-05	8.00E-04	5.32E-03	8.97E-02	1.40E+00	1.09E-03	1.42E-02	2.16E-01
Cf-248	7.77E-05	5.78E-04	1.61E-02	1.04E+00	1.97E+00	3.59E-04	9.67E-02	3.06E-04
Cf-249	7.76E-05	5.80E-04	1.56E-02	3.51E-01	5.80E+00	1.06E-03	2.72E-01	9.22E-01
Cf-250	7.77E-05	1.60E-02	1.32E-01	1.04E+00	1.50E+00	7.42E-02	1.21E-03	9.35E-03
Cf-251	7.76E-05	5.81E-04	1.54E-02	1.41E-01	1.35E+01	2.44E-03	6.12E-01	8.11E-01
Cf-252	7.77E-05	5.78E-04	5.96E-02	1.05E+00	1.49E+00	2.73E-04	1.39E-01	4.33E-01
Cf-253	7.55E-05	6.51E-04	4.25E-03	2.01E-02	6.05E+00	1.31E-03	5.10E-02	2.11E-01
Cf-254	7.77E-05	3.59E-03	4.15E-02	9.73E-01	5.08E-03	3.70E-05	7.98E-01	1.75E+01
Cl-36	1.33E-06	1.29E-05	2.29E-03	2.91E-01	2.69E-15	7.46E-02	1.31E-03	5.06E-03
Cm-241	7.21E-05	5.68E-04	1.46E-02	2.87E-01	3.02E+01	5.20E-03	1.14E+00	1.69E+00
Cm-242	7.20E-05	5.37E-04	1.50E-02	1.64E-01	2.58E+00	4.22E-04	1.19E-01	4.61E-05
Cm-243	7.20E-05	5.53E-04	1.40E-02	1.59E-01	2.06E+01	3.44E-03	6.20E-01	7.85E-01
Cm-244	7.21E-05	1.50E-02	1.28E-01	1.05E+00	2.21E+00	1.02E-01	3.16E-05	1.63E-05
Cm-245	7.20E-05	1.44E-02	1.15E-01	1.12E+00	1.60E+01	6.62E-01	8.53E-01	6.66E-08
Cm-246	7.21E-05	1.51E-02	1.36E-01	1.05E+00	1.76E+00	8.16E-02	3.80E-04	3.43E-03
Cm-247	7.20E-05	5.36E-04	1.45E-02	3.80E-01	5.18E-01	8.33E-05	2.32E-02	8.24E-01
Cm-248	7.20E-05	5.37E-04	8.15E-02	1.06E+00	1.65E+00	2.71E-04	2.64E-01	1.24E+00
Cm-249	7.82E-05	6.45E-04	4.86E-03	4.81E-01	8.51E+00	1.68E-03	5.04E-02	4.24E-02
Cm-250	7.20E-05	3.39E-03	2.74E-02	9.59E-01	4.46E-01	3.02E-03	3.70E-01	1.41E+01

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Co-56	1.25E-05	6.52E-04	6.43E-03	1.25E+00	4.64E+00	6.27E-03	2.42E-01	2.91E+00
Co-57	1.25E-05	6.52E-04	7.57E-03	1.25E-01	1.05E+01	1.42E-02	6.40E-01	9.65E-01
Co-58	1.25E-05	6.52E-04	6.43E-03	7.46E-01	4.88E+00	6.59E-03	2.54E-01	1.31E+00
Co-60	1.45E-05	7.33E-03	9.59E-02	1.25E+00	1.50E-03	1.09E-04	1.68E-03	2.00E+00
Co-60m	1.35E-05	7.24E-04	1.02E-02	1.31E+00	5.22E+00	8.84E-03	3.26E-01	2.51E-03
Cs-134	1.86E-05	4.44E-03	3.28E-02	6.97E-01	1.48E-01	1.15E-03	8.62E-03	2.23E+00
Cs-135	8.94E-02	0.00E+00	0.00E+00	0.00E+00	1.56E-03	0.00E+00	0.00E+00	0.00E+00
Cs-137	1.86E-05	6.87E-04	4.67E-03	2.06E-01	4.46E-06	2.05E-09	3.25E-08	3.30E-03
Dy-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dy-159	1.38E-05	1.67E-04	6.22E-03	4.58E-02	1.10E+01	4.89E-04	2.14E-01	9.63E-01
Es-253	7.85E-05	6.07E-04	1.73E-02	3.98E-01	7.24E-01	1.40E-04	3.09E-02	6.45E-04
Es-254	7.84E-05	1.60E-02	3.10E-01	7.36E+00	3.28E+01	1.06E+00	4.24E-03	1.58E-10
Es-255	8.17E-02	5.34E-01	1.79E+00	7.36E+00	1.38E-03	3.82E-04	2.65E-04	2.36E-07
Eu-146	1.45E-05	1.45E-04	3.54E-02	8.35E-01	9.45E+00	2.89E-04	8.91E-01	2.84E+00
Eu-148	1.45E-05	1.45E-04	3.56E-02	6.74E-01	1.01E+01	3.09E-04	9.44E-01	3.26E+00
Eu-149	1.46E-05	1.46E-04	3.25E-02	3.27E-01	1.67E+01	5.25E-04	1.04E+00	9.83E-02
Eu-150	1.45E-05	1.45E-04	3.54E-02	5.20E-01	1.03E+01	3.17E-04	9.56E-01	2.93E+00
Eu-152	1.46E-05	1.46E-04	3.49E-02	7.13E-01	1.04E+01	3.20E-04	9.04E-01	1.61E+00
Eu-154	1.94E-05	6.01E-03	1.08E-01	9.89E-01	4.32E+00	7.96E-02	7.41E-01	1.18E+00
Eu-155	1.94E-05	1.62E-04	6.03E-03	7.77E-02	4.62E+00	1.85E-04	8.42E-02	7.80E-01
Fe-55	1.15E-05	5.84E-04	5.92E-03	1.26E-01	6.05E+00	6.51E-03	2.69E-01	1.28E-09
Fe-59	1.35E-05	7.24E-04	6.96E-03	1.14E+00	3.24E-03	5.47E-06	1.99E-04	1.04E+00
Fe-60	6.47E-02	0.00E+00	0.00E+00	0.00E+00	1.13E-03	0.00E+00	0.00E+00	0.00E+00
Fm-254	7.46E-05	6.20E-04	1.81E-02	1.04E+00	1.66E+00	3.41E-04	8.73E-02	6.69E-03
Fm-255	7.47E-05	1.70E-02	3.72E-01	7.36E+00	2.24E+01	8.96E-01	2.05E-04	1.15E-09
Fm-257	7.45E-05	6.24E-04	1.61E-02	1.74E-01	1.79E+01	3.65E-03	8.33E-01	7.92E-01
Fr-221	4.43E-05	3.86E-04	1.17E-02	1.92E-01	7.19E-01	7.15E-05	2.46E-02	1.51E-01
Fr-223	7.13E-05	2.90E-03	4.35E-02	3.28E-01	9.45E+00	4.92E-02	8.28E-01	7.20E-02
Ga-68	1.64E-05	9.71E-04	8.69E-03	5.25E-01	5.22E-01	1.51E-03	4.57E-02	1.83E+00
Gd-146	1.42E-05	1.54E-04	5.79E-03	7.88E-02	2.23E+01	7.80E-04	3.66E-01	3.17E+00
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-150	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-151	1.43E-05	1.58E-04	5.86E-03	6.76E-02	1.88E+01	6.90E-04	2.88E-01	1.02E+00
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	1.42E-05	1.54E-04	5.81E-03	5.94E-02	1.51E+01	5.31E-04	2.48E-01	1.75E+00
Ge-68	1.58E-05	1.04E-04	1.06E-03	9.32E-03	6.20E+00	9.62E-05	1.51E-02	4.29E-01
H-3	5.68E-03	0.00E+00	0.00E+00	0.00E+00	9.94E-05	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.40E-05	2.12E-04	7.54E-03	5.97E-02	2.66E+01	1.72E-03	6.63E-01	1.69E+00
Hf-174	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-175	1.40E-05	2.11E-04	7.52E-03	1.94E-01	1.12E+01	7.22E-04	2.85E-01	1.81E+00
Hf-178m	1.94E-05	2.20E-04	7.81E-03	3.11E-01	2.16E+01	1.53E-03	5.98E-01	7.19E+00
Hf-181	2.50E-05	2.31E-04	8.07E-03	2.97E-01	6.05E+00	4.55E-04	1.76E-01	1.79E+00
Hf-182	2.51E-05	2.30E-04	8.06E-03	2.29E-01	1.88E+00	1.39E-04	5.70E-02	1.04E+00
Hg-194	1.11E-05	5.59E-05	3.07E-04	9.24E-03	1.55E+01	4.84E-06	1.03E-03	2.75E-01
Hg-203	2.07E-05	3.27E-04	1.02E-02	2.50E-01	2.32E+00	1.74E-04	6.40E-02	9.48E-01
Hg-206	2.07E-05	3.27E-04	1.02E-02	2.76E-01	1.59E+00	1.19E-04	4.37E-02	4.49E-01
Ho-163	1.53E-05	2.46E-05	1.90E-04	1.30E-03	4.21E+00	1.80E-07	3.72E-04	1.70E-03
Ho-166m	1.35E-05	1.87E-04	4.21E-02	5.31E-01	8.76E+00	5.24E-04	7.24E-01	3.00E+00
I-125	1.36E-05	5.34E-04	3.91E-03	2.84E-02	2.50E+01	7.27E-03	1.49E-01	1.48E+00
I-129	1.66E-05	6.09E-04	4.28E-03	3.13E-02	1.11E+01	4.53E-03	8.11E-02	7.89E-01

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
In-113m	8.13E-06	4.33E-04	2.29E-02	3.92E-01	5.09E+00	8.96E-04	2.72E-01	6.49E-01
In-114	1.71E-05	3.99E-04	2.20E-02	8.14E-01	3.69E-02	1.08E-05	3.90E-03	1.57E-02
In-114m	8.33E-06	4.31E-04	2.20E-02	3.23E-01	1.08E+01	1.96E-03	4.14E-01	2.20E-01
In-115	1.53E-01	0.00E+00	0.00E+00	0.00E+00	2.67E-03	0.00E+00	0.00E+00	0.00E+00
In-115m	8.13E-06	4.33E-04	2.28E-02	3.36E-01	7.05E+00	1.24E-03	3.71E-01	4.59E-01
Ir-192	1.70E-05	2.81E-04	9.25E-03	3.54E-01	2.49E+00	1.70E-04	6.45E-02	2.31E+00
Ir-192n	4.56E-05	2.74E-04	9.31E-03	7.78E-02	1.41E+01	1.46E-03	5.74E-01	7.53E-03
Ir-194	1.01E-05	2.88E-04	9.43E-03	4.58E-01	1.84E-01	1.14E-05	4.31E-03	2.24E-01
Ir-194m	1.01E-05	2.88E-04	9.51E-03	4.65E-01	5.78E+00	3.60E-04	1.37E-01	5.02E+00
K-40	1.70E-05	2.02E-04	2.95E-03	1.38E+00	3.85E-01	1.19E-04	9.53E-03	1.18E-01
K-42	3.84E-06	3.65E-05	5.29E-03	1.50E+00	8.33E-17	6.67E-05	2.90E-06	2.11E-01
Kr-81	1.76E-05	1.46E-03	1.20E-02	2.76E-01	7.13E+00	2.25E-02	5.16E-01	2.97E-03
Kr-83m	1.94E-05	1.41E-04	1.57E-03	1.19E-02	1.11E+01	4.44E-04	3.75E-02	2.08E-01
Kr-85	1.53E-05	1.68E-03	1.92E-02	3.82E-01	2.82E-04	8.53E-07	2.19E-05	8.72E-03
La-137	1.86E-05	6.87E-04	4.68E-03	3.29E-02	1.34E+01	6.12E-03	9.66E-02	7.39E-01
La-138	1.86E-05	4.43E-03	3.30E-02	1.22E+00	8.79E+00	6.61E-02	3.88E-01	1.00E+00
Lu-172	8.66E-06	2.02E-04	7.34E-03	5.61E-01	2.02E+01	1.19E-03	4.88E-01	3.48E+00
Lu-172m	1.40E-05	2.10E-04	7.18E-03	4.19E-02	8.46E+00	5.30E-04	1.94E-01	3.76E-05
Lu-173	8.63E-06	2.02E-04	7.30E-03	8.99E-02	1.92E+01	1.13E-03	4.53E-01	2.00E+00
Lu-174	8.65E-06	2.02E-04	4.20E-02	1.24E+00	1.42E+01	8.37E-04	1.22E+00	5.24E-02
Lu-174m	1.39E-05	2.12E-04	3.74E-02	9.91E-01	2.59E+01	1.67E-03	1.51E+00	5.77E-03
Lu-176	1.94E-05	2.20E-04	7.88E-03	2.18E-01	9.36E+00	6.66E-04	2.69E-01	2.20E+00
Lu-177	1.94E-05	2.20E-04	7.87E-03	1.47E-01	1.28E+00	9.10E-05	3.67E-02	2.39E-01
Lu-177m	1.84E-05	2.19E-04	7.77E-03	1.97E-01	1.94E+01	1.35E-03	5.39E-01	5.06E+00
Mn-53	6.39E-06	9.95E-05	5.25E-04	5.43E-03	6.41E+00	7.17E-05	5.36E-03	2.42E-01
Mn-54	6.39E-06	5.19E-04	5.43E-03	8.35E-01	6.42E+00	5.44E-03	2.42E-01	1.00E+00
Mo-93	5.83E-06	2.05E-04	2.17E-03	1.69E-02	1.09E+01	6.65E-04	3.67E-02	6.26E-01
Na-22	5.11E-01	1.27E+00	2.15E-01	8.35E-01	1.80E+00	9.99E-01	3.39E-03	8.04E-06
Nb-91	6.52E-06	1.84E-04	1.53E-02	5.11E-01	1.20E+01	5.51E-04	6.63E-01	3.14E-03
Nb-91m	5.86E-06	2.04E-04	1.68E-02	1.20E+00	1.09E+01	6.62E-04	5.71E-01	2.02E-02
Nb-92	6.52E-06	1.84E-04	1.53E-02	7.48E-01	1.20E+01	5.52E-04	6.42E-01	2.00E+00
Nb-93m	5.83E-06	2.05E-04	2.15E-03	1.69E-02	9.26E+00	5.71E-04	3.03E-02	1.12E-01
Nb-94	6.85E-06	2.27E-04	1.69E-02	7.87E-01	2.91E-02	2.32E-06	2.05E-03	1.98E+00
Nb-95	6.85E-06	2.26E-03	2.88E-02	7.66E-01	1.49E-02	6.05E-05	1.75E-03	9.99E-01
Nb-95m	5.83E-06	2.05E-04	1.60E-02	2.34E-01	7.54E+00	4.62E-04	4.45E-01	2.68E-01
Nd-144	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-59	1.35E-05	7.24E-04	6.96E-03	5.11E-01	5.41E+00	9.05E-03	3.26E-01	3.04E-05
Ni-63	1.74E-02	0.00E+00	0.00E+00	0.00E+00	3.05E-04	0.00E+00	0.00E+00	0.00E+00
Np-235	7.54E-05	5.11E-04	1.33E-02	9.76E-02	1.32E+01	1.91E-03	4.20E-01	5.42E-03
Np-236	7.52E-05	5.03E-04	1.42E-02	1.20E-01	3.63E+01	5.36E-03	1.56E+00	1.12E+00
Np-237	7.65E-05	4.84E-04	3.18E-03	3.69E-02	1.65E+01	2.27E-03	9.68E-02	9.05E-01
Np-238	7.20E-05	5.37E-04	1.75E-02	9.92E-01	8.52E+00	1.40E-03	4.04E-01	5.86E-01
Np-239	7.19E-05	5.56E-04	1.42E-02	1.51E-01	2.22E+01	3.69E-03	7.07E-01	1.15E+00
Np-240	7.20E-05	5.37E-04	1.50E-02	5.59E-01	2.39E+01	3.91E-03	1.10E+00	1.86E+00
Np-240m	7.20E-05	5.36E-04	1.50E-02	6.52E-01	7.63E+00	1.25E-03	3.51E-01	4.98E-01
Os-185	3.76E-05	8.48E-03	6.47E-02	6.76E-01	8.56E+00	2.84E-01	7.39E-01	9.48E-01
Os-186	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Os-194	4.52E-05	2.78E-04	2.00E-03	1.81E-02	6.66E+00	6.75E-04	3.18E-02	2.29E-01
P-32	6.95E-01	0.00E+00	0.00E+00	0.00E+00	1.22E-02	0.00E+00	0.00E+00	0.00E+00
Pa-231	7.95E-05	4.61E-04	1.50E-02	2.55E-01	2.13E+01	2.63E-03	7.25E-01	1.27E-01

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Pa-232	7.55E-05	4.99E-04	1.42E-02	6.79E-01	1.28E+01	1.87E-03	5.53E-01	1.37E+00
Pa-233	7.55E-05	5.02E-04	1.37E-02	2.24E-01	1.63E+01	2.34E-03	6.23E-01	9.53E-01
Pa-234	7.55E-05	4.99E-04	1.40E-02	5.61E-01	2.55E+01	3.71E-03	1.08E+00	2.59E+00
Pa-234m	7.57E-05	1.38E-02	1.00E-01	8.86E-01	2.03E-01	8.14E-03	5.25E-03	3.07E-02
Pb-202	2.07E-05	3.24E-04	2.29E-03	1.06E-02	1.07E+01	7.61E-04	3.71E-02	2.07E-01
Pb-205	2.07E-05	3.24E-04	2.29E-03	1.06E-02	1.09E+01	7.69E-04	3.75E-02	2.09E-01
Pb-209	1.97E-01	0.00E+00	0.00E+00	0.00E+00	3.46E-03	0.00E+00	0.00E+00	0.00E+00
Pb-210	3.25E-05	3.61E-04	2.48E-03	1.73E-02	1.18E+01	1.01E-03	4.84E-02	2.79E-01
Pb-211	3.25E-05	3.57E-04	5.38E-02	5.88E-01	2.20E-01	1.90E-05	1.69E-02	1.14E-01
Pb-212	3.25E-05	3.56E-04	1.08E-02	1.71E-01	5.56E+00	4.79E-04	1.70E-01	8.36E-01
Pb-214	3.25E-05	3.58E-04	1.07E-02	2.71E-01	5.73E+00	4.94E-04	1.61E-01	9.31E-01
Pd-107	9.58E-03	0.00E+00	0.00E+00	0.00E+00	1.68E-04	0.00E+00	0.00E+00	0.00E+00
Pm-143	1.52E-05	1.34E-04	3.34E-02	7.42E-01	1.06E+01	2.51E-04	8.95E-01	3.85E-01
Pm-144	1.52E-05	1.34E-04	3.34E-02	6.26E-01	1.08E+01	2.54E-04	9.15E-01	2.45E+00
Pm-145	1.52E-05	1.34E-04	5.20E-03	3.92E-02	1.19E+01	2.84E-04	1.44E-01	7.79E-01
Pm-146	1.52E-05	1.34E-04	3.34E-02	5.88E-01	7.13E+00	1.68E-04	6.01E-01	1.24E+00
Pm-147	1.45E-05	1.45E-04	5.58E-03	6.30E-02	2.83E-04	8.64E-09	4.26E-06	1.13E-03
Pm-148	1.45E-05	1.45E-04	3.64E-02	9.78E-01	2.54E-02	7.75E-07	2.43E-03	5.98E-01
Pm-148m	1.47E-05	1.43E-04	5.49E-03	5.95E-01	1.51E+00	4.35E-05	2.18E-02	3.35E+00
Po-208	3.25E-05	3.59E-04	1.06E-02	3.54E-01	7.58E-04	6.53E-08	2.03E-05	5.97E-05
Po-209	2.67E-05	3.65E-04	1.06E-02	3.76E-01	4.26E+00	6.94E-04	3.03E-03	1.63E-02
Po-210	2.66E-05	3.41E-04	5.54E-02	8.03E-01	1.55E-06	1.25E-10	1.40E-07	1.21E-05
Po-211	2.66E-05	3.41E-04	5.54E-02	7.35E-01	3.31E-03	2.67E-07	3.00E-04	1.11E-02
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	2.66E-05	3.41E-04	5.62E-02	7.79E-01	2.13E-05	1.71E-09	1.98E-06	4.80E-05
Po-214	2.66E-05	3.41E-04	5.51E-02	7.97E-01	1.41E-05	1.14E-09	1.26E-06	1.04E-04
Po-215	2.66E-05	3.42E-04	1.06E-02	4.29E-01	1.98E-04	1.61E-08	5.85E-06	4.11E-04
Po-216	2.66E-05	3.41E-04	5.54E-02	8.05E-01	2.42E-06	1.95E-10	2.18E-07	1.90E-05
Po-218	7.14E-02	0.00E+00	0.00E+00	0.00E+00	2.50E-07	0.00E+00	0.00E+00	0.00E+00
Pr-144	1.52E-05	1.34E-04	3.35E-02	1.23E+00	7.59E-04	1.78E-08	6.53E-05	4.45E-02
Pr-144m	1.56E-05	4.94E-03	3.69E-02	9.52E-01	1.06E+01	1.12E-01	2.98E-01	1.72E-03
Pt-190	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pt-193	4.48E-05	2.80E-04	2.00E-03	1.00E-02	8.98E+00	9.24E-04	4.13E-02	2.09E-01
Pu-236	7.55E-05	4.98E-04	1.44E-02	5.85E-01	3.18E+00	4.66E-04	1.39E-01	5.26E-06
Pu-237	7.44E-05	5.23E-04	1.40E-02	1.00E-01	1.44E+01	2.20E-03	5.51E-01	4.48E-01
Pu-238	7.55E-05	4.98E-04	1.43E-02	7.97E-01	2.94E+00	4.31E-04	1.28E-01	3.85E-07
Pu-239	7.54E-05	5.31E-04	1.34E-02	3.85E-01	2.98E+00	4.50E-04	6.18E-02	6.29E-05
Pu-240	7.55E-05	4.98E-04	1.43E-02	1.02E+00	2.77E+00	4.05E-04	1.21E-01	7.85E-07
Pu-241	7.54E-05	5.19E-04	6.45E-03	1.07E-01	5.78E-04	8.50E-08	1.08E-04	1.42E-05
Pu-242	7.55E-05	4.98E-04	1.43E-02	1.09E+00	2.37E+00	3.47E-04	1.03E-01	7.07E-05
Pu-243	7.21E-05	5.63E-04	1.48E-02	9.23E-02	3.88E+00	6.64E-04	1.56E-01	2.57E-01
Pu-244	7.56E-05	1.44E-02	9.66E-01	7.36E+00	1.97E+00	8.62E-02	2.07E-02	5.66E-06
Pu-246	7.22E-05	5.60E-04	3.59E-03	9.22E-02	1.30E+01	2.22E-03	8.90E-02	1.54E+00
Ra-223	5.01E-05	4.10E-04	1.11E-02	1.54E-01	1.47E+01	1.62E-03	3.04E-01	8.90E-01
Ra-224	5.01E-05	4.02E-04	1.21E-02	2.27E-01	1.27E-01	1.34E-05	4.55E-03	4.56E-02
Ra-225	7.96E-05	4.49E-04	2.99E-03	3.21E-02	4.51E+00	5.48E-04	2.46E-02	4.42E-01
Ra-226	5.01E-05	4.02E-04	1.22E-02	1.71E-01	2.69E-01	2.87E-05	9.72E-03	4.25E-02
Ra-228	7.95E-05	4.67E-04	3.02E-03	1.55E-02	6.36E+00	8.45E-04	2.78E-02	1.59E-01
Rb-83	1.94E-05	1.57E-03	1.27E-02	5.32E-01	8.04E+00	2.87E-02	5.68E-01	9.10E-01
Rb-84	1.94E-05	1.57E-03	1.28E-02	7.26E-01	4.68E+00	1.72E-02	3.87E-01	1.25E+00

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Rb-87	1.15E-01	0.00E+00	0.00E+00	0.00E+00	2.02E-03	0.00E+00	0.00E+00	0.00E+00
Re-183	3.12E-05	2.42E-04	8.22E-03	8.76E-02	2.22E+01	1.80E-03	6.65E-01	1.73E+00
Re-184	3.13E-05	8.29E-03	6.90E-02	8.33E-01	1.18E+01	3.82E-01	1.05E+00	9.79E-01
Re-184m	3.53E-05	8.29E-03	1.20E-01	8.56E-01	1.69E+01	5.35E-01	1.41E+00	2.45E-01
Re-186	3.85E-05	2.54E-04	8.68E-03	1.08E-01	1.60E+00	1.43E-04	5.67E-02	2.05E-01
Re-186m	3.76E-05	2.54E-04	8.41E-03	5.72E-02	2.22E+01	1.94E-03	6.44E-01	2.52E-01
Re-187	6.18E-04	0.00E+00	0.00E+00	0.00E+00	1.08E-05	0.00E+00	0.00E+00	0.00E+00
Re-188	4.41E-05	2.63E-04	8.94E-03	2.70E-01	9.60E-01	9.23E-05	3.64E-02	2.64E-01
Rh-101	8.91E-06	2.80E-04	1.85E-02	1.77E-01	1.03E+01	1.33E-03	8.32E-01	1.54E+00
Rh-102	8.91E-06	2.79E-04	1.85E-02	5.35E-01	5.59E+00	7.21E-04	4.60E-01	9.32E-01
Rh-102m	8.91E-06	2.80E-04	1.87E-02	6.80E-01	9.06E+00	1.17E-03	7.39E-01	3.15E+00
Rh-103m	9.96E-06	3.07E-04	2.73E-03	2.07E-02	6.87E+00	1.13E-03	4.18E-02	7.43E-02
Rh-106	7.86E-06	3.37E-04	2.03E-02	6.59E-01	1.27E-02	2.54E-06	1.22E-03	3.67E-01
Rn-218	3.84E-05	3.70E-04	5.66E-02	6.09E-01	3.00E-04	2.78E-08	2.76E-05	1.24E-03
Rn-219	3.84E-05	3.71E-04	1.13E-02	2.98E-01	3.78E-01	3.52E-05	1.23E-02	1.96E-01
Rn-220	3.84E-05	3.70E-04	1.12E-02	5.42E-01	3.48E-04	3.22E-08	1.13E-05	1.16E-03
Rn-222	3.84E-05	3.71E-04	1.12E-02	5.01E-01	2.76E-04	2.56E-08	8.95E-06	7.76E-04
Ru-103	9.96E-06	2.66E-03	3.31E-02	5.03E-01	1.24E-01	7.49E-04	1.61E-02	9.85E-01
Ru-106	1.00E-02	0.00E+00	0.00E+00	0.00E+00	1.76E-04	0.00E+00	0.00E+00	0.00E+00
S-35	4.87E-02	0.00E+00	0.00E+00	0.00E+00	8.53E-04	0.00E+00	0.00E+00	0.00E+00
Sb-124	1.36E-05	3.75E-03	2.87E-02	9.81E-01	7.68E-02	4.85E-04	4.62E-03	1.89E+00
Sb-125	1.36E-05	3.75E-03	2.87E-02	4.85E-01	8.49E+00	5.36E-02	5.43E-01	8.70E-01
Sb-126	1.36E-05	5.34E-04	2.58E-02	6.40E-01	3.75E-01	1.10E-04	2.40E-02	4.31E+00
Sb-126m	1.24E-05	3.59E-03	2.80E-02	5.98E-01	1.81E+00	1.05E-02	1.37E-02	2.60E+00
Sc-44	3.84E-06	3.65E-05	3.69E-03	7.37E-01	2.58E-13	2.07E-01	8.11E-03	2.91E+00
Sc-46	8.00E-06	4.05E-04	4.52E-03	1.00E+00	1.85E-03	9.22E-07	4.99E-05	2.00E+00
Se-75	1.42E-05	1.25E-03	1.06E-02	2.15E-01	8.88E+00	2.11E-02	5.46E-01	1.78E+00
Se-79	5.29E-02	0.00E+00	0.00E+00	0.00E+00	9.26E-04	0.00E+00	0.00E+00	0.00E+00
Si-32	6.86E-02	0.00E+00	0.00E+00	0.00E+00	1.20E-03	0.00E+00	0.00E+00	0.00E+00
Sm-145	1.48E-05	1.39E-04	3.63E-02	4.92E-01	1.82E+01	4.88E-04	1.76E+00	3.33E-05
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	1.43E-05	1.62E-04	1.04E-03	1.15E-02	9.08E-02	3.51E-06	1.11E-04	1.84E-03
Sn-113	8.13E-06	4.33E-04	2.30E-02	2.55E-01	1.41E+01	2.48E-03	7.92E-01	2.11E-02
Sn-119m	1.09E-05	4.71E-04	3.59E-03	2.51E-02	2.45E+01	4.98E-03	1.10E-01	5.74E-01
Sn-121	1.16E-01	0.00E+00	0.00E+00	0.00E+00	2.02E-03	0.00E+00	0.00E+00	0.00E+00
Sn-121m	1.12E-05	4.75E-04	3.53E-03	2.82E-02	1.09E+01	2.44E-03	4.97E-02	1.74E-01
Sn-123	1.22E-05	4.99E-04	3.72E-03	7.54E-01	1.64E-04	4.05E-08	8.96E-07	1.55E-02
Sn-126	1.22E-05	5.05E-04	3.78E-03	6.04E-02	2.13E+01	5.09E-03	1.05E-01	9.32E-01
Sr-85	1.53E-05	1.43E-04	1.30E-02	5.14E-01	9.07E+00	3.07E-04	6.08E-01	9.57E-01
Sr-89	5.30E-06	1.67E-04	1.45E-02	5.88E-01	1.08E-05	3.74E-10	5.34E-07	1.03E-02
Sr-90	1.96E-01	0.00E+00	0.00E+00	0.00E+00	3.43E-03	0.00E+00	0.00E+00	0.00E+00
Ta-179	1.93E-05	2.23E-04	7.72E-03	5.72E-02	9.44E+00	6.71E-04	2.30E-01	4.14E-01
Ta-182	3.13E-05	8.32E-03	9.99E-02	1.18E+00	8.78E+00	2.81E-01	1.29E+00	9.87E-01
Tb-157	1.95E-05	1.69E-04	6.14E-03	4.40E-02	9.65E+00	4.26E-04	1.44E-01	1.04E-01
Tb-158	1.90E-05	6.05E-03	6.38E-02	9.38E-01	1.48E+01	2.70E-01	1.12E+00	7.80E-01
Tb-160	1.37E-05	1.73E-04	4.86E-02	8.04E-01	5.16E+00	2.53E-04	4.52E-01	1.37E+00
Tc-95	6.85E-06	2.27E-04	1.69E-02	7.79E-01	1.01E+01	8.03E-04	7.02E-01	1.01E+00
Tc-95m	6.88E-06	2.28E-04	1.69E-02	4.87E-01	1.03E+01	8.27E-04	7.02E-01	1.39E+00

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Tc-97	6.85E-06	2.28E-04	2.30E-03	1.78E-02	1.00E+01	7.99E-04	3.94E-02	6.31E-01
Tc-97m	7.88E-06	2.53E-04	2.43E-03	1.92E-02	8.97E+00	9.17E-04	4.02E-02	4.90E-01
Tc-98	8.91E-06	2.79E-04	1.85E-02	6.99E-01	3.90E-02	5.03E-06	3.25E-03	2.02E+00
Tc-99	8.91E-06	2.79E-04	2.58E-03	1.01E-01	8.45E-05	1.09E-08	4.43E-07	1.78E-03
Te-121	1.22E-05	4.99E-04	2.50E-02	5.60E-01	1.36E+01	3.36E-03	8.33E-01	9.94E-01
Te-121m	1.33E-05	5.29E-04	2.45E-02	2.40E-01	1.48E+01	4.18E-03	6.14E-01	8.42E-01
Te-123	1.22E-05	4.98E-04	3.62E-03	2.69E-02	1.07E+01	2.71E-03	5.26E-02	1.26E-03
Te-123m	1.36E-05	5.35E-04	3.89E-03	1.11E-01	1.41E+01	4.10E-03	8.19E-02	1.33E+00
Te-125m	1.36E-05	5.34E-04	3.90E-03	2.86E-02	2.43E+01	7.10E-03	1.44E-01	1.23E+00
Te-127	1.53E-05	3.91E-03	3.58E-02	3.54E-01	1.77E-02	1.24E-04	1.40E-03	1.62E-02
Te-127m	1.36E-05	3.73E-03	2.86E-02	4.85E-01	1.21E+01	7.36E-02	3.77E-01	2.56E-04
Te-129	1.52E-05	5.81E-04	2.15E-02	4.94E-01	1.04E+01	3.39E-03	2.25E-01	1.26E-01
Te-129m	1.36E-05	3.74E-03	2.84E-02	6.96E-01	7.75E+00	4.74E-02	2.77E-01	4.54E-02
Th-227	7.12E-05	4.33E-04	1.26E-02	1.93E-01	1.76E+01	2.06E-03	6.42E-01	6.33E-01
Th-228	7.13E-05	1.29E-02	1.13E-01	8.25E-01	2.78E+00	1.08E-01	1.79E-02	2.23E-07
Th-229	7.12E-05	4.39E-04	1.32E-02	1.10E-01	2.95E+01	3.45E-03	9.81E-01	7.47E-01
Th-230	7.13E-05	1.29E-02	8.36E-02	5.77E-01	2.44E+00	9.46E-02	4.61E-03	4.68E-08
Th-231	7.65E-05	4.92E-04	3.19E-03	2.65E-02	2.44E+01	3.38E-03	1.37E-01	9.32E-01
Th-232	7.12E-05	4.32E-04	2.89E-03	1.64E-02	2.26E+00	2.68E-04	1.15E-02	7.87E-02
Th-234	7.65E-05	4.88E-04	1.32E-02	7.99E-02	3.49E+00	4.75E-04	1.19E-01	1.09E-01
Ti-44	6.75E-06	3.51E-04	4.09E-03	7.32E-02	8.35E+00	3.10E-03	1.83E-01	1.90E+00
Tl-202	1.47E-05	3.14E-04	9.88E-03	2.72E-01	1.35E+01	9.32E-04	3.44E-01	1.70E+00
Tl-204	1.47E-05	3.15E-04	9.78E-03	1.07E-01	3.89E-01	2.68E-05	9.35E-03	2.04E-02
Tl-206	2.66E-05	3.41E-04	1.05E-02	5.05E-01	1.24E-02	9.94E-07	3.57E-04	1.03E-02
Tl-207	2.66E-05	3.41E-04	1.05E-02	5.86E-01	8.61E-04	6.90E-08	2.50E-05	1.13E-02
Tl-208	2.66E-05	3.41E-04	5.59E-02	1.46E+00	1.23E+00	9.88E-05	1.13E-01	2.30E+00
Tl-209	2.66E-05	3.41E-04	1.05E-02	7.05E-01	3.48E+00	2.80E-04	1.03E-01	3.05E+00
Tl-210	2.66E-05	3.42E-04	1.08E-02	8.82E-01	7.79E+00	6.47E-04	2.36E-01	3.16E+00
Tm-168	1.36E-05	1.88E-04	6.90E-03	3.81E-01	1.50E+01	9.01E-04	3.73E-01	3.26E+00
Tm-170	8.74E-06	2.01E-04	7.38E-03	8.84E-02	1.37E+00	8.14E-05	3.39E-02	6.38E-02
Tm-171	8.66E-06	2.01E-04	7.33E-03	5.42E-02	1.66E-01	9.79E-06	4.04E-03	1.11E-02
U-232	8.23E-05	4.64E-04	1.36E-02	8.18E-02	3.22E+00	4.26E-04	1.33E-01	2.92E-03
U-233	8.23E-05	1.37E-02	1.56E-01	1.04E+00	1.85E+00	6.90E-02	1.28E-03	1.80E-07
U-234	8.23E-05	4.64E-04	1.44E-02	5.05E-01	2.95E+00	3.90E-04	1.23E-01	5.38E-07
U-235	8.22E-05	4.86E-04	1.29E-02	1.69E-01	1.44E+01	1.93E-03	3.66E-01	9.54E-01
U-235m	7.65E-05	0.00E+00	0.00E+00	0.00E+00	1.00E-10	0.00E+00	0.00E+00	0.00E+00
U-236	8.23E-05	4.64E-04	3.07E-03	1.57E-02	2.68E+00	3.54E-04	1.49E-02	9.67E-02
U-237	7.44E-05	5.30E-04	1.42E-02	1.14E-01	2.30E+01	3.56E-03	8.00E-01	1.15E+00
U-238	8.24E-05	1.40E-02	1.06E+00	7.36E+00	2.16E+00	8.97E-02	7.86E-06	2.51E-09
U-240	7.44E-05	5.25E-04	1.38E-02	9.72E-02	9.57E+00	1.46E-03	3.41E-01	4.74E-02
V-49	8.00E-06	9.08E-05	4.14E-04	4.52E-03	7.20E+00	9.86E-05	3.46E-03	1.90E-01
V-50	8.00E-06	4.44E-03	7.51E-02	1.42E+00	5.98E+00	1.61E-01	2.24E-04	1.00E+00
W-181	2.49E-05	2.31E-04	7.65E-03	5.90E-02	1.24E+01	9.21E-04	2.71E-01	6.45E-01
W-185	3.76E-05	2.51E-04	8.51E-03	1.17E-01	4.32E-03	3.76E-07	1.49E-04	2.83E-03
W-188	3.75E-05	2.54E-04	8.41E-03	1.87E-01	5.62E-02	4.92E-06	1.68E-03	1.10E-02
Xe-127	1.53E-05	3.92E-03	2.96E-02	2.20E-01	1.47E+01	1.02E-01	8.99E-01	1.15E+00
Y-88	2.09E-05	1.80E-03	1.43E-02	1.38E+00	8.32E+00	2.94E-02	5.96E-01	1.94E+00
Y-90	6.52E-06	1.84E-04	1.53E-02	9.33E-01	1.39E-03	6.36E-08	7.79E-05	1.63E-02
Y-91	6.52E-06	1.84E-04	2.04E-03	7.23E-01	1.40E-05	6.40E-10	4.00E-08	1.32E-02
Yb-169	1.35E-05	1.96E-04	7.02E-03	9.05E-02	3.04E+01	2.06E-03	6.80E-01	3.59E+00

Table C-5 (Cont.)

Radionuclide	EPT(1)	EPT(2)	EPT(3)	EPT(4)	FPT(1)	FPT(2)	FPT(3)	FPT(4)
Zn-65	9.87E-06	8.80E-04	8.09E-03	1.08E+00	4.82E+00	1.19E-02	3.77E-01	5.34E-01
Zr-88	5.30E-06	1.68E-04	1.45E-02	3.93E-01	1.34E+01	4.67E-04	6.58E-01	9.73E-01
Zr-93	1.91E-02	3.02E-02	0.00E+00	0.00E+00	3.27E-04	1.32E-05	0.00E+00	0.00E+00
Zr-95	5.83E-06	2.04E-04	1.61E-02	7.41E-01	1.60E-02	9.82E-07	1.02E-03	9.89E-01

C.1.3 Off-set Factor

The off-set factor $F_{OFF\text{-}SET}$ is the ratio of the dose estimates for contamination enclosed in a noncircular area (the given shape of the actual source) to contamination enclosed in a circular area (the reference shape) of the same size. The concept of the shape factor is used to calculate the off-set factor. To derive the off-set factor, draw a reference shape that is a circular area encompassing the given shape, centered about the receptor, and has a series of concentric circles (forming a series of annuli) within. The off-set factor is derived by considering the area of the given shape, the area and material factors of the series of concentric circles within the reference shape, and the fraction of each annular region that is taken up by the contamination. It is calculated with Equation C.9, by multiplying the area and material factor of each annulus by the fraction of the annulus area taken up by the contamination, f_i, summing the products over the annuli, and dividing by the area and material factor of a circular contamination of equivalent size as the irregularly shaped contamination:

$$F_{OFF-SET} = \frac{\sum_{i=1}^{n} f_i [F_{AM}(A_i) - F_{AM}(A_{i-1})]}{F_{AM}\left[\sum_{i=1}^{n} f_i (A_i - A_{i-1})\right]} \tag{C.9}$$

where $F_{AM}(A_i)$ is the area and material factor for a circular source with an area A_i and the same thickness and cover thickness as the given source. f_i is the fraction of annulus i, between concentric circles A_i and A_{i-1}, that is taken up by the given contamination. $F_{AM}(A_i)$ is calculated with Equation C.4.

C.2 EXTERNAL DOSE AND RISK FROM A CONTAMINATED POINT SOURCE

In RESRAD-BUILD, the direct external dose from a point source is calculated by considering the photon energy of the radiation, photon flux at the receptor location, photon flux attenuation in the total distance traveled (from source location to the receptor location), buildup in the distance traveled, energy absorption by air, and conversion from energy absorption to dose rate. The total external dose over the exposure duration, *ED*, that a receptor would incur from exposure to a point source containing radionuclide *n* in compartment *i* inside the building, $D_{iP}^{n}(t)$ at time *t*, is:

$$D_{iP}^{n}(t) = F_{in}F_i\left[\int_t^{t+ED} Q_{sP}^{n}(t)\,dt\right] \sum_j y_{nj}E_{nj}\ B(\mu_a t_a + \mu_c t_c)d\left[\frac{\mu_{en}(E_{nj})}{\rho}\right]_{air} \frac{e^{-\mu_a t_a - \mu_c t_c}}{4\pi(t_a+t_c)^2} \tag{C.10}$$

where:

F_{in} = fraction of time spent indoors;

F_i = fraction of time spent in compartment *i*;

ED = exposure duration (yr);

$Q_{sP}^{n}(t)$ = instantaneous total activity of radionuclide *n* in the source at time t (pCi);

Y_{nj} = yield for gamma *j* from radionuclide *n*;

E_{nj} = energy for gamma *j* from radionuclide *n* (MeV);

$B(\mu_a t_a + \mu_c t_c)$ = buildup factor for photon transport in air and in the shield material;

d = unit dose rate per energy absorption;

$\left[\frac{\mu_{en}(E_{nj})}{\rho}\right]_{air}$ = mass energy absorption coefficient in air (cm^2/g);

t_c = shielding thickness between the point source and the receptor (cm);

t_a = distance from the receptor to the point source in air (cm);

μ_a = attenuation coefficient in air (cm); and

μ_c = attenuation coefficient in shielding material (cm).

The calculation of time-integrated total activity, $\left[\int_t^{t+ED} Q_{sP}^{n}(t)\,dt\right]$, is discussed in Section B.5 of Appendix B. The unit dose rate per photon absorption, *d*, includes the conversion from Gy to Sv and conversion from energy absorbed in air to dose in Gy. 1 MeV of energy is equivalent to 1.6E-06 ergs, and 100 ergs of energy absorbed in one gram results in 0.01 Gy absorbed dose in air. 1 MeV energy absorbed in one gram from 1 pCi source activity results in 1.8682E-04 Gy/yr (1 MeV/g × 1.6E-06 erg/MeV × 0.01 Gy/100 erg/g × 0.037/s × 3600 s/h × 24 h/d × 365.25 d/yr = 1.8682E-04) dose. Note the Gy to Sv conversion is different in ICRP--26/30 and ICRP-60 methodologies. Table C-6 provides Gy to Sv conversion factors.

Table C-6 Conversion Factors for ICRP-26/30 and ICRP-60 Dose Estimation Methodologies

Photon Energy (MeV)	ICRP-26/30 Methodology		ICRP-60 Methodology	
	Absorbed Dose to Effective Dose Equivalent Conversion (Sv/Gy)	Fluence to Effective Dose Equivalent Conversion (pSv cm^2)	Absorbed Dose to Effective Dose Conversion (Sv/Gy)	Fluence to Effective Dose Conversion (pSv cm^2)
0.01	0.0039	0.029	0.00326	0.024
0.015	0.023	0.071	0.0153	0.048
0.02	0.065	0.11	0.0462	0.078
0.03	0.230	0.166	0.191	0.138
0.04	0.464	0.199	0.426	0.183
0.05	0.687	0.222	0.661	0.214

Table C-6 (Cont.)

Photon Energy (MeV)	ICRP-26/30 Methodology: Absorbed Dose to Effective Dose Equivalent Conversion (Sv/Gy)	ICRP-26/30 Methodology: Fluence to Effective Dose Equivalent Conversion (pSv cm^2)	ICRP-60 Methodology: Absorbed Dose to Effective Dose Conversion (Sv/Gy)	ICRP-60 Methodology: Fluence to Effective Dose Conversion (pSv cm^2)
0.06	0.830	0.24	0.828	0.239
0.08	0.954	0.293	0.961	0.295
0.1	0.962	0.357	0.96	0.356
0.15	0.891	0.534	0.892	0.534
0.2	0.854	0.731	0.854	0.731
0.3	0.826	1.14	0.824	1.14
0.4	0.820	1.55	0.814	1.54
0.5	0.824	1.96	0.812	1.93
0.6	0.824	2.34	0.814	2.31
0.8	0.832	3.07	0.821	3.03
1	0.839	3.75	0.831	3.71
1.5	0.856	5.24	0.851	5.23
2	0.875	6.56	0.871	6.58
3	0.902	8.9	0.89	8.86
4	0.917	11	0.909	11.0
5	0.935	13	0.917	13.0
6	0.943	14.9	0.925	14.9
8	0.969	18.9	0.934	18.8
10	0.991	22.9	0.941	22.6

Source: ICRP-51 and ICRP-74.

For calculating the total cancer risk from exposure to a point source, the dose calculated by Equation C.10 is multiplied by the ratio of slope factor to dose coefficient of radionuclide *n*, both for an infinite volume source.

C.3 EXTERNAL DOSE AND RISK FROM A CONTAMINATED LINE SOURCE

In RESRAD-BUILD, radiation dose from a line source is calculated by considering the photon energy of the radiation, photon flux at the receptor location, photon flux attenuation in the total distance traveled (from source location to the receptor location), buildup in the distance traveled, energy absorption in air, and conversion from energy absorption to dose rate. The model for line sources differs from that of point sources in that a more complicated geometrical factor, G_L, is used for line sources. The total external dose over the exposure duration, *ED*, from exposure to a line source containing radionuclide *n* in compartment *I* inside the building, $D_{iL}^n(t)$ at time *t*, is expressed as:

$$D_{iL}^n(t) = F_{in}F_i\left[\int_t^{t+ED} Q_{sP}^n(t)\,dt\right]\sum_j y_{nj}E_{nj}B(z')\;d\left[\frac{\mu_{en}(E_{nj})}{\rho}\right]_{air} G_L \qquad \text{(C.11)}$$

$$z' = \mu_a t'_{air} + \mu_c t_c \qquad \text{(C.12)}$$

$$G_L = e^{-\mu_c t_c} \int_{line} \frac{e^{-\mu_a \sqrt{x^2+t_a^2}}}{4\pi(x^2+t_a^2)} dx \quad (C.13)$$

where:

t_a = perpendicular distance to receptor (include the distance in air and cover, $t_{air} + t_c$), and

$t_{a'}$ = distance from the receptor to the midpoint of the line source (include the distance in air and cover, $t'_{air} + t_c$).

$B(z')$ = buildup factor for photon transport in air and cover, if any;

t_c = shielding thickness between the line source and the receptor (cm);

μ_a = attenuation coefficient in air (cm); and

μ_c = attenuation coefficient in shielding material (cm).

The calculation of time-integrated total activity, $\left[\int_t^{t+ED} Q_{SP}^n(t)\, dt\right]$, is discussed in Section B.5 of Appendix B. The geometrical parameters are shown in Figure C-2 and are calculated on the basis of the input geometrical parameters of the source (coordinates, direction, and length) and the location of the receptor (coordinates).

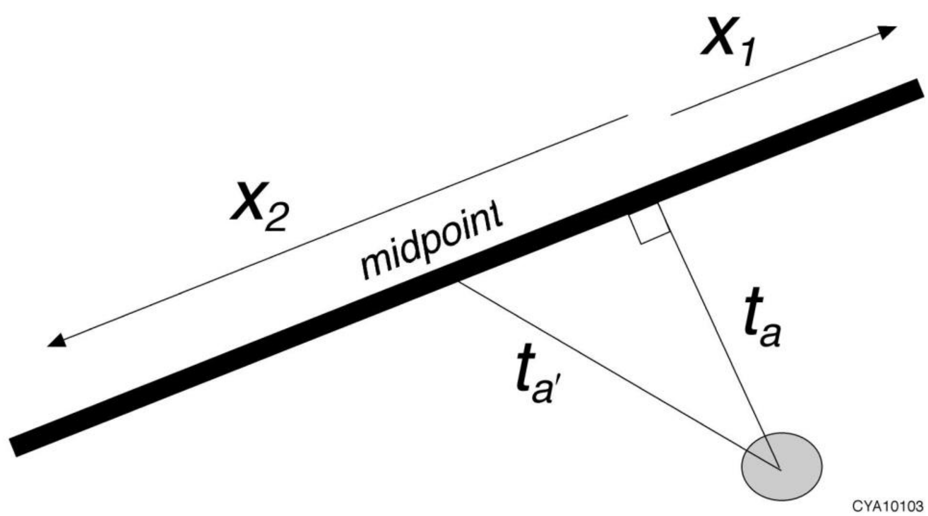

Figure C-2 Geometry in the Line Source Model

For calculating risk associated with direct external exposure to a line source containing radionuclide *n*, the dose calculated by Equation C.11 is multiplied by the ratio of its slope factor for an infinite volume source to its dose coefficient for an infinite volume source.

C.4 EXTERNAL DOSE AND RISK FROM CONTAMINATED DUST IN INDOOR AIR

The total external dose over the exposure duration *ED* starting at time *t*, $D_{i,sub}^{n}(t)$, associated with exposure to airborne contaminated dust particles in compartment *I* is calculated by using the following equation:

$$D_{i,sub}^{n}(t) = \left(\frac{ED}{365}\right) F_{in} F_i \overline{C_i^n(t)} \; DCF_{sub}^{n} \tag{C.14}$$

where:

$D_{i,sub}^{n}(t)$ = total air submersion dose over the exposure duration, *ED*, starting at time *t*, from radionuclide *n* in compartment *i* (mrem);

ED = exposure duration (d);

365 = time conversion factor (d/yr);

$\overline{C_i^n(t)}$ = average concentration of radionuclide *n* over the exposure duration, *ED*, starting at time *t* in the indoor air of compartment *i* (pCi)/m^3); and

DCF_{sub}^{n} = air submersion dose coefficient for radionuclide *n* (mrem/yr per pCi/m^3).

The calculation of $\overline{C_i^n(t)}$ is discussed in Section B.6 of Appendix B. The DCF_{sub}^{n} is for an infinite cloud source; no correction (reduction) to account for the finite indoor air volume is performed in the RESRAD-BUILD code. In general, the radiation dose from the air submersion pathway is much lower than that from the direct external pathway.

For calculating the total risk from air submersion associated with radionuclide *n*, the air submersion slope factor instead of the air submersion dose coefficient of radionuclide *n* is used in Equation C.14.

C.5 DOSE COEFFICIENTS

Values of dose coefficients for external exposure were taken from FGR 12, FGR 13, and DCFPAK3.02. Tables C-7, C-8, and C-9 list the dose coefficients for radionuclides with half-life of at least 30 days and their associated progeny for a surface (infinite plane) source, a volume source with 1-cm, 5-cm, 15-cm, and infinite depth, and for the air submersion exposure from FGR 12, FGR 13, and DCFPAK3.02, respectively.

Table C-7 Effective Dose Equivalent Coefficients for External Exposure from FGR 12 for Radionuclides with Half-life of at least 30 Days and Their Associated Progeny

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Ac-225	1.84E-06	1.12E-08	2.92E-08	3.90E-08	3.98E-08	6.37E-02	8.42E-05
Ac-227	1.83E-08	8.99E-11	2.31E-10	3.06E-10	3.09E-10	4.95E-04	6.79E-07
Ac-228	1.08E-04	6.97E-07	2.02E-06	3.22E-06	3.74E-06	5.98E+00	5.58E-03
Ag-105	5.97E-05	3.77E-07	1.08E-06	1.66E-06	1.82E-06	2.91E+00	2.86E-03
Ag-108	2.32E-06	1.46E-08	4.16E-08	6.43E-08	7.15E-08	1.14E-01	1.08E-04
Ag-108m	1.87E-04	1.19E-06	3.44E-06	5.38E-06	6.02E-06	9.64E+00	9.10E-03
Ag-110	4.46E-06	2.83E-08	8.06E-08	1.25E-07	1.40E-07	2.24E-01	2.08E-04
Ag-110m	3.09E-04	2.00E-06	5.79E-06	9.26E-06	1.07E-05	1.72E+01	1.59E-02
Al-26	2.91E-04	1.89E-06	5.53E-06	9.03E-06	1.09E-05	1.74E+01	1.59E-02
Am-241	3.21E-06	1.34E-08	2.55E-08	2.73E-08	2.73E-08	4.37E-02	9.55E-05
Am-242	1.83E-06	9.55E-09	2.42E-08	3.12E-08	3.12E-08	4.99E-02	7.18E-05
Am-242m	3.53E-07	5.01E-10	8.80E-10	1.05E-09	1.06E-09	1.69E-03	3.70E-06
Am-243	6.25E-06	3.46E-08	7.69E-08	8.87E-08	8.87E-08	1.42E-01	2.54E-04
Am-245	3.62E-06	2.27E-08	6.24E-08	8.77E-08	9.05E-08	1.45E-01	1.70E-04
Ar-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.48E-08
Ar-39	3.95E-08	1.83E-10	4.19E-10	5.31E-10	5.39E-10	8.63E-04	1.06E-06
As-73	6.95E-07	3.19E-09	5.63E-09	5.88E-09	5.88E-09	9.42E-03	2.22E-05
At-217	3.54E-08	2.28E-10	6.53E-10	1.01E-09	1.11E-09	1.77E-03	1.73E-06
At-218	4.88E-07	2.00E-09	3.50E-09	3.65E-09	3.65E-09	5.85E-03	1.39E-05
Au-194	1.17E-04	7.54E-07	2.17E-06	3.47E-06	4.08E-06	6.52E+00	6.17E-03
Au-195	9.15E-06	5.11E-08	1.13E-07	1.30E-07	1.30E-07	2.07E-01	3.75E-04
Ba-133	4.64E-05	2.79E-07	7.75E-07	1.15E-06	1.24E-06	1.98E+00	2.08E-03
Ba-137m	6.84E-05	4.39E-07	1.27E-06	2.00E-06	2.25E-06	3.61E+00	3.36E-03
Be-10	4.81E-08	2.27E-10	5.20E-10	6.62E-10	6.73E-10	1.08E-03	1.31E-06
Be-7	5.71E-06	3.68E-08	1.06E-07	1.63E-07	1.80E-07	2.88E-01	2.75E-04
Bi-207	1.73E-04	1.11E-06	3.20E-06	5.07E-06	5.86E-06	9.38E+00	8.80E-03
Bi-210	1.23E-07	6.47E-10	1.61E-09	2.17E-09	2.25E-09	3.61E-03	3.84E-06
Bi-210m	2.92E-05	1.89E-07	5.43E-07	8.09E-07	8.61E-07	1.38E+00	1.42E-03
Bi-211	5.35E-06	3.46E-08	9.90E-08	1.49E-07	1.60E-07	2.56E-01	2.59E-04
Bi-212	2.09E-05	1.34E-07	3.90E-07	6.26E-07	7.32E-07	1.17E+00	1.08E-03
Bi-213	1.54E-05	9.95E-08	2.85E-07	4.38E-07	4.79E-07	7.66E-01	7.46E-04
Bi-214	1.65E-04	1.07E-06	3.13E-06	5.09E-06	6.13E-06	9.81E+00	8.93E-03
Bk-247	1.18E-05	7.31E-08	1.94E-07	2.64E-07	2.72E-07	4.35E-01	5.50E-04
Bk-249	8.00E-10	1.83E-12	2.72E-12	2.90E-12	2.91E-12	4.65E-06	9.58E-09
Bk-250	9.94E-05	6.36E-07	1.86E-06	2.97E-06	3.47E-06	5.55E+00	5.11E-03
C-14	1.88E-09	5.02E-12	7.89E-12	8.41E-12	8.41E-12	1.34E-05	2.61E-08
Ca-41[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-45	5.38E-09	1.86E-11	3.43E-11	3.91E-11	3.91E-11	6.26E-05	1.01E-07
Cd-109	2.63E-06	4.86E-09	8.02E-09	9.20E-09	9.19E-09	1.47E-02	3.43E-05
Cd-113	8.16E-09	3.06E-11	6.04E-11	7.06E-11	7.09E-11	1.13E-04	1.69E-07
Cd-113m	3.07E-08	1.40E-10	3.16E-10	3.99E-10	4.05E-10	6.48E-04	8.10E-07
Cd-115m	2.73E-06	1.73E-08	5.00E-08	7.96E-08	9.27E-08	1.48E-01	1.37E-04
Ce-139	1.82E-05	1.05E-07	2.79E-07	3.89E-07	3.98E-07	6.37E-01	7.85E-04
Ce-141	8.62E-06	5.31E-08	1.42E-07	1.96E-07	1.98E-07	3.18E-01	4.00E-04
Ce-144	2.37E-06	1.34E-08	3.36E-08	4.44E-08	4.48E-08	7.17E-02	9.96E-05
Cf-248	9.04E-08	7.62E-11	7.79E-11	7.79E-11	7.79E-11	1.25E-04	5.52E-07

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Cf-249	3.83E-05	2.46E-07	7.08E-07	1.07E-06	1.16E-06	1.85E+00	1.84E-03
Cf-250	8.61E-08	7.25E-11	7.40E-11	7.40E-11	7.40E-11	1.18E-04	5.25E-07
Cf-251	1.42E-05	8.62E-08	2.34E-07	3.22E-07	3.29E-07	5.27E-01	6.51E-04
Cf-252	8.43E-08	8.12E-11	1.01E-10	1.10E-10	1.10E-10	1.76E-04	5.91E-07
Cf-253	7.53E-09	2.25E-11	4.18E-11	4.79E-11	4.80E-11	7.68E-05	1.26E-07
Cf-254	2.80E-10	2.36E-13	2.42E-13	2.42E-13	2.42E-13	3.87E-07	1.72E-09
Cl-36	7.86E-08	4.12E-10	1.03E-09	1.42E-09	1.49E-09	2.39E-03	2.60E-06
Cm-241	5.66E-05	3.58E-07	1.01E-06	1.52E-06	1.65E-06	2.63E+00	2.70E-03
Cm-242	1.12E-07	8.86E-11	1.00E-10	1.06E-10	1.07E-10	1.71E-04	6.64E-07
Cm-243	1.46E-05	9.10E-08	2.50E-07	3.53E-07	3.64E-07	5.83E-01	6.86E-04
Cm-244	1.03E-07	7.64E-11	7.87E-11	7.87E-11	7.87E-11	1.26E-04	5.73E-07
Cm-245	1.02E-05	6.12E-08	1.60E-07	2.10E-07	2.13E-07	3.40E-01	4.62E-04
Cm-246	9.17E-08	6.96E-11	7.25E-11	7.26E-11	7.26E-11	1.16E-04	5.21E-07
Cm-247	3.62E-05	2.34E-07	6.74E-07	1.03E-06	1.11E-06	1.78E+00	1.75E-03
Cm-248	7.01E-08	5.28E-11	5.49E-11	5.49E-11	5.49E-11	8.78E-05	3.96E-07
Cm-249	2.27E-06	1.45E-08	4.15E-08	6.43E-08	7.16E-08	1.15E-01	1.09E-04
Cm-250[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-56	3.84E-04	2.50E-06	7.33E-06	1.20E-05	1.47E-05	2.35E+01	2.14E-02
Co-57	1.34E-05	8.65E-08	2.32E-07	3.11E-07	3.13E-07	5.01E-01	6.55E-04
Co-58	1.11E-04	7.12E-07	2.07E-06	3.27E-06	3.72E-06	5.96E+00	5.56E-03
Co-60	2.74E-04	1.77E-06	5.20E-06	8.47E-06	1.01E-05	1.62E+01	1.47E-02
Co-60m	5.16E-07	3.14E-09	8.44E-09	1.30E-08	1.54E-08	2.47E-02	2.53E-05
Cs-134	1.77E-04	1.14E-06	3.30E-06	5.22E-06	5.92E-06	9.47E+00	8.83E-03
Cs-135	3.89E-09	1.23E-11	2.16E-11	2.39E-11	2.39E-11	3.83E-05	6.59E-08
Cs-137	3.33E-08	1.56E-10	3.58E-10	4.60E-10	4.69E-10	7.51E-04	9.03E-07
Dy-159	5.43E-06	2.16E-08	3.39E-08	3.44E-08	3.44E-08	5.51E-02	1.46E-04
Es-253	9.55E-08	2.88E-10	7.10E-10	1.03E-09	1.10E-09	1.76E-03	2.14E-06
Es-254	1.48E-06	3.09E-09	6.10E-09	7.78E-09	8.07E-09	1.29E-02	2.25E-05
Eu-146	2.83E-04	1.81E-06	5.23E-06	8.34E-06	9.63E-06	1.54E+01	1.43E-02
Eu-148	2.48E-04	1.59E-06	4.57E-06	7.22E-06	8.21E-06	1.31E+01	1.24E-02
Eu-149	7.48E-06	3.65E-08	8.52E-08	1.19E-07	1.26E-07	2.02E-01	2.63E-04
Eu-150	1.70E-04	1.09E-06	3.14E-06	4.88E-06	5.45E-06	8.73E+00	8.37E-03
Eu-152	1.28E-04	8.21E-07	2.37E-06	3.76E-06	4.38E-06	7.01E+00	6.59E-03
Eu-154	1.39E-04	8.90E-07	2.58E-06	4.11E-06	4.80E-06	7.68E+00	7.17E-03
Eu-155	6.89E-06	3.93E-08	9.27E-08	1.14E-07	1.14E-07	1.82E-01	2.91E-04
Fe-55[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-59	1.31E-04	8.48E-07	2.48E-06	4.02E-06	4.78E-06	7.64E+00	6.97E-03
Fe-60	1.73E-09	4.39E-12	6.66E-12	7.01E-12	7.01E-12	1.12E-05	2.28E-08
Fm-257	1.20E-05	7.20E-08	1.94E-07	2.64E-07	2.69E-07	4.30E-01	5.44E-04
Fr-221	3.48E-06	2.25E-08	6.38E-08	9.22E-08	9.60E-08	1.54E-01	1.70E-04
Fr-223	6.60E-06	3.62E-08	8.80E-08	1.18E-07	1.24E-07	1.98E-01	2.67E-04
Ga-68	1.10E-04	7.09E-07	2.04E-06	3.18E-06	3.51E-06	5.62E+00	5.34E-03
Gd-146	2.87E-05	1.58E-07	3.81E-07	4.96E-07	5.01E-07	8.02E-01	1.16E-03
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-149	4.81E-05	2.97E-07	8.23E-07	1.24E-06	1.34E-06	2.15E+00	2.24E-03
Gd-151	7.45E-06	3.57E-08	7.97E-08	1.05E-07	1.09E-07	1.74E-01	2.57E-04
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Gd-153	1.24E-05	6.02E-08	1.27E-07	1.53E-07	1.53E-07	2.45E-01	4.33E-04
Ge-68	2.52E-09	4.97E-13	4.97E-13	4.97E-13	4.97E-13	7.96E-07	8.60E-09
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.86E-08
Hf-172	1.32E-05	6.63E-08	1.35E-07	1.55E-07	1.55E-07	2.49E-01	4.74E-04
Hf-175	4.24E-05	2.65E-07	7.34E-07	1.09E-06	1.16E-06	1.86E+00	1.97E-03
Hf-178m	2.70E-04	1.74E-06	4.95E-06	7.50E-06	8.14E-06	1.30E+01	1.31E-02
Hf-181	6.38E-05	4.09E-07	1.16E-06	1.75E-06	1.90E-06	3.05E+00	3.06E-03
Hf-182	2.72E-05	1.76E-07	5.02E-07	7.41E-07	7.80E-07	1.25E+00	1.33E-03
Hg-194	2.39E-08	6.88E-12	6.88E-12	6.88E-12	6.88E-12	1.10E-05	8.08E-08
Hg-203	2.71E-05	1.75E-07	5.03E-07	7.47E-07	7.89E-07	1.26E+00	1.32E-03
Ho-166m	1.98E-04	1.27E-06	3.68E-06	5.72E-06	6.43E-06	1.03E+01	9.86E-03
I-125	4.99E-06	9.56E-09	1.04E-08	1.03E-08	1.03E-08	1.66E-02	6.09E-05
I-129	3.01E-06	6.95E-09	8.08E-09	8.09E-09	8.09E-09	1.30E-02	4.43E-05
In-113m	2.97E-05	1.89E-07	5.42E-07	8.28E-07	8.97E-07	1.43E+00	1.41E-03
In-114	3.15E-07	1.97E-09	5.71E-09	9.27E-09	1.11E-08	1.77E-02	1.62E-05
In-114m	1.07E-05	6.41E-08	1.82E-07	2.77E-07	3.02E-07	4.84E-01	4.88E-04
In-115	2.11E-08	9.20E-11	2.01E-10	2.48E-10	2.51E-10	4.02E-04	5.25E-07
Ir-192	9.38E-05	6.07E-07	1.75E-06	2.66E-06	2.88E-06	4.61E+00	4.56E-03
Ir-192m	1.81E-05	1.18E-07	3.28E-07	4.59E-07	4.69E-07	7.51E-01	8.91E-04
Ir-194	1.07E-05	6.90E-08	2.00E-07	3.07E-07	3.42E-07	5.47E-01	5.30E-04
Ir-194m	2.69E-04	1.73E-06	4.99E-06	7.72E-06	8.52E-06	1.36E+01	1.31E-02
K-40	1.70E-05	1.11E-07	3.25E-07	5.34E-07	6.50E-07	1.04E+00	9.39E-04
Kr-81	7.18E-07	4.12E-09	1.19E-08	1.77E-08	1.87E-08	2.99E-02	3.12E-05
Kr-83m	4.44E-08	1.81E-11	1.89E-11	1.89E-11	1.89E-11	3.03E-05	1.75E-07
Kr-85	3.08E-07	1.90E-09	5.35E-09	8.14E-09	8.93E-09	1.43E-02	1.39E-05
La-137	3.00E-06	7.41E-09	8.78E-09	8.80E-09	8.80E-09	1.41E-02	4.74E-05
La-138	1.35E-04	8.71E-07	2.55E-06	4.15E-06	4.97E-06	7.96E+00	7.24E-03
Lu-172	2.11E-04	1.34E-06	3.88E-06	6.17E-06	7.18E-06	1.15E+01	1.08E-02
Lu-173	1.49E-05	8.19E-08	1.90E-07	2.51E-07	2.60E-07	4.17E-01	5.95E-04
Lu-174	1.40E-05	8.12E-08	2.07E-07	3.09E-07	3.58E-07	5.73E-01	6.37E-04
Lu-174m	7.05E-06	3.55E-08	7.24E-08	8.71E-08	9.14E-08	1.46E-01	2.54E-04
Lu-176	5.58E-05	3.60E-07	1.02E-06	1.49E-06	1.58E-06	2.52E+00	2.71E-03
Lu-177	3.96E-06	2.51E-08	6.84E-08	9.62E-08	9.91E-08	1.59E-01	1.89E-04
Lu-177m	1.14E-04	7.26E-07	2.03E-06	2.97E-06	3.13E-06	5.01E+00	5.45E-03
Md-258	5.27E-07	8.33E-10	1.30E-09	1.42E-09	1.42E-09	2.28E-03	5.93E-06
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	9.48E-05	6.08E-07	1.76E-06	2.80E-06	3.22E-06	5.16E+00	4.77E-03
Mo-93	6.24E-07	3.71E-10	3.69E-10	3.69E-10	3.69E-10	5.90E-04	2.94E-06
Na-22	2.45E-04	1.59E-06	4.61E-06	7.37E-06	8.55E-06	1.37E+01	1.26E-02
Nb-93m	1.10E-07	6.53E-11	6.50E-11	6.50E-11	6.50E-11	1.04E-04	5.18E-07
Nb-94	1.79E-04	1.15E-06	3.34E-06	5.29E-06	6.05E-06	9.68E+00	8.99E-03
Nb-95	8.73E-05	5.60E-07	1.62E-06	2.57E-06	2.93E-06	4.69E+00	4.36E-03
Nb-95m	7.31E-06	4.52E-08	1.30E-07	1.90E-07	2.00E-07	3.19E-01	3.42E-04
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-235	4.26E-07	7.87E-10	1.65E-09	2.02E-09	2.02E-09	3.23E-03	5.95E-06
Np-236	1.40E-05	8.28E-08	2.17E-07	2.86E-07	2.88E-07	4.61E-01	6.25E-04

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Np-237	3.35E-06	1.61E-08	3.86E-08	4.86E-08	4.87E-08	7.79E-02	1.20E-04
Np-238	6.18E-05	3.95E-07	1.15E-06	1.84E-06	2.15E-06	3.44E+00	3.17E-03
Np-239	1.90E-05	1.19E-07	3.26E-07	4.55E-07	4.71E-07	7.53E-01	8.98E-04
Np-240m	3.82E-05	2.43E-07	7.04E-07	1.11E-06	1.26E-06	2.02E+00	1.89E-03
Os-185	8.22E-05	5.22E-07	1.48E-06	2.31E-06	2.60E-06	4.17E+00	4.00E-03
Os-194	1.33E-07	4.80E-10	7.18E-10	7.27E-10	7.27E-10	1.16E-03	3.21E-06
P-32	3.40E-07	1.91E-09	4.99E-09	7.01E-09	7.37E-09	1.18E-02	1.15E-05
Pa-231	4.75E-06	2.69E-08	7.54E-08	1.12E-07	1.19E-07	1.91E-01	2.01E-04
Pa-233	2.28E-05	1.45E-07	4.10E-07	6.02E-07	6.38E-07	1.02E+00	1.09E-03
Pa-234	2.15E-04	1.38E-06	3.98E-06	6.28E-06	7.22E-06	1.16E+01	1.09E-02
Pa-234m	1.79E-06	1.11E-08	3.15E-08	4.90E-08	5.60E-08	8.97E-02	8.39E-05
Pb-202	1.56E-08	3.85E-12	3.85E-12	3.85E-12	3.85E-12	6.16E-06	5.27E-08
Pb-205	1.75E-08	4.41E-12	4.41E-12	4.41E-12	4.41E-12	7.06E-06	5.90E-08
Pb-209	3.51E-08	1.63E-10	3.74E-10	4.76E-10	4.83E-10	7.73E-04	9.48E-07
Pb-210	2.90E-07	9.66E-10	1.51E-09	1.53E-09	1.53E-09	2.45E-03	6.58E-06
Pb-211	5.93E-06	3.79E-08	1.09E-07	1.70E-07	1.91E-07	3.06E-01	2.91E-04
Pb-212	1.67E-05	1.06E-07	2.95E-07	4.23E-07	4.40E-07	7.04E-01	8.02E-04
Pb-214	2.85E-05	1.83E-07	5.22E-07	7.82E-07	8.38E-07	1.34E+00	1.38E-03
Pd-107[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-143	3.62E-05	2.21E-07	6.22E-07	9.75E-07	1.11E-06	1.77E+00	1.70E-03
Pm-144	1.80E-04	1.14E-06	3.29E-06	5.15E-06	5.78E-06	9.25E+00	8.73E-03
Pm-145	3.81E-06	1.25E-08	1.79E-08	1.83E-08	1.83E-08	2.93E-02	8.27E-05
Pm-146	8.65E-05	5.50E-07	1.58E-06	2.46E-06	2.76E-06	4.41E+00	4.19E-03
Pm-147	3.98E-09	1.39E-11	2.67E-11	3.12E-11	3.13E-11	5.01E-05	8.09E-08
Pm-148	6.40E-05	4.13E-07	1.20E-06	1.95E-06	2.30E-06	3.68E+00	3.37E-03
Pm-148m	2.29E-04	1.47E-06	4.25E-06	6.68E-06	7.51E-06	1.20E+01	1.13E-02
Po-209[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	9.68E-10	6.21E-12	1.80E-11	2.86E-11	3.27E-11	5.23E-05	4.85E-08
Po-211	8.89E-07	5.71E-09	1.66E-08	2.62E-08	2.98E-08	4.76E-02	4.45E-05
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-214	9.49E-09	6.10E-11	1.76E-10	2.80E-10	3.21E-10	5.14E-04	4.76E-07
Po-215	2.03E-08	1.32E-10	3.78E-10	5.81E-10	6.35E-10	1.02E-03	9.84E-07
Po-216	1.93E-09	1.24E-11	3.58E-11	5.69E-11	6.52E-11	1.04E-04	9.68E-08
Po-218	1.04E-09	6.66E-12	1.93E-11	3.07E-11	3.53E-11	5.64E-05	5.23E-08
Pr-144	4.41E-06	2.83E-08	8.16E-08	1.32E-07	1.58E-07	2.52E-01	2.28E-04
Pr-144m	1.52E-06	4.89E-09	7.43E-09	8.56E-09	8.98E-09	1.44E-02	3.26E-05
Pt-193	1.39E-08	3.54E-12	3.54E-12	3.54E-12	3.54E-12	5.66E-06	4.65E-08
Pu-236	1.15E-07	9.74E-11	1.28E-10	1.40E-10	1.42E-10	2.28E-04	7.41E-07
Pu-237	5.43E-06	3.13E-08	7.93E-08	1.01E-07	1.01E-07	1.62E-01	2.36E-04
Pu-238	9.78E-08	7.40E-11	8.87E-11	9.42E-11	9.46E-11	1.51E-04	5.70E-07
Pu-239	4.29E-08	6.55E-11	1.34E-10	1.77E-10	1.84E-10	2.95E-04	4.95E-07
Pu-240	9.38E-08	7.24E-11	8.69E-11	9.15E-11	9.17E-11	1.47E-04	5.54E-07
Pu-241	2.25E-10	1.12E-12	2.85E-12	3.68E-12	3.69E-12	5.90E-06	8.46E-09
Pu-242	7.79E-08	6.11E-11	7.51E-11	8.00E-11	8.00E-11	1.28E-04	4.68E-07
Pu-243	2.81E-06	1.61E-08	3.92E-08	4.90E-08	4.97E-08	7.96E-02	1.20E-04
Pu-244	6.52E-08	4.50E-11	4.72E-11	4.72E-11	4.72E-11	7.55E-05	3.47E-07

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Pu-246	1.55E-05	9.33E-08	2.50E-07	3.46E-07	3.54E-07	5.66E-01	7.01E-04
Ra-223	1.49E-05	9.46E-08	2.57E-07	3.62E-07	3.77E-07	6.03E-01	7.11E-04
Ra-224	1.12E-06	7.26E-09	2.08E-08	3.06E-08	3.20E-08	5.12E-02	5.50E-05
Ra-225	1.55E-06	4.95E-09	6.84E-09	6.89E-09	6.89E-09	1.10E-02	3.26E-05
Ra-226	7.52E-07	4.85E-09	1.35E-08	1.93E-08	1.98E-08	3.18E-02	3.68E-05
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Rb-83	5.74E-05	3.69E-07	1.06E-06	1.66E-06	1.83E-06	2.93E+00	2.79E-03
Rb-84	1.04E-04	6.68E-07	1.94E-06	3.06E-06	3.50E-06	5.61E+00	5.22E-03
Rb-87	1.03E-08	3.85E-11	7.54E-11	8.78E-11	8.80E-11	1.41E-04	2.12E-07
Re-184	1.01E-04	6.40E-07	1.82E-06	2.86E-06	3.27E-06	5.23E+00	5.01E-03
Re-184m	4.38E-05	2.76E-07	7.64E-07	1.15E-06	1.27E-06	2.04E+00	2.12E-03
Re-186	2.38E-06	1.45E-08	3.67E-08	4.81E-08	4.88E-08	7.81E-02	1.07E-04
Re-186m	1.70E-06	8.23E-09	1.58E-08	1.73E-08	1.73E-08	2.77E-02	5.84E-05
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Re-188	6.90E-06	4.39E-08	1.23E-07	1.83E-07	2.01E-07	3.21E-01	3.35E-04
Rh-101	2.98E-05	1.86E-07	5.21E-07	7.41E-07	7.66E-07	1.23E+00	1.41E-03
Rh-102	2.43E-04	1.56E-06	4.52E-06	7.12E-06	8.10E-06	1.30E+01	1.21E-02
Rh-102m	5.56E-05	3.55E-07	1.02E-06	1.60E-06	1.77E-06	2.84E+00	2.70E-03
Rh-103m	1.46E-07	1.47E-10	1.52E-10	1.52E-10	1.52E-10	2.43E-04	1.03E-06
Rh-106	2.48E-05	1.59E-07	4.59E-07	7.18E-07	8.07E-07	1.29E+00	1.21E-03
Rn-219	6.41E-06	4.16E-08	1.19E-07	1.80E-07	1.93E-07	3.08E-01	3.13E-04
Rn-220	4.45E-08	2.86E-10	8.27E-10	1.28E-09	1.44E-09	2.30E-03	2.16E-06
Rn-222	4.61E-08	2.97E-10	8.56E-10	1.33E-09	1.47E-09	2.35E-03	2.23E-06
Ru-103	5.41E-05	3.49E-07	1.01E-06	1.55E-06	1.72E-06	2.75E+00	2.63E-03
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	1.96E-09	5.39E-12	8.68E-12	9.31E-12	9.31E-12	1.49E-05	2.84E-08
Sb-124	2.00E-04	1.30E-06	3.78E-06	6.13E-06	7.31E-06	1.17E+01	1.07E-02
Sb-125	4.96E-05	3.12E-07	8.94E-07	1.38E-06	1.53E-06	2.45E+00	2.36E-03
Sb-126	3.25E-04	2.09E-06	6.04E-06	9.49E-06	1.07E-05	1.71E+01	1.60E-02
Sb-126m	1.77E-04	1.14E-06	3.30E-06	5.18E-06	5.81E-06	9.30E+00	8.75E-03
Sc-44	2.42E-04	1.55E-06	4.52E-06	7.17E-06	8.26E-06	1.32E+01	1.22E-02
Sc-46	2.25E-04	1.45E-06	4.22E-06	6.77E-06	7.93E-06	1.27E+01	1.16E-02
Se-75	4.40E-05	2.86E-07	8.12E-07	1.18E-06	1.24E-06	1.98E+00	2.16E-03
Se-79	2.42E-09	6.74E-12	1.08E-11	1.16E-11	1.16E-11	1.86E-05	3.54E-08
Si-32	3.62E-09	1.14E-11	2.00E-11	2.22E-11	2.22E-11	3.55E-05	6.11E-08
Sm-145	7.99E-06	2.81E-08	4.17E-08	4.26E-08	4.26E-08	6.82E-02	1.88E-04
Sm-146[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	5.87E-10	6.10E-13	6.15E-13	6.15E-13	6.15E-13	9.85E-07	4.21E-09
Sn-113	2.49E-06	6.28E-09	1.30E-08	1.77E-08	1.86E-08	2.97E-02	4.46E-05
Sn-119m	1.21E-06	1.82E-09	1.88E-09	1.88E-09	1.88E-09	3.01E-03	1.18E-05
Sn-121	1.23E-08	4.93E-11	1.02E-10	1.21E-10	1.23E-10	1.96E-04	2.77E-07
Sn-121m	5.71E-07	1.10E-09	1.23E-09	1.23E-09	1.23E-09	1.96E-03	7.03E-06
Sn-123	9.77E-07	6.10E-09	1.74E-08	2.73E-08	3.16E-08	5.06E-02	4.70E-05
Sn-126	6.39E-06	3.33E-08	7.68E-08	9.22E-08	9.21E-08	1.47E-01	2.46E-04
Sr-85	5.84E-05	3.75E-07	1.08E-06	1.68E-06	1.86E-06	2.97E+00	2.82E-03
Sr-89	2.65E-07	1.48E-09	3.84E-09	5.39E-09	5.67E-09	9.08E-03	9.02E-06

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Sr-90	3.32E-08	1.53E-10	3.44E-10	4.34E-10	4.40E-10	7.04E-04	8.79E-07
Ta-179	3.69E-06	1.81E-08	3.39E-08	3.61E-08	3.61E-08	5.77E-02	1.27E-04
Ta-180	6.36E-05	4.04E-07	1.13E-06	1.66E-06	1.75E-06	2.80E+00	3.02E-03
Ta-182	1.44E-04	9.18E-07	2.64E-06	4.22E-06	4.96E-06	7.94E+00	7.47E-03
Tb-157	3.12E-07	1.18E-09	1.79E-09	1.81E-09	1.81E-09	2.90E-03	7.91E-06
Tb-158	9.01E-05	5.66E-07	1.61E-06	2.56E-06	2.95E-06	4.73E+00	4.48E-03
Tb-160	1.26E-04	8.09E-07	2.35E-06	3.72E-06	4.32E-06	6.91E+00	6.47E-03
Tc-95	9.01E-05	5.74E-07	1.67E-06	2.64E-06	3.01E-06	4.82E+00	4.48E-03
Tc-95m	7.62E-05	4.87E-07	1.40E-06	2.18E-06	2.45E-06	3.92E+00	3.77E-03
Tc-97	7.57E-07	5.08E-10	5.06E-10	5.06E-10	5.06E-10	8.09E-04	3.89E-06
Tc-97m	7.22E-07	7.31E-10	1.05E-09	1.19E-09	1.19E-09	1.91E-03	5.42E-06
Tc-98	1.61E-04	1.04E-06	3.01E-06	4.74E-06	5.37E-06	8.59E+00	8.01E-03
Tc-99	9.11E-09	3.41E-11	6.70E-11	7.82E-11	7.85E-11	1.25E-04	1.89E-07
Te-121	6.66E-05	4.17E-07	1.20E-06	1.87E-06	2.08E-06	3.33E+00	3.15E-03
Te-121m	2.45E-05	1.52E-07	4.29E-07	6.33E-07	6.70E-07	1.07E+00	1.15E-03
Te-123	2.28E-06	3.91E-09	4.11E-09	4.10E-09	4.10E-09	6.56E-03	2.51E-05
Te-123m	1.67E-05	1.01E-07	2.76E-07	3.84E-07	3.92E-07	6.28E-01	7.60E-04
Te-125m	4.22E-06	8.27E-09	9.31E-09	9.46E-09	9.47E-09	1.52E-02	5.29E-05
Te-127	6.05E-07	3.83E-09	1.09E-08	1.65E-08	1.79E-08	2.86E-02	2.82E-05
Te-127m	1.32E-06	2.66E-09	3.20E-09	3.37E-09	3.41E-09	5.45E-03	1.72E-05
Te-129	7.02E-06	4.27E-08	1.21E-07	1.87E-07	2.07E-07	3.31E-01	3.21E-04
Te-129m	4.41E-06	2.39E-08	6.59E-08	1.03E-07	1.16E-07	1.85E-01	1.81E-04
Th-227	1.21E-05	7.58E-08	2.13E-07	3.09E-07	3.26E-07	5.21E-01	5.70E-04
Th-228	2.74E-07	1.42E-09	3.67E-09	4.87E-09	4.96E-09	7.94E-03	1.07E-05
Th-229	9.97E-06	5.94E-08	1.52E-07	1.98E-07	2.01E-07	3.21E-01	4.47E-04
Th-230	8.76E-08	2.72E-10	6.10E-10	7.46E-10	7.55E-10	1.21E-03	2.03E-06
Th-231	2.16E-06	8.22E-09	1.86E-08	2.27E-08	2.28E-08	3.64E-02	6.09E-05
Th-232	6.43E-08	1.35E-10	2.76E-10	3.25E-10	3.26E-10	5.21E-04	1.02E-06
Th-234	9.71E-07	5.32E-09	1.25E-08	1.51E-08	1.51E-08	2.41E-02	3.94E-05
Ti-44	1.54E-05	8.77E-08	1.95E-07	2.24E-07	2.24E-07	3.59E-01	6.45E-04
Tl-202	5.36E-05	3.41E-07	9.57E-07	1.44E-06	1.56E-06	2.50E+00	2.54E-03
Tl-204	1.73E-07	9.39E-10	2.11E-09	2.51E-09	2.53E-09	4.05E-03	6.52E-06
Tl-206	2.32E-07	1.28E-09	3.32E-09	4.59E-09	4.81E-09	7.70E-03	7.85E-06
Tl-207	4.39E-07	2.64E-09	7.31E-09	1.11E-08	1.24E-08	1.98E-02	1.89E-05
Tl-208	3.48E-04	2.29E-06	6.76E-06	1.13E-05	1.44E-05	2.30E+01	2.07E-02
Tl-209	2.22E-04	1.44E-06	4.18E-06	6.76E-06	8.08E-06	1.29E+01	1.19E-02
Tl-210[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tm-170	6.90E-07	3.68E-09	7.95E-09	9.32E-09	9.34E-09	1.49E-02	2.60E-05
Tm-171	7.48E-08	3.58E-10	6.59E-10	6.98E-10	6.98E-10	1.12E-03	2.51E-06
U-232	1.18E-07	2.20E-10	4.52E-10	5.57E-10	5.64E-10	9.02E-04	1.66E-06
U-233	8.36E-08	2.52E-10	6.19E-10	8.45E-10	8.73E-10	1.40E-03	1.90E-06
U-234	8.73E-08	1.18E-10	2.13E-10	2.50E-10	2.51E-10	4.02E-04	8.91E-07
U-235	1.73E-05	1.11E-07	3.09E-07	4.38E-07	4.51E-07	7.21E-01	8.40E-04
U-236	7.59E-08	7.62E-11	1.18E-10	1.33E-10	1.34E-10	2.15E-04	5.85E-07
U-237	1.55E-05	9.29E-08	2.42E-07	3.25E-07	3.32E-07	5.31E-01	6.97E-04
U-238	6.43E-08	5.16E-11	6.36E-11	6.45E-11	6.45E-11	1.03E-04	3.98E-07
U-240	4.94E-07	6.56E-10	8.70E-10	8.90E-10	8.90E-10	1.42E-03	4.59E-06

Table C-7 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
V-49[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W-181	4.59E-06	2.31E-08	4.44E-08	4.78E-08	4.78E-08	7.64E-02	1.63E-04
W-185	2.15E-08	9.97E-11	2.20E-10	2.69E-10	2.71E-10	4.33E-04	6.27E-07
W-188	2.24E-07	1.41E-09	3.93E-09	5.74E-09	6.05E-09	9.68E-03	1.06E-05
Xe-127	3.19E-05	1.94E-07	5.41E-07	7.86E-07	8.22E-07	1.32E+00	1.46E-03
Y-88	2.88E-04	1.88E-06	5.51E-06	9.07E-06	1.11E-05	1.78E+01	1.60E-02
Y-90	6.21E-07	3.62E-09	9.70E-09	1.40E-08	1.49E-08	2.39E-02	2.22E-05
Y-91	6.70E-07	4.09E-09	1.14E-08	1.77E-08	2.03E-08	3.25E-02	3.03E-05
Yb-169	3.55E-05	2.04E-07	5.03E-07	6.71E-07	6.90E-07	1.10E+00	1.51E-03
Zn-65	6.46E-05	4.17E-07	1.21E-06	1.96E-06	2.31E-06	3.70E+00	3.38E-03
Zr-88	4.57E-05	2.93E-07	8.45E-07	1.30E-06	1.40E-06	2.24E+00	2.19E-03
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	8.44E-05	5.42E-07	1.58E-06	2.49E-06	2.83E-06	4.52E+00	4.20E-03

[a] Density used is 1.6 g/cm^3.

[b] No values available.

Table C-8 Effective Dose Coefficients for External Exposure from FGR 13 for 30 Day Cut-off Half-life Principal Radionuclides and Associated Radionuclides

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Ac-225	1.72E-06	1.03E-08	2.66E-08	3.54E-08	3.61E-08	5.78E-02	7.44E-05
Ac-227	1.65E-08	8.23E-11	2.10E-10	2.76E-10	2.79E-10	4.49E-04	5.98E-07
Ac-228	1.10E-04	6.73E-07	1.93E-06	3.06E-06	3.54E-06	5.66E+00	5.24E-03
Ag-105	5.72E-05	3.58E-07	1.02E-06	1.55E-06	1.69E-06	2.71E+00	2.64E-03
Ag-108	1.05E-05	1.87E-08	4.40E-08	6.50E-08	7.16E-08	1.15E-01	1.46E-04
Ag-108m	1.81E-04	1.14E-06	3.26E-06	5.06E-06	5.64E-06	9.03E+00	8.45E-03
Ag-110	1.90E-05	4.38E-08	9.29E-08	1.34E-07	1.48E-07	2.37E-01	2.87E-04
Ag-110m	3.01E-04	1.91E-06	5.52E-06	8.77E-06	1.01E-05	1.62E+01	1.48E-02
Al-26	2.88E-04	1.83E-06	5.30E-06	8.58E-06	1.03E-05	1.65E+01	1.50E-02
Am-241	2.72E-06	1.15E-08	2.16E-08	2.32E-08	2.32E-08	3.72E-02	7.87E-05
Am-242	1.88E-06	8.73E-09	2.20E-08	2.80E-08	2.80E-08	4.50E-02	7.11E-05
Am-242m	2.64E-07	4.05E-10	7.44E-10	8.94E-10	9.00E-10	1.44E-03	2.91E-06
Am-243	5.59E-06	3.07E-08	6.75E-08	7.76E-08	7.76E-08	1.25E-01	2.16E-04
Am-245	4.81E-06	2.15E-08	5.77E-08	8.06E-08	8.33E-08	1.33E-01	1.69E-04
Ar-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ar-39	2.95E-07	1.84E-10	3.93E-10	4.94E-10	5.02E-10	8.06E-04	1.34E-05
As-73	6.05E-07	2.70E-09	4.71E-09	4.90E-09	4.90E-09	7.87E-03	1.81E-05
At-217	3.42E-08	2.17E-10	6.14E-10	9.40E-10	1.03E-09	1.65E-03	1.60E-06
At-218	4.25E-07	1.69E-09	2.92E-09	3.05E-09	3.05E-09	4.88E-03	1.13E-05
Au-194	1.13E-04	7.24E-07	2.07E-06	3.28E-06	3.85E-06	6.17E+00	5.77E-03
Au-195	8.23E-06	4.53E-08	9.87E-08	1.13E-07	1.13E-07	1.82E-01	3.19E-04
Ba-133	4.36E-05	2.62E-07	7.22E-07	1.07E-06	1.14E-06	1.82E+00	1.89E-03

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Ba-137m	6.76E-05	4.20E-07	1.20E-06	1.88E-06	2.11E-06	3.38E+00	3.14E-03
Be-10	3.98E-07	2.29E-10	4.92E-10	6.19E-10	6.28E-10	1.01E-03	1.61E-05
Be-7	5.51E-06	3.50E-08	9.98E-08	1.53E-07	1.68E-07	2.69E-01	2.56E-04
Bi-207	1.69E-04	1.07E-06	3.05E-06	4.80E-06	5.52E-06	8.84E+00	8.22E-03
Bi-210	4.10E-06	1.97E-09	2.84E-09	3.35E-09	3.41E-09	5.48E-03	3.01E-05
Bi-210m	2.80E-05	1.79E-07	5.07E-07	7.51E-07	7.96E-07	1.28E+00	1.31E-03
Bi-211	5.14E-06	3.27E-08	9.26E-08	1.39E-07	1.48E-07	2.37E-01	2.38E-04
Bi-212	2.63E-05	1.34E-07	3.77E-07	5.98E-07	6.96E-07	1.11E+00	1.05E-03
Bi-213	1.96E-05	9.66E-08	2.71E-07	4.10E-07	4.48E-07	7.16E-01	7.19E-04
Bi-214	1.68E-04	1.04E-06	3.00E-06	4.86E-06	5.84E-06	9.33E+00	8.47E-03
Bk-247	1.10E-05	6.76E-08	1.77E-07	2.41E-07	2.48E-07	3.96E-01	4.90E-04
Bk-249	6.24E-10	1.45E-12	2.17E-12	2.34E-12	2.35E-12	3.78E-06	5.47E-08
Bk-250	9.84E-05	6.15E-07	1.77E-06	2.83E-06	3.28E-06	5.25E+00	4.81E-03
C-14	1.48E-09	4.03E-12	6.42E-12	6.87E-12	6.87E-12	1.11E-05	3.04E-07
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-45	4.40E-09	1.55E-11	2.92E-11	3.33E-11	3.33E-11	5.36E-05	1.79E-06
Cd-109	1.94E-06	3.82E-09	6.62E-09	7.65E-09	7.64E-09	1.22E-02	2.66E-05
Cd-113	6.77E-09	2.62E-11	5.20E-11	6.10E-11	6.12E-11	9.83E-05	2.95E-06
Cd-113m	2.07E-07	1.40E-10	2.97E-10	3.71E-10	3.76E-10	6.04E-04	1.06E-05
Cd-115m	1.08E-05	2.14E-08	5.23E-08	8.00E-08	9.21E-08	1.47E-01	1.73E-04
Ce-139	1.67E-05	9.64E-08	2.56E-07	3.55E-07	3.62E-07	5.81E-01	6.97E-04
Ce-141	8.09E-06	4.90E-08	1.31E-07	1.79E-07	1.81E-07	2.90E-01	3.62E-04
Ce-144	2.15E-06	1.21E-08	3.05E-08	4.00E-08	4.04E-08	6.47E-02	8.91E-05
Cf-248	6.52E-08	5.34E-11	5.48E-11	5.48E-11	5.48E-11	8.75E-05	3.80E-07
Cf-249	3.68E-05	2.34E-07	6.63E-07	9.98E-07	1.08E-06	1.72E+00	1.69E-03
Cf-250	6.21E-08	5.07E-11	5.20E-11	5.20E-11	5.20E-11	8.32E-05	3.61E-07
Cf-251	1.32E-05	8.00E-08	2.15E-07	2.94E-07	3.00E-07	4.80E-01	5.85E-04
Cf-252	4.97E-05	3.21E-07	9.33E-07	1.52E-06	1.84E-06	2.95E+00	2.70E-03
Cf-253	6.04E-09	1.88E-11	3.55E-11	4.08E-11	4.09E-11	6.58E-05	2.04E-06
Cf-254	1.81E-03	1.18E-05	3.41E-05	5.55E-05	6.75E-05	1.08E+02	9.87E-02
Cl-36	1.31E-06	5.69E-10	1.13E-09	1.49E-09	1.55E-09	2.50E-03	1.94E-05
Cm-241	5.43E-05	3.39E-07	9.48E-07	1.41E-06	1.53E-06	2.45E+00	2.46E-03
Cm-242	8.20E-08	6.40E-11	7.45E-11	7.95E-11	8.03E-11	1.29E-04	4.69E-07
Cm-243	1.38E-05	8.48E-08	2.31E-07	3.23E-07	3.34E-07	5.35E-01	6.19E-04
Cm-244	7.52E-08	5.39E-11	5.59E-11	5.59E-11	5.59E-11	8.95E-05	3.97E-07
Cm-245	9.40E-06	5.63E-08	1.46E-07	1.90E-07	1.91E-07	3.07E-01	4.08E-04
Cm-246	6.73E-08	4.94E-11	5.17E-11	5.18E-11	5.18E-11	8.32E-05	3.62E-07
Cm-247	3.49E-05	2.22E-07	6.32E-07	9.56E-07	1.03E-06	1.65E+00	1.61E-03
Cm-248	1.42E-04	9.22E-07	2.67E-06	4.36E-06	5.30E-06	8.48E+00	7.74E-03
Cm-249	3.88E-06	1.41E-08	3.96E-08	6.07E-08	6.73E-08	1.08E-01	1.19E-04
Cm-250	1.05E-03	6.81E-06	1.97E-05	3.21E-05	3.91E-05	6.26E+01	5.71E-02
Co-56	3.77E-04	2.43E-06	7.04E-06	1.15E-05	1.40E-05	2.24E+01	2.02E-02
Co-57	1.26E-05	8.00E-08	2.11E-07	2.81E-07	2.85E-07	4.56E-01	5.80E-04
Co-58	1.08E-04	6.85E-07	1.96E-06	3.08E-06	3.50E-06	5.61E+00	5.18E-03
Co-60	2.69E-04	1.72E-06	4.99E-06	8.07E-06	9.63E-06	1.54E+01	1.39E-02
Co-60m	5.11E-07	2.98E-09	7.96E-09	1.23E-08	1.45E-08	2.32E-02	2.34E-05
Cs-134	1.73E-04	1.10E-06	3.14E-06	4.92E-06	5.57E-06	8.90E+00	8.24E-03

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Cs-135	3.14E-09	1.02E-11	1.81E-11	2.01E-11	2.01E-11	3.23E-05	1.11E-06
Cs-137	3.49E-07	2.42E-10	4.23E-10	5.14E-10	5.22E-10	8.37E-04	1.08E-05
Dy-159	4.52E-06	1.76E-08	2.74E-08	2.79E-08	2.79E-08	4.47E-02	1.16E-04
Es-253	7.74E-08	2.59E-10	6.49E-10	9.41E-10	1.01E-09	1.61E-03	1.87E-06
Es-254	1.14E-06	2.60E-09	5.30E-09	6.83E-09	7.09E-09	1.13E-02	1.83E-05
Eu-146	2.74E-04	1.74E-06	4.99E-06	7.88E-06	9.08E-06	1.45E+01	1.34E-02
Eu-148	2.41E-04	1.52E-06	4.33E-06	6.80E-06	7.72E-06	1.23E+01	1.15E-02
Eu-149	6.61E-06	3.26E-08	7.69E-08	1.08E-07	1.15E-07	1.83E-01	2.28E-04
Eu-150	1.66E-04	1.04E-06	2.97E-06	4.58E-06	5.10E-06	8.17E+00	7.75E-03
Eu-152	1.26E-04	7.89E-07	2.25E-06	3.56E-06	4.13E-06	6.62E+00	6.17E-03
Eu-154	1.37E-04	8.57E-07	2.45E-06	3.90E-06	4.54E-06	7.27E+00	6.71E-03
Eu-155	6.25E-06	3.53E-08	8.24E-08	1.01E-07	1.01E-07	1.62E-01	2.50E-04
Fe-55	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-59	1.28E-04	8.20E-07	2.37E-06	3.82E-06	4.53E-06	7.25E+00	6.56E-03
Fe-60	1.37E-09	3.49E-12	5.37E-12	5.65E-12	5.65E-12	9.10E-06	2.09E-07
Fm-257	1.11E-05	6.67E-08	1.77E-07	2.41E-07	2.44E-07	3.91E-01	4.85E-04
Fr-221	3.32E-06	2.11E-08	5.91E-08	8.50E-08	8.83E-08	1.41E-01	1.54E-04
Fr-223	9.06E-06	3.37E-08	8.06E-08	1.08E-07	1.13E-07	1.81E-01	2.57E-04
Ga-68	1.17E-04	6.83E-07	1.94E-06	2.98E-06	3.29E-06	5.27E+00	5.01E-03
Gd-146	2.59E-05	1.41E-07	3.42E-07	4.45E-07	4.50E-07	7.20E-01	1.01E-03
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-149	4.58E-05	2.79E-07	7.69E-07	1.15E-06	1.25E-06	2.00E+00	2.04E-03
Gd-151	6.50E-06	3.14E-08	7.10E-08	9.42E-08	9.71E-08	1.56E-01	2.20E-04
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	1.08E-05	5.24E-08	1.11E-07	1.33E-07	1.33E-07	2.13E-01	3.63E-04
Ge-68	4.79E-09	8.10E-13	8.10E-13	8.10E-13	8.10E-13	1.30E-06	1.18E-08
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.16E-05	5.76E-08	1.17E-07	1.34E-07	1.34E-07	2.17E-01	3.97E-04
Hf-175	4.03E-05	2.49E-07	6.83E-07	1.01E-06	1.08E-06	1.72E+00	1.80E-03
Hf-178m	2.59E-04	1.65E-06	4.64E-06	6.98E-06	7.57E-06	1.21E+01	1.20E-02
Hf-181	6.13E-05	3.86E-07	1.08E-06	1.63E-06	1.76E-06	2.82E+00	2.83E-03
Hf-182	2.60E-05	1.66E-07	4.67E-07	6.85E-07	7.20E-07	1.15E+00	1.20E-03
Hg-194	2.62E-08	6.67E-12	6.67E-12	6.67E-12	6.67E-12	1.07E-05	7.27E-08
Hg-203	2.59E-05	1.66E-07	4.68E-07	6.91E-07	7.30E-07	1.17E+00	1.21E-03
Ho-166m	1.93E-04	1.21E-06	3.48E-06	5.38E-06	6.04E-06	9.66E+00	9.15E-03
I-125	3.67E-06	6.87E-09	7.43E-09	7.43E-09	7.43E-09	1.19E-02	4.36E-05
I-129	2.28E-06	5.14E-09	5.97E-09	5.97E-09	5.97E-09	9.61E-03	3.28E-05
In-113m	2.84E-05	1.79E-07	5.09E-07	7.71E-07	8.34E-07	1.33E+00	1.31E-03
In-114	3.22E-07	1.90E-09	5.46E-09	8.82E-09	1.05E-08	1.68E-02	1.86E-05
In-114m	1.01E-05	6.07E-08	1.70E-07	2.58E-07	2.83E-07	4.52E-01	4.54E-04
In-115	4.17E-08	8.14E-11	1.77E-10	2.20E-10	2.22E-10	3.57E-04	7.65E-06
Ir-192	9.07E-05	5.76E-07	1.65E-06	2.48E-06	2.67E-06	4.28E+00	4.22E-03
Ir-192m	1.72E-05	1.10E-07	3.01E-07	4.20E-07	4.30E-07	6.88E-01	7.99E-04
Ir-194	2.11E-05	7.46E-08	1.96E-07	2.97E-07	3.28E-07	5.25E-01	5.52E-04
Ir-194m	2.60E-04	1.65E-06	4.71E-06	7.23E-06	7.96E-06	1.27E+01	1.21E-02
K-40	2.38E-05	1.11E-07	3.15E-07	5.14E-07	6.22E-07	9.96E-01	9.25E-04
Kr-81	6.99E-07	3.90E-09	1.11E-08	1.65E-08	1.73E-08	2.77E-02	2.85E-05

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Kr-83m	4.17E-08	1.53E-11	1.58E-11	1.58E-11	1.58E-11	2.52E-05	1.40E-07
Kr-85	1.23E-06	1.93E-09	5.14E-09	7.72E-09	8.44E-09	1.35E-02	2.80E-05
La-137	2.29E-06	5.52E-09	6.53E-09	6.53E-09	6.53E-09	1.05E-02	3.50E-05
La-138	1.32E-04	8.42E-07	2.44E-06	3.95E-06	4.72E-06	7.55E+00	6.82E-03
Lu-172	2.06E-04	1.30E-06	3.69E-06	5.84E-06	6.78E-06	1.09E+01	1.01E-02
Lu-173	1.35E-05	7.33E-08	1.70E-07	2.25E-07	2.35E-07	3.76E-01	5.16E-04
Lu-174	1.31E-05	7.54E-08	1.93E-07	2.88E-07	3.35E-07	5.36E-01	5.77E-04
Lu-174m	6.22E-06	3.09E-08	6.33E-08	7.67E-08	8.06E-08	1.29E-01	2.15E-04
Lu-176	5.34E-05	3.37E-07	9.47E-07	1.39E-06	1.46E-06	2.34E+00	2.46E-03
Lu-177	3.75E-06	2.32E-08	6.29E-08	8.80E-08	9.07E-08	1.45E-01	1.75E-04
Lu-177m	1.09E-04	6.81E-07	1.88E-06	2.73E-06	2.88E-06	4.62E+00	4.95E-03
Md-258	3.88E-07	6.50E-10	1.05E-09	1.16E-09	1.16E-09	1.87E-03	4.54E-06
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	9.24E-05	5.86E-07	1.68E-06	2.65E-06	3.04E-06	4.86E+00	4.47E-03
Mo-93	4.53E-07	2.62E-10	2.60E-10	2.60E-10	2.60E-10	4.17E-04	2.02E-06
Na-22	2.39E-04	1.53E-06	4.39E-06	6.97E-06	8.07E-06	1.29E+01	1.19E-02
Nb-93m	7.96E-08	4.60E-11	4.60E-11	4.60E-11	4.60E-11	7.34E-05	3.56E-07
Nb-94	1.74E-04	1.11E-06	3.18E-06	5.00E-06	5.70E-06	9.12E+00	8.41E-03
Nb-95	8.50E-05	5.39E-07	1.54E-06	2.43E-06	2.77E-06	4.43E+00	4.08E-03
Nb-95m	6.90E-06	4.25E-08	1.20E-07	1.76E-07	1.83E-07	2.93E-01	3.20E-04
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-235	3.34E-07	6.73E-10	1.44E-09	1.76E-09	1.76E-09	2.82E-03	4.89E-06
Np-236	1.30E-05	7.61E-08	1.97E-07	2.58E-07	2.60E-07	4.17E-01	5.54E-04
Np-237	2.94E-06	1.45E-08	3.46E-08	4.33E-08	4.34E-08	6.97E-02	1.04E-04
Np-238	6.24E-05	3.82E-07	1.10E-06	1.75E-06	2.03E-06	3.25E+00	2.99E-03
Np-239	1.80E-05	1.11E-07	3.00E-07	4.17E-07	4.31E-07	6.90E-01	8.12E-04
Np-240m	4.52E-05	2.38E-07	6.73E-07	1.05E-06	1.19E-06	1.91E+00	1.81E-03
Os-185	7.95E-05	4.99E-07	1.40E-06	2.17E-06	2.44E-06	3.91E+00	3.71E-03
Os-194	1.12E-07	3.86E-10	5.74E-10	5.83E-10	5.83E-10	9.36E-04	2.53E-06
P-32	9.95E-06	7.75E-09	1.06E-08	1.24E-08	1.27E-08	2.04E-02	6.26E-05
Pa-231	4.41E-06	2.52E-08	7.03E-08	1.04E-07	1.10E-07	1.76E-01	1.83E-04
Pa-233	2.17E-05	1.37E-07	3.82E-07	5.57E-07	5.88E-07	9.42E-01	9.98E-04
Pa-234	2.10E-04	1.32E-06	3.78E-06	5.93E-06	6.81E-06	1.09E+01	1.02E-02
Pa-234m	1.26E-05	1.96E-08	3.89E-08	5.51E-08	6.17E-08	9.87E-02	1.41E-04
Pb-202	2.23E-08	4.59E-12	4.59E-12	4.59E-12	4.59E-12	7.34E-06	5.79E-08
Pb-205	2.43E-08	5.13E-12	5.13E-12	5.13E-12	5.13E-12	8.20E-06	6.36E-08
Pb-209	3.72E-07	1.84E-10	3.72E-10	4.64E-10	4.71E-10	7.55E-04	1.17E-05
Pb-210	2.49E-07	7.90E-10	1.23E-09	1.24E-09	1.24E-09	1.98E-03	5.23E-06
Pb-211	1.11E-05	3.86E-08	1.06E-07	1.62E-07	1.82E-07	2.92E-01	3.02E-04
Pb-212	1.58E-05	9.95E-08	2.73E-07	3.89E-07	4.04E-07	6.47E-01	7.29E-04
Pb-214	2.80E-05	1.74E-07	4.88E-07	7.26E-07	7.76E-07	1.24E+00	1.27E-03
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-143	3.47E-05	2.10E-07	5.88E-07	9.18E-07	1.04E-06	1.66E+00	1.58E-03
Pm-144	1.74E-04	1.09E-06	3.12E-06	4.83E-06	5.42E-06	8.67E+00	8.12E-03
Pm-145	3.05E-06	9.88E-09	1.41E-08	1.45E-08	1.45E-08	2.32E-02	6.41E-05
Pm-146	8.40E-05	5.24E-07	1.49E-06	2.31E-06	2.58E-06	4.13E+00	3.90E-03

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Pm-147	3.27E-09	1.18E-11	2.29E-11	2.67E-11	2.69E-11	4.32E-05	1.01E-06
Pm-148	7.13E-05	4.06E-07	1.16E-06	1.86E-06	2.18E-06	3.50E+00	3.22E-03
Pm-148m	2.23E-04	1.41E-06	4.03E-06	6.28E-06	7.04E-06	1.13E+01	1.05E-02
Po-209[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	9.45E-10	5.98E-12	1.72E-11	2.70E-11	3.08E-11	4.93E-05	4.54E-08
Po-211	8.66E-07	5.49E-09	1.58E-08	2.46E-08	2.80E-08	4.49E-02	4.16E-05
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-214	9.26E-09	5.86E-11	1.68E-10	2.65E-10	3.02E-10	4.84E-04	4.45E-07
Po-215	1.96E-08	1.25E-10	3.56E-10	5.43E-10	5.91E-10	9.46E-04	9.10E-07
Po-216	1.88E-09	1.19E-11	3.41E-11	5.38E-11	6.14E-11	9.83E-05	9.05E-08
Po-218	1.01E-09	6.41E-12	1.83E-11	2.91E-11	3.33E-11	5.33E-05	4.92E-08
Pr-144	1.90E-05	4.47E-08	9.54E-08	1.42E-07	1.67E-07	2.67E-01	3.09E-04
Pr-144m	1.23E-06	3.90E-09	6.05E-09	7.11E-09	7.51E-09	1.20E-02	2.57E-05
Pt-193	1.80E-08	3.95E-12	3.95E-12	3.95E-12	3.95E-12	6.32E-06	4.75E-08
Pu-236	8.58E-08	7.39E-11	1.01E-10	1.12E-10	1.13E-10	1.81E-04	5.47E-07
Pu-237	4.96E-06	2.86E-08	7.15E-08	9.06E-08	9.07E-08	1.45E-01	2.06E-04
Pu-238	7.31E-08	5.49E-11	6.75E-11	7.24E-11	7.29E-11	1.17E-04	4.09E-07
Pu-239	3.32E-08	5.56E-11	1.18E-10	1.58E-10	1.65E-10	2.64E-04	4.06E-07
Pu-240	7.02E-08	5.37E-11	6.61E-11	7.03E-11	7.03E-11	1.13E-04	3.99E-07
Pu-241	2.01E-10	1.02E-12	2.57E-12	3.30E-12	3.32E-12	5.33E-06	7.39E-09
Pu-242	5.81E-08	4.54E-11	5.77E-11	6.20E-11	6.20E-11	9.94E-05	3.39E-07
Pu-243	2.65E-06	1.46E-08	3.51E-08	4.39E-08	4.45E-08	7.12E-02	1.12E-04
Pu-244	2.36E-06	1.51E-08	4.36E-08	7.08E-08	8.62E-08	1.38E-01	1.26E-04
Pu-246	1.44E-05	8.62E-08	2.29E-07	3.15E-07	3.23E-07	5.18E-01	6.25E-04
Ra-223	1.41E-05	8.80E-08	2.37E-07	3.32E-07	3.46E-07	5.53E-01	6.39E-04
Ra-224	1.07E-06	6.84E-09	1.94E-08	2.83E-08	2.95E-08	4.73E-02	5.01E-05
Ra-225	1.25E-06	3.89E-09	5.35E-09	5.37E-09	5.38E-09	8.63E-03	2.80E-05
Ra-226	7.13E-07	4.53E-09	1.25E-08	1.76E-08	1.82E-08	2.92E-02	3.32E-05
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Rb-83	5.56E-05	3.53E-07	1.01E-06	1.55E-06	1.72E-06	2.75E+00	2.58E-03
Rb-84	1.02E-04	6.42E-07	1.84E-06	2.90E-06	3.29E-06	5.27E+00	4.88E-03
Rb-87	8.52E-09	3.28E-11	6.48E-11	7.57E-11	7.59E-11	1.22E-04	3.85E-06
Re-184	9.77E-05	6.13E-07	1.73E-06	2.70E-06	3.08E-06	4.92E+00	4.66E-03
Re-184m	4.19E-05	2.60E-07	7.16E-07	1.07E-06	1.19E-06	1.91E+00	1.95E-03
Re-186	5.16E-06	1.40E-08	3.41E-08	4.43E-08	4.50E-08	7.20E-02	1.16E-04
Re-186m	1.49E-06	7.06E-09	1.34E-08	1.47E-08	1.47E-08	2.36E-02	4.83E-05
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Re-188	1.69E-05	4.93E-08	1.23E-07	1.79E-07	1.95E-07	3.12E-01	3.66E-04
Rh-101	2.80E-05	1.74E-07	4.81E-07	6.81E-07	7.03E-07	1.13E+00	1.27E-03
Rh-102	2.36E-04	1.49E-06	4.29E-06	6.71E-06	7.61E-06	1.22E+01	1.13E-02
Rh-102m	5.57E-05	3.40E-07	9.67E-07	1.49E-06	1.66E-06	2.65E+00	2.51E-03
Rh-103m	1.03E-07	1.02E-10	1.06E-10	1.06E-10	1.06E-10	1.70E-04	7.03E-07
Rh-106	4.03E-05	1.74E-07	4.57E-07	6.97E-07	7.79E-07	1.25E+00	1.24E-03
Rn-219	6.17E-06	3.93E-08	1.12E-07	1.67E-07	1.79E-07	2.86E-01	2.87E-04
Rn-220	4.31E-08	2.73E-10	7.80E-10	1.20E-09	1.34E-09	2.13E-03	2.01E-06
Rn-222	4.46E-08	2.83E-10	8.07E-10	1.24E-09	1.37E-09	2.19E-03	2.07E-06

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Ru-103	5.24E-05	3.33E-07	9.48E-07	1.46E-06	1.61E-06	2.56E+00	2.43E-03
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	1.55E-09	4.36E-12	7.10E-12	7.65E-12	7.65E-12	1.23E-05	3.63E-07
Sb-124	1.98E-04	1.25E-06	3.62E-06	5.84E-06	6.92E-06	1.11E+01	1.01E-02
Sb-125	4.78E-05	2.97E-07	8.42E-07	1.30E-06	1.42E-06	2.28E+00	2.18E-03
Sb-126	3.18E-04	2.01E-06	5.72E-06	8.93E-06	1.00E-05	1.61E+01	1.50E-02
Sb-126m	1.81E-04	1.10E-06	3.14E-06	4.88E-06	5.45E-06	8.73E+00	8.19E-03
Sc-44	2.43E-04	1.49E-06	4.30E-06	6.78E-06	7.78E-06	1.25E+01	1.15E-02
Sc-46	2.20E-04	1.40E-06	4.03E-06	6.42E-06	7.50E-06	1.20E+01	1.09E-02
Se-75	4.22E-05	2.69E-07	7.54E-07	1.09E-06	1.14E-06	1.83E+00	1.96E-03
Se-79	1.91E-09	5.44E-12	8.89E-12	9.56E-12	9.56E-12	1.54E-05	4.60E-07
Si-32	2.92E-09	9.42E-12	1.67E-11	1.86E-11	1.86E-11	2.99E-05	1.01E-06
Sm-145	6.49E-06	2.25E-08	3.33E-08	3.40E-08	3.40E-08	5.48E-02	1.47E-04
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.13E-10	4.18E-13	4.23E-13	4.23E-13	4.23E-13	6.77E-07	2.87E-09
Sn-113	1.90E-06	5.25E-09	1.14E-08	1.59E-08	1.66E-08	2.65E-02	3.68E-05
Sn-119m	8.72E-07	1.27E-09	1.32E-09	1.31E-09	1.31E-09	2.11E-03	8.22E-06
Sn-121	1.03E-08	4.25E-11	8.85E-11	1.06E-10	1.07E-10	1.72E-04	4.55E-06
Sn-121m	4.20E-07	7.94E-10	8.92E-10	8.96E-10	8.96E-10	1.44E-03	6.12E-06
Sn-123	7.59E-06	9.13E-09	1.97E-08	2.91E-08	3.32E-08	5.31E-02	8.15E-05
Sn-126	5.63E-06	2.97E-08	6.80E-08	8.14E-08	8.13E-08	1.30E-01	2.15E-04
Sr-85	5.65E-05	3.57E-07	1.02E-06	1.56E-06	1.73E-06	2.77E+00	2.62E-03
Sr-89	8.01E-06	5.62E-09	7.79E-09	9.19E-09	9.45E-09	1.51E-02	5.10E-05
Sr-90	1.91E-07	1.47E-10	3.18E-10	3.98E-10	4.04E-10	6.47E-04	1.15E-05
Ta-179	3.21E-06	1.55E-08	2.86E-08	3.05E-08	3.05E-08	4.88E-02	1.05E-04
Ta-180	6.05E-05	3.78E-07	1.05E-06	1.53E-06	1.61E-06	2.58E+00	2.74E-03
Ta-182	1.40E-04	8.84E-07	2.52E-06	4.00E-06	4.69E-06	7.51E+00	6.99E-03
Tb-157	2.57E-07	9.56E-10	1.42E-09	1.45E-09	1.45E-09	2.32E-03	6.24E-06
Tb-158	8.75E-05	5.43E-07	1.54E-06	2.42E-06	2.79E-06	4.45E+00	4.18E-03
Tb-160	1.24E-04	7.79E-07	2.23E-06	3.53E-06	4.09E-06	6.54E+00	6.06E-03
Tc-95	8.76E-05	5.52E-07	1.59E-06	2.49E-06	2.84E-06	4.54E+00	4.18E-03
Tc-95m	7.38E-05	4.66E-07	1.33E-06	2.06E-06	2.30E-06	3.68E+00	3.49E-03
Tc-97	5.43E-07	3.55E-10	3.53E-10	3.53E-10	3.53E-10	5.64E-04	2.64E-06
Tc-97m	5.20E-07	5.52E-10	8.38E-10	9.60E-10	9.59E-10	1.54E-03	4.34E-06
Tc-98	1.58E-04	9.97E-07	2.86E-06	4.47E-06	5.04E-06	8.07E+00	7.49E-03
Tc-99	7.55E-09	2.91E-11	5.77E-11	6.75E-11	6.77E-11	1.09E-04	3.35E-06
Te-121	6.39E-05	3.98E-07	1.13E-06	1.75E-06	1.94E-06	3.10E+00	2.92E-03
Te-121m	2.31E-05	1.42E-07	3.98E-07	5.85E-07	6.20E-07	9.92E-01	1.05E-03
Te-123	1.66E-06	2.77E-09	2.91E-09	2.90E-09	2.90E-09	4.65E-03	1.76E-05
Te-123m	1.54E-05	9.33E-08	2.52E-07	3.50E-07	3.57E-07	5.72E-01	6.78E-04
Te-125m	3.11E-06	6.00E-09	6.78E-09	6.95E-09	6.95E-09	1.11E-02	3.91E-05
Te-127	1.20E-06	3.70E-09	1.03E-08	1.54E-08	1.67E-08	2.67E-02	3.90E-05
Te-127m	9.99E-07	1.96E-09	2.41E-09	2.57E-09	2.60E-09	4.19E-03	1.31E-05
Te-129	1.33E-05	4.37E-08	1.17E-07	1.77E-07	1.96E-07	3.14E-01	3.34E-04
Te-129m	6.66E-06	2.41E-08	6.35E-08	9.77E-08	1.10E-07	1.76E-01	1.82E-04
Th-227	1.15E-05	7.10E-08	1.97E-07	2.86E-07	3.00E-07	4.80E-01	5.17E-04

Table C-8 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m²)	1 cm (mrem/yr per pCi/m³)	5 cm (mrem/yr per pCi/ m³)	15 cm (mrem/yr per pCi/m³)	Infinite (mrem/yr per pCi/m³)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m³)
Th-228	2.49E-07	1.31E-09	3.33E-09	4.40E-09	4.48E-09	7.18E-03	9.46E-06
Th-229	9.21E-06	5.44E-08	1.38E-07	1.79E-07	1.81E-07	2.90E-01	3.92E-04
Th-230	7.44E-08	2.41E-10	5.39E-10	6.61E-10	6.69E-10	1.07E-03	1.73E-06
Th-231	1.81E-06	7.25E-09	1.65E-08	2.00E-08	2.01E-08	3.21E-02	5.35E-05
Th-232	5.31E-08	1.17E-10	2.39E-10	2.83E-10	2.85E-10	4.56E-04	8.45E-07
Th-234	8.75E-07	4.78E-09	1.11E-08	1.33E-08	1.33E-08	2.13E-02	3.43E-05
Ti-44	1.38E-05	7.79E-08	1.72E-07	1.96E-07	1.96E-07	3.14E-01	5.49E-04
Tl-202	5.14E-05	3.22E-07	8.96E-07	1.34E-06	1.46E-06	2.32E+00	2.34E-03
Tl-204	1.26E-06	1.03E-09	2.07E-09	2.42E-09	2.43E-09	3.89E-03	2.00E-05
Tl-206	7.09E-06	4.68E-09	6.53E-09	7.68E-09	7.89E-09	1.26E-02	4.61E-05
Tl-207	6.49E-06	5.30E-09	9.67E-09	1.32E-08	1.44E-08	2.30E-02	5.29E-05
Tl-208	3.47E-04	2.23E-06	6.52E-06	1.08E-05	1.37E-05	2.19E+01	1.97E-02
Tl-209	2.24E-04	1.39E-06	4.00E-06	6.42E-06	7.66E-06	1.23E+01	1.13E-02
Tl-210	3.06E-04	1.91E-06	5.50E-06	8.86E-06	1.04E-0.5	1.66E+01	0.00E+00
Tm-170	3.08E-06	3.86E-09	7.59E-09	8.78E-09	8.80E-09	1.41E-02	4.29E-05
Tm-171	6.48E-08	3.06E-10	5.55E-10	5.87E-10	5.87E-10	9.42E-04	2.07E-06
U-232	9.42E-08	1.89E-10	3.95E-10	4.89E-10	4.95E-10	7.94E-04	1.37E-06
U-233	6.99E-08	2.28E-10	5.62E-10	7.65E-10	7.90E-10	1.27E-03	1.66E-06
U-234	6.84E-08	9.76E-11	1.81E-10	2.15E-10	2.15E-10	3.44E-04	7.13E-07
U-235	1.63E-05	1.03E-07	2.86E-07	4.02E-07	4.12E-07	6.60E-01	7.54E-04
U-236	5.87E-08	6.08E-11	9.76E-11	1.11E-10	1.11E-10	1.78E-04	4.51E-07
U-237	1.44E-05	8.54E-08	2.20E-07	2.94E-07	3.01E-07	4.82E-01	6.18E-04
U-238	4.94E-08	3.93E-11	4.90E-11	4.97E-11	4.97E-11	7.96E-05	2.92E-07
U-240	3.72E-07	5.04E-10	6.76E-10	6.94E-10	6.94E-10	1.11E-03	6.85E-06
V-49	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W-181	4.02E-06	1.98E-08	3.78E-08	4.06E-08	4.06E-08	6.52E-02	1.35E-04
W-185	2.00E-08	8.76E-11	1.94E-10	2.37E-10	2.39E-10	3.83E-04	5.80E-06
W-188	2.13E-07	1.32E-09	3.65E-09	5.30E-09	5.57E-09	8.91E-03	1.28E-05
Xe-127	2.99E-05	1.81E-07	5.00E-07	7.24E-07	7.57E-07	1.21E+00	1.31E-03
Y-88	2.81E-04	1.82E-06	5.29E-06	8.66E-06	1.06E-05	1.69E+01	1.52E-02
Y-90	1.28E-05	1.47E-08	2.03E-08	2.43E-08	2.51E-08	4.04E-02	9.25E-05
Y-91	8.71E-06	8.50E-09	1.54E-08	2.13E-08	2.37E-08	3.79E-02	7.26E-05
Yb-169	3.25E-05	1.84E-07	4.54E-07	6.07E-07	6.24E-07	9.98E-01	1.32E-03
Zn-65	6.32E-05	4.03E-07	1.16E-06	1.86E-06	2.20E-06	3.51E+00	3.18E-03
Zr-88	4.40E-05	2.79E-07	7.94E-07	1.20E-06	1.31E-06	2.07E+00	2.02E-03
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	8.22E-05	5.21E-07	1.49E-06	2.35E-06	2.65E-06	4.24E+00	3.92E-03

[a] Density used is 1.6 g/cm^3.

Table C-9 Effective Dose Coefficients for External Exposure from DCFPAK3.02 for 30 Day Cut-off Half-life Principal Radionuclides and Associated Radionuclides

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Ac-225	1.54E-06	9.12E-09	2.38E-08	3.21E-08	3.30E-08	5.29E-02	6.61E-05
Ac-227	2.77E-08	5.88E-11	1.27E-10	1.61E-10	1.63E-10	2.62E-04	4.26E-07
Ac-228	9.80E-05	6.01E-07	1.73E-06	2.72E-06	3.15E-06	5.04E+00	4.68E-03
Ag-105	5.58E-05	3.50E-07	9.94E-07	1.51E-06	1.66E-06	2.65E+00	2.58E-03
Ag-108	1.05E-05	1.90E-08	4.52E-08	6.69E-08	7.37E-08	1.18E-01	1.48E-04
Ag-108m	1.80E-04	1.14E-06	3.25E-06	5.03E-06	5.62E-06	8.99E+00	8.44E-03
Ag-110	1.90E-05	4.38E-08	9.31E-08	1.34E-07	1.48E-07	2.37E-01	2.87E-04
Ag-110m	3.02E-04	1.93E-06	5.55E-06	8.79E-06	1.02E-05	1.63E+01	1.50E-02
Al-26	2.88E-04	1.82E-06	5.29E-06	8.58E-06	1.03E-05	1.65E+01	1.50E-02
Am-241	2.55E-06	1.14E-08	2.16E-08	2.32E-08	2.32E-08	3.72E-02	7.85E-05
Am-242	1.88E-06	8.72E-09	2.20E-08	2.80E-08	2.81E-08	4.50E-02	7.13E-05
Am-242m	2.42E-07	3.21E-10	5.51E-10	6.59E-10	6.63E-10	1.06E-03	2.31E-06
Am-243	5.79E-06	3.18E-08	6.98E-08	8.03E-08	8.03E-08	1.29E-01	2.24E-04
Am-245	4.79E-06	2.14E-08	5.76E-08	8.04E-08	8.30E-08	1.33E-01	1.69E-04
Am-246m	1.12E-04	6.81E-07	1.96E-06	3.12E-06	3.62E-06	5.79E+00	5.34E-03
Ar-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ar-39	2.94E-07	1.84E-10	3.95E-10	4.96E-10	5.03E-10	8.05E-04	1.34E-05
Ar-42	4.76E-07	2.31E-10	4.75E-10	5.95E-10	6.05E-10	9.68E-04	1.47E-05
As-73	6.00E-07	2.69E-09	4.68E-09	4.88E-09	4.88E-09	7.81E-03	1.80E-05
At-217	2.65E-08	1.68E-10	4.69E-10	6.94E-10	7.41E-10	1.19E-03	1.24E-06
At-218	1.46E-08	1.97E-11	2.77E-11	3.34E-11	3.48E-11	5.57E-05	1.14E-07
At-219	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Au-194	1.10E-04	7.04E-07	2.01E-06	3.19E-06	3.74E-06	5.98E+00	5.62E-03
Au-195	8.09E-06	4.47E-08	9.74E-08	1.12E-07	1.12E-07	1.79E-01	3.15E-04
Ba-133	4.36E-05	2.62E-07	7.22E-07	1.07E-06	1.14E-06	1.82E+00	1.89E-03
Ba-137m	6.74E-05	4.20E-07	1.20E-06	1.88E-06	2.11E-06	3.38E+00	3.14E-03
Be-10	4.02E-07	2.31E-10	4.96E-10	6.25E-10	6.34E-10	1.01E-03	1.62E-05
Be-7	5.56E-06	3.54E-08	1.01E-07	1.54E-07	1.69E-07	2.71E-01	2.58E-04
Bi-207	1.69E-04	1.06E-06	3.04E-06	4.79E-06	5.51E-06	8.82E+00	8.21E-03
Bi-208	2.58E-04	1.70E-06	5.01E-06	8.48E-06	1.10E-05	1.77E+01	1.58E-02
Bi-210	4.10E-06	1.96E-09	2.84E-09	3.35E-09	3.42E-09	5.47E-03	3.01E-05
Bi-210m	2.85E-05	1.82E-07	5.14E-07	7.62E-07	8.12E-07	1.30E+00	1.33E-03
Bi-211	5.20E-06	3.32E-08	9.36E-08	1.40E-07	1.51E-07	2.41E-01	2.42E-04
Bi-212	1.80E-05	7.81E-08	2.15E-07	3.37E-07	3.91E-07	6.26E-01	6.04E-04
Bi-213	1.91E-05	9.28E-08	2.59E-07	3.93E-07	4.30E-07	6.87E-01	6.94E-04
Bi-214	1.66E-04	1.02E-06	2.94E-06	4.76E-06	5.71E-06	9.14E+00	8.30E-03
Bi-215	3.58E-05	1.82E-07	5.07E-07	7.71E-07	8.56E-07	1.37E+00	1.38E-03
Bk-247	1.54E-05	9.61E-08	2.58E-07	3.57E-07	3.70E-07	5.92E-01	6.99E-04
Bk-249	6.62E-10	1.77E-12	3.19E-12	3.85E-12	3.97E-12	6.35E-06	5.10E-08
Bk-250	9.95E-05	6.24E-07	1.80E-06	2.86E-06	3.33E-06	5.32E+00	4.88E-03
Bk-251	1.10E-05	5.50E-08	1.44E-07	1.91E-07	1.94E-07	3.10E-01	4.16E-04
C-14	1.49E-09	4.05E-12	6.47E-12	6.91E-12	6.91E-12	1.11E-05	3.04E-07
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-45	4.41E-09	1.55E-11	2.93E-11	3.34E-11	3.34E-11	5.34E-05	1.78E-06
Cd-109	1.93E-06	3.79E-09	6.59E-09	7.61E-09	7.60E-09	1.22E-02	2.65E-05
Cd-113	6.70E-09	2.57E-11	5.11E-11	6.00E-11	6.02E-11	9.64E-05	2.91E-06

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Cd-113m	2.08E-07	1.82E-10	4.16E-10	5.46E-10	5.62E-10	8.99E-04	1.08E-05
Cd-115m	1.19E-05	2.88E-08	7.41E-08	1.15E-07	1.33E-07	2.13E-01	2.32E-04
Ce-139	1.67E-05	9.64E-08	2.56E-07	3.54E-07	3.62E-07	5.79E-01	6.98E-04
Ce-141	8.14E-06	4.94E-08	1.32E-07	1.80E-07	1.82E-07	2.91E-01	3.66E-04
Ce-144	2.02E-06	1.16E-08	2.95E-08	3.91E-08	3.95E-08	6.31E-02	8.58E-05
Cf-248	1.11E-07	2.91E-10	7.22E-10	1.12E-09	1.34E-09	2.15E-03	2.34E-06
Cf-249	3.60E-05	2.29E-07	6.50E-07	9.80E-07	1.05E-06	1.69E+00	1.67E-03
Cf-250	1.14E-06	6.76E-09	1.94E-08	3.14E-08	3.82E-08	6.11E-02	5.63E-05
Cf-251	1.25E-05	7.69E-08	2.07E-07	2.83E-07	2.88E-07	4.61E-01	5.65E-04
Cf-252	5.04E-05	3.12E-07	8.98E-07	1.46E-06	1.77E-06	2.84E+00	2.60E-03
Cf-253	2.48E-07	3.19E-10	3.86E-10	3.92E-10	3.92E-10	6.28E-04	3.68E-06
Cf-254	1.87E-03	1.15E-05	3.32E-05	5.38E-05	6.55E-05	1.05E+02	9.62E-02
Cl-36	1.30E-06	5.59E-10	1.11E-09	1.46E-09	1.52E-09	2.43E-03	1.94E-05
Cm-241	5.42E-05	3.39E-07	9.48E-07	1.41E-06	1.53E-06	2.45E+00	2.48E-03
Cm-242	7.80E-08	6.21E-11	7.34E-11	7.93E-11	8.04E-11	1.29E-04	4.55E-07
Cm-243	1.38E-05	8.51E-08	2.31E-07	3.25E-07	3.35E-07	5.36E-01	6.22E-04
Cm-244	6.83E-08	6.22E-11	9.01E-11	1.13E-10	1.25E-10	2.00E-04	4.67E-07
Cm-245	1.06E-05	6.45E-08	1.67E-07	2.18E-07	2.21E-07	3.53E-01	4.67E-04
Cm-246	4.52E-07	2.51E-09	7.16E-09	1.16E-08	1.41E-08	2.26E-02	2.09E-05
Cm-247	3.48E-05	2.22E-07	6.32E-07	9.55E-07	1.03E-06	1.65E+00	1.61E-03
Cm-248	1.46E-04	8.98E-07	2.58E-06	4.19E-06	5.10E-06	8.16E+00	7.49E-03
Cm-249	3.85E-06	1.41E-08	3.95E-08	6.06E-08	6.73E-08	1.08E-01	1.19E-04
Cm-250	1.48E-03	9.14E-06	2.63E-05	4.26E-05	5.18E-05	8.29E+01	7.61E-02
Co-56	3.82E-04	2.46E-06	7.15E-06	1.17E-05	1.42E-05	2.28E+01	2.06E-02
Co-57	1.27E-05	8.01E-08	2.13E-07	2.81E-07	2.85E-07	4.56E-01	5.82E-04
Co-58	1.08E-04	6.84E-07	1.96E-06	3.08E-06	3.50E-06	5.60E+00	5.18E-03
Co-60	2.69E-04	1.72E-06	4.99E-06	8.07E-06	9.62E-06	1.54E+01	1.39E-02
Co-60m	4.95E-07	2.88E-09	7.69E-09	1.18E-08	1.40E-08	2.24E-02	2.27E-05
Cs-134	1.73E-04	1.10E-06	3.14E-06	4.92E-06	5.56E-06	8.89E+00	8.26E-03
Cs-135	5.91E-09	2.18E-11	4.23E-11	4.88E-11	4.89E-11	7.83E-05	2.53E-06
Cs-137	3.65E-07	2.51E-10	4.38E-10	5.34E-10	5.43E-10	8.69E-04	1.10E-05
Dy-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dy-159	4.57E-06	1.79E-08	2.77E-08	2.83E-08	2.83E-08	4.52E-02	1.17E-04
Es-253	5.84E-08	2.41E-10	6.33E-10	9.26E-10	9.92E-10	1.59E-03	1.75E-06
Es-254	1.03E-06	2.43E-09	5.02E-09	6.50E-09	6.76E-09	1.08E-02	1.72E-05
Es-255	7.97E-08	4.82E-10	1.38E-09	2.21E-09	2.69E-09	4.30E-03	5.78E-06
Eu-146	2.62E-04	1.66E-06	4.76E-06	7.55E-06	8.77E-06	1.40E+01	1.30E-02
Eu-148	2.45E-04	1.55E-06	4.44E-06	6.95E-06	7.89E-06	1.26E+01	1.18E-02
Eu-149	6.83E-06	3.37E-08	8.03E-08	1.13E-07	1.20E-07	1.92E-01	2.37E-04
Eu-150	1.72E-04	1.08E-06	3.08E-06	4.76E-06	5.31E-06	8.50E+00	8.08E-03
Eu-152	1.27E-04	8.03E-07	2.30E-06	3.63E-06	4.22E-06	6.74E+00	6.28E-03
Eu-154	1.37E-04	8.63E-07	2.48E-06	3.92E-06	4.55E-06	7.29E+00	6.75E-03
Eu-155	6.29E-06	3.56E-08	8.34E-08	1.02E-07	1.02E-07	1.63E-01	2.53E-04
Fe-55	1.69E-14	1.08E-16	2.86E-16	3.81E-16	3.84E-16	6.15E-10	7.81E-13
Fe-59	1.28E-04	8.20E-07	2.37E-06	3.82E-06	4.52E-06	7.23E+00	6.56E-03
Fe-60	2.67E-09	8.14E-12	1.39E-11	1.52E-11	1.52E-11	2.43E-05	8.09E-07
Fm-254	8.47E-07	4.86E-09	1.39E-08	2.24E-08	2.73E-08	4.37E-02	4.05E-05

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Fm-255	8.36E-07	1.56E-09	2.85E-09	3.34E-09	3.36E-09	5.38E-03	1.11E-05
Fm-257	1.54E-05	9.33E-08	2.55E-07	3.63E-07	3.89E-07	6.22E-01	7.03E-04
Fr-221	3.14E-06	2.00E-08	5.58E-08	8.01E-08	8.33E-08	1.33E-01	1.46E-04
Fr-223	9.03E-06	3.29E-08	7.79E-08	1.04E-07	1.10E-07	1.76E-01	2.51E-04
Ga-68	1.16E-04	6.82E-07	1.93E-06	2.98E-06	3.28E-06	5.25E+00	5.01E-03
Gd-146	2.62E-05	1.44E-07	3.47E-07	4.52E-07	4.57E-07	7.30E-01	1.02E-03
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-150	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-151	7.20E-06	3.57E-08	8.28E-08	1.11E-07	1.15E-07	1.83E-01	2.51E-04
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	1.08E-05	5.23E-08	1.11E-07	1.33E-07	1.33E-07	2.13E-01	3.63E-04
Ge-68	4.22E-09	7.06E-13	7.06E-13	7.06E-13	7.06E-13	1.13E-06	1.04E-08
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.04E-05	5.22E-08	1.07E-07	1.25E-07	1.25E-07	2.00E-01	3.61E-04
Hf-174	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-175	3.84E-05	2.37E-07	6.49E-07	9.55E-07	1.02E-06	1.63E+00	1.72E-03
Hf-178m	2.46E-04	1.56E-06	4.40E-06	6.63E-06	7.18E-06	1.15E+01	1.14E-02
Hf-181	5.86E-05	3.70E-07	1.04E-06	1.56E-06	1.69E-06	2.71E+00	2.71E-03
Hf-182	2.60E-05	1.66E-07	4.67E-07	6.85E-07	7.20E-07	1.15E+00	1.21E-03
Hg-194	1.89E-08	4.80E-12	4.80E-12	4.80E-12	4.80E-12	7.68E-06	5.24E-08
Hg-203	2.59E-05	1.66E-07	4.68E-07	6.90E-07	7.29E-07	1.17E+00	1.21E-03
Hg-206	1.74E-05	8.66E-08	2.42E-07	3.58E-07	3.83E-07	6.13E-01	6.49E-04
Ho-163	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ho-166m	1.79E-04	1.13E-06	3.23E-06	5.00E-06	5.60E-06	8.97E+00	8.51E-03
I-125	3.72E-06	6.94E-09	7.51E-09	7.50E-09	7.50E-09	1.20E-02	4.41E-05
I-129	2.32E-06	5.22E-09	6.06E-09	6.06E-09	6.06E-09	9.70E-03	3.34E-05
In-113m	2.87E-05	1.81E-07	5.14E-07	7.79E-07	8.42E-07	1.35E+00	1.32E-03
In-114	1.13E-05	1.17E-08	1.83E-08	2.35E-08	2.53E-08	4.05E-02	8.49E-05
In-114m	8.50E-06	5.08E-08	1.42E-07	2.14E-07	2.32E-07	3.72E-01	3.81E-04
In-115	4.37E-08	8.27E-11	1.80E-10	2.23E-10	2.25E-10	3.61E-04	7.71E-06
In-115m	1.77E-05	1.10E-07	3.12E-07	4.68E-07	5.00E-07	8.00E-01	8.10E-04
Ir-192	9.05E-05	5.76E-07	1.63E-06	2.48E-06	2.67E-06	4.28E+00	4.22E-03
Ir-192n	9.91E-08	3.53E-10	7.88E-10	9.50E-10	9.59E-10	1.53E-03	7.77E-06
Ir-194	2.11E-05	7.51E-08	1.97E-07	2.99E-07	3.30E-07	5.29E-01	5.57E-04
Ir-194m	2.59E-04	1.65E-06	4.71E-06	7.22E-06	7.95E-06	1.27E+01	1.21E-02
K-40	2.38E-05	1.11E-07	3.16E-07	5.14E-07	6.24E-07	9.98E-01	9.27E-04
K-42	4.67E-05	2.20E-07	5.95E-07	9.59E-07	1.16E-06	1.86E+00	1.74E-03
Kr-81	1.83E-07	5.99E-10	1.67E-09	2.45E-09	2.59E-09	4.15E-03	4.46E-06
Kr-83m	3.81E-08	1.40E-11	1.46E-11	1.46E-11	1.46E-11	2.34E-05	1.28E-07
Kr-85	1.23E-06	1.95E-09	5.18E-09	7.79E-09	8.51E-09	1.36E-02	2.81E-05
La-137	2.35E-06	5.65E-09	6.68E-09	6.69E-09	6.69E-09	1.07E-02	3.59E-05
La-138	1.31E-04	8.38E-07	2.43E-06	3.92E-06	4.71E-06	7.53E+00	6.80E-03
Lu-172	2.13E-04	1.34E-06	3.83E-06	6.06E-06	7.03E-06	1.13E+01	1.05E-02
Lu-172m	5.31E-10	6.26E-13	8.64E-13	8.68E-13	8.68E-13	1.39E-06	4.55E-09
Lu-173	1.91E-05	1.07E-07	2.56E-07	3.44E-07	3.60E-07	5.75E-01	7.56E-04
Lu-174	1.20E-05	6.85E-08	1.73E-07	2.55E-07	2.94E-07	4.71E-01	5.21E-04
Lu-174m	6.07E-06	3.00E-08	6.04E-08	7.20E-08	7.54E-08	1.21E-01	2.08E-04

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Lu-176	5.22E-05	3.29E-07	9.24E-07	1.35E-06	1.42E-06	2.28E+00	2.42E-03
Lu-177	3.75E-06	2.32E-08	6.29E-08	8.80E-08	9.07E-08	1.45E-01	1.75E-04
Lu-177m	1.08E-04	6.80E-07	1.88E-06	2.73E-06	2.88E-06	4.61E+00	4.94E-03
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	9.21E-05	5.86E-07	1.68E-06	2.65E-06	3.04E-06	4.86E+00	4.47E-03
Mo-93	4.47E-07	2.57E-10	2.56E-10	2.56E-10	2.56E-10	4.09E-04	1.99E-06
Na-22	2.39E-04	1.53E-06	4.39E-06	6.97E-06	8.06E-06	1.29E+01	1.19E-02
Nb-91	5.53E-07	1.33E-09	3.43E-09	5.18E-09	5.70E-09	9.12E-03	9.87E-06
Nb-91m	3.06E-06	1.74E-08	4.97E-08	7.97E-08	9.45E-08	1.51E-01	1.40E-04
Nb-92	1.66E-04	1.05E-06	3.01E-06	4.74E-06	5.39E-06	8.63E+00	7.98E-03
Nb-93m	7.97E-08	4.58E-11	4.57E-11	4.57E-11	4.57E-11	7.30E-05	3.55E-07
Nb-94	1.73E-04	1.10E-06	3.14E-06	4.95E-06	5.64E-06	9.02E+00	8.33E-03
Nb-95	8.48E-05	5.38E-07	1.54E-06	2.43E-06	2.76E-06	4.41E+00	4.08E-03
Nb-95m	7.30E-06	4.38E-08	1.24E-07	1.81E-07	1.89E-07	3.03E-01	3.30E-04
Nd-144	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-59	1.73E-09	1.10E-11	3.14E-11	4.83E-11	5.34E-11	8.54E-05	8.08E-08
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-235	2.52E-07	4.53E-10	9.59E-10	1.18E-09	1.18E-09	1.89E-03	3.32E-06
Np-236	1.49E-05	8.92E-08	2.34E-07	3.09E-07	3.13E-07	5.01E-01	6.50E-04
Np-237	2.85E-06	1.40E-08	3.34E-08	4.18E-08	4.19E-08	6.71E-02	1.00E-04
Np-238	6.57E-05	4.06E-07	1.17E-06	1.86E-06	2.16E-06	3.46E+00	3.18E-03
Np-239	1.89E-05	1.17E-07	3.16E-07	4.39E-07	4.53E-07	7.25E-01	8.58E-04
Np-240	1.17E-04	7.26E-07	2.07E-06	3.22E-06	3.65E-06	5.85E+00	5.52E-03
Np-240m	4.38E-05	2.30E-07	6.48E-07	1.01E-06	1.15E-06	1.83E+00	1.74E-03
Os-185	7.64E-05	4.79E-07	1.35E-06	2.09E-06	2.35E-06	3.76E+00	3.57E-03
Os-186	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Os-194	2.58E-07	9.10E-10	1.35E-09	1.38E-09	1.38E-09	2.20E-03	5.94E-06
P-32	9.95E-06	7.75E-09	1.06E-08	1.24E-08	1.27E-08	2.04E-02	6.26E-05
Pa-231	4.05E-06	2.34E-08	6.46E-08	9.49E-08	1.01E-07	1.61E-01	1.69E-04
Pa-233	2.36E-05	1.48E-07	4.12E-07	6.02E-07	6.36E-07	1.02E+00	1.08E-03
Pa-234	1.61E-04	1.01E-06	2.90E-06	4.53E-06	5.17E-06	8.28E+00	7.79E-03
Pa-234m	1.31E-05	2.27E-08	4.79E-08	6.96E-08	7.86E-08	1.26E-01	1.66E-04
Pb-202	2.20E-08	4.45E-12	4.45E-12	4.45E-12	4.45E-12	7.12E-06	5.66E-08
Pb-205	2.22E-08	4.51E-12	4.51E-12	4.51E-12	4.51E-12	7.21E-06	5.75E-08
Pb-209	3.72E-07	1.84E-10	3.72E-10	4.64E-10	4.71E-10	7.53E-04	1.17E-05
Pb-210	2.53E-07	8.31E-10	1.28E-09	1.31E-09	1.31E-09	2.09E-03	5.50E-06
Pb-211	1.26E-05	4.85E-08	1.33E-07	2.06E-07	2.30E-07	3.68E-01	3.76E-04
Pb-212	1.54E-05	9.71E-08	2.66E-07	3.78E-07	3.95E-07	6.31E-01	7.13E-04
Pb-214	2.84E-05	1.75E-07	4.94E-07	7.34E-07	7.86E-07	1.26E+00	1.30E-03
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-143	3.47E-05	2.10E-07	5.88E-07	9.18E-07	1.04E-06	1.66E+00	1.58E-03
Pm-144	1.74E-04	1.09E-06	3.12E-06	4.83E-06	5.42E-06	8.67E+00	8.12E-03
Pm-145	3.08E-06	9.89E-09	1.40E-08	1.42E-08	1.42E-08	2.28E-02	6.42E-05
Pm-146	8.37E-05	5.23E-07	1.48E-06	2.30E-06	2.57E-06	4.11E+00	3.89E-03
Pm-147	3.28E-09	1.18E-11	2.30E-11	2.69E-11	2.70E-11	4.32E-05	1.01E-06
Pm-148	7.13E-05	4.06E-07	1.16E-06	1.86E-06	2.18E-06	3.49E+00	3.22E-03
Pm-148m	2.22E-04	1.40E-06	4.02E-06	6.25E-06	7.02E-06	1.12E+01	1.05E-02

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Po-208	2.34E-09	1.47E-11	4.15E-11	6.32E-11	7.01E-11	1.12E-04	1.09E-07
Po-209	6.74E-07	4.26E-09	1.20E-08	1.84E-08	2.08E-08	3.33E-02	3.22E-05
Po-210	1.08E-09	6.84E-12	1.96E-11	3.08E-11	3.53E-11	5.64E-05	5.20E-08
Po-211	9.06E-07	5.74E-09	1.65E-08	2.58E-08	2.94E-08	4.71E-02	4.36E-05
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	4.17E-09	2.64E-11	7.55E-11	1.19E-10	1.35E-10	2.17E-04	2.00E-07
Po-214	9.19E-09	5.84E-11	1.67E-10	2.64E-10	3.00E-10	4.80E-04	4.44E-07
Po-215	1.96E-08	1.25E-10	3.56E-10	5.42E-10	5.91E-10	9.45E-04	9.11E-07
Po-216	1.69E-09	1.08E-11	3.08E-11	4.86E-11	5.55E-11	8.87E-05	8.17E-08
Po-218	7.76E-13	2.71E-15	5.07E-15	5.77E-15	5.77E-15	9.23E-09	3.06E-10
Pr-144	1.88E-05	4.26E-08	8.94E-08	1.32E-07	1.54E-07	2.47E-01	2.93E-04
Pr-144m	1.27E-06	4.32E-09	7.40E-09	9.39E-09	1.03E-08	1.65E-02	2.94E-05
Pt-190	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pt-193	1.25E-08	2.73E-12	2.73E-12	2.73E-12	2.73E-12	4.37E-06	3.30E-08
Pu-236	7.81E-08	6.83E-11	9.52E-11	1.06E-10	1.08E-10	1.72E-04	5.06E-07
Pu-237	4.99E-06	2.90E-08	7.25E-08	9.20E-08	9.21E-08	1.47E-01	2.09E-04
Pu-238	6.99E-08	5.23E-11	6.47E-11	6.94E-11	6.95E-11	1.11E-04	3.92E-07
Pu-239	3.57E-08	6.04E-11	1.26E-10	1.67E-10	1.73E-10	2.77E-04	4.40E-07
Pu-240	6.63E-08	5.15E-11	6.49E-11	7.01E-11	7.06E-11	1.13E-04	3.84E-07
Pu-241	1.67E-10	9.91E-13	2.52E-12	3.26E-12	3.27E-12	5.23E-06	7.18E-09
Pu-242	6.49E-08	9.42E-11	2.01E-10	2.99E-10	3.53E-10	5.64E-04	7.51E-07
Pu-243	2.65E-06	1.47E-08	3.53E-08	4.40E-08	4.47E-08	7.15E-02	1.13E-04
Pu-244	2.24E-06	1.35E-08	3.90E-08	6.33E-08	7.69E-08	1.23E-01	1.13E-04
Pu-246	1.46E-05	8.73E-08	2.31E-07	3.19E-07	3.27E-07	5.23E-01	6.34E-04
Ra-223	1.48E-05	9.22E-08	2.48E-07	3.47E-07	3.62E-07	5.79E-01	6.70E-04
Ra-224	1.12E-06	7.18E-09	2.03E-08	2.97E-08	3.09E-08	4.95E-02	5.27E-05
Ra-225	1.28E-06	4.04E-09	5.55E-09	5.57E-09	5.57E-09	8.91E-03	2.88E-05
Ra-226	7.80E-07	4.95E-09	1.37E-08	1.94E-08	1.98E-08	3.18E-02	3.63E-05
Ra-228	8.57E-08	4.12E-11	4.11E-11	4.11E-11	4.11E-11	6.58E-05	3.37E-07
Rb-83	5.42E-05	3.43E-07	9.80E-07	1.51E-06	1.67E-06	2.67E+00	2.52E-03
Rb-84	1.02E-04	6.35E-07	1.82E-06	2.86E-06	3.25E-06	5.19E+00	4.82E-03
Rb-87	9.21E-09	3.58E-11	7.17E-11	8.41E-11	8.43E-11	1.35E-04	4.17E-06
Re-183	1.60E-05	9.08E-08	2.17E-07	2.80E-07	2.86E-07	4.58E-01	6.46E-04
Re-184	9.75E-05	6.13E-07	1.73E-06	2.70E-06	3.07E-06	4.91E+00	4.66E-03
Re-184m	4.11E-05	2.56E-07	7.03E-07	1.05E-06	1.17E-06	1.87E+00	1.92E-03
Re-186	5.07E-06	1.40E-08	3.40E-08	4.41E-08	4.48E-08	7.17E-02	1.16E-04
Re-186m	1.53E-06	7.26E-09	1.39E-08	1.52E-08	1.52E-08	2.43E-02	4.97E-05
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Re-188	1.73E-05	5.17E-08	1.30E-07	1.89E-07	2.06E-07	3.29E-01	3.84E-04
Rh-101	3.00E-05	1.87E-07	5.17E-07	7.32E-07	7.57E-07	1.21E+00	1.37E-03
Rh-102	5.77E-05	3.53E-07	1.01E-06	1.55E-06	1.73E-06	2.77E+00	2.62E-03
Rh-102m	2.37E-04	1.51E-06	4.31E-06	6.76E-06	7.66E-06	1.23E+01	1.14E-02
Rh-103m	9.64E-08	9.52E-11	9.88E-11	9.88E-11	9.88E-11	1.58E-04	6.55E-07
Rh-106	4.04E-05	1.75E-07	4.59E-07	7.01E-07	7.82E-07	1.25E+00	1.25E-03
Rn-218	8.45E-08	5.36E-10	1.53E-09	2.38E-09	2.66E-09	4.26E-03	3.97E-06
Rn-219	6.42E-06	4.11E-08	1.16E-07	1.74E-07	1.86E-07	2.97E-01	2.99E-04
Rn-220	7.02E-08	4.46E-10	1.27E-09	1.96E-09	2.17E-09	3.47E-03	3.28E-06

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Rn-222	4.34E-08	2.76E-10	7.86E-10	1.21E-09	1.33E-09	2.13E-03	2.02E-06
Ru-103	5.53E-05	3.51E-07	1.00E-06	1.54E-06	1.69E-06	2.71E+00	2.58E-03
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	1.55E-09	4.36E-12	7.09E-12	7.62E-12	7.62E-12	1.22E-05	3.59E-07
Sb-124	2.02E-04	1.27E-06	3.69E-06	5.94E-06	7.06E-06	1.13E+01	1.03E-02
Sb-125	4.83E-05	3.01E-07	8.54E-07	1.31E-06	1.45E-06	2.32E+00	2.22E-03
Sb-126	3.09E-04	1.95E-06	5.57E-06	8.69E-06	9.76E-06	1.56E+01	1.46E-02
Sb-126m	1.81E-04	1.10E-06	3.14E-06	4.87E-06	5.45E-06	8.72E+00	8.20E-03
Sc-44	2.43E-04	1.49E-06	4.30E-06	6.78E-06	7.78E-06	1.24E+01	1.15E-02
Sc-46	2.20E-04	1.40E-06	4.03E-06	6.42E-06	7.50E-06	1.20E+01	1.09E-02
Se-75	4.16E-05	2.65E-07	7.44E-07	1.08E-06	1.13E-06	1.81E+00	1.94E-03
Se-79	1.69E-09	4.66E-12	7.46E-12	7.97E-12	7.96E-12	1.27E-05	3.56E-07
Si-32	3.35E-09	1.11E-11	2.01E-11	2.24E-11	2.24E-11	3.59E-05	1.23E-06
Sm-145	6.38E-06	2.21E-08	3.25E-08	3.33E-08	3.33E-08	5.32E-02	1.44E-04
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	4.45E-10	4.50E-13	4.53E-13	4.53E-13	4.53E-13	7.25E-07	3.09E-09
Sn-113	1.98E-06	5.72E-09	1.27E-08	1.79E-08	1.86E-08	2.97E-02	4.03E-05
Sn-119m	1.15E-06	1.66E-09	1.72E-09	1.72E-09	1.72E-09	2.75E-03	1.08E-05
Sn-121	1.06E-08	4.37E-11	9.11E-11	1.10E-10	1.10E-10	1.76E-04	4.65E-06
Sn-121m	4.26E-07	8.02E-10	9.00E-10	9.04E-10	9.04E-10	1.45E-03	6.20E-06
Sn-123	7.65E-06	9.19E-09	1.98E-08	2.92E-08	3.32E-08	5.31E-02	8.19E-05
Sn-126	5.63E-06	2.97E-08	6.80E-08	8.15E-08	8.14E-08	1.30E-01	2.13E-04
Sr-85	5.51E-05	3.49E-07	9.96E-07	1.53E-06	1.69E-06	2.71E+00	2.56E-03
Sr-89	8.03E-06	5.65E-09	7.83E-09	9.25E-09	9.52E-09	1.52E-02	5.13E-05
Sr-90	1.91E-07	1.47E-10	3.18E-10	3.99E-10	4.04E-10	6.46E-04	1.15E-05
Ta-179	2.48E-06	1.19E-08	2.22E-08	2.36E-08	2.36E-08	3.77E-02	8.13E-05
Ta-182	1.39E-04	8.82E-07	2.51E-06	3.99E-06	4.68E-06	7.49E+00	6.98E-03
Tb-157	4.72E-07	1.76E-09	2.63E-09	2.66E-09	2.66E-09	4.26E-03	1.15E-05
Tb-158	8.79E-05	5.48E-07	1.55E-06	2.44E-06	2.80E-06	4.48E+00	4.22E-03
Tb-160	1.24E-04	7.80E-07	2.24E-06	3.54E-06	4.09E-06	6.54E+00	6.07E-03
Tc-95	8.73E-05	5.52E-07	1.59E-06	2.49E-06	2.84E-06	4.54E+00	4.19E-03
Tc-95m	7.51E-05	4.75E-07	1.35E-06	2.10E-06	2.35E-06	3.76E+00	3.57E-03
Tc-97	5.32E-07	3.47E-10	3.44E-10	3.44E-10	3.44E-10	5.51E-04	2.58E-06
Tc-97m	5.10E-07	5.43E-10	8.29E-10	9.49E-10	9.49E-10	1.52E-03	4.30E-06
Tc-98	1.56E-04	9.97E-07	2.86E-06	4.47E-06	5.04E-06	8.07E+00	7.49E-03
Tc-99	7.65E-09	2.95E-11	5.87E-11	6.88E-11	6.90E-11	1.10E-04	3.36E-06
Te-121	6.39E-05	3.98E-07	1.13E-06	1.75E-06	1.94E-06	3.10E+00	2.93E-03
Te-121m	2.31E-05	1.42E-07	3.99E-07	5.86E-07	6.21E-07	9.94E-01	1.05E-03
Te-123	2.88E-09	4.80E-12	5.03E-12	5.02E-12	5.02E-12	8.03E-06	3.07E-08
Te-123m	1.54E-05	9.31E-08	2.52E-07	3.50E-07	3.57E-07	5.72E-01	6.78E-04
Te-125m	3.13E-06	6.00E-09	6.81E-09	6.95E-09	6.95E-09	1.11E-02	3.92E-05
Te-127	1.23E-06	3.71E-09	1.03E-08	1.54E-08	1.67E-08	2.67E-02	3.91E-05
Te-127m	9.97E-07	1.94E-09	2.38E-09	2.53E-09	2.57E-09	4.11E-03	1.31E-05
Te-129	1.35E-05	4.57E-08	1.23E-07	1.87E-07	2.06E-07	3.29E-01	3.49E-04
Te-129m	6.81E-06	2.42E-08	6.39E-08	9.81E-08	1.10E-07	1.77E-01	1.83E-04

Table C-9 (Cont.)

Radionuclide	Surface (mrem/yr per pCi/m^2)	1 cm (mrem/yr per pCi/m^3)	5 cm (mrem/yr per pCi/ m^3)	15 cm (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/m^3)	Infinite (mrem/yr per pCi/g)[a]	Air Submersion (mrem/yr per pCi/m^3)
Th-227	1.34E-05	8.37E-08	2.32E-07	3.36E-07	3.53E-07	5.64E-01	6.10E-04
Th-228	2.52E-07	1.33E-09	3.39E-09	4.45E-09	4.53E-09	7.25E-03	9.63E-06
Th-229	9.05E-06	5.36E-08	1.37E-07	1.77E-07	1.80E-07	2.88E-01	3.88E-04
Th-230	7.48E-08	2.46E-10	5.55E-10	6.82E-10	6.91E-10	1.11E-03	1.78E-06
Th-231	1.77E-06	7.32E-09	1.67E-08	2.03E-08	2.03E-08	3.25E-02	5.41E-05
Th-232	5.29E-08	1.28E-10	2.59E-10	2.98E-10	2.99E-10	4.78E-04	9.22E-07
Th-234	9.56E-07	5.24E-09	1.20E-08	1.45E-08	1.45E-08	2.32E-02	3.76E-05
Ti-44	1.44E-05	8.08E-08	1.77E-07	2.03E-07	2.03E-07	3.25E-01	5.70E-04
Tl-202	5.10E-05	3.21E-07	8.91E-07	1.33E-06	1.45E-06	2.32E+00	2.32E-03
Tl-204	1.27E-06	1.11E-09	2.23E-09	2.60E-09	2.62E-09	4.18E-03	2.04E-05
Tl-206	7.15E-06	4.74E-09	6.61E-09	7.79E-09	7.99E-09	1.28E-02	4.64E-05
Tl-207	6.55E-06	5.44E-09	9.99E-09	1.37E-08	1.49E-08	2.39E-02	5.38E-05
Tl-208	3.46E-04	2.22E-06	6.48E-06	1.08E-05	1.35E-05	2.17E+01	1.96E-02
Tl-209	2.36E-04	1.47E-06	4.23E-06	6.76E-06	8.04E-06	1.29E+01	1.19E-02
Tl-210	3.08E-04	1.91E-06	5.50E-06	8.84E-06	1.05E-05	1.68E+01	1.54E-02
Tm-168	1.37E-04	8.58E-07	2.42E-06	3.74E-06	4.19E-06	6.71E+00	6.43E-03
Tm-170	2.91E-06	3.15E-09	6.10E-09	7.08E-09	7.10E-09	1.14E-02	3.80E-05
Tm-171	6.20E-08	2.92E-10	5.31E-10	5.63E-10	5.63E-10	9.00E-04	1.99E-06
U-232	8.52E-08	1.73E-10	3.61E-10	4.46E-10	4.52E-10	7.23E-04	1.26E-06
U-233	5.56E-08	1.69E-10	4.10E-10	5.56E-10	5.74E-10	9.19E-04	1.24E-06
U-234	6.77E-08	9.80E-11	1.82E-10	2.15E-10	2.16E-10	3.46E-04	7.17E-07
U-235	1.74E-05	1.10E-07	3.04E-07	4.26E-07	4.38E-07	7.01E-01	8.02E-04
U-235m	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-236	5.63E-08	5.95E-11	9.64E-11	1.10E-10	1.10E-10	1.76E-04	4.41E-07
U-237	1.44E-05	8.50E-08	2.18E-07	2.93E-07	2.99E-07	4.78E-01	6.17E-04
U-238	4.57E-08	4.97E-11	8.35E-11	1.01E-10	1.07E-10	1.71E-04	3.74E-07
U-240	6.53E-07	2.92E-09	7.16E-09	9.25E-09	9.34E-09	1.49E-02	2.42E-05
V-49	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
V-50	1.49E-04	9.67E-07	2.81E-06	4.60E-06	5.59E-06	8.95E+00	8.02E-03
W-181	3.97E-06	1.97E-08	3.74E-08	4.00E-08	4.00E-08	6.41E-02	1.34E-04
W-185	1.95E-08	8.49E-11	1.87E-10	2.29E-10	2.31E-10	3.70E-04	5.79E-06
W-188	2.11E-07	1.32E-09	3.64E-09	5.29E-09	5.56E-09	8.89E-03	1.28E-05
Xe-127	2.99E-05	1.81E-07	5.00E-07	7.24E-07	7.57E-07	1.21E+00	1.32E-03
Y-88	2.81E-04	1.82E-06	5.30E-06	8.68E-06	1.06E-05	1.69E+01	1.52E-02
Y-90	1.28E-05	1.47E-08	2.03E-08	2.42E-08	2.51E-08	4.02E-02	9.24E-05
Y-91	8.68E-06	8.20E-09	1.45E-08	1.97E-08	2.18E-08	3.49E-02	7.02E-05
Yb-169	3.44E-05	1.95E-07	4.74E-07	6.29E-07	6.47E-07	1.04E+00	1.39E-03
Zn-65	6.27E-05	4.00E-07	1.16E-06	1.86E-06	2.18E-06	3.49E+00	3.18E-03
Zr-88	4.27E-05	2.71E-07	7.72E-07	1.17E-06	1.26E-06	2.02E+00	1.97E-03
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.53E-11
Zr-95	8.13E-05	5.16E-07	1.48E-06	2.32E-06	2.63E-06	4.20E+00	3.89E-03

[a] Density used is 1.6 g/cm^3.

C.6 SLOPE FACTORS

The default morbidity and mortality slope factors for external exposure used in RESRAD-BUILD are from FGR 13 (Eckerman et al. 1999) and DCFPAK3.02. Tables C-10 and C-11 list the morbidity and mortality slope factors for external exposure from an infinite volume source and from submersion in contaminated air from FGR13 and DCFPAK3.02, respectively.

Table C-10 Morbidity and Mortality Slope Factors for External Exposure from FGR 13 for 30 Day Cut-off Half-life Principal and Associated Radionuclides

Radionuclide	FGR 13 Morbidity Slope Factors		FGR 13 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Ac-225	4.50E-08	5.79E-11	3.06E-08	3.91E-11
Ac-227	3.48E-10	4.62E-13	2.36E-10	3.12E-13
Ac-228	4.53E-06	4.22E-09	3.08E-06	2.86E-09
Ag-105	2.15E-06	2.11E-09	1.46E-06	1.44E-09
Ag-108	8.56E-08	8.49E-11	5.85E-08	5.91E-11
Ag-108m	7.18E-06	6.80E-09	4.89E-06	4.62E-09
Ag-110	1.69E-07	1.65E-10	1.16E-07	1.15E-10
Ag-110m	1.30E-05	1.20E-08	8.84E-06	8.14E-09
Al-26	1.33E-05	1.21E-08	9.03E-06	8.24E-09
Am-241	2.76E-08	5.84E-11	1.86E-08	3.89E-11
Am-242	3.48E-08	4.93E-11	2.36E-08	3.34E-11
Am-242m	1.05E-09	2.07E-12	6.97E-10	1.31E-12
Am-243	9.47E-08	1.65E-10	6.41E-08	1.10E-10
Am-245	1.04E-07	1.23E-10	7.09E-08	8.31E-11
Am-246m	4.83E-06	4.45E-09	3.29E-06	3.02E-09
Ar-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ar-39	5.94E-10	1.94E-12	4.04E-10	1.71E-12
As-73	5.78E-09	1.33E-11	3.88E-09	8.84E-12
At-217	1.32E-09	1.27E-12	8.94E-10	8.68E-13
At-218	3.57E-09	8.34E-12	2.39E-09	5.54E-12
Au-194	4.93E-06	4.66E-09	3.36E-06	3.16E-09
Au-195	1.38E-07	2.42E-10	9.35E-08	1.62E-10
Ba-133	1.44E-06	1.50E-09	9.77E-07	1.02E-09
Ba-137m	2.69E-06	2.52E-09	1.83E-06	1.72E-09
Be-10	7.43E-10	2.36E-12	5.04E-10	2.08E-12
Be-7	2.13E-07	2.06E-10	1.45E-07	1.39E-10
Bi-207	7.08E-06	6.62E-09	4.82E-06	4.50E-09
Bi-210	2.76E-09	5.28E-12	1.94E-09	4.43E-12
Bi-210m	1.01E-06	1.04E-09	6.85E-07	7.05E-10
Bi-211	1.88E-07	1.89E-10	1.28E-07	1.28E-10
Bi-212	8.87E-07	8.20E-10	6.05E-07	5.58E-10
Bi-213	5.65E-07	5.55E-10	3.85E-07	3.78E-10
Bi-214	7.48E-06	6.83E-09	5.10E-06	4.65E-09
Bk-247	3.09E-07	3.83E-10	2.10E-07	2.59E-10
Bk-249	2.63E-12	9.90E-15	1.74E-12	8.05E-15
Bk-250	4.23E-06	3.88E-09	2.87E-06	2.64E-09
C-14	7.83E-12	4.27E-14	5.21E-12	3.77E-14
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors External (risk/yr per pCi/g)	FGR 13 Morbidity Slope Factors Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Slope Factors External (risk/yr per pCi/g)	FGR 13 Mortality Slope Factors Submersion (risk/yr per pCi/m^3)
Ca-45	3.96E-11	2.30E-13	2.66E-11	2.09E-13
Cd-109	8.73E-09	1.86E-11	5.79E-09	1.18E-11
Cd-113	7.36E-11	3.84E-13	4.95E-11	3.49E-13
Cd-113m	4.45E-10	1.51E-12	3.02E-10	1.33E-12
Cd-115m	1.13E-07	1.08E-10	7.72E-08	7.46E-11
Ce-139	4.54E-07	5.44E-10	3.08E-07	3.68E-10
Ce-141	2.27E-07	2.79E-10	1.54E-07	1.89E-10
Ce-144	5.02E-08	6.75E-11	3.41E-08	4.55E-11
Cf-248	4.73E-11	2.38E-13	2.79E-11	1.35E-13
Cf-249	1.37E-06	1.35E-09	9.26E-07	9.19E-10
Cf-250	4.48E-11	2.27E-13	2.65E-11	1.30E-13
Cf-251	3.76E-07	4.55E-10	2.56E-07	3.08E-10
Cf-252	8.66E-11	2.78E-13	5.51E-11	1.65E-13
Cf-253	4.86E-11	2.67E-13	3.26E-11	2.42E-13
Cf-254	1.46E-13	7.39E-16	8.65E-14	4.20E-16
Cl-36	1.74E-09	3.50E-12	1.19E-09	2.92E-12
Cm-241	1.94E-06	1.96E-09	1.32E-06	1.33E-09
Cm-242	7.73E-11	3.02E-13	4.79E-11	1.75E-13
Cm-243	4.19E-07	4.86E-10	2.85E-07	3.28E-10
Cm-244	4.85E-11	2.51E-13	2.87E-11	1.43E-13
Cm-245	2.38E-07	3.16E-10	1.62E-07	2.14E-10
Cm-246	4.57E-11	2.30E-13	2.72E-11	1.31E-13
Cm-247	1.31E-06	1.30E-09	8.90E-07	8.76E-10
Cm-248	3.42E-11	1.74E-13	2.03E-11	9.90E-14
Cm-249	8.51E-08	8.30E-11	5.79E-08	5.70E-11
Cm-250	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Co-56	1.80E-05	1.64E-08	1.23E-05	1.12E-08
Co-57	3.55E-07	4.54E-10	2.42E-07	3.07E-10
Co-58	4.48E-06	4.18E-09	3.06E-06	2.84E-09
Co-60	1.24E-05	1.12E-08	8.44E-06	7.65E-09
Co-60m	1.86E-08	1.86E-11	1.26E-08	1.26E-11
Cs-134	7.10E-06	6.63E-09	4.83E-06	4.51E-09
Cs-135	2.36E-11	1.44E-13	1.58E-11	1.31E-13
Cs-137	5.32E-10	1.60E-12	3.67E-10	1.40E-12
Dy-159	3.19E-08	8.34E-11	2.13E-08	5.49E-11
Es-253	1.25E-09	1.44E-12	8.50E-10	9.58E-13
Es-254	8.55E-09	1.35E-11	5.74E-09	8.79E-12
Eu-146	1.16E-05	1.08E-08	7.92E-06	7.34E-09
Eu-148	9.84E-06	9.25E-09	6.70E-06	6.28E-09
Eu-149	1.42E-07	1.75E-10	9.66E-08	1.18E-10
Eu-150b	6.49E-06	6.22E-09	4.41E-06	4.23E-09
Eu-152	5.30E-06	4.96E-09	3.61E-06	3.37E-09
Eu-154	5.83E-06	5.41E-09	3.97E-06	3.68E-09
Eu-155	1.24E-07	1.92E-10	8.43E-08	1.28E-10
Fe-55	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Fe-59	5.83E-06	5.30E-09	3.97E-06	3.61E-09
Fe-60	6.38E-12	3.15E-14	4.23E-12	2.71E-14
Fm-257	3.06E-07	3.78E-10	2.08E-07	2.56E-10

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors External (risk/yr per pCi/g)	FGR 13 Morbidity Slope Factors Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Slope Factors External (risk/yr per pCi/g)	FGR 13 Mortality Slope Factors Submersion (risk/yr per pCi/m^3)
Fr-221	1.11E-07	1.21E-10	7.57E-08	8.27E-11
Fr-223	1.40E-07	1.83E-10	9.53E-08	1.24E-10
Ga-68	4.17E-06	3.99E-09	2.84E-06	2.71E-09
Gd-146	5.56E-07	7.74E-10	3.77E-07	5.21E-10
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-151	1.20E-07	1.67E-10	8.12E-08	1.12E-10
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	1.62E-07	2.73E-10	1.09E-07	1.83E-10
Ge-68	4.69E-13	5.71E-15	3.01E-13	3.50E-15
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.62E-07	2.98E-10	1.10E-07	2.00E-10
Hf-175	1.35E-06	1.43E-09	9.24E-07	9.66E-10
Hf-178m	9.57E-06	9.58E-09	6.52E-06	6.49E-09
Hf-181	2.24E-06	2.25E-09	1.53E-06	1.53E-09
Hf-182	9.10E-07	9.60E-10	6.19E-07	6.50E-10
Hg-194	5.04E-12	4.37E-14	3.01E-12	2.55E-14
Hg-203	9.21E-07	9.60E-10	6.27E-07	6.50E-10
Ho-166m	7.69E-06	7.36E-09	5.24E-06	5.00E-09
I-125	7.24E-09	2.81E-11	4.54E-09	1.73E-11
I-129	6.10E-09	2.16E-11	3.90E-09	1.37E-11
In-113m	1.05E-06	1.04E-09	7.18E-07	7.06E-10
In-114	1.35E-08	1.27E-11	9.22E-09	8.71E-12
In-114m	3.57E-07	3.59E-10	2.43E-07	2.43E-10
In-115	2.70E-10	1.05E-12	1.83E-10	9.42E-13
Ir-192	3.40E-06	3.36E-09	2.31E-06	2.29E-09
Ir-192m	5.39E-07	6.29E-10	3.67E-07	4.26E-10
Ir-194	4.09E-07	3.99E-10	2.78E-07	2.73E-10
Ir-194m	1.01E-05	9.74E-09	6.88E-06	6.62E-09
K-40	7.97E-07	7.24E-10	5.44E-07	4.94E-10
Kr-81	2.18E-08	2.27E-11	1.48E-08	1.54E-11
Kr-83m	1.34E-11	8.89E-14	8.16E-12	5.18E-14
Kr-85	1.05E-08	1.17E-11	7.18E-09	8.44E-12
La-137	6.75E-09	2.35E-11	4.33E-09	1.48E-11
La-138	6.07E-06	5.52E-09	4.13E-06	3.76E-09
Lu-172	8.70E-06	8.13E-09	5.92E-06	5.52E-09
Lu-173	2.92E-07	3.97E-10	1.97E-07	2.67E-10
Lu-174	4.26E-07	4.57E-10	2.91E-07	3.08E-10
Lu-174m	9.88E-08	1.62E-10	6.68E-08	1.09E-10
Lu-176	1.83E-06	1.95E-09	1.25E-06	1.32E-09
Lu-177	1.14E-07	1.33E-10	7.74E-08	9.05E-11
Lu-177m	3.63E-06	3.91E-09	2.48E-06	2.65E-09
Md-258	1.31E-09	3.14E-12	8.59E-10	1.99E-12
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	3.89E-06	3.60E-09	2.65E-06	2.45E-09
Mo-93	2.17E-10	1.27E-12	1.25E-10	7.08E-13
Na-22	1.03E-05	9.56E-09	7.03E-06	6.50E-09
Nb-93m	3.83E-11	2.24E-13	2.21E-11	1.25E-13
Nb-94	7.29E-06	6.76E-09	4.96E-06	4.60E-09

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors		FGR 13 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Nb-95	3.53E-06	3.28E-09	2.41E-06	2.23E-09
Nb-95m	2.32E-07	2.48E-10	1.58E-07	1.68E-10
Ni-59	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Np-235	2.13E-09	3.61E-12	1.42E-09	2.35E-12
Np-236a	3.25E-07	4.29E-10	2.21E-07	2.90E-10
Np-237	5.36E-08	7.93E-11	3.63E-08	5.32E-11
Np-238	2.62E-06	2.41E-09	1.77E-06	1.64E-09
Np-239	5.41E-07	6.33E-10	3.68E-07	4.29E-10
Np-240m	1.51E-06	1.43E-09	1.03E-06	9.67E-10
Os-185	3.11E-06	2.98E-09	2.11E-06	2.02E-09
Os-194	6.57E-10	1.80E-12	4.36E-10	1.18E-12
P-32	9.41E-09	1.33E-11	6.70E-09	1.06E-11
Pa-231	1.39E-07	1.45E-10	9.45E-08	9.82E-11
Pa-233	7.43E-07	7.88E-10	5.04E-07	5.35E-10
Pa-234	8.71E-06	8.20E-09	5.93E-06	5.57E-09
Pa-234m	6.87E-08	6.87E-11	4.72E-08	4.87E-11
Pb-202	3.09E-12	3.13E-14	1.90E-12	1.87E-14
Pb-205	3.50E-12	3.47E-14	2.15E-12	2.07E-14
Pb-209	5.37E-10	1.71E-12	3.65E-10	1.51E-12
Pb-210	1.41E-09	3.76E-12	9.41E-10	2.46E-12
Pb-211	2.29E-07	2.21E-10	1.56E-07	1.51E-10
Pb-212	5.09E-07	5.71E-10	3.47E-07	3.87E-10
Pb-214	9.82E-07	1.01E-09	6.68E-07	6.83E-10
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-143	1.33E-06	1.26E-09	9.03E-07	8.56E-10
Pm-144	6.90E-06	6.52E-09	4.69E-06	4.43E-09
Pm-145	1.61E-08	4.51E-11	1.06E-08	2.92E-11
Pm-146	3.29E-06	3.13E-09	2.24E-06	2.13E-09
Pm-147	3.21E-11	1.44E-13	2.16E-11	1.27E-13
Pm-148	2.80E-06	2.57E-09	1.90E-06	1.75E-09
Pm-148m	8.98E-06	8.47E-09	6.12E-06	5.76E-09
Po-209[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-210	3.95E-11	3.66E-14	2.69E-11	2.49E-14
Po-211	3.58E-08	3.34E-11	2.44E-08	2.28E-11
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-214	3.86E-10	3.59E-13	2.64E-10	2.44E-13
Po-215	7.48E-10	7.29E-13	5.09E-10	4.95E-13
Po-216	7.87E-11	7.29E-14	5.36E-11	4.95E-14
Po-218	4.26E-11	3.95E-14	2.90E-11	2.69E-14
Pr-144	1.94E-07	1.82E-10	1.33E-07	1.27E-10
Pr-144m	8.73E-09	1.82E-11	5.83E-09	1.18E-11
Pt-193	2.78E-12	2.69E-14	1.69E-12	1.59E-14
Pu-236	1.19E-10	3.66E-13	7.66E-11	2.18E-13
Pu-237	1.12E-07	1.59E-10	7.64E-08	1.07E-10
Pu-238	7.22E-11	2.66E-13	4.53E-11	1.57E-13
Pu-239	2.00E-10	2.99E-13	1.34E-10	1.93E-13

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors		FGR 13 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Pu-240	6.98E-11	2.62E-13	4.39E-11	1.53E-13
Pu-241	4.11E-12	5.71E-15	2.79E-12	3.84E-15
Pu-242	6.25E-11	2.23E-13	3.95E-11	1.31E-13
Pu-243	5.50E-08	8.12E-11	3.74E-08	5.49E-11
Pu-244	3.01E-11	0.00E+00	1.80E-11	0.00E+00
Pu-246	4.04E-07	4.88E-10	2.74E-07	3.30E-10
Ra-223	4.34E-07	5.02E-10	2.95E-07	3.40E-10
Ra-224	3.72E-08	3.97E-11	2.53E-08	2.69E-11
Ra-225	5.91E-09	1.79E-11	3.89E-09	1.17E-11
Ra-226	2.29E-08	2.60E-11	1.55E-08	1.76E-11
Ra-228	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Rb-83	2.18E-06	2.08E-09	1.48E-06	1.41E-09
Rb-84	4.22E-06	3.92E-09	2.87E-06	2.66E-09
Rb-87	9.11E-11	4.96E-13	6.13E-11	4.52E-13
Re-184	3.93E-06	3.74E-09	2.69E-06	2.55E-09
Re-184m	1.52E-06	1.55E-09	1.03E-06	1.05E-09
Re-186	5.49E-08	7.52E-11	3.74E-08	5.15E-11
Re-186m	1.75E-08	3.60E-11	1.18E-08	2.39E-11
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Re-188	2.38E-07	2.50E-10	1.62E-07	1.72E-10
Rh-101	8.84E-07	1.00E-09	6.01E-07	6.77E-10
Rh-102	9.73E-06	9.10E-09	6.62E-06	6.19E-09
Rh-102m	2.11E-06	2.01E-09	1.44E-06	1.37E-09
Rh-103m	9.31E-11	4.41E-13	5.55E-11	2.53E-13
Rh-106	9.66E-07	9.17E-10	6.59E-07	6.26E-10
Rn-219	2.25E-07	2.29E-10	1.53E-07	1.55E-10
Rn-220	1.70E-09	1.61E-12	1.16E-09	1.10E-12
Rn-222	1.74E-09	1.66E-12	1.18E-09	1.13E-12
Ru-103	2.04E-06	1.95E-09	1.39E-06	1.33E-09
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	8.77E-12	4.99E-14	5.84E-12	4.43E-14
Sb-124	8.89E-06	8.14E-09	6.05E-06	5.54E-09
Sb-125	1.81E-06	1.75E-09	1.24E-06	1.19E-09
Sb-126	1.28E-05	1.20E-08	8.72E-06	8.17E-09
Sb-126m	6.94E-06	6.55E-09	4.73E-06	4.45E-09
Sc-44	9.95E-06	9.26E-09	6.77E-06	6.29E-09
Sc-46	9.63E-06	8.83E-09	6.56E-06	6.00E-09
Se-75	1.45E-06	1.55E-09	9.82E-07	1.05E-09
Se-79	1.10E-11	6.29E-14	7.30E-12	5.61E-14
Si-32	2.18E-11	1.32E-13	1.46E-11	1.19E-13
Sm-145	3.83E-08	1.04E-10	2.53E-08	6.78E-11
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	3.60E-13	1.78E-15	2.11E-13	1.01E-15
Sn-113	2.02E-08	2.71E-11	1.37E-08	1.78E-11
Sn-119m	1.20E-09	5.18E-12	7.36E-10	3.08E-12
Sn-121	1.30E-10	6.04E-13	8.76E-11	5.47E-13
Sn-121m	8.85E-10	3.41E-12	5.59E-10	2.14E-12

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors External (risk/yr per pCi/g)	FGR 13 Morbidity Slope Factors Submersion (risk/yr per pCi/m^3)	FGR 13 Mortality Slope Factors External (risk/yr per pCi/g)	FGR 13 Mortality Slope Factors Submersion (risk/yr per pCi/m^3)
Sn-123	3.88E-08	3.90E-11	2.65E-08	2.77E-11
Sn-126	9.96E-08	1.61E-10	6.75E-08	1.08E-10
Sr-85	2.20E-06	2.10E-09	1.49E-06	1.43E-09
Sr-89	7.19E-09	1.06E-11	5.10E-09	8.52E-12
Sr-90	4.82E-10	1.64E-12	3.27E-10	1.45E-12
Ta-179	3.62E-08	7.81E-11	2.44E-08	5.21E-11
Ta-180	2.03E-06	2.17E-09	1.38E-06	1.47E-09
Ta-182	6.04E-06	5.64E-09	4.11E-06	3.83E-09
Tb-157	1.63E-09	4.45E-12	1.09E-09	2.92E-12
Tb-158	3.57E-06	3.36E-09	2.43E-06	2.28E-09
Tb-160	5.23E-06	4.87E-09	3.56E-06	3.32E-09
Tc-95	3.63E-06	3.37E-09	2.48E-06	2.29E-09
Tc-95m	2.93E-06	2.80E-09	2.00E-06	1.90E-09
Tc-97	2.94E-10	1.66E-12	1.69E-10	9.21E-13
Tc-97m	1.04E-09	2.73E-12	6.77E-10	1.67E-12
Tc-98	6.45E-06	6.01E-09	4.39E-06	4.09E-09
Tc-99	8.14E-11	4.34E-13	5.48E-11	3.95E-13
Te-121	2.46E-06	2.35E-09	1.68E-06	1.59E-09
Te-121m	7.83E-07	8.31E-10	5.34E-07	5.64E-10
Te-123	2.73E-09	1.13E-11	1.69E-09	6.82E-12
Te-123m	4.48E-07	5.31E-10	3.05E-07	3.60E-10
Te-125m	6.95E-09	2.50E-11	4.40E-09	1.54E-11
Te-127	2.10E-08	2.21E-11	1.42E-08	1.54E-11
Te-127m	2.73E-09	8.38E-12	1.76E-09	5.24E-12
Te-129	2.45E-07	2.41E-10	1.67E-07	1.65E-10
Te-129m	1.38E-07	1.34E-10	9.40E-08	9.14E-11
Th-227	3.78E-07	4.09E-10	2.57E-07	2.77E-10
Th-228	5.59E-09	7.34E-12	3.79E-09	4.95E-12
Th-229	2.25E-07	3.05E-10	1.53E-07	2.06E-10
Th-230	8.19E-10	1.31E-12	5.53E-10	8.71E-13
Th-231	2.45E-08	3.92E-11	1.66E-08	2.63E-11
Th-232	3.42E-10	6.25E-13	2.30E-10	4.10E-13
Th-234	1.63E-08	2.60E-11	1.11E-08	1.75E-11
Ti-44	2.39E-07	4.17E-10	1.62E-07	2.80E-10
Tl-202	1.83E-06	1.87E-09	1.25E-06	1.26E-09
Tl-204	2.76E-09	5.66E-12	1.88E-09	4.27E-12
Tl-206	6.05E-09	9.32E-12	4.30E-09	7.56E-12
Tl-207	1.52E-08	1.74E-11	1.05E-08	1.30E-11
Tl-208	1.76E-05	1.60E-08	1.20E-05	1.09E-08
Tl-209	9.83E-06	9.10E-09	6.70E-06	6.19E-09
Tl-210[a]	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tm-170	1.01E-08	1.88E-11	6.84E-09	1.32E-11
Tm-171	6.97E-10	1.53E-12	4.68E-10	1.02E-12
U-232	5.98E-10	1.01E-12	4.03E-10	6.61E-13
U-233	9.82E-10	1.27E-12	6.66E-10	8.45E-13
U-234	2.52E-10	5.10E-13	1.68E-10	3.26E-13
U-235	5.18E-07	5.94E-10	3.53E-07	4.03E-10
U-236	1.25E-10	3.12E-13	8.21E-11	1.94E-13

Table C-10 (Cont.)

Radionuclide	FGR 13 Morbidity Slope Factors		FGR 13 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
U-237	3.76E-07	4.80E-10	2.56E-07	3.23E-10
U-238	4.99E-11	1.94E-13	3.15E-11	1.16E-13
U-240	7.33E-10	2.67E-12	4.75E-10	1.79E-12
V-49	0.00E+00	0.00E+00	0.00E+00	0.00E+00
W-181	4.86E-08	1.01E-10	3.27E-08	6.75E-11
W-185	2.92E-10	9.29E-13	1.97E-10	7.95E-13
W-188	7.02E-09	7.88E-12	4.78E-09	5.44E-12
Xe-127	9.52E-07	1.04E-09	6.47E-07	7.02E-10
Y-88	1.37E-05	1.23E-08	9.27E-06	8.37E-09
Y-90	1.91E-08	2.29E-11	1.35E-08	1.79E-11
Y-91	2.51E-08	2.70E-11	1.73E-08	1.97E-11
Yb-169	7.75E-07	1.02E-09	5.27E-07	6.87E-10
Zn-65	2.81E-06	2.57E-09	1.91E-06	1.75E-09
Zr-88	1.65E-06	1.62E-09	1.12E-06	1.10E-09
Zr-93	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zr-95	3.40E-06	3.16E-09	2.31E-06	2.15E-09

[a] No values available, database list - 1

Table C-11 Morbidity and Mortality Slope Factors for External Exposure from DCFPAK3.02 for 30 Day Cut-off Half-life Principal and Associated Radionuclides

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Ac-225	4.12E-08	5.15E-11	2.80E-08	3.48E-11
Ac-227	1.99E-10	3.15E-13	1.34E-10	2.07E-13
Ac-228	4.04E-06	3.76E-09	2.76E-06	2.56E-09
Ag-105	2.10E-06	2.07E-09	1.42E-06	1.40E-09
Ag-108	8.83E-08	8.76E-11	6.04E-08	6.08E-11
Ag-108m	7.16E-06	6.77E-09	4.88E-06	4.60E-09
Ag-110	1.71E-07	1.65E-10	1.17E-07	1.15E-10
Ag-110m	1.31E-05	1.20E-08	8.87E-06	8.17E-09
Al-26	1.33E-05	1.21E-08	9.03E-06	8.24E-09
Am-241	2.77E-08	5.80E-11	1.86E-08	3.87E-11
Am-242	3.48E-08	4.92E-11	2.37E-08	3.34E-11
Am-242m	7.58E-10	1.61E-12	5.01E-10	1.01E-12
Am-243	9.78E-08	1.71E-10	6.62E-08	1.14E-10
Am-245	1.04E-07	1.21E-10	7.06E-08	8.29E-11
Am-246m	4.66E-06	4.29E-09	3.18E-06	2.91E-09
Ar-37	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ar-39	5.95E-10	1.94E-12	4.04E-10	1.71E-12
Ar-42	6.97E-10	2.16E-12	4.74E-10	1.89E-12
As-73	5.73E-09	1.32E-11	3.85E-09	8.78E-12

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
At-217	9.36E-10	9.76E-13	6.38E-10	6.62E-13
At-218	2.74E-11	3.08E-14	1.94E-11	2.36E-14
At-219	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Au-194	4.79E-06	4.53E-09	3.26E-06	3.07E-09
Au-195	1.37E-07	2.38E-10	9.24E-08	1.60E-10
Ba-133	1.44E-06	1.50E-09	9.77E-07	1.02E-09
Ba-137m	2.69E-06	2.52E-09	1.83E-06	1.72E-09
Be-10	7.50E-10	2.37E-12	5.09E-10	2.09E-12
Be-7	2.15E-07	2.07E-10	1.46E-07	1.40E-10
Bi-207	7.06E-06	6.61E-09	4.81E-06	4.50E-09
Bi-208	1.42E-05	1.28E-08	9.73E-06	8.77E-09
Bi-210	2.77E-09	5.29E-12	1.95E-09	4.43E-12
Bi-210m	1.03E-06	1.06E-09	6.98E-07	7.17E-10
Bi-211	1.90E-07	1.92E-10	1.30E-07	1.30E-10
Bi-212	4.96E-07	4.61E-10	3.39E-07	3.14E-10
Bi-213	5.43E-07	5.32E-10	3.69E-07	3.63E-10
Bi-214	7.34E-06	6.69E-09	5.00E-06	4.55E-09
Bi-215	1.08E-06	1.07E-09	7.38E-07	7.27E-10
Bk-247	4.65E-07	5.47E-10	3.16E-07	3.70E-10
Bk-249	4.68E-12	1.13E-14	3.14E-12	8.82E-15
Bk-250	4.27E-06	3.92E-09	2.91E-06	2.67E-09
Bk-251	2.41E-07	3.11E-10	1.64E-07	2.10E-10
C-14	7.86E-12	4.29E-14	5.22E-12	3.77E-14
Ca-41	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ca-45	3.96E-11	2.29E-13	2.66E-11	2.08E-13
Cd-109	8.69E-09	1.85E-11	5.76E-09	1.17E-11
Cd-113	7.23E-11	3.78E-13	4.87E-11	3.43E-13
Cd-113m	6.80E-10	1.75E-12	4.61E-10	1.50E-12
Cd-115m	1.66E-07	1.55E-10	1.13E-07	1.07E-10
Ce-139	4.53E-07	5.43E-10	3.08E-07	3.67E-10
Ce-141	2.28E-07	2.80E-10	1.55E-07	1.90E-10
Ce-144	4.92E-08	6.49E-11	3.34E-08	4.38E-11
Cf-248	1.69E-09	1.81E-12	1.15E-09	1.20E-12
Cf-249	1.33E-06	1.33E-09	9.08E-07	9.01E-10
Cf-250	4.89E-08	4.53E-11	3.34E-08	3.08E-11
Cf-251	3.62E-07	4.39E-10	2.45E-07	2.97E-10
Cf-252	2.28E-06	2.09E-09	1.55E-06	1.43E-09
Cf-253	3.92E-10	1.55E-12	2.49E-10	1.00E-12
Cf-254	8.41E-05	7.74E-08	5.72E-05	5.27E-08
Cl-36	1.69E-09	3.46E-12	1.16E-09	2.88E-12
Cm-241	1.94E-06	1.97E-09	1.32E-06	1.33E-09
Cm-242	7.86E-11	2.94E-13	4.89E-11	1.71E-13
Cm-243	4.20E-07	4.87E-10	2.86E-07	3.29E-10
Cm-244	1.40E-10	3.15E-13	9.12E-11	1.89E-13
Cm-245	2.74E-07	3.62E-10	1.87E-07	2.45E-10
Cm-246	1.80E-08	1.68E-11	1.23E-08	1.14E-11

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Cm-247	1.31E-06	1.28E-09	8.90E-07	8.76E-10
Cm-248	6.54E-06	6.03E-09	4.46E-06	4.10E-09
Cm-249	8.50E-08	8.30E-11	5.79E-08	5.70E-11
Cm-250	6.66E-05	6.12E-08	4.53E-05	4.17E-08
Co-56	1.83E-05	1.67E-08	1.25E-05	1.14E-08
Co-57	3.55E-07	4.54E-10	2.42E-07	3.07E-10
Co-58	4.48E-06	4.17E-09	3.06E-06	2.84E-09
Co-60	1.24E-05	1.12E-08	8.44E-06	7.65E-09
Co-60m	1.79E-08	1.80E-11	1.21E-08	1.21E-11
Cs-134	7.10E-06	6.63E-09	4.83E-06	4.51E-09
Cs-135	5.84E-11	3.26E-13	3.92E-11	2.98E-13
Cs-137	5.52E-10	1.62E-12	3.79E-10	1.43E-12
Dy-154	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Dy-159	3.22E-08	8.40E-11	2.15E-08	5.52E-11
Es-253	1.25E-09	1.37E-12	8.45E-10	9.15E-13
Es-254	8.17E-09	1.26E-11	5.50E-09	8.26E-12
Es-255	3.44E-09	3.37E-12	2.35E-09	2.35E-12
Eu-146	1.12E-05	1.04E-08	7.66E-06	7.08E-09
Eu-148	1.01E-05	9.46E-09	6.87E-06	6.42E-09
Eu-149	1.49E-07	1.82E-10	1.01E-07	1.23E-10
Eu-150	6.76E-06	6.48E-09	4.60E-06	4.40E-09
Eu-152	5.41E-06	5.06E-09	3.68E-06	3.43E-09
Eu-154	5.85E-06	5.44E-09	3.98E-06	3.70E-09
Eu-155	1.25E-07	1.93E-10	8.51E-08	1.30E-10
Fe-55	4.79E-16	6.11E-19	3.26E-16	4.12E-19
Fe-59	5.81E-06	5.30E-09	3.97E-06	3.61E-09
Fe-60	1.76E-11	1.07E-13	1.18E-11	9.61E-14
Fm-254	3.50E-08	3.26E-11	2.38E-08	2.21E-11
Fm-255	3.93E-09	7.88E-12	2.62E-09	5.04E-12
Fm-257	4.90E-07	5.52E-10	3.34E-07	3.74E-10
Fr-221	1.05E-07	1.15E-10	7.13E-08	7.81E-11
Fr-223	1.35E-07	1.78E-10	9.22E-08	1.20E-10
Ga-68	4.17E-06	3.98E-09	2.84E-06	2.71E-09
Gd-146	5.64E-07	7.82E-10	3.83E-07	5.27E-10
Gd-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-150	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-151	1.41E-07	1.92E-10	9.61E-08	1.28E-10
Gd-152	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Gd-153	1.61E-07	2.72E-10	1.09E-07	1.82E-10
Ge-68	4.05E-13	4.99E-15	2.60E-13	3.07E-15
H-3	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-172	1.51E-07	2.71E-10	1.02E-07	1.81E-10
Hf-174	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Hf-175	1.28E-06	1.35E-09	8.75E-07	9.19E-10
Hf-178m	9.08E-06	9.10E-09	6.19E-06	6.18E-09
Hf-181	2.14E-06	2.15E-09	1.46E-06	1.46E-09

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Hf-182	9.10E-07	9.60E-10	6.19E-07	6.50E-10
Hg-194	3.61E-12	3.15E-14	2.16E-12	1.83E-14
Hg-203	9.20E-07	9.59E-10	6.26E-07	6.50E-10
Hg-206	4.83E-07	4.96E-10	3.29E-07	3.37E-10
Ho-163	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ho-166m	7.15E-06	6.83E-09	4.87E-06	4.64E-09
I-125	7.27E-09	2.84E-11	4.57E-09	1.74E-11
I-129	6.18E-09	2.20E-11	3.95E-09	1.38E-11
In-113m	1.07E-06	1.05E-09	7.25E-07	7.13E-10
In-114	2.35E-08	2.64E-11	1.64E-08	1.97E-11
In-114m	2.94E-07	2.99E-10	2.00E-07	2.02E-10
In-115	2.74E-10	1.06E-12	1.86E-10	9.49E-13
In-115m	6.33E-07	6.38E-10	4.31E-07	4.32E-10
Ir-192	3.39E-06	3.36E-09	2.30E-06	2.28E-09
Ir-192n	1.17E-09	2.43E-12	7.94E-10	1.80E-12
Ir-194	4.12E-07	4.03E-10	2.80E-07	2.76E-10
Ir-194m	1.01E-05	9.74E-09	6.88E-06	6.61E-09
K-40	7.99E-07	7.25E-10	5.44E-07	4.94E-10
K-42	1.47E-06	1.33E-09	1.00E-06	9.10E-10
Kr-81	3.26E-09	3.50E-12	2.22E-09	2.36E-12
Kr-83m	1.25E-11	8.15E-14	7.54E-12	4.76E-14
Kr-85	1.06E-08	1.18E-11	7.24E-09	8.50E-12
La-137	6.87E-09	2.38E-11	4.41E-09	1.51E-11
La-138	6.05E-06	5.50E-09	4.12E-06	3.74E-09
Lu-172	9.01E-06	8.43E-09	6.14E-06	5.73E-09
Lu-172m	9.32E-13	3.01E-15	6.14E-13	1.95E-15
Lu-173	4.47E-07	5.83E-10	3.04E-07	3.92E-10
Lu-174	3.75E-07	4.10E-10	2.55E-07	2.77E-10
Lu-174m	9.19E-08	1.57E-10	6.21E-08	1.04E-10
Lu-176	1.79E-06	1.90E-09	1.21E-06	1.28E-09
Lu-177	1.14E-07	1.33E-10	7.74E-08	9.03E-11
Lu-177m	3.63E-06	3.91E-09	2.48E-06	2.65E-09
Mn-53	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Mn-54	3.89E-06	3.60E-09	2.65E-06	2.45E-09
Mo-93	2.13E-10	1.25E-12	1.23E-10	6.95E-13
Na-22	1.03E-05	9.56E-09	7.03E-06	6.50E-09
Nb-91	7.15E-09	7.66E-12	4.85E-09	5.08E-12
Nb-91m	1.21E-07	1.12E-10	8.28E-08	7.63E-11
Nb-92	6.90E-06	6.42E-09	4.71E-06	4.37E-09
Nb-93m	3.81E-11	2.23E-13	2.18E-11	1.24E-13
Nb-94	7.22E-06	6.70E-09	4.92E-06	4.55E-09
Nb-95	3.53E-06	3.28E-09	2.41E-06	2.23E-09
Nb-95m	2.38E-07	2.55E-10	1.62E-07	1.73E-10
Nd-144	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Ni-59	6.77E-11	6.48E-14	4.61E-11	4.40E-14
Ni-63	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Np-235	1.41E-09	2.43E-12	9.52E-10	1.58E-12
Np-236	3.90E-07	5.04E-10	2.65E-07	3.41E-10
Np-237	5.17E-08	7.67E-11	3.50E-08	5.15E-11
Np-238	2.78E-06	2.55E-09	1.89E-06	1.74E-09
Np-239	5.69E-07	6.68E-10	3.86E-07	4.53E-10
Np-240	4.67E-06	4.43E-09	3.19E-06	3.01E-09
Np-240m	1.46E-06	1.37E-09	9.94E-07	9.33E-10
Os-185	2.98E-06	2.86E-09	2.03E-06	1.94E-09
Os-186	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Os-194	1.54E-09	4.22E-12	1.02E-09	2.76E-12
P-32	9.42E-09	1.33E-11	6.70E-09	1.07E-11
Pa-231	1.27E-07	1.34E-10	8.63E-08	9.05E-11
Pa-232	4.29E-06	4.01E-09	2.92E-06	2.72E-09
Pa-233	8.03E-07	8.54E-10	5.46E-07	5.79E-10
Pa-234	6.62E-06	6.26E-09	4.52E-06	4.25E-09
Pa-234m	9.06E-08	8.89E-11	6.21E-08	6.24E-11
Pb-202	2.99E-12	3.04E-14	1.85E-12	1.82E-14
Pb-205	3.02E-12	3.08E-14	1.86E-12	1.85E-14
Pb-209	5.37E-10	1.71E-12	3.65E-10	1.51E-12
Pb-210	1.48E-09	3.94E-12	9.89E-10	2.58E-12
Pb-211	2.91E-07	2.79E-10	1.99E-07	1.90E-10
Pb-212	4.96E-07	5.57E-10	3.37E-07	3.77E-10
Pb-214	9.94E-07	1.02E-09	6.76E-07	6.92E-10
Pd-107	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pm-143	1.33E-06	1.26E-09	9.03E-07	8.56E-10
Pm-144	6.90E-06	6.52E-09	4.69E-06	4.43E-09
Pm-145	1.58E-08	4.47E-11	1.04E-08	2.90E-11
Pm-146	3.27E-06	3.12E-09	2.23E-06	2.11E-09
Pm-147	3.22E-11	1.44E-13	2.16E-11	1.27E-13
Pm-148	2.80E-06	2.57E-09	1.90E-06	1.75E-09
Pm-148m	8.94E-06	8.43E-09	6.09E-06	5.73E-09
Po-208	8.91E-11	8.73E-14	6.07E-11	5.93E-14
Po-209	2.65E-08	2.58E-11	1.81E-08	1.75E-11
Po-210	4.51E-11	4.18E-14	3.07E-11	2.84E-14
Po-211	3.76E-08	3.50E-11	2.56E-08	2.38E-11
Po-212	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Po-213	1.73E-10	1.61E-13	1.18E-10	1.09E-13
Po-214	3.85E-10	3.57E-13	2.62E-10	2.43E-13
Po-215	7.48E-10	7.29E-13	5.09E-10	4.95E-13
Po-216	7.10E-11	6.59E-14	4.83E-11	4.47E-14
Po-218	6.84E-15	3.95E-17	4.59E-15	3.60E-17
Pr-144	1.79E-07	1.68E-10	1.23E-07	1.18E-10
Pr-144m	1.24E-08	2.13E-11	8.30E-09	1.39E-11
Pt-190	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Pt-193	1.92E-12	1.87E-14	1.17E-12	1.11E-14
Pu-236	1.14E-10	3.39E-13	7.37E-11	2.03E-13

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Pu-237	1.14E-07	1.61E-10	7.75E-08	1.09E-10
Pu-238	6.91E-11	2.56E-13	4.34E-11	1.50E-13
Pu-239	2.09E-10	3.22E-13	1.40E-10	2.09E-13
Pu-240	7.12E-11	2.52E-13	4.51E-11	1.48E-13
Pu-241	4.06E-12	5.56E-15	2.76E-12	3.75E-15
Pu-242	4.36E-10	5.56E-13	2.94E-10	3.59E-13
Pu-243	5.52E-08	8.13E-11	3.75E-08	5.50E-11
Pu-244	9.87E-08	9.10E-11	6.73E-08	6.19E-11
Pu-246	4.09E-07	4.94E-10	2.78E-07	3.34E-10
Ra-223	4.55E-07	5.25E-10	3.09E-07	3.56E-10
Ra-224	3.91E-08	4.17E-11	2.66E-08	2.83E-11
Ra-225	6.11E-09	1.85E-11	4.02E-09	1.20E-11
Ra-226	2.50E-08	2.85E-11	1.71E-08	1.93E-11
Ra-228	3.43E-11	2.15E-13	1.99E-11	1.19E-13
Rb-83	2.13E-06	2.02E-09	1.45E-06	1.38E-09
Rb-84	4.16E-06	3.88E-09	2.83E-06	2.64E-09
Rb-87	1.01E-10	5.39E-13	6.82E-11	4.92E-13
Re-183	3.55E-07	4.96E-10	2.41E-07	3.34E-10
Re-184	3.93E-06	3.74E-09	2.69E-06	2.55E-09
Re-184m	1.48E-06	1.52E-09	1.01E-06	1.03E-09
Re-186	5.48E-08	7.53E-11	3.72E-08	5.15E-11
Re-186m	1.81E-08	3.69E-11	1.21E-08	2.45E-11
Re-187	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Re-188	2.52E-07	2.64E-10	1.73E-07	1.81E-10
Rh-101	9.50E-07	1.08E-09	6.47E-07	7.30E-10
Rh-102	2.20E-06	2.09E-09	1.49E-06	1.43E-09
Rh-102m	9.77E-06	9.15E-09	6.66E-06	6.22E-09
Rh-103m	8.65E-11	4.11E-13	5.16E-11	2.36E-13
Rh-106	9.71E-07	9.20E-10	6.63E-07	6.29E-10
Rn-218	3.39E-09	3.19E-12	2.30E-09	2.17E-12
Rn-219	2.35E-07	2.38E-10	1.60E-07	1.61E-10
Rn-220	2.77E-09	2.63E-12	1.88E-09	1.79E-12
Rn-222	1.69E-09	1.62E-12	1.15E-09	1.10E-12
Ru-103	2.15E-06	2.07E-09	1.47E-06	1.40E-09
Ru-106	0.00E+00	0.00E+00	0.00E+00	0.00E+00
S-35	8.72E-12	4.94E-14	5.80E-12	4.39E-14
Sb-124	9.06E-06	8.30E-09	6.18E-06	5.64E-09
Sb-125	1.83E-06	1.78E-09	1.25E-06	1.20E-09
Sb-126	1.25E-05	1.17E-08	8.48E-06	7.95E-09
Sb-126m	6.94E-06	6.55E-09	4.73E-06	4.45E-09
Sc-44	9.95E-06	9.26E-09	6.77E-06	6.29E-09
Sc-46	9.63E-06	8.83E-09	6.56E-06	6.00E-09
Se-75	1.42E-06	1.53E-09	9.70E-07	1.04E-09
Se-79	9.08E-12	5.00E-14	6.04E-12	4.40E-14
Si-32	2.64E-11	1.58E-13	1.78E-11	1.44E-13
Sm-145	3.72E-08	1.01E-10	2.46E-08	6.61E-11

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Sm-146	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-147	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-148	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Sm-151	3.85E-13	1.90E-15	2.27E-13	1.08E-15
Sn-113	2.28E-08	2.99E-11	1.54E-08	1.95E-11
Sn-119m	1.56E-09	6.75E-12	9.54E-10	4.02E-12
Sn-121	1.33E-10	6.17E-13	9.01E-11	5.57E-13
Sn-121m	8.91E-10	3.42E-12	5.63E-10	2.15E-12
Sn-123	3.89E-08	3.91E-11	2.66E-08	2.78E-11
Sn-126	9.95E-08	1.60E-10	6.75E-08	1.08E-10
Sr-85	2.15E-06	2.06E-09	1.46E-06	1.39E-09
Sr-89	7.24E-09	1.06E-11	5.14E-09	8.56E-12
Sr-90	4.83E-10	1.64E-12	3.28E-10	1.45E-12
Ta-179	2.80E-08	6.03E-11	1.88E-08	4.02E-11
Ta-182	6.02E-06	5.63E-09	4.10E-06	3.82E-09
Tb-157	3.00E-09	8.16E-12	2.00E-09	5.35E-12
Tb-158	3.60E-06	3.39E-09	2.45E-06	2.30E-09
Tb-160	5.24E-06	4.88E-09	3.57E-06	3.32E-09
Tc-95	3.63E-06	3.37E-09	2.48E-06	2.29E-09
Tc-95m	2.99E-06	2.86E-09	2.03E-06	1.94E-09
Tc-97	2.86E-10	1.62E-12	1.65E-10	9.01E-13
Tc-97m	1.03E-09	2.69E-12	6.73E-10	1.65E-12
Tc-98	6.45E-06	6.01E-09	4.39E-06	4.09E-09
Tc-99	8.28E-11	4.36E-13	5.58E-11	3.97E-13
Te-121	2.46E-06	2.35E-09	1.68E-06	1.59E-09
Te-121m	7.86E-07	8.34E-10	5.35E-07	5.64E-10
Te-123	4.72E-12	1.95E-14	2.92E-12	1.18E-14
Te-123m	4.47E-07	5.30E-10	3.05E-07	3.59E-10
Te-125m	6.91E-09	2.50E-11	4.39E-09	1.54E-11
Te-127	2.10E-08	2.21E-11	1.44E-08	1.54E-11
Te-127m	2.67E-09	8.29E-12	1.73E-09	5.18E-12
Te-129	2.57E-07	2.52E-10	1.75E-07	1.73E-10
Te-129m	1.39E-07	1.34E-10	9.43E-08	9.17E-11
Th-227	4.45E-07	4.81E-10	3.02E-07	3.26E-10
Th-228	5.64E-09	7.45E-12	3.83E-09	5.02E-12
Th-229	2.24E-07	3.00E-10	1.53E-07	2.03E-10
Th-230	8.45E-10	1.34E-12	5.72E-10	8.92E-13
Th-231	2.49E-08	3.97E-11	1.68E-08	2.65E-11
Th-232	3.58E-10	6.81E-13	2.42E-10	4.48E-13
Th-234	1.78E-08	2.85E-11	1.20E-08	1.92E-11
Ti-44	2.48E-07	4.32E-10	1.68E-07	2.91E-10
Tl-202	1.83E-06	1.86E-09	1.24E-06	1.26E-09
Tl-204	2.99E-09	6.06E-12	2.03E-09	4.54E-12
Tl-206	6.11E-09	9.40E-12	4.33E-09	7.63E-12
Tl-207	1.59E-08	1.81E-11	1.09E-08	1.34E-11
Tl-208	1.75E-05	1.59E-08	1.19E-05	1.08E-08

Table C-11 (Cont.)

Radionuclide	DCFPAK3.02 Morbidity Slope Factors		DCFPAK3.02 Mortality Slope Factors	
	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)	External (risk/yr per pCi/g)	Submersion (risk/yr per pCi/m^3)
Tl-209	1.03E-05	9.58E-09	7.03E-06	6.52E-09
Tl-210	1.34E-05	1.24E-08	9.17E-06	8.43E-09
Tm-168	5.35E-06	5.16E-09	3.64E-06	3.50E-09
Tm-170	7.99E-09	1.51E-11	5.44E-09	1.08E-11
Tm-171	6.66E-10	1.46E-12	4.47E-10	9.72E-13
U-232	5.44E-10	9.25E-13	3.67E-10	6.05E-13
U-233	7.11E-10	9.38E-13	4.82E-10	6.25E-13
U-234	2.53E-10	5.13E-13	1.69E-10	3.28E-13
U-235	5.51E-07	6.32E-10	3.75E-07	4.27E-10
U-235m	0.00E+00	0.00E+00	0.00E+00	0.00E+00
U-236	1.24E-10	3.06E-13	8.13E-11	1.90E-13
U-237	3.72E-07	4.76E-10	2.53E-07	3.22E-10
U-238	1.24E-10	2.62E-13	8.21E-11	1.64E-13
U-240	1.16E-08	1.65E-11	7.83E-09	1.11E-11
V-49	0.00E+00	0.00E+00	0.00E+00	0.00E+00
V-50	7.22E-06	6.52E-09	4.92E-06	4.44E-09
W-181	4.79E-08	1.00E-10	3.22E-08	6.68E-11
W-185	2.81E-10	9.14E-13	1.90E-10	7.86E-13
W-188	7.02E-09	7.86E-12	4.76E-09	5.43E-12
Xe-127	9.52E-07	1.04E-09	6.48E-07	7.02E-10
Y-88	1.37E-05	1.24E-08	9.28E-06	8.38E-09
Y-90	1.90E-08	2.29E-11	1.35E-08	1.79E-11
Y-91	2.28E-08	2.48E-11	1.58E-08	1.82E-11
Yb-169	8.04E-07	1.07E-09	5.45E-07	7.18E-10
Zn-65	2.80E-06	2.56E-09	1.92E-06	1.74E-09
Zr-88	1.60E-06	1.58E-09	1.09E-06	1.07E-09
Zr-93	0.00E+00	7.52E-18	0.00E+00	7.52E-18
Zr-95	3.36E-06	3.13E-09	2.29E-06	2.13E-09

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APPENDIX D:

INHALATION OF AIRBORNE RADIOACTIVE DUST

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APPENDIX D:

INHALATION OF AIRBORNE RADIOACTIVE DUST

D.1 INHALATION DOSE AND RISK

Loose materials from a radiation source could be released to the air and could transport to the other compartments (rooms) in the same building through ventilation. Therefore, inhalation exposure to radionuclides from that source can be experienced by a receptor who is in the same room as the source as well as by a receptor who is not in the same room as the source. The inhalation dose and risk a receptor would receive is calculated using the average air concentration of radionuclides in the room where the receptor is located that are attributed to the source. Summing the dose/risk from all the sources gives the total inhalation dose/risk incurred by each receptor.

Section B.6.1 of Appendix B discusses the calculation of the amount of loose materials released to the air from a radiation source. Section B.6.2 discusses the fate and transport modeling for the airborne loose materials. The modeling formulates equations considering source release, air exchanges, deposition from the air to the floor, and resuspension from the floor to the air. Instantaneous concentration of source particles in the air and on the floor in each room/compartment from the contamination source are solved either analytically or numerically. The source particle concentrations are expressed as fractions of the initial contamination per unit volume in the air and per unit area on the floor. These instantaneous source particle concentrations are multiplied by the amount of each radionuclide in the source, based on the initial inventory of the parent nuclides in the source and factoring into account ingrowth and decay over time, to obtain the instantaneous radionuclide concentrations in the air and on the floor. Based on the instantaneous concentrations, average concentrations of radionuclides over the exposure duration are then calculated.

The radiation dose and cancer risk incurred by a receptor, *iRcp*, over the exposure duration starting at time *t* can be calculated with the following two equations:

$$Dose_{inh,iRcp}^{Src}(t) = ED\ F_{in}\ F_{iRcp}\ IR_{iRcp} \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} DCF_{inh}^{j} \bar{C}_{air}^{i \to j}(t) \qquad \text{(D.1)}$$

$$Risk_{inh,iRcp}^{Src}(t) = ED\ F_{in} F_{iRcp}\ IR_{iRcp} \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} SF_{inh}^{j} \bar{C}_{air}^{i \to j}(t) \qquad \text{(D.2)}$$

where:

$Dose_{inh,iRcp}^{Src}(t)$ is the radiation dose the receptor *iRcp* would incur over the exposure duration that starts at time *t* from inhalation of radionuclides associated with a radiation source, *Src*,

ED I = the exposure duration,

F_{in} = the indoor fraction (of the exposure duration),

F_{iRcp} = fraction of time (the indoor time) spent by the receptor *iRcp* in the room where the receptor is located, which may not be the same room as the source,

IR_{iRcp} = the inhalation rate of the receptor, *iRcp*,

$nNucSrc$ = the number of initially existing radionuclides in the source,

$nNucDChain, i$ = the number of radionuclides in the decay chain of radionuclide *i* that initially exists in the source,

DCF_{inh}^{j} = the inhalation dose conversion factor of the jth radionuclide in the decay chain of radionuclide i that initially exists in the source,

$\bar{C}_{fair}^{i \to j}(t)$ = the average concentration (over the exposure duration starting at time *t*) of radionuclide j in the air of the room where the receptor *iRcp* is located,

$Risk_{inh,iRcp}^{Src}(t)$ = the cancer risk the receptor *iRcp* would incur over the exposure duration that starts at time *t* from inhalation of radionuclides associated with the radiation source, *Src*, and

SF_{inh}^{j} = the inhalation slope factor of the jth radionuclide in the decay chain of radionuclide i that initially exists in the source.

D.2 INHALATION DOSE AND RISK COEFFICIENTS

The default inhalation dose coefficients and slope factors used in the RESRAD-BUILD code are discussed in Appendix A.

For ICRP-38-based transformations (ICRP 1983), the values of dose coefficients were taken from either FGR 11 (Eckerman et al. 1988) or ICRP-72 (1996) where values for different age groups are available. The dose coefficients are based on dust particles with an activity median aerodynamic diameter (AMAD) of 1 μm. Dose coefficients depend on the lung clearance class; for radionuclides that assume different lung clearance classes with different chemical forms, there could be multiple dose coefficients. The values of slope factors were taken from a U.S. Environmental Protection Agency report, FGR 13 (EPA 1999). The largest dose coefficient and slope factor for a radionuclide over the considered lung clearance classes are set as default for that radionuclide.

For ICRP-107-based transformations (ICRP 2008), the values of dose coefficients were taken from either DOE STD-1196-2011 for reference person (DOE 2011) or DCFPAK 3.02 where values for different age groups are available. The values of slope factors were taken from DCFPAK 3.02. When multiple values for different lung clearance classes are available for a radionuclide, the largest dose coefficient or slope factor is set as its default value.

D.3 REFERENCES

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APPENDIX E:

RADON MODEL AND INHALATION EXPOSURE

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APPENDIX E:

RADON MODEL AND INHALATION EXPOSURE

The general principles of computing the dose/risk associated with the radon pathway are provided in this appendix. The radiation dose/risk incurred by a receptor results from inhalation of the first three short-lived progeny of the radon isotope, Rn-220 or Rn-222. The computation of the dose/risk requires knowledge of air concentrations of the three short-lived progenies, which depend on the air concentration of the radon isotope that decays to the three progenies. The general models for computing the release of radon gas from non-volume sources (point, line, and area) and from multilayered volume sources containing radon precursors are discussed in Sections E.1 and E.2, respectively. The general models for computing the steady-state radon concentration based on the releases and the concentration of each progeny in different states based on the radon concentration are detailed in Section E.3. Sections E.4 to E.6 then detail the computation of dose and risk using the concentrations of the three progenies. Only the general principles and governing equations are described in this appendix; the solutions to the equations to obtain the air concentrations over time, which were implemented in the code, are detailed in Section B.7 of Appendix B.

E.1 RELEASES OF RADON

In the RESRAD-BUILD modeling of indoor radon concentrations, three releases of radon to the indoor air are considered: (1) from the *in-situ* radon precursor in the source that decays to radon, (2) from the airborne radon precursor that attaches to particulates and decays to radon, and (3) from the deposited radon precursor on the floor that attaches to particulates and decays to radon. Releases (2) and (3) are calculated with the air and floor concentrations of Ra-226 (precursor for Rn-222) or Th-228 (precursor for Rn-220) that are available after the ventilation modeling considering the erosion of the source materials was performed. Equations E.1 and E.2 give the integrated release of Rn over the exposure duration from releases (2) and (3), respectively. Release (1) is obtained by modeling the diffusion flux of radon gas through the exterior surface area of a volume source (Equation E.3) or by multiplying the amount of radon generated by the decay of its precursor in a non-volume source with a radon release fraction (Equation B.18, shown as Equation E.4 here). Section E.2 provides discussions on the diffusion modeling to obtain release (1) from a volume source.

$$TIrel_{air,n}^{Rn}(t_k^{ER}) = V_n\, \lambda_{Rn} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} a_n^{RnP}(t)dt \tag{E.1}$$

$$TIrel_{floor,n}^{Rn}(t_k^{ER}) = A_n\, \lambda_{Rn} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} d_n^{RnP}(t)dt \tag{E.2}$$

$$TIrel_{s,n}^{i\rightarrow Rn}(t_k^{ER}) = A_s \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} F_{s,n}^{i\rightarrow Rn}(t)dt \tag{E.3}$$

$$TIrel_{s,n}^{i\rightarrow Rn}(t_k^{ER}) = f_{air}^{Rn}\lambda_{Rn} \int_{t_k^{ER}}^{t_k^{ER}+t_{ed}} Q_{s,n}^{i\rightarrow RnP}(t)dt \tag{E.4}$$

where:

$TIrel_{air,n}^{Rn}(t_k^{ER})$ = the time-integrated release of radon to room n, derived from the decay of its precursor attaching to airborne particulates;

t_k^{ER} = the k^{th} exposure reporting time;

Rn = the isotope of radon, either ^{220}Rn or ^{222}Rn;

n = the index for room in the building;

V_n = the volume of room n;

λ_{Rn} = the transformation rate coefficient, i.e., the radiological decay constant, of the radon isotope;

t_{ed} = the exposure duration;

$a_n^{RnP}(t)$ = the air concentration of the radon precursor, Ra-226 or Th-228, in room n;

$TIrel_{floor,n}^{Rn}(t_k^{ER})$ = the time-integrated release of radon to room n, derived from the decay of its precursor attaching to particulates on the floor;

A_n = the floor area of room n;

$d_n^{RnP}(t)$ = the floor concentration of the radon precursor, Ra-226 or Th-228, in room n;

$TIrel_{s,n}^{i \to Rn}(t_k^{ER})$ = the time-integrated release of radon to room n, derived from the transformation of initially present radionuclide i in a source s, which is located in room n;

A_s = area of the exterior surface of a volume source s;

$F_{s,n}^{i \to Rn}(t)$ = flux density of radon at time t through the exterior surface of a volume source located in room n, derived by modeling the diffusion of radon which is generated by the transformation of initially present radionuclide i in the source;

f_{air}^{Rn} = fraction of radon generated within a non-volume source that is released to the air in the room;

$Q_{s,n}^{i \to RnP}(t)$ = quantity at time t of the radon precursor, derived from the transformation of initially present radionuclide i in the non-volume source s, which is located in room n; and

t = a variable representing time in the integral.

The three integrated releases of radon are summed, and the sum is used in a steady-state ventilation model that considers the radon release, air exchange between rooms, air exchange between the rooms and the outside environment, as well as radiological decay to calculate the time-integrated air concentration of radon in each room of the building over the same time period (detailed in Section B.7.4 of Appendix B). Up to nine rooms are allowed in the building, if the new interface is used for data entry. If the traditional interface is used for data entry, the number of rooms is limited to three.

E.2 DIFFUSION RELEASE

As mentioned in Section E.1, to calculate the radon concentration in each room of a building with the steady-state ventilation model, the radon release directly from a source containing the radon precursor (parent) needs to be calculated. For a volume source, this direct radon release is simulated with a diffusion model. The rate of radon release into the indoor air, $rel_{s,n}^{i\to Rn}(t)$, depends on the concentration of the radon parent (precursor) within the source and on the geometric and physical properties of the source.

$$rel_{s,n}^{i\to Rn}(t) = A_s\, F_{s,n}^{i\to Rn}(t) \tag{E.5}$$

where:

$rel_{s,n}^{i\to Rn}(t)$ = the instantaneous radon release rate, due to the transformation of initial radionuclide i in the volume source,

A_s = the area of the external surface of the volume source that is exposed to the indoor air of room n, and

$F_{s,n}^{i\to Rn}(t)$ = radon flux per unit area, i.e., radon flux density, through the external surface of the volume source, resulting from the transformation of initial radionuclide i in the volume source.

E.2.1 Mathematical Model

Consider an initial three-dimensional configuration of a volume source composed of up to five distinct regions, as shown in Figure E.1. The present conceptual model assumes that because of geometric considerations, the total flow of radon activity from the lateral (smaller) faces of the volume source is negligible compared with the total flow through the larger faces that are exposed to the indoor air. This assumption implies that, if the lateral flux, $J_{lateral}$, is neglected, the distribution of radon concentration in the lateral (boundary) zones within the source could be assumed invariable. Neglecting the value of $J_{lateral}$ increases the calculated values of J_i and J_j, resulting in a higher (more conservative) estimation of indoor radon concentration. Under these assumptions, the three-dimensional configuration in Figure E-1 can be further simplified and represented by a five-zone, one-dimensional configuration, as shown in Figure E-2.

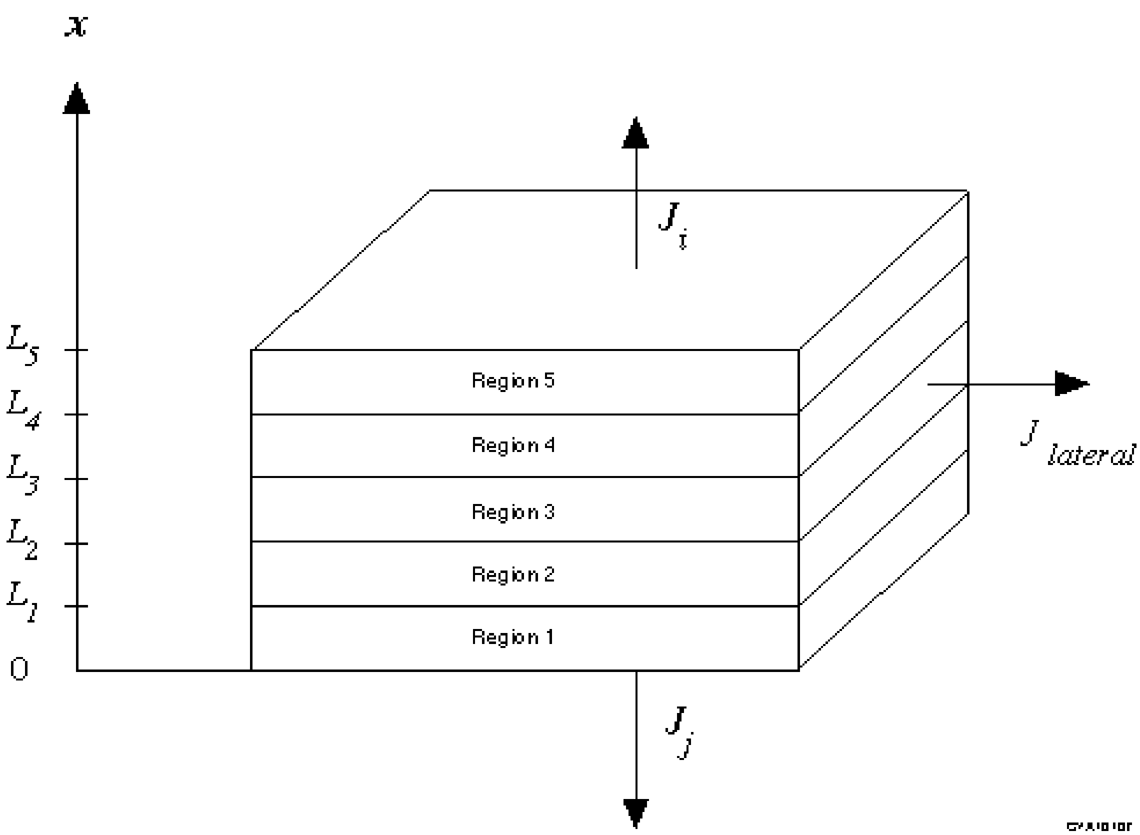

Figure E-1 Three-Dimensional Schematic Representation of a Volume Source (showing its five distinct regions and the radon flux densities at the surfaces of the source)

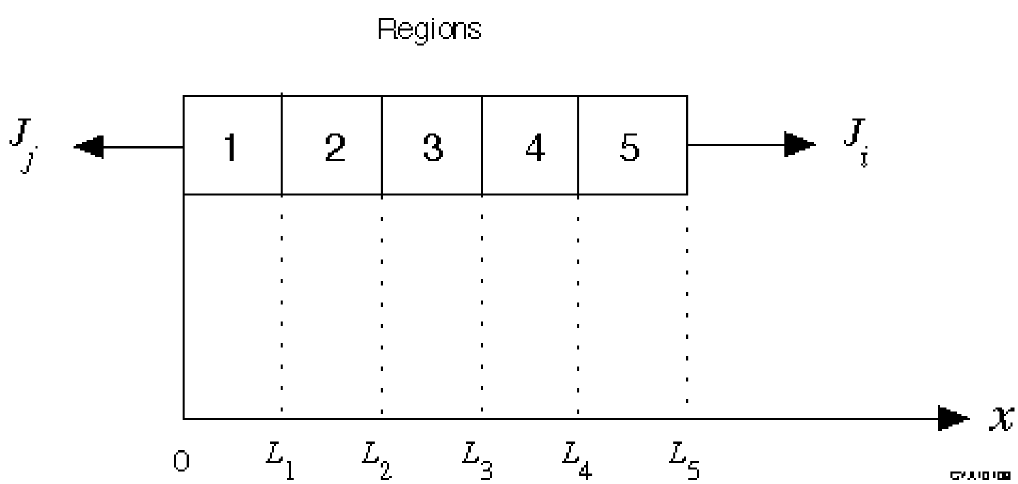

Figure E-2 One-Dimensional Schematic Representation of a Volume Source (showing its five distinct regions and radon flux at the surfaces of the source)

The general mass balance equation for radon activity in a two-phase porous system composed of a solid phase and a gas phase (no moisture content) in any region represented in Figure E.2 can be expressed as:

$$\frac{\partial(nC)}{\partial t} = -\vec{\nabla} \times \vec{J} - nR + nS \ , \qquad \text{(E.6)}$$

where:

C = radon activity concentration in the pore space (pCi/m^3),

J = bulk flux density of radon activity through the matrix (pCi/m^2/s),

R = radon sink term (pCi/m^3/s),

S = radon source term (pCi/m^3/s), and

n = total (volumetric) porosity of the source material.

Each term of Equation E.6 expresses the variation of radon activity per unit of total volume and time. These terms are functions of time and/or space. For simplicity in expression, the time and space dependencies are omitted in the notation.

In the absence of convective flow of the gaseous phase in the porous medium, the bulk flux density of radon activity, J, can be expressed by the Fickian diffusion equation:

$$\vec{J} = -\, n\, D\, \vec{\nabla} C \ , \qquad \text{(E.7)}$$

where D is the diffusion coefficient of radon in the pore space (m^2/s).

The source of radon activity into the pore volume of the porous medium can be evaluated by the following expression:

$$S = \frac{r_{Rn}^{V}}{n} = \frac{\varepsilon_s \lambda_{Rn} \rho_b^s C_s^{i \to RnP}}{n} \qquad \text{(E.8)}$$

where:

r_{Rn}^{V} = rate of emanation of radon from the solid phase into the pores of the volume source per unit volume of the source (pCi/m^3/s),

ε_s = radon emanating factor of the source,

ρ_b^s = bulk density of the source material (kg/m^3),

$C_s^{i \to RnP}$ = concentration of the radon parent in the source material, resulting from the decay of radionuclide i that is initially present in the source (pCi/kg),

λ_{Rn} = radiological decay constant of radon (1/s), and

n = total porosity of the source material.

The decay of radon activity (the sink term) in the pore volume can be expressed as:

$$R = \lambda_{Rn}\, C \tag{E.9}$$

Considering the steady-state condition in the one-dimensional configuration and the constitutive expressions above, the general mass balance equation for radon becomes:

$$-\frac{d}{dx}\left(n\, D\, \frac{dC}{dx}\right) + n\, \lambda_{Rn}\, C = n\, S\ , \tag{E.10a}$$

$$-n\, D\ \frac{d^2 C}{dx^2} + n\, \lambda_{Rn}\, C = n\, S\ , \tag{E.10b}$$

or

$$-D\ \frac{d^2 C}{dx^2} + \lambda_{Rn}\, C = S\ , \tag{E.10c}$$

where the porosity n and the diffusion coefficient D are assumed invariable with distance.

Equation E.10a is a nonhomogeneous, linear (constant coefficients), second-order, ordinary differential equation representing the transport of radon activity in a one-dimensional porous medium configuration. The general solution for the nonhomogeneous transport equation above can be expressed as:

$$C = K_1 e^{\alpha x} + K_2\, e^{-\alpha x} + \frac{S}{\lambda_{Rn}}\ , \tag{E.11}$$

where K_1 and K_2 are linear coefficients to be determined from the boundary conditions, and α represents the inverse of the diffusion length, L_D, and is given by:

$$\alpha = \frac{1}{L_D} = \sqrt{\frac{\lambda_{Rn}}{D}}, \tag{E.12}$$

where L_D is the diffusion length (m).

Equation E.11 represents the profile of radon activity concentration, C, within a specific one-dimensional region where all the parameters (such as D, ε, S, ρ_s, and n) are assumed to be constant and where the coefficients K_1 and K_2 are calculated on the basis of the boundary conditions imposed on the defined region of the domain. Equation E.11 can also be used to represent the profile of C in a multiple-region, one-dimensional configuration, if each defined region has constant and homogeneous properties. In this case, the constants K_{i1} and K_{i2}, for each region i, must be evaluated on the basis of the boundary conditions imposed on the external boundaries of the domain and on each interface between two defined regions.

E.2.2 General Boundary Conditions

Two types of physical boundaries need to be considered in solving a problem of radon diffusion in a one-dimensional porous medium configuration: (1) at the interface between the porous medium and open air (either outdoor atmosphere or indoor air) and (2) at the interface between two defined porous medium regions of the domain.

Different boundary conditions are imposed at these boundaries. Thus, at the open-air/porous-medium interface, the radon activity concentration is assumed to be substantially smaller than the values of *C* inside the medium, where the radon source is present. Therefore, as an approximation, the value of $C = 0$ is assumed at this boundary. That means, at values of $x = 0$ and $x = L_5$, this boundary condition would be expressed as follows:

$$C_{(x=0)} = 0 \tag{E.13a}$$

and

$$C_{(x=L_5)} = 0\,. \tag{E.13b}$$

At the interfaces between two different regions in the porous medium domain, the principle of continuity is applied as a boundary condition. That means at an interface *I*, located at a generic point x_i, the values of radon activity concentration, *C*, and the bulk flux density of radon activity, *J,* should satisfy the following limit expressions:

$$C_{(x=x_i-)} = C_{(x=x_i+)} \tag{E.14a}$$

and

$$\left[n\,D \frac{dC}{dx} \right]_{(x=x_i-)} = \left[n\,D \frac{dC}{dx} \right]_{(x=x_i+)}. \tag{E.14b}$$

E.2.3 Analytical Solution: General Multilayer Configuration

The general solution for the one-dimensional radon diffusion equation, Equation E.11, can be applied to represent the profile of radon activity concentration and flux density along a multi-region, one-dimensional configuration representing the source within the wall.

To simplify the equations, a three-layer source will be considered as an example here. Thus, consider a one-dimensional physical configuration of three porous layers, with thicknesses L_1, L_2, and L_3 and homogeneous properties within each layer. Also, assume the system of coordinates is at the origin of the configuration. The boundaries of the system will be located at the distances $x = 0$, L_1, L_2, and L_3. Applying Equation E.11 into this configuration results in the following system of equations:

$$C(x) = K_{11} e^{\alpha_1 x} + K_{12} e^{-\alpha_1 x} + \frac{S_1}{\lambda_{Rn}}\,, \quad 0 \le x \le L_1\,, \tag{E.15a}$$

$$C(x) = K_{21}e^{\alpha_2 x} + K_{22}e^{-\alpha_2 x} + \frac{S_2}{\lambda_{Rn}}, \quad L_1 \leq x \leq L_2, \tag{E.15b}$$

$$C(x) = K_{31}e^{\alpha_3 x} + K_{32}e^{-\alpha_3 x} + \frac{S_3}{\lambda_{Rn}}, \quad L_2 \leq x \leq L_3. \tag{E.15c}$$

This set of equations involves six ($2n = 6$) unknown parameters K_{ij}, where $i = 1, 2, 3$ and $j = 1, 2$. The values of these parameters specify a defined physical system. A three-layer configuration has two ($n - 1 = 2$) internal boundaries, which, from the boundary conditions represented by Equation E.14, generate four ($2n - 2 = 4$) equations. The two external boundaries provide the other two needed equations for solving the system. The conditions imposed on these external boundaries can be represented by Equation E.13a or E.13b.

Thus, applying the condition represented by Equation E.13 on the first boundary of the system (at $x = 0$) yields:

$$K_{11} + K_{12} = -\frac{S_1}{\lambda_{Rn}}. \tag{E.16a}$$

Then, applying the condition represented by Equation E.13 on an internal boundary between region i and region ($i + 1$) at the distance ($x = L_i$) of the system yields:

$$\left(e^{\alpha_i L_i}\right)K_{i1} + \left(e^{-\alpha_i L_i}\right)K_{i2} + \frac{S_i}{\lambda_{Rn}} = \left(e^{\alpha_{i+1} L_i}\right)K_{(i+1)1} + \left(e^{-\alpha_{i+1} L_i}\right)K_{(i+1)2} + \frac{S_{i+1}}{\lambda_{Rn}}, \tag{E.16b}$$

and

$$(n_i D_i \alpha_i e^{\alpha_i L_i})K_{i1} - (n_i D_i \alpha_i e^{-\alpha_i L_i})K_{i2} =$$

$$(n_{i+1} D_{i+1} \alpha_{i+1} e^{\alpha_{i+1} L_i})K_{(i+1)1} - (n_{i+1} D_{i+1} \alpha_{i+1} e^{-\alpha_{i+1} L_i})K_{(i+1)2} \tag{E.16c}$$

For the last boundary of the system, or the external boundary of the third layer, the condition imposed there could be represented by the following expression:

$$\left(e^{\alpha_3 L_3}\right)K_{31} + \left(e^{-\alpha_3 L_3}\right)K_{32} = -\frac{S_3}{\lambda_{Rn}}. \tag{E.16d}$$

The system of equations represented by Equations E.16a through E.16d contains six ($2n = 6$) equations related to the six unknowns, K_{ij}. It can be represented by the following matrix equation:

$$A \times k = b, \tag{E.17}$$

where A is a pentadiagonal coefficient matrix that can be written as:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ e^{\alpha_1 L_1} & e^{-\alpha_1 L_1} & -e^{\alpha_2 L_1} & -e^{-\alpha_2 L_1} & 0 & 0 \\ n_1 D_1 \alpha_1 e^{\alpha_1 L_1} & -n_1 D_1 \alpha_1 e^{-\alpha_1 L_1} & -n_2 D_2 \alpha_2 e^{\alpha_2 L_1} & n_2 D_2 \alpha_2 e^{-\alpha_2 L_1} & 0 & 0 \\ 0 & 0 & e^{\alpha_2 L_2} & e^{-\alpha_2 L_2} & -e^{\alpha_3 L_2} & -e^{-\alpha_3 L_2} \\ 0 & 0 & n_2 D_2 \alpha_2 e^{\alpha_2 L_2} & -n_2 D_2 \alpha_2 e^{-\alpha_2 L_2} & -n_3 D_3 \alpha_3 e^{\alpha_3 L_2} & n_3 D_3 \alpha_3 e^{-\alpha_3 L_2} \\ 0 & 0 & 0 & 0 & e^{\alpha_3 L_3} & e^{-\alpha_3 L_3} \end{bmatrix} \quad \text{(E.18a)}$$

The vectors of the unknown variables and the independent terms k and b are written, respectively, as:

$$k = \begin{bmatrix} K_{11} \\ K_{12} \\ K_{21} \\ K_{22} \\ K_{31} \\ K_{32} \end{bmatrix} \quad \text{and} \quad b = \begin{bmatrix} -\frac{S_1}{\lambda_{Rn}} \\ \left(\frac{S_2 - S_1}{\lambda_{Rn}}\right) \\ 0 \\ \left(\frac{S_3 - S_2}{\lambda_{Rn}}\right) \\ 0 \\ -\frac{S_3}{\lambda_{Rn}} \end{bmatrix}. \quad \text{(E.18b)}$$

The solution of Equation E.17 provides the values of the coefficients K_{ij}, which could then be used in Equation E.15 to represent the profile of radon activity concentration throughout the multilayer configuration.

The flux density of radon activity at both extremities of the system (at $x = 0$ and $x = L_3$) could then be derived from Equations E.7 and E.15. Thus, at $x = 0$, the flux $J_{(x=0)}$ is given by:

$$J_{(x=0)} = -n_1 D_1 \frac{dC}{dx}_{(x=0)}$$

$$= -n_1 D_1 (\alpha_1 K_{11} e^{\alpha_1 x} - \alpha_1 K_{12} e^{-\alpha_1 x})_{(x=0)}$$

or

$$J_{(x=0)} = -n_1 D_1 \alpha_1 (K_{11} - K_{12}) \quad \text{(E.19)}$$

Similarly, for $x = L_3$, the flux density $J_{(x=L_3)}$ is given by:

$$J_{(x=L_3)} = -n_3 D_3 \alpha_3 (K_{31} e^{\alpha_3 L_3} - K_{32} e^{-\alpha_3 L_3}) \quad \text{(E.20)}$$

In RESRAD-BUILD, only one region in a volume source can be specified as contaminated. Although the radon flux densities, $J_{(x=0)}$ and $J_{(x=L_3)}$, were solved assuming steady-state conditions, their values would change over time because of the change in the source term, S_i, due to radiological transformation (Equation E.8). The radon fluxes at both external boundaries of the volume source are considered to be released to the same room where the source is located. Therefore, the sum of the two radon flux densities, $J_{(x=0)} + J_{(x=L_3)}$, equivalent to $F_{s,n}^{i \to Rn}(t)$ in Equation (E.5), is multiplied by the area of the external surface of the volume source, A_s, to obtain the instantaneous release rate of radon, $rel_{s,n}^{i \to Rn}(t)$. This is the Release (1) mentioned in Section E.1 from a volume source. Sections B.7.2 and B.7.3 detail the calculations of the coefficients, K_{ij}'s, and the radon release rate that were implemented in the RESRAD-BUILD code.

E.3 RADON PROGENY

The objective of the radon dosimetry model is to evaluate the effective dose equivalent incurred by a receptor due to inhalation of the airborne radon progenies. The model presented here is an adaptation of the radon dosimetry model currently used in the RESRAD-ONSITE (Yu et al. 2001) and RESRAD-OFFSITE (Yu et al. 2020) computer codes.

Although RESRAD-BUILD can analyze a building containing up to nine compartments (rooms), as an example to demonstrate calculations of radon progeny concentrations for the radon pathway, consider a three-compartment building as shown in Figure E-3. The terms shown in the figure and used in this appendix are defined as follows: F_{out} is the fraction of time spent outside the building (dimensionless); F_{in} is the fraction of time spent inside the building (dimensionless); F_i is the fraction of the indoor time the receptor spends in the compartment i (with i = 1, 2, 3 for the first, second, and third compartment, respectively) (dimensionless); IR is the air inhalation rate of the receptor; C_i^n is the indoor air concentration of radon (n = 1) and radon decay products (n = 2, 3, 4) for either radon-222 or radon-220 in the compartment i (i = 1, 2, 3) (pCi/m^3); WL_i is the working level concentration of radon decay products for either radon-222 or radon-220 progeny in the indoor air of compartment i (i = 1, 2, 3) (in units of WL); WLM_i is the exposure to the indoor air concentration of radon progeny for either radon-222 or radon-220, in the compartment i (i = 1, 2, 3) (in units of working level month [WLM]); $Dose_i^{Rn}$ is the effective dose equivalent due to the inhalation of radon decay products in the indoor air of compartment i (i = 1, 2, 3) (mrem); SF^n is the slope factor of radon decay products (n = 2, 3, 4) for either radon-222 or radon-220 (1/pCi); and $Risk_i^{Rn}$ is the cancer risk due to the inhalation of radon decay products in the indoor air of compartment i (i = 1, 2, 3).

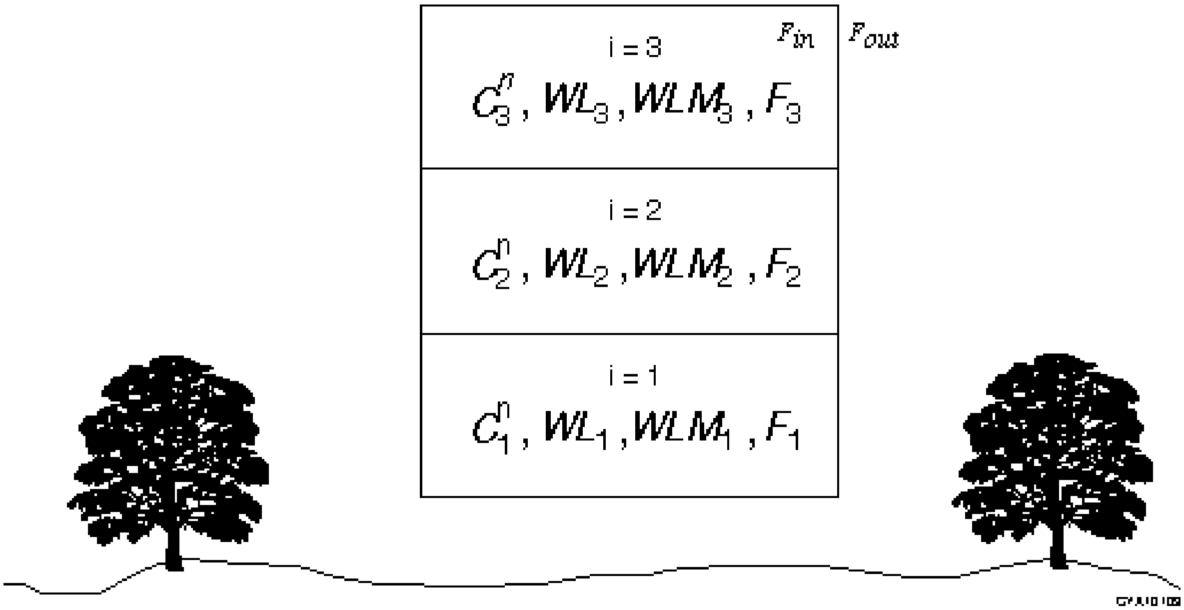

Figure E-3 Schematic Representation of the Three-Compartment Building

The algorithm of the radon dosimetry model to calculate the effective dose and the use of slope factors to calculate the cancer risk from exposure to radon decay products can be summarized in the following five steps:

1. Calculate C_i^n , the indoor air concentration of radon and its decay products (obtained by applying the steady-state ventilation model, described in the following sections).

2. Calculate the WL_i, based on the values of C_i^n (see Section E.4).

3. Calculate the exposure (WLM_i) to the radon decay products, based on the WL_i and the exposure time (see Section E.5).

4. Calculate the effective dose equivalent, $Dose_i^{Rn}$, based on the WLM_i and the related *WLM*-to-dose conversion factors (see Section E.6).

5. Calculate the cancer risk, $Risk_i^{Rn}$, based on the indoor air concentration, C_i^n, of radon decay products, the air inhalation rate of the receptor, *IR*, the exposure duration, *ED*, time fraction inside the building, F_{in}, time fraction in the room, F_i, and the slope factors of the radon decay product, SF^n (see Section E.6).

E.3.1 Airborne Radon Progeny Concentrations

The calculation of the airborne concentration of the radon short-lived decay products in the indoor air of compartment *i* is based on a variation of the model proposed by Jacobi (1972) and extended by Porstendörfer (1984) and Bruno (1983). Figure E-4 schematically represents the main interactions among the different stages of the radon decay products, as addressed in the model. According to the adopted notation, the radon progeny is designated by the index *n*, where *n* is equal to 1, 2, 3, and 4 for radon and its first, second, and third decay products, respectively. For convenience, the first, second, and third radon decay products are designated, in general, as elements *A*, *B*, and *C*, respectively. For example, in the case of the radon-222 family, the *n* index would represent radon-222, polonium-218, lead-214, and bismuth-214, for *n* equal to 1, 2, 3, and 4, respectively. In this case, polonium-218, lead-214, and bismuth-214 are described as elements *A*, *B*, and *C*, respectively. Similarly, for the case of the radon-220 family, the *n* index would represent radon-220, polonium-216, lead-212, and bismuth-212, respectively. The subscripts *fr, at, po, and dep* designate, respectively, the free, attached, plated-out, and deposited states in which the radon decay products may exist.

As discussed in Section E.1 and shown in Figure E-4, the release of radon gas to the indoor air of compartment *i* can come from three sources: directly from the radiation source ($rel_{s,i}$), the airborne source particulates ($rel_{air,i}$), and the deposited source particulates ($rel_{floor,i}$) that contain the radon parent that decays to radon. In the air, the radon gas can decay to element *A* or be ventilated out from compartment *i*.

The atom of element *A* is formed as a free ion as a result of the decay of a radon atom. Soon after being formed, the ions of element *A* join with other ions to form an ionized molecular cluster. The molecular cluster and the ions recently formed are usually considered together in what is designated as the "free state" (*fr*) of the decay product. This state is represented by the second block from the top, in the center-left of Figure E-4. At this free state, the atom of element *A* may follow several possible courses: (1) attach to airborne particulates (one block at right in Figure E-4); (2) plate out to exposed surfaces, such as walls within the compartment (one block at left); (3) decay to the free stage of element *B* (one block below, in Figure E-4); or (4) be ventilated out of compartment *i* (not shown in Figure E-4).

At the "attached state" (*at*), the atoms of element *A* are attached to the airborne dust particulates and may have the following fate: (1) decay to element *B* and remain attached to the surface of the airborne dust particulate; (2) decay to element *B* and be ejected out of the host particle, due to the recoil energy from the alpha-decay process; (3) deposit onto the floor surface, due to the deposition of the airborne particulates; or (4) be ventilated out of compartment *i* (not shown in Figure E-4). The atoms of element *A* that deposit onto the floor surface may have the following fate: (1) decay to element *B* and remain deposited on the floor; (2) decay to element *B* and be ejected out of the host particle, due to the recoil energy from the alpha-decay process, so element *B* is introduced as a free-state atom into the indoor air; and (3) be resuspended to the air, returning to the "attached state."

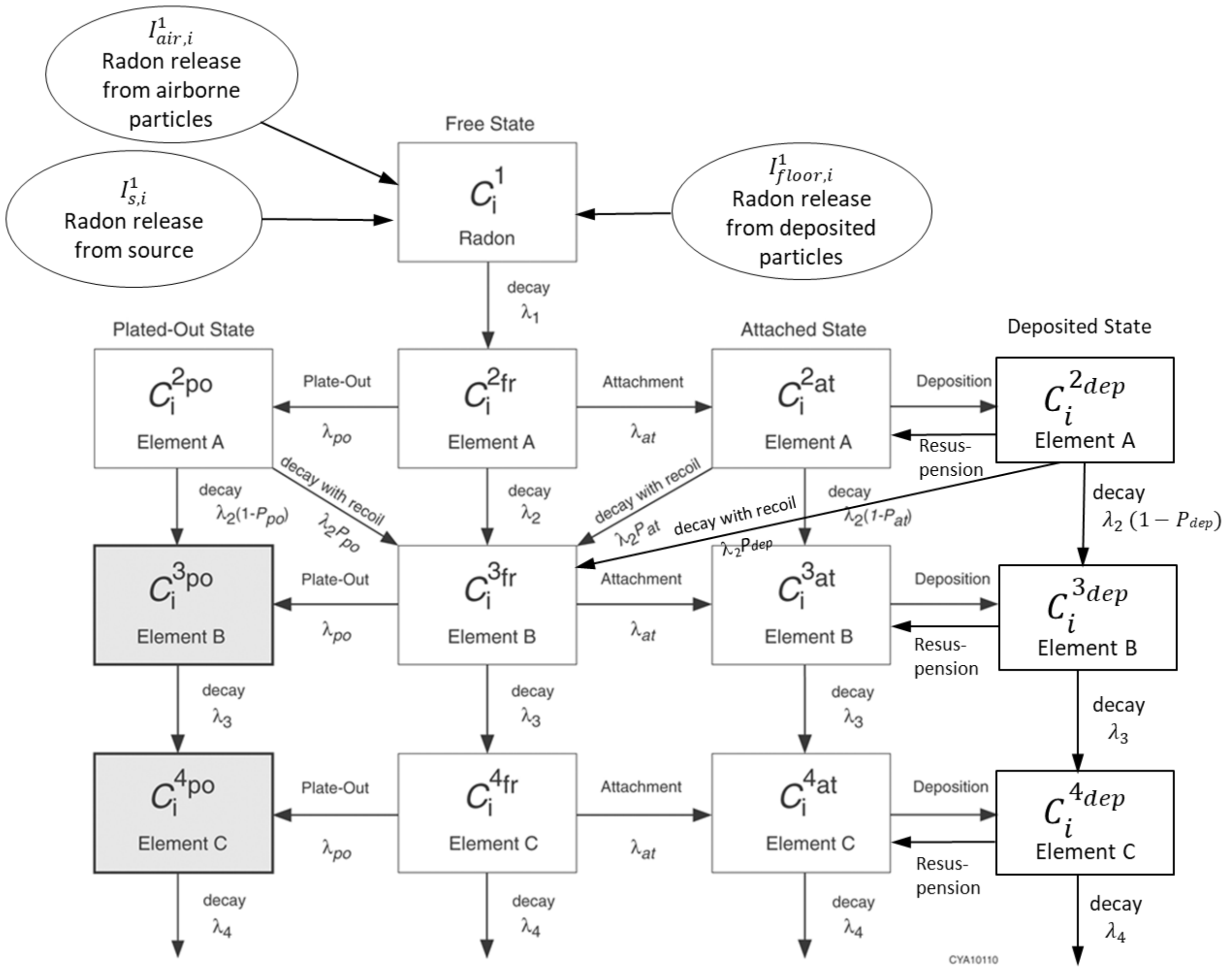

Figure E-4 Schematic Representation of the Interrelationships among the Several States of the Short-Lived Radon Decay Products (the superscripts 1, 2, 3, and 4 represent radon and its first three decay products, respectively)

At the "plated-out state" (*po*), the atoms of element *A* are plated onto exposed surfaces in the compartment and, consequently, are removed from the indoor air. However, the atoms of element *B* generated from the radioactive decay of element *A* in the plated-out location can be reintroduced, as a free-state atom, into the indoor air due to the recoil energy from the alpha-decay process.[1]

The atoms of element *B* are faced with almost the same destiny as described for element *A*. Yet, because the recoil energy from beta-decay is not sufficient to promote detachment, the atoms of element *C* formed from the decay of element *B* mostly remain attached to their host.

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1 The recoil process is usually considered only for polonium-218 because of the substantial recoil energy (6 MeV) associated with alpha decay.

The rate constant for the decay pathway of radon and its progeny is simply the radioactive decay constant, λ_n, where n is equal to 1, 2, 3, and 4, representing radon and the elements A, B, and C, respectively. The rate constant for the decay of element A, in the attached, plated-out, or deposited state, followed by detachment and the generation of element B in a free state, is equal to the decay constant λ_2 multiplied by the appropriate probability that a free atom will be created due to recoil. P_{at}, P_{po}, and P_{dep} are the probabilities that a free atom of element B will be created due to recoil and detachment from attached, plated-out, or deposited atoms of element A, respectively. The rate constant for the attachment pathway is called the attachment rate, λ_{at}. It depends mainly on the airborne particle concentration and size distribution (Bruno 1983). Similarly, the rate constant for the plate-out pathway is called the plate-out rate, λ_{po}. It depends on the surface-to-volume ratio of the compartment and on the transport properties of the free atoms within the air in the compartment. A list of the range of measured and reported values for the constants discussed above, as reported by Bruno (1983), is presented in Table E-1. The default value used in the code for the attachment rate and plate-out rate is 0.03 s^{-1}.

The airborne concentration of radon progeny will be calculated sequentially by applying the mass balance equation (described in the following sections) to find the radon concentration first and then to each unshaded rectangular block of Figure E-4 to find the concentration of the radon progeny at each state. Therefore, in relation to the radon progeny calculations, the steady-state air ventilation model will be applied in eight consecutive steps to calculate (1) the radon concentration; (2) the concentrations of element A in the free, attached/deposited, and plated-out states; (3) the concentrations of element B in the free and attached/deposited states; and (4) the concentrations of element C in the free and attached/deposited states. Finally, the airborne concentration of each radon decay product will be evaluated as a sum of the respective concentrations in the free and attached states.

Table E-1 Values of Rate Constants Used in the Radon Progeny Model

Symbol	Name	Value	Unit
λ_{at}	Attachment rate	$6.0 \times 10^{-3} - 5.0 \times 10^{-2}$	s^{-1}
λ_{po}	Plate-out rate	$3.0 \times 10^{-4} - 6.0 \times 10^{-2}$	s^{-1}
P_{at}	Probability of detachment from particles	0.50	–
P_{po}	Probability of detachment from surfaces	0.25	–

Source: Bruno (1983).

E.3.1.1 Mass Balance of Radon

Equation E.21 relates the air concentration of radon in compartment i and other compartments with the release rate of radon into compartment i due to the decay of the radon parent under the steady-state condition:

$$0 = I_i^{Rn} - \lambda_1 V_i C_i^1 + \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji}\, C_j^1 - C_i^1 \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij} \tag{E.21}$$

$$\left(\sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij} + \lambda_1 V_i\right) C_i^1 - \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji}\, C_j^1 = I_i^{Rn} \tag{E.22}$$

where:

Q_{ij} = air flow rate from room *i* to room *j* (m^3/s),

V_i = volume of room *i* (m^3),

I_i^{Rn} = total radon release rate to room *i* from the three sources discussed in Section E.1 (pCi/s).

Both sides of Equation E.21 or Equation E.22 can be integrated over the exposure duration so that the time-integrated radon concentration in compartment *i* and all other compartments are related to the time-integrated release of radon to compartment *i*. The solution of the time-integrated concentration of radon is detailed in Section B.7.4 of Appendix B.

E.3.1.2 Mass Balance of Element A—Free State

Under steady-state conditions, a mass balance of element *A* in the free state within compartment *i* yields:

$$0 = \lambda_2 V_i C_i^1 + \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji} C_j^{2\,fr} - C_i^{2\,fr} \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij} - \left(\lambda_2 + \lambda_{at} + \lambda_{po}\right) V_i C_i^{2\,fr}\,, \tag{E.23}$$

Equation E.23 can be rewritten in the appropriate format to get Equation E.24:

$$\left[\left(\lambda_2 + \lambda_{at} + \lambda_{po}\right) V_i + \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij}\right] C_i^{2\,fr} - \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji} C_j^{2\,fr} = \lambda_2 V_i C_i^1\,. \tag{E.24}$$

Section B.7.5 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element A in the free state.

E.3.1.3 Mass Balance of Element A—Attached and Deposited State

A mass balance of element *A* in the attached state within compartment *i* yields:

$$0 = \lambda_{at} V_i C_i^{2\,fr} + \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji}\, C_j^{2\,at} - C_i^{2\,at} \sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij} - \lambda_2 V_i C_i^{2\,at} - \upsilon_d A_i C_i^{2\,at} + \gamma_i A_i C_i^{2\,dep} \tag{E.25}$$

or

$$-\sum_{\substack{j=0\\j\neq i}}^{9} Q_{ji}\, C_j^{2\,at} + \left(\sum_{\substack{j=0\\j\neq i}}^{9} Q_{ij} + \lambda_2 V_i + \upsilon_d A_i\right) C_i^{2\,at} - \gamma_i A_i C_i^{2\,dep} = \lambda_{at} V_i C_i^{2\,fr} \tag{E.26}$$

For element *A* in the deposited state within compartment *i*, a mass balance yields:

$$0 = \upsilon_d A_i C_i^{2\,at} - \gamma_i A_i C_i^{2\,dep} - \lambda_2 A_i\, C_i^{2\,dep} \tag{E.27}$$

or

$$C_i^{2\,dep} = \frac{\upsilon_d A_i}{\gamma_i A_i + \lambda_2 A_i} C_i^{2\,at} \tag{E.28}$$

where:

υ_d = deposition velocity of airborne particulates (m/s),

γ_i = resuspension rate of deposited particulates on the floor of room *i* (1/s), and

A_i = floor area of room *i* (m^2).

Section B.7.6 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element A in the attached and deposited state.

E.3.1.4 Mass Balance of Element A—Plated-Out State

A mass balance of element *A* in the plated-out state within compartment *i* yields:

$$0 = \lambda_{po} V_i C_i^{2\,fr} - \lambda_2 V_i C_i^{2\,po}\,, \tag{E.29}$$

or

$$C_i^{2\,po} = \left(\frac{\lambda_{po}}{\lambda_2}\right) C_i^{2\,fr}\,. \tag{E.30}$$

Section B.7.7 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element A in the plated-out state.

E.3.1.5 Mass Balance of Element B—Free State

A mass balance of element *B* in the free state within compartment *i* yields:

$$\begin{aligned} 0 = {} & \lambda_3 V_i C_i^{2\,fr} + P_{at}\lambda_3 V_i C_i^{2at} + P_{po}\lambda_3 V_i C_i^{2\,po} + P_{dep}\lambda_3 A_i C_i^{2\,dep} + \sum_{\substack{j=0 \\ j\neq i}}^{9} Q_{ji} C_j^{3\,fr} \\ & - C_i^{3\,fr} \sum_{\substack{j=0 \\ j\neq i}}^{9} Q_{ij} - \left(\lambda_3 + \lambda_{at} + \lambda_{po}\right) V_i C_i^{3\,fr}\,, \end{aligned} \tag{E.31}$$

or

$$\left[\left(\lambda_3+\lambda_{at}+\lambda_{po}\right) V_i+\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij}\right] C_i^{3\,fr}-\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji} C_j^{3\,fr}$$

$$= \lambda_3 V_i C_i^{2\,fr}+P_{at}\lambda_3 V_i C_i^{2\,at}+P_{po}\lambda_3 V_i C_i^{2\,po}+P_{dep}\lambda_3 A_i C_i^{2\,dep}. \tag{E.32}$$

where P_{dep} is the probability of detachment from particles deposited on the floor, which is equivalent to P_{at}, the probability of detachment from particles suspended in the air.

Section B.7.8 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element B in the free state.

E.3.1.6 Mass Balance of Element B—Attached and Deposited State

A mass balance of element *B* in the attached state within compartment *i* yields:

$$0 = (1-P_{at})\lambda_3 V_i C_i^{2\,at}+\lambda_{at} V_i C_i^{3\,fr}+\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji}\, C_j^{3\,at}-C_i^{3\,at}\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij}-\lambda_3 V_i C_i^{3\,at}-\upsilon_d A_i C_i^{3\,at}+\gamma_i A_i C_i^{3\,dep} \tag{E.33}$$

or

$$-\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji}\, C_j^{3\,at}+\left(\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij}+\lambda_3 V_i+\upsilon_d A_i\right) C_i^{3\,at}-\gamma_i A_i C_i^{3\,dep} = (1-P_{at})\lambda_3 V_i C_i^{2\,at}+\lambda_{at} V_i C_i^{3\,fr} \tag{E.34}$$

For element B in the deposited state within compartment *i*, neglecting ingrowth from the decay of element A, a mass balance yields:

$$0 = \lambda_3(1-P_{dep})A_i\, C_i^{2\,dep}+\upsilon_d A_i C_i^{3\,at}-\gamma_i A_i C_i^{3\,dep}-\lambda_3 A_i\, C_i^{3\,dep} \tag{E.35}$$

or

$$\upsilon_d C_i^{3\,at}-(\gamma_i+\lambda_3)\, C_i^{3\,dep} = -\lambda_3(1-P_{dep}) C_i^{2\,dep} \tag{E.36}$$

Section B.7.9 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element B in the attached and deposited state.

E.3.1.7 Mass Balance of Element C—Free State

A mass balance of element *C* in the free state within compartment *i* yields:

$$0 = \lambda_4 V_i C_i^{3\,fr}+\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji} C_j^{4\,fr}-C_i^{4\,fr}\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij}-\left(\lambda_4+\lambda_{at}+\lambda_{po}\right) V_i C_i^{4\,fr}, \tag{E.37}$$

or

$$\left[\left(\lambda_4 + \lambda_{at} + \lambda_{po}\right)V_i + \sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij}\right] C_i^{4\,fr} - \sum_{\substack{j\neq i\\ j=0}}^{9} Q_{ji} C_j^{4\,fr} = \lambda_4 V_i C_i^{3\,fr}\,. \tag{E.38}$$

Section B.7.10 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element C in the free state.

E.3.1.8 Mass Balance of Element C—Attached and Deposited State

A mass balance of element *C* in the attached state within compartment *i* yields:

$$0 = \lambda_4 V_i C_i^{3\,at} + \lambda_{at} V_i C_i^{4\,fr} + \sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji}\, C_j^{4\,at} - C_i^{4\,at} \sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij} - \lambda_4 V_i C_i^{4\,at} - \upsilon_d A_i C_i^{4\,at} + \gamma_i A_i C_i^{4\,dep} \tag{E.39}$$

or

$$-\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ji}\, C_j^{4\,at} + \left(\sum_{\substack{j=0\\ j\neq i}}^{9} Q_{ij} + \lambda_4 V_i + \upsilon_d A_i\right) C_i^{4\,at} - \gamma_i A_i C_i^{4\,dep} = \lambda_4 V_i C_i^{3\,at} + \lambda_{at} V_i C_i^{4\,fr} \tag{E.40}$$

For element C in the deposited state within compartment *i*, a mass balance yields:

$$0 = \lambda_4 A_i C_i^{3\,dep} + \upsilon_d A_i C_i^{4\,at} - \gamma_i A_i C_i^{4\,dep} - \lambda_4 A_i\, C_i^{4\,dep} \tag{E.41}$$

or

$$\upsilon_d C_i^{4\,at} - (\gamma_i + \lambda_4) C_i^{4\,dep} = -\lambda_4 C_i^{3\,dep} \tag{E.42}$$

Section B.7.11 in Appendix B discusses the solution implemented in the RESRAD-BUILD code to obtain the time-integrated concentrations of element C in the attached and deposited state.

E.4 WORKING LEVEL

Calculation of the WL_i value associated with different radon isotopes follows a different formulation depending on the radionuclide being considered. Thus, the WL_i value in compartment *i* for an indoor atmosphere containing a mixture of radon (radon-222) progeny can be evaluated as:

$$WL_i^{\text{Rn-222}} = \left(1.03 \times 10^{-6}\right) C_i^2 + \left(5.07 \times 10^{-6}\right) C_i^3 + \left(3.73 \times 10^{-6}\right) C_i^4\ , \tag{E.43}$$

Using time-integrated concentrations, the time-integrated WL_i, i.e., $TIWL_i^{Rn-222}$, can be calculated:

$$TIWL_i^{Rn-222} = \left(1.03 \times 10^{-6}\right) TIC_i^2 + \left(5.07 \times 10^{-6}\right) TIC_i^3 + \left(3.73 \times 10^{-6}\right) TIC_i^4 \tag{E.44}$$

where C_i^2, C_i^3, and C_i^4 are the concentrations of polonium-218, lead-214, and bismuth-214, respectively, in the indoor air of compartment *i* (pCi/m^3). TIC_i^2, TIC_i^3, and TIC_i^4 are time-integrated concentrations (pCi/m^3•d) over the exposure duration of the three progenies. Similarly, for thoron (radon-220), the WL_i value is evaluated as:

$$WL_i^{\text{Rn-220}} = \left(9.48 \times 10^{-10}\right) C_i'^2 + \left(1.23 \times 10^{-4}\right) C_i'^3 + \left(1.17 \times 10^{-5}\right) C_i'^4 , \tag{E.45}$$

where C'^2_i, C'^3_i, and C'^4_i are the concentrations of polonium-216, lead-212, and bismuth-212, respectively, in the indoor air of compartment *i* (pCi/m^3). The time-integrated $TIWL_i$ can be calculated with the time-integrated concentrations:

$$TIWL_i^{Rn-220} = \left(9.48 \times 10^{-10}\right) TIC'^2_i + (1.23 \times 10^{-4}) TIC'^3_i + (1.17 \times 10^{-5}) TIC'^4_i \tag{E.46}$$

E.5 WORKING LEVEL MONTH

The exposure to the radon progeny concentration for the exposure duration, *ED*, is measured in units of *WLM*, which for each compartment *i* can be calculated as:

$$WLM_i = \left(\frac{24}{170}\right) F_{in} F_i \, TIWL_i \tag{E.47}$$

where:

24 = number of hours per day (h/d),

170 = number of working hours per month (h/mo),

ED = exposure duration (*d*), and

$TIWL_i$ = time-integrated working level in compartment *i* for the exposure duration (WL•d).

The indoor time fraction F_{in} in Equation E.47 and the outdoor time fraction F_{out} (not an input parameter) should sum up to 1. That is:

$$F_{in} + F_{out} = 1.0 \tag{E.48}$$

The time fraction of the indoor time that a receptor spends in compartment *i*, F_i, should be less than or equal to 1 in the RESRAD-BUILD code.

Note that Equation E.47 can be used to calculate the *WLM* from exposure to either radon-222 or radon-220 progenies.

E.6 RADON PROGENY DOSIMETRY AND CANCER RISK

The effective dose equivalent due to the exposure to radon decay products in the indoor air of each compartment *i* can be evaluated as:

$$Dose_i = WLM_i \times DCFrn \tag{E.49}$$

where:

$Dose_i$ = effective dose equivalent due to exposure to radon decay products (from either radon-222 or radon-220) in compartment *i* (mrem),

DCF_{rn} = dose conversion factor for the inhalation of radon decay products (mrem/WLM).

For the radon-222 decay products, the values of the DCF_{rn} for indoor exposure are equal to 760 (mrem/WLM) to go with the FGR 11 dose library (Eckerman et al. 1988) and 388 (mrem/WLM) to go with the ICRP-72 dose library (ICRP 1996). For the radon-220 decay products, the values of the DCF_{rn} for indoor exposure are equal to 150 (mrem/WLM) to go with the FGR 11 dose library and 188 (mrem/WLM) to go with the ICRP-72 dose library.

If both radon-222 and radon-220 progenies are present in the indoor air, the final calculated effective dose equivalent should be the sum of the contributions from each decay series. That is:

$$Dose_{total,i} = Dose_{Rn-222,i} + Dose_{Rn-220,i} \tag{E.50}$$

If an exposed individual would spend time in multiple rooms and is represented by multiple receptors in the analysis, then the total effetive dose he would incur is the sum of the radon dose of the receptors that represent him.

The cancer risk from inhalation of radon progenies is calculated with the exposure and the slope factors of the progenies, as shown in the following equations:

$$Risk_i^{Rn-222} = \ 24\ \times ED\ \times F_{in}\ \times F_i\ \times IR_i \times \sum_{n=1}^{4}(SF^n \times C_i^n) \tag{E.51}$$

$$Risk_i^{Rn-220} = \ 24\ \times ED\ \times F_{in}\ \times F_i\ \times IR_i \times \sum_{n=1}^{4}(SF'^n \times C'^n_i) \tag{E.52}$$

where:

$Risk_i^{Rn-222}$ = cancer risk from inhalation of radon-222 progenies in room *i*,

24 = convervsion factor (h/d),

ED = exposure duration (d),

IR_i = inhalation rate of the receptor in room *i* (m^3/h),

SF^1, SF^2, SF^3, SF^4 = inhalation slope factors of radon-222 and progenies, polonium-218, lead-214, and bismuth-214, respectively (1/pCi) (see Table E.2),

$Risk_i^{Rn-220}$ = cancer risk from inhalation of radon-220 progenies in room *i*, and

$SF'^1, SF'^2, SF'^3, SF'^4$ = inhalation slope factors of radon-220 and progenies, polonium-216, lead-212, and bismuth-212, respectively (1/pCi) (see Table E-2).

Using the time-integrated concentrations, the cancer risk from inhalation of radon progenies is calculated as:

$$Risk_i^{Rn-222} = 24 \times F_{in} \times F_i \times IR_i \times \sum_{n=1}^{4}(SF^n \times TIC_i^n) \tag{E.53}$$

$$Risk_i^{Rn-220} = 24 \times F_{in} \times F_i \times IR_i \times \sum_{n=1}^{4}(SF'^n \times TIC'^n_i) \tag{E.54}$$

Table E-2 Default Inhalation Slope Factors of Radon and Radon Progenies in RESRAD-BUILD

Radon	Nuclide in Decay Chain	Inhalation Slope Factor (1/pCi)[a]
Rn-222	Rn-222	1.8×10^{-12}
	Po-218	3.7×10^{-12}
	Pb-214	6.2×10^{-12}
	Bi-214	1.5×10^{-11}
Rn-220	Rn-220	1.9×10^{-13}
	Po-216	3.5×10^{-15}
	Pb-212	3.9×10^{-11}
	Bi-212	3.7×10^{-11}

[a] Source of slope factors: FGR 13 (Eckerman et al. 1999).

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APPENDIX F:

EXPOSURES TO TRITIUM IN BUILDINGS

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APPENDIX F:

EXPOSURES TO TRITIUM IN BUILDINGS

F.1 INTRODUCTION

Except for radon, most of the radionuclides considered in the RESRAD-BUILD code are in solid forms that attach to building materials. These radionuclides are available for inhalation or ingestion when the building materials containing them are eroded due to mechanical forces or weathering. These external factors would erode or loosen the contaminated building materials so that they could be dispersed into the indoor air and be inhaled, or could attach to the hands of a human receptor when there are contacts and inadvertently be ingested. Tritium contamination requires special consideration, because in addition to erosion, tritium, which most often exists in the environment as tritiated water (HTO), can vaporize, enter the pore space of the building materials, diffuse out through the building materials, and be released to the indoor air. The amount of vaporization and the vaporization rate depend on the amount of free HTO molecules (i.e., those that can vaporize to the pore space, thereby escaping the confinement of the building materials) in the contaminated region of the building (source) materials. This appendix discusses the special tritium model developed for estimating the release rate of tritium due to vaporization and diffusion and the calculations of subsequent exposures from various pathways. The forms of non-vaporizable tritium (as HTO or in other chemical forms such as tritiated organic compounds and metal tritides) are considered to be bound to the building materials and cannot vaporize while they are within the source; they are released to the indoor air as the building materials containing them are eroded away. Therefore, their releases and exposures from different pathways are modeled in the same manner as are those of other solid radionuclides.

F.2 SURFACE SOURCES

The surface sources defined in this section are the point, line, and area sources. Volume sources are discussed in Section F.3. The external radiation dose/risk for tritium is essentially zero, because tritium emits only low-energy beta radiation. Tritium that does not penetrate to the bulk of the building materials and remains at the surface is considered to be non-vaporizable. (If it is vaporizable, i.e., as HTO, it would evaporate completely in a short period of time, reducing the concern for radiation exposure.) As such, the radiation exposures to tritium in surface sources from the inhalation and ingestion pathways are evaluated in the same manner as the exposures to other solid radionuclides. One pathway that is unique to tritium is exposure through dermal absorption. This pathway is discussed in Section F.2.2.

F.2.1 Inhalation and Ingestion

For surface sources, the release of tritium can proceed with up to ten removal phases (if the new interface is used for input data entry). The release rate of source material during each removal phase (m) is constant but can be different during different removal phases. The release rate of source material to the air is determined by (1) the fraction removed ($f^{m}_{removed}$), (2) the duration of the removal phase ($t^{m}_{end} - t^{m}_{start}$), and (3) the air release fraction (f^{m}_{air}). When only one removal phase is considered, i.e., inputs are specified with the traditional (before Version 4.0) interface, the duration of the removal is defined by the lifetime parameter rather than by the interval between the end time (t_{end}^{m}) and the start time (t_{start}^{m}) of the removal phase, which are specified with the new (Version 4.0) interface. (See Section B.3.1 and Table B.2 in Appendix B for discussions on modeling the removal of source.)

The instantaneous air release rate of source material, which is expressed as the fraction of the initial contamination per unit time, at the selected simulation time points are calculated and used in the ventilation model that simulates the fate of released source materials to obtain the concentration of source particles in the air and on the floor in each room of the building at the simulation time points (see Sections B.6.1-B.6.4 and B.6.7 in Appendix B for detailed modeling discussion). With the source particles concentrations available, expressed as the fraction of the initial contamination per unit air volume and the fraction of the initial contamination per unit floor area, tritium concentrations in the air and on the floor can be calculated, by multiplying the source particles concentration with the initial inventory of tritium in the source adjusted by radiological decay over time (see Sections B.6.5 and B.6.8 in Appendix B for detailed modeling discussions). The instantaneous tritium concentrations in the air and on the floor are averaged over the exposure duration (Sections B.6.6 and B.6.7 in Appendix B) for calculating the inhalation and indirect (secondary) ingestion exposures, respectively, as well as the radiation dose and cancer risk associated with the exposures (see Appendices A and D).

Only loose contamination that is not released to the air is available for direct ingestion. Therefore, to evaluate exposures from the direct ingestion pathway, the input direct ingestion rate, which is expressed as a fraction of the initial contamination per unit time and is applied to all the receptors in the source room, is checked against an upper bound determined by the release rate, the air release fraction, the number of receptors in the source room, and the time fraction spent by each receptor in that room. The input value is replaced with the upper bound value, if the upper bound value is exceeded. The direct ingestion rate is then multiplied by the initial inventory of tritium in the source, adjusted by radiological decay over time, to obtain the direct ingestion rate of tritium at any time. The instantaneous direct ingestion rate of tritium is integrated over the exposure duration (Section B.5.2 in Appendix B) and used with the amount of time each receptor spent in the source room to obtain the integrated exposure of each receptor, for calculating the radiation dose and cancer risk associated with the direct ingestion pathway (Equations G.5 and G.6 in Appendix G and dose and risk calculations, respectively).

F.2.2 Dermal Absorption

In the form of HTO, tritium can be absorbed easily by the human body through skin contact. To account for the potential dose and cancer risk from dermal absorption, the inhalation dose/risk is increased by 50%. The radiation doses/risks listed for the inhalation pathway in the text or graphic output of the code include the contribution from dermal absorption.

F.3 VOLUME SOURCES

Tritium, as HTO, in volume sources that are vaporizable, could evaporate to the pore space in the source material and diffuse out to the indoor air. A special model was developed to estimate the release rate of vaporizable HTO (characterized by $f_{air}^{H_2O}$, the water fraction available for vaporization, an input parameter). Vaporizable HTO, when released, is mixed with the indoor air instantaneously. The remaining fraction of tritium, $(1-f_{air}^{H_2O})$, as HTO or in other chemical form, is non-vaporizable. Non-vaporizable forms of tritium can be released only when the source material that contains them is eroded away. A fraction of the tritium in the eroded source material (attached to source particles and characterized by f_{air}) is mixed instantaneously with the indoor air. The other fraction $(1- f_{air})$ is assumed to drop to the floor and is removed from the room and would not contribute to radiation exposures. The methodology used to estimate the release rate of non-vaporizable tritium to the air is the same as that used to estimate other solid radionuclides in a volume source. The two estimated air release rates of tritium (vaporizable and non-vaporizable) are separately used with the ventilation model to calculate the concentration of tritium in the air (both vaporizable and non-vaporizable) and on the floor (only non-vaporizable) in each room of the building at the simulation time points. The instantaneous concentrations are averaged over the exposure duration; the average concentrations are then used to evaluate the exposures, radiation dose, and cancer risk from the inhalation and indirect ingestion pathways (see Equations D.1 and D.2 in Appendix D for inhalation dose and risk calculations and Equations G.7 and G.8 in Appendix G for indirect ingestion dose and risk calculations).

The vaporizable HTO molecules would vaporize and diffuse out prior to the source materials that initially contain them become loose and are eroded, leaving behind the non-vaporizable tritium in the source materials. Therefore, it is considered that only non-vaporizable tritium in loose source materials can be directly ingested. The methodology used to estimate the direct ingestion rate of tritium is the same as that used to estimate the direct ingestion rate of other solid radionuclides.

Because tritium emits only low-energy beta radiation, potential radiation exposures would occur through the inhalation, ingestion, and dermal absorption pathways. The methodologies used to estimate the potential exposures are discussed below.

F.3.1 Inhalation and Ingestion

The potential release of tritium from a volume source can proceed through erosion and through vaporization followed by diffusion. To simplify the modeling of releases, HTO molecules were assumed to behave exactly the same as the H_2O molecules that also exist in the source material (walls or equipment). On the basis of this assumption, the HTO molecules would follow the fate and transport of the H_2O molecules.

For the RESRAD-BUILD code to analyze the release of vaporizable H-3 with the special tritium transport model (see Section F.4), a volume source containing only H-3 needs to be established. If the source also contains other radionuclides, a separate volume source with those radionuclides at the same location can be created. It is up to users to ensure consistency in geometric dimensions and physical properties of the source materials between these two sources. A volume source containing H-3 can have two regions (an uncontaminated region, i.e., a dry region/zone, and a contaminated region, i.e., a wet region/zone). The dry zone/region, if specified, is assumed to be exposed and needs to be eroded away before erosion can get into the wet zone/region. An input erosion rate is applied to both regions/zones.

To estimate the release rate of non-vaporizable tritium (bound to source materials) to the air, the air release rate of source material is estimated first, which is expressed as a fraction of the initial contamination per unit time. The release rate of source material is constant and is determined by (1) the erosion rate (ε_r), (2) the area of the volume source (A_s), (3) the bulk density of the source material (ρ_b^s), and (4) the air release fraction (f_{air}). (See Section B.3.3 and Table B-2 in Appendix B for discussions on modeling the removal of source.) The instantaneous air release rates of source material at the selected simulation time points are used in the ventilation model to obtain the concentration of source particles in the air and on the floor in each room of the building at the simulation time points, which is then multiplied by the initial inventory of tritium in the source, adjusted by radiological decay over time, and (1- $f_{air}^{H_2O}$) to obtain the instantaneous non-vaporizable tritium concentration in the air and on the floor. (See Sections B.6.7 to B.6.9 in Appendix B for detailed modeling discussions.) The instantaneous non-vaporizable tritium concentrations in the air and on the floor are averaged over the exposure duration (Section B.6.10) for calculating the inhalation and indirect ingestion exposures, respectively, as well as the radiation dose and cancer risk associated with the exposures (see Equations D.1 and D.2 in Appendix D for inhalation dose and risk calculations and Equations G.7 and G.8 in Appendix G for indirect ingestion dose and risk calculations).

To evaluate exposures to vaporizable tritium, the instantaneous air release rate of vaporizable H_2O is estimated first (Equation F.6 in Section F.4 of Appendix F). The instantaneous release rate is expressed as a fraction of the initial amount of H_2O in the wet zone per unit time. The instantaneous air release rate of vaporizable H_2O is used in the ventilation model to obtain the instantaneous air concentration of vaporizable H_2O in each room at the simulation time points (see Section B.6.11 in Appendix B). A deposition velocity of 0 m/s is used so there is no deposition on the floor. The instantaneous vaporizable H_2O concentration is multiplied by the initial inventory of tritium in the source, adjusted by radiological decay over time, to obtain the instantaneous vaporizable tritium concentration in the air. The instantaneous vaporizable tritium concentrations are integrated over the exposure duration to estimate the average concentration (Section B.6.12 in Appendix B), which is then used to estimate the exposure to vaporizable tritium and the corresponding radiation dose and cancer risk from the inhalation pathway (Equations D.1 and D.2 in Appendix D).

The reported dose and risk results for tritium from the inhalation pathway are the sum of exposures to both vaporizable and non-vaporizable tritium from inhalation as well as from dermal absorption (see Section F.3.2). (Note: the same dose conversion factor and slope factor are used for both vaporizable and non-vaporizable tritium. The default value is the largest one among the several values reported for H-3.)

Only non-vaporizable tritium attaching to source materials that are becoming loose can be directly ingested by receptors in the same room. Therefore, the input direct ingestion rate, which is expressed as the mass of source material per unit time, is checked against an upper bound determined by the erosion rate (expressed in length of the contamination source per unit time), the area of the contamination source, the bulk density of the source, the air release fraction, the number of receptors in the source room, and the time fraction spent by each receptor in that room. The input value is replaced with the upper bound value, if the upper bound value is exceeded, and converted to a fraction of the initial contamination per unit time. The direct ingestion rate is then multiplied by the initial inventory of non-vaporizable tritium in the source, adjusted by radiological decay over time, to obtain the direct ingestion rate of tritium at any time. The instantaneous direct ingestion rate of tritium is integrated over the exposure duration (Sections B.5.2 in Appendix B) used with the amount of time each receptor spent in the source room to obtain the integrated exposure of each receptor, for calculating the radiation dose and cancer risk associated with the direct ingestion pathway (Equations G.5 and G.6 in Appendix G).

F.3.2 Dermal Absorption

The potential dermal absorption from the volume source is considered by increasing the inhalation dose by 50%, same as the handling of surface sources.

F.4 TRITIUM TRANSPORT MODEL

The tritium transport model incorporated into the RESRAD-BUILD code is used to estimate the release rate of HTO molecules into the indoor air from vaporization. It was adapted from the landfarming model developed by Thibodeaux and Hwang (1982) for considering volatilization of petroleum hydrocarbons from contaminated soils. The tritium transport model assumes that an amount of water containing HTO may somehow penetrate into a building wall/floor or equipment material and be distributed homogeneously within a depth of $T_d(0)$ (cm) to $T_d(0) + T_c(0)$ (cm) (from the surface) within the material (shown in Figure F.1). The region where the water is distributed is called the wet zone; the dry zone is between the wet zone and the surface of the contaminated material exposed to the indoor air. To simplify the consideration, it is further assumed that the material properties of the dry zone and the wet zone are the same, as are the physical properties of the HTO and H_2O molecules. Although the second assumption is not necessarily valid, it would result in more conservative estimates of the potential exposures to tritium because the release rate of HTO would be overestimated using the diffusivity and saturated vapor pressure values of H_2O. Since the HTO molecules would behave the same as H_2O molecules, the use of the term water in the following discussion would actually mean water containing HTO, because any discussion about H_2O molecules can also be applied to HTO molecules.

In the pore space of the contaminated material, free H_2O molecules (not bound to the source material) can be present as liquid and vapor. Assuming the equilibrium condition, the amount of water in the vapor phase is saturated; that is, the partial pressure of water is equivalent to the saturated vapor pressure of water. Because of the difference in the water vapor concentration in the indoor air and in the pore space of the wet zone, the water vapor molecules will diffuse from the region with the higher concentration to the region with the lower concentration; in this case, from the wet zone to the indoor air. With the water vapor molecules diffusing out, the H_2O molecules in the liquid phase will vaporize to sustain the equilibrium condition until no free water molecules are available for vaporization. When the H_2O molecules reach the exposed surface of the source material, they are released to the indoor air. The effects of surface characteristics are not considered in this model. It is assumed that the release rate of H_2O molecules is controlled by the diffusion rate of H_2O molecules through the dry zone and that the H_2O molecules at a smaller depth (closer to the dry zone) would vaporize earlier than those at a greater depth. As a result, at any time, the vaporization process would proceed by peeling the free H_2O molecules from the top of the wet zone. As time passes, the thickness of the dry zone (T_d) would increase and the thickness of the wet zone (T_c) would decrease (see Figure F-1).

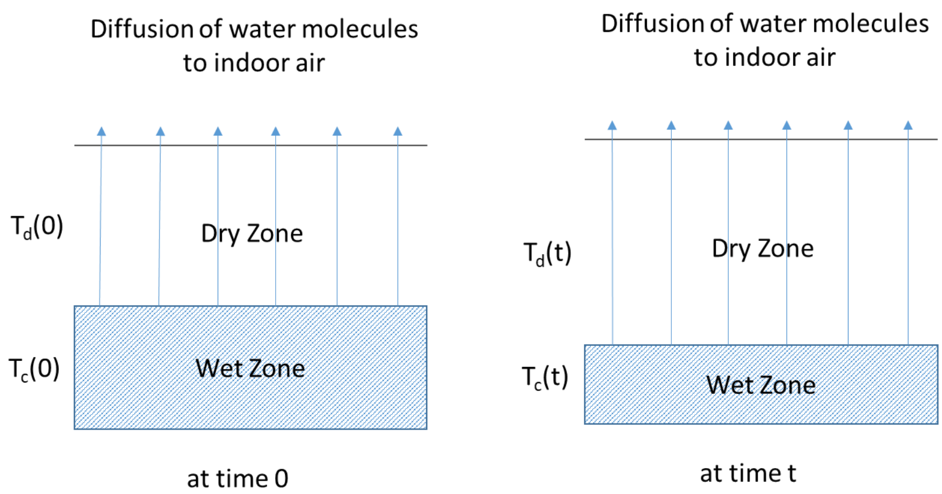

Figure F-1 Schematic Representation of the Dry Zone and Wet Zone Considered in the Tritium Transport Model

According to Fick's law, the diffusion rate of H_2O molecules through the dry zone can be expressed as:

$$q_{water}(t) = D_e \frac{C_g - H}{T_d(t)} A_s \tag{F.1}$$

where:

$q_{water}(t)$ = diffusion rate of H_2O molecules over the exposed surface of the source material per unit time at time t (g/s),

D_e = effective diffusion coefficient of H_2O molecules in the pore space of the source material (cm^2/s),

C_g = concentration of H_2O molecules in the pore space of the source material (g/cm^3),

H = concentration of water vapor in the indoor air, that is, the absolute humidity in the indoor air (g/cm^3),

$T_d(t)$ = dry zone thickness in the source material at time t (cm), and

A_s = surface area of the contaminated zone (cm^2).

Under the steady-state assumption, the vaporization rate from the wet zone is equivalent to the diffusion rate through the dry zone. Therefore,

$$q_{water}(t) = \frac{dT_d(t)}{dt} f_{air}^{H_2O} \theta \rho_w A_s \tag{F.2}$$

where:

$f_{air}^{H_2O}$ = fraction of free H_2O molecules available for vaporization,

θ = volumetric water content in the wet zone (cm^3/cm^3), and

ρ_w = density of water (g/cm^3).

After combining Equations F.1 and F.2 and rearranging parameters, integration can be performed on both sides of the equation to obtain Equation F.3:

$$\int_0^t \frac{D_e(C_g - H)}{f_{air}^{H_2O}\,\theta\,\rho_w}\,dt = \int_{T_d(0)}^{T_d(t)} T_d\,dT_d \tag{F.3}$$

where:

$T_d(0)$ = dry zone thickness at the beginning of time (t = 0) (cm).

Assuming that the values of C_g and H are not functions of time, the dry zone thickness at any time t can be calculated by the following equation:

$$T_d(t) = \sqrt{2D_e \frac{c_g - H}{f_{air}^{H_2O}\theta\rho_w} t + {T_d}^2(0)} \tag{F.4}$$

where:

t = elapsed time since the beginning of the vaporization process (s).

Replacing parameter $T_d(t)$ in Equation F.1 with Equation F.4, the water release rate at any time t can be calculated as:

$$q_{water}(t) = D_e A_s \frac{c_g - H}{\sqrt{2D_e \frac{c_g - H}{f_{air}^{H_2O}\theta\rho_w} t + {T_d}^2(0)}} \tag{F.5}$$

The fractional release rate of water due to vaporization is the ratio between the release rate of water and the initial amount of water in the contaminated zone:

$$\gamma_{H_2O}(t) = \frac{D_e}{\theta T_c(0)} \frac{c_g - H}{\sqrt{2D_e \frac{c_g - H}{f_{air}^{H_2O}\theta\rho_w} t + {T_d}^2(0)}} \tag{F.6}$$

where:

$T_c(0)$ = wet zone thickness at the beginning of time (t = 0) (cm).

The fractional release rate of water can be applied to HTO, more specifically, H-3, to calculate the release rate of tritium due to vaporization. The release rate of tritium is the ratio in Equation F.6 multiplied by the initial inventory of tritium in the contaminated zone, adjusted by radiological decay over time.

$$q_{H3}(t) = C_{H3}\,A_s\,T_c(0)\,\rho_b\,e^{-\lambda_{H3}t}\,\gamma_{H_2O}(t), \tag{F.7}$$

where:

$q_{H3}(t)$ = release rate of tritium due to vaporization at time t (pCi/s),

C_{H3} = initial activity concentration of tritium in the wet zone (pCi/g),

ρ_b = bulk density of contaminated material (g/cm^3), and

λ_{H3} = radiological decay constant of tritium (1/s).

The effective diffusion coefficient (D_e) used in the above equations is dependent on the internal geometry and porosity of the porous source material (Currie 1960) and can be correlated to the air diffusion coefficient (D_i). According to the theoretical derivation by Millington and Quirk (1961), the correlation can be expressed as follows:

$$D_e = D_i\, n^{4/3} \tag{F.8}$$

where n is the total porosity of the source material and D_i equals 0.2444 cm^2/s.

The concentration of water in the pore space of the wet zone, C_g, is related to the saturated vapor pressure of water, P_{sat}, by the following equation:

$$C_g = \frac{P_{sat}\ MW}{R \quad T} \tag{F.9}$$

where:

P_{sat} = saturated vapor pressure of water (0.0245 atm),

MW = molecular weight of water (18 g/mol),

R = the universal gas constant [82 (atm × cm^3)/(mol × K)], and

T = room temperature (294K, about 70 F).

By the time all the free water molecules vaporize, T_d would be equivalent to $T_d(0) + T_c(0)$ (wet + dry zone thickness, an input parameter). Therefore, the amount of time required to complete the vaporization release can be derived with Equation F.5, after setting $T_d(t)$ to $T_d(0) + T_c(0)$. The resulting equation is:

$$t_d = \frac{f_{air}^{H_2O}\ \theta\ \rho_w\ [T_c(0) + 2T_d(0)]\ T_c(0)}{2\ D_e\ (c_g - H)} \tag{F.10}$$

where t_d is expressed in seconds and can be converted to another time unit with an appropriate unit conversion factor.

The release of vaporizable water (H_2O) molecules and vaporizable tritium will cease after a period of time, t_d. However, the release of non-vaporizable tritium may continue, if $f_{air}^{H_2O}$ is less than 1 and the erosion rate, ε_r, is greater than 0.

F.5 REFERENCES

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APPENDIX G:

INGESTION OF RADIOACTIVE MATERIAL

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APPENDIX G:

INGESTION OF RADIOACTIVE MATERIAL

The ingestion pathway considered in the RESRAD-BUILD code includes (1) inadvertent ingestion of removable (loose) material directly from a source, i.e., direct ingestion, and (2) inadvertent ingestion of radioactive dust particulates that were released from a source and deposited onto surfaces (floors) or food within the compartments of the building, i.e., indirect ingestion or secondary ingestion. The dose and risk results listed in the text report or shown in the graphic output for the ingestion pathway are the sum of these two components. Results for each component are available in the intermediate outputs.

Section B.5 of Appendix B discusses the modeling and calculations of the amount of direct ingestion of radionuclides from a source by each receptor. Section B.6 discusses the modeling and calculations of the average deposition concentration of radionuclides from a source that can be used to calculate the amount of secondary ingestion of radionuclides from a source by each receptor. The amount of radionuclides ingested can be converted to dose and risk with the dose and risk coefficient of each radionuclide. Summing the dose/risk over all radionuclides in a source gives the ingestion dose/risk incurred by each receptor from that source; summing the dose/risk from all the sources gives the total ingestion dose/risk incurred by each receptor.

G.1 DIRECT INGESTION OF REMOVABLE MATERIAL

Direct ingestion of loose material from a source by a receptor is possible only when the receptor and the source are in the same room (compartment) of a building. When multiple receptors are in the same room as a source, the same direct ingestion rate for that source is applied to each receptor. Only loose material that is being removed (eroded) and is not released to the air can be directly ingested. Because of the above considerations, an upper bound to the direct ingestion rate can be determined with the (1) erosion rate of source material, (2) air fraction of eroded (released) material, (3) number of receptors in the source room, and (4) time fraction of receptors in the room. The input direct ingestion rate for each source is checked against the upper bound and is limited by the upper bound, if the input value is greater before being used for dose/risk calculations. For a point, line, or area source, the input direct ingestion rate is expressed as a fraction of the initial contamination per unit time. For a volume source, the input direct ingestion rate is expressed as the mass of contaminated material per unit time, which is converted to the fraction of the initial contamination per unit time by dividing the input with the total mass of the initial contamination.

The following two equations are from Section B.5.2 of Appendix B. The first one determines the value of the direct ingestion rate to be used for dose/risk calculation for a point, line, or area source, and the second one is for a volume source.

$$r_{di} = minimum\left(r_{di}^{user}, \frac{r_s^m(1-f_{air}^m)}{\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}}\right) \tag{G.1}$$

$$r_{di} = minimum\left(\frac{r_{di}^{user}}{T_c A_s \rho_b^s}, \frac{r_s \ (1 - f_{air})}{\sum_{iRcp=1}^{nRcp(SrcRm)} TF_{iRcp}^{SrcRm}}\right) \tag{G.2}$$

where:

r_{di} = the direct ingestion rate of the source to be used for dose/risk calculation,

r_{di}^{user} = the user input of the direct ingestion rate for the source,

r_s^m, r_s = the erosion rate of the source material,

f_{air}^m, f_{air} = the air fraction of the eroded source material,

TF_{iRcp}^{SrcRm} = the fraction of time (the exposure duration) receptor $iRcp$ occupies the room where the source is located,

T_c = the thickness of the contaminated region c of the source,

A_s = the area of the volume source, and

ρ_b^s = the dry bulk density of the contaminated region of the volume source.

The instantaneous ingestion rate of nuclide *j*, which is a decay product of the initial nuclide *i* in the source by receptor *iRcp*, is calculated with the following equation taken from Section B.5.2:

$$\dot{Q}_{ing,iRcp}^{j}(t) = TF_{iRcp}^{SrcRm} r_{di} Q_s^i(0) \sum_{k=1}^{j} B_j^k e^{-\lambda_k t} \tag{G.3}$$

where:

$\dot{Q}_{ing,iRcp}^{j}(t)$ = the instantaneous ingestion rate of the jth radionuclide in the decay chain of radionuclide i,

$Q_s^i(0)$ = the initial amount of radionuclide *i* in the source, and

$\sum_{k=1}^{j} B_j^k e^{-\lambda_k t}$ relates the amount of radionuclide *j* at time *t* to the initial amount of radionuclide *i*, due to ingrowth and decay of radionuclides in the decay chain. B_j^k's are coefficients from the Bateman equation.

The total amount of radionuclide *j* ingested by receptor *iRcp* over the exposure duration starting at time *t* can be calculated with Equation B.9 in Section B.5.2, by replacing t_1 with *t* and t_2 with *t+ED*:

$$Q_{ing,iRcp}^{j}(t) = TF_{iRcp}^{SrcRm} r_{di} Q_s^i(0) \sum_{k=1}^{j} B_j^k \frac{e^{-\lambda_k t} - e^{-\lambda_k (t+ED)}}{\lambda_k}$$

$$= F_{in}\, F_{iRcp}^{SrcRm} r_{di}\, Q_s^i(0) \sum_{k=1}^{j} B_j^k\, \frac{e^{-\lambda_k t} - e^{-\lambda_k (t+ED)}}{\lambda_k} \tag{G.4}$$

where:

$Q_{ing,iRcp}^{j}(t)$ = the total amount of the jth radionuclide in the decay chain of radionuclide i that is ingested by receptor *iRcp*,

ED = the exposure duration,

F_{in} = the indoor fraction (of the exposure duration), an input parameter,

F_{iRcp}^{SrcRm} = the fraction of time (the indoor time) spent by the receptor *iRcp* in the room where the source is located; and

λ_k = decay constant of radionuclide k.

The direct ingestion dose and cancer risk a receptor would incur from a contamination source over the exposure duration that starts at time *t* are calculated with the following equations:

$$Dose_{ing1,iRcp}^{Src}(t) = \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} DCF_{ing}^{j} Q_{ing,iRcp}^{j}(t) \tag{G.5}$$

$$Risk_{ing1,iRcp}^{Src}(t) = \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} SF_{ing}^{j} Q_{ing,iRcp}^{j}(t) \tag{G.6}$$

where:

$Dose_{ing1,iRcp}^{Src}\ (t)$ = the radiation dose the receptor *iRcp* would incur from directly ingesting a source,

DCF_{ing}^{j} = the ingestion dose conversion factor of the jth radionuclide in the decay chain of radionuclide i that initially exists in a source,

$Risk_{ing1,iRcp}^{Src}\ (t)$ = the cancer risk the receptor *iRcp* would incur from directly ingesting radioactive materials from a source,

SF_{ing}^{j} = the ingestion slope factor of the jth radionuclide in the decay chain of radionuclide i that initially exists in a source,

$nNucSrc$ = the number of initially existing radionuclides in a source, and

$nNucDChain, i$ = the number of radionuclides in the decay chain of radionuclide *i* that initially exists in a source.

G.2 INGESTION OF DEPOSITED RADIOACTIVE DUST

Unlike direct ingestion, secondary ingestion of loose material from a source can be experienced by a receptor who is not located in the same room as the source. The loose material from a source is released to the air and can transport to the other rooms through ventilation; the airborne source particulates can then deposit onto surfaces (floor) of each room. A receptor can incur radiation exposure when his/her hands touch the surfaces (floor) and he/she incidentally ingests the source particles that attach to his/her hands. The secondary ingestion rate, in m^2/hr, can be different for different receptors.

Section B.5.3 discusses the calculation of the amount of loose source materials released to the air. Section B.6 discusses the fate and transport modeling for the air-released loose materials. The modeling formulates equations considering source release, air exchanges, deposition from the air to the floor, and resuspension from the floor to the air. The instantaneous concentration of source particles in the air and on the floor in each room from a contamination source are solved analytically or numerically. The source-particle concentrations are expressed as fractions of the initial contamination per unit volume in the air and per unit area on the floor. These instantaneous source-particle concentrations are multiplied by the amount of each radionuclide in the source, based on the initial inventory of the parent nuclide in the source and factoring into account ingrowth and decay over time, to obtain the instantaneous radionuclide concentrations in the air and on the floor. Based on the instantaneous concentrations, the average concentrations of radionuclides over the exposure duration are then calculated.

The radiation dose and cancer risk incurred by a receptor, *iRcp*, over the exposure duration starting at time *t* can be calculated with the following two equations:

$$Dose_{ing2,iRcp}^{Src}(t) = ED\ F_{in}\ F_{iRcp}\ SER_{iRcp} \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} DCF_{ing}^{j} \bar{C}_{floor}^{i\to j}(t) \tag{G.7}$$

$$Risk_{ing2,iRcp}^{Src}(t) = ED\ F_{in} F_{iRcp}\ SER_{iRcp} \sum_{i=1}^{nNucSrc} \sum_{j=1}^{nNucDchain,i} SF_{ing}^{j} \bar{C}_{floor}^{i\to j}(t) \tag{G.8}$$

where:

$Dose_{ing2,iRcp}^{Src}(t)$ = the radiation dose the receptor *iRcp* would incur from secondary ingestion associated with the source,

$Risk_{ing2,iRcp}^{Src}(t)$ = the cancer risk the receptor *iRcp* would incur from secondary ingestion associated with the source,

F_{iRcp} = the fraction of time (the indoor time) spent by the receptor *iRcp* in the room where he/she is located, which may not be the same room as the source,

SER_{iRcp} = the secondary (indirect) ingestion rate of dust particles deposited on surfaces (floor) for the receptor *iRcp*, and

$\bar{C}_{floor}^{i \rightarrow j}(t)$ = the average concentration (over the exposure duration starting at time t) of radionuclide j on the floor of the room where the receptor *iRcp* is located. Radionuclide j is in the decay chain of radionuclide i, which exists in the source from the beginning.

G.3 DOSE COEFFICIENTS AND SLOPE FACTORS

The default ingestion dose coefficients and slope factors used in the RESRAD-BUILD code are discussed in Appendix A.

For ICRP-38-based transformations (ICRP 1983), values of dose coefficients were taken from either FGR 11 (Eckerman et al. 1988) or ICRP-72 (ICRP 1996) (values for different age groups are available). Dose coefficients depend on the chemical form, which determines the fraction f_1 of a radionuclide entering the gastrointestinal (GI) tract that reaches body fluids. Data on the appropriate fractions for different chemical forms are given in Publication 30 of the International Commission on Radiological Protection (ICRP) (1979–1982) for FGR 11 dose coefficients. For ICRP-72 dose coefficients, the GI absorption fractions are given in ICRP-60 (ICRP 1991). Values of slope factors were taken from FGR 13 (EPA 1999). The largest dose coefficient and slope factor for a radionuclide over the considered f_1 factors are set as default for that radionuclide.

For ICRP-107-based transformations (ICRP 2008), values of dose coefficients were taken from either DOE STD-1196-2011 for reference person (DOE 2011) or DCFPAK 3.02 where values for different age groups are available. The values of slope factors were taken from DCFPAK 3.02. When multiple values for different absorption fractions are available for a radionuclide, the largest dose coefficient or slope factor is set as its default value.

G.4 REFERENCES

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APPENDIX H:

UNCERTAINTY ANALYSIS

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APPENDIX H:

UNCERTAINTY ANALYSIS

Uncertainty or probabilistic analysis in RESRAD-BUILD is the computation of the total uncertainty induced in the output (dose) as a result of either the uncertainty in or the probabilistic nature of the input parameters. This analysis helps determine the relative importance of the inputs in terms of their contributions to the total uncertainty. Also, the results of uncertainty analysis can be used as a basis for determining the cost-effectiveness of obtaining additional information or data on input variables.

The RESRAD-BUILD code is designed to facilitate the analysis of the effects of uncertainty in or the probabilistic nature of input parameters in the RESRAD-BUILD model. A standard Monte Carlo method or a stratified Monte Carlo method can be applied to generate random samples of input variables. Each set of input variables is used to generate one set of output results. The results from applying all input samples are analyzed and presented in a statistical format in terms of the average value, standard deviation, minimum value, and maximum value. The cumulative probability distribution of the output is obtained and presented in a tabular form in terms of percentile values. Graphical presentations of the uncertainty results are also provided, including cumulative probability plots and scatter plots. Further analysis using regression methods can be performed to find the correlation of the resultant doses with the input variables. Partial correlation coefficients, partial rank correlation coefficients, standardized partial regression coefficients, and standardized partial rank regression coefficients can be computed to provide tools for determining the relative importance of input variables in influencing the output. The scatter plots are also useful in determining the inputs that have a significant influence on the output.

H.1 SAMPLING METHOD

Samples of the input variables are generated using an updated (1994) version of the Latin hypercube sampling (LHS) computer code (Iman and Shortencarier 1984). The uncertainty input form of the RESRAD-BUILD user interface collects all the data necessary for the sample generation and prepares the input file for the LHS code. When the RESRAD-BUILD code is executed (run), the LHS code will be called if the user has requested a probabilistic/uncertainty analysis. Parameters for the sample generation include the initial seed value for the random number generator, the number of observations (N_{obs}), the number of repetitions (N_{rep}), the sampling technique, the method of grouping the samples generated for the different variables, the type of statistical distribution for each input variable, the parameters defining each of the distributions, and any correlations between input variables.

Two sampling techniques are available—LHS and simple random sampling (SRS). The LHS technique is a constrained sampling scheme developed by McKay et al. (1979). It divides the distribution of each input variable into N_{obs} nonoverlapping regions of equal probability. One sample value is obtained at random (using the current random seed) from each region on the basis of the probability density function for that region. Each time a sample is obtained, a new random seed is also generated using the current random seed for use in the next region. The sequence of random seeds generated in this manner can be reproduced if there is ever a need to regenerate the same set of samples. After a complete set of N_{obs} samples of one probabilistic/uncertain variable has been generated, the same procedure is repeated to generate the samples for the next variable. The Monte Carlo sampling or SRS technique also obtains the N_{obs} samples at random; however, it picks out each sample from the entire distribution using the probability density function for the whole range of the variable. Report No. 100 of the International Atomic Energy Agency (IAEA) safety series (IAEA 1989) discusses the relative advantages of the two sampling techniques.

The N_{obs} samples generated for each probabilistic/uncertain variable must be combined to produce N_{obs} sets of inputs to run the RESRAD-BUILD code. Two methods of grouping (or combining) are available—random grouping (RG) or correlated/uncorrelated grouping (CG). Under random grouping, the N_{obs} samples generated for each of the variables are combined randomly to produce N_{obs} sets of inputs. For the number of probabilistic/uncertain variables (N_{var}), there are $(N_{obs}!)^{N_{var} - 1}$ ways of combining the samples. It is possible that some pairs of variables may be correlated to some degree in the randomly selected grouping, especially if N_{obs} is not sufficiently larger than N_{var}. In the correlated/uncorrelated grouping, the user specifies the degree of correlation between each pair of correlated variables by inputting the correlation coefficient between the ranks of the variables. The pairs of variables for which the degree of correlation is not specified are treated as being uncorrelated, that is, as having a zero correlation. The code checks whether the user-specified rank correlation matrix is positive definite and suggests an alternative rank correlation matrix, if necessary. It then groups the samples so that the rank correlation matrix is as close as possible to the one specified. Both matrices are in the Example1.un6 file, and the user should examine them to verify that the grouping is acceptable.

Iman and Helton (1985) suggest ways of choosing the number of samples for a given situation. The minimum and maximum doses vary with the number of samples chosen. The accuracies of the mean dose and the dose values for a particular percentile depend on the number of samples and also on the percentile of interest in the latter case. The confidence interval or the (upper or lower) confidence limit of the mean can be determined from the results of a single set of samples. Distribution-free upper (u%, v%) statistical tolerance limits can be computed by using the SRS technique according to the methodology in IAEA Report No. 100 (IAEA 1989). For example, if the user is interested in the u% dose (e.g., 95 percentile dose), a specific set of samples will yield an estimate of this u% dose. The user may want to find the v% upper confidence limit of this u% dose, which is called the upper (u%, v%) statistical tolerance limit. That is, the user can be v% confident that the u% dose will not exceed the upper (u%, v%) statistical tolerance limit. The upper (u%, v%) statistical tolerance limit is the maximum dose predicted by a sample of size *n*, where *n* is the smallest integer that satisfies the relation $1 - (u\%/100)^n \geq v\%/100$. This applies to SRS. If LHS is used, a number of repetitions of the specified number of samples can be performed in order to assess the range of the percentile dose of interest.

While the expression above can be used with simple random sampling, it is not applicable for LHS. When LHS is used, it is necessary to repeat the analysis with N_{rep} different sets of N_{obs} observations in order to assess the range of the percentile dose of interest. When the user specifies N_{rep} repetitions, the LHS computer code will first generate the first set of N_{obs} observations as described in the second paragraph of this section. The code then uses the last seed it computed when generating the previous set of N_{obs} observations to generate the next set of N_{obs} observations. RESRAD-BUILD uses the N_{rep} sets of N_{obs} observations to produce N_{rep} sets of the desired output.

H.2 DISTRIBUTION PARAMETERS

The set of input variables for uncertainty analysis is chosen via the code's interface. Each variable so chosen must have a probability distribution assigned to it and may be correlated with other input variables included in the uncertainty analysis. Thirty-four types of distributions are available in the LHS routine. These distribution types and distribution parameters are summarized in Table H-1, at the end of this appendix.

H.3 UNCERTAINTY ANALYSIS RESULTS

The printable results of the uncertainty analysis are presented in the text file RESBMC.RPT. The probabilistic inputs, their distributions, and the parameters of the distributions are listed at the beginning of this file. This is followed by the statistics (mean, standard deviation, minimum, and maximum) of the grand total dose, the total dose from each source, the total dose to each receptor, and the total dose attributed to each source and receptor combination. These statistics are provided at each user-specified time. The same statistics and the cumulative probability for percentile values in steps of 5% are tabulated for the dose from each pathway and for the dose due to each nuclide. These tables are provided for each user-specified time, source, and receptor combination. Tabulations of the correlation and regression coefficients of the doses (total dose, pathway doses, dose from each source, and the dose to each receptor) against the input variables are provided for each repetition at the end of the report, at the user's request. The input variables are ranked according to their relative contribution to the overall uncertainty in these correlation and regression coefficient tables.

Tabular and graphical uncertainty results can be viewed in the interactive probabilistic output (see User's Guide [Vol. 2 of this report] for guidance on viewing the outputs). Graphical results include scatter plots and cumulative density plots. Scatter plots can be viewed to observe any trends between each of the inputs and any of the following outputs: dose to each receptor via each or all pathways from each or all nuclides in each source at each user-specified time, and dose to each receptor via each or all pathways from all sources at each user-specified time. Cumulative probability plots of these outputs are also available. Tabulations of the minimum, maximum, mean, standard deviation, and percentile values in steps of 5% are also available for the same set of outputs. The 95% confidence range of these statistics is computed, when appropriate.

Detailed information pertinent to the samples processed is provided in a separate file, EXAMPLE1.UN6. This file contains the actual Latin hypercube samples for each observation and for each repetition. The file first provides the initial seed value of the random number generator with which the code started, the number of variables selected for uncertainty analysis, the number of observations, and the number of repetitions. Next is a table for the input variables and their distributions. The table provides the ranges of these variables rather than the distribution parameters, which are provided in the file RESBMC.RPT. The input rank correlation matrix is displayed, if the user chooses to introduce some correlation among the input variables. Following that, tables for the actual observations and their ranks are provided. The rank of observations is applied in an ascending manner with rank 1 assigned to the lowest value. The correlation of the input variables is then displayed for raw (actual) and for rank data. The correlation matrix should be examined to ensure that the correlation introduced by the user is applied and that undesired correlation is not significant. This information is provided in the EXAMPLE1.UN6 file for every repetition.

The primary results of the probabilistic runs are stored in files Uncout.asc and Uncbuild.cdl. The probabilistic inputs used by the code are in file LHSBIN.DAT. The data in Uncout.asc are used in the input-output correlation analysis, while Uncbuild.cdl is used to generate the interactive output. These files may be accessed to analyze the complete set of raw output.

H.3.1 Description of Uncout.asc (ASCII)

Header lines:

Line 1: Blank.

Line 2: Uncertainty output.

Line 3: NTime, NSrc, NRcp, and NPath: the number of evaluation times, the number of sources, the number of receptors, and the number of exposure pathways, respectively.

Line 4: Headings for the columns of data. There is a column of data for each pathway, each source, and each receptor at every evaluation time. The number of columns of data is NTime × (NPath + NSrc + NRcp).

Data lines:

The remaining $N_{obs} \times N_{rep}$ lines in this file: Data for each sample are in a single line. The columns are described in line 4.

H.3.2 Description of Uncbuild.cdl (comma delimited ASCII)

Header lines:

Line 1: $N_{obs} \times N_{rep}$, NTime, NRcp, NSrc, and Npath: the number of evaluation times, the number of receptors, the number of sources, and the number of pathways, respectively.

The following lines are repeated for each source:

Line i: NNucs(isrc): number of nuclides in source, isrc.

Lines ii through i+NNucs(isrc): names of nuclides in source, one to a line.

Data lines:

There are as many columns of data as there are pathways. The titles for the pathways are the same as those listed in Uncout.asc, except that there is no total dose column.

The following NTime × NRcp × 3NNucs(isrc) lines are repeated for each of the N_{obs} × N_{rep} uncertainty samples:

For each evaluation time, a set of lines as follows,

For each receptor, a set of lines as follows,

For each source, a set of lines as follows, and

A line for each of the nuclides in the source.

Table H-1 Statistical Distributions Used in RESRAD-BUILD and Their Defining Parameters

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Normal		
Normal	Mean (μ) Standard deviation (σ)	There are two ways of specifying the “complete” normal distribution. The RESRAD-BUILD code actually cuts off the lower and upper 0.1% tails and samples between V0.001 and V0.999 in the latter case. The relationship between the two sets of defining parameters follows: $\mu = (V0.999 + V0.001)/2$ and $\sigma = (V0.999 - V0.001)/2/3.09$.
Normal-B	Value of the 0.1% (V0.001) Value of the 99.9% (V0.999)	Conditions on inputs: $\sigma > 0$, $V0.001 < V0.999$. Probability density function (pdf): $f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right].$
Bounded Normal	Mean (μ) Standard deviation (σ) Minimum value (min) Maximum value (max)	Both parameters specify a normal distribution with the tails cut off. The lower cut-off is the minimum value or the lower quantile, and the upper cut-off is the maximum value or the upper quantile, which are related by min = VLq and max = VUq.
Truncated Normal	Mean (μ) Standard deviation (σ) Lower quantile (Lq) Upper quantile (Uq)	Conditions on inputs: min < max, Lq < Uq. pdf: $f(x) = \frac{\frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right]}{Uq - Lq}.$

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Lognormal		
Lognormal	Mean (M) Error factor (EF)	There are three ways of specifying the "complete" lognormal distribution. The RESRAD-BUILD code actually cuts off the lower and upper 0.1% tails and samples between V0.001 and V0.999 in the second case. The relationship between the three sets of defining parameters follows:
Lognormal-B	Value of the 0.1% (V0.001) Value of the 99.9% (V0.999)	μ = (ln V0.999 + ln V0.001)/2 = ln M – σ2/2 and σ = (ln V0.999 – ln V0.001)/2/3.09 = ln EF/1.645. The error factor (EF) is the ratio between the 95th percentile value and the median (50th percentile) value. It is also the ratio between the median value and the 5th percentile value.
Lognormal-N	Mean (μ) of the underlying normal distribution Standard deviation (σ) of the underlying normal distribution	Conditions on inputs: M > 0, EF > 1, σ > 0, V0.001 < V0.999. pdf: $f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right].$

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Bounded Lognormal	Mean (M) Error factor (EF) Minimum value (min) Maximum value (max)	These four parameters specify a lognormal distribution with the tails cut off. The lower cut-off is the minimum value or the lower quantile, and the upper cut-off is the maximum value or the upper quantile, which are related by min = VLq and max = VUq.
Bounded Lognormal-N	Mean (μ) of the underlying normal distribution Standard deviation (σ) of the underlying normal distribution Minimum value (min) Maximum value (max)	Conditions on inputs: min < max, Lq < Uq. pdf: $f(x)=\dfrac{\dfrac{1}{x\sigma\sqrt{2\pi}}\exp\left[-\dfrac{1}{2}\left(\dfrac{\ln x-\mu}{\sigma}\right)^2\right]}{Uq-Lq}.$
Truncated Lognormal	Mean (M) Error factor (EF) Lower quantile (Lq) Upper quantile (Uq)	
Truncated Lognormal-N	Mean (μ) of the underlying normal distribution Standard deviation (σ) of the underlying normal distribution Lower quantile (Lq) Upper quantile (Uq)	

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Uniform	Minimum value (min) Maximum value (max)	Conditions on inputs: min < max pdf: $f(x) = \dfrac{1}{\max - \min}$.
Loguniform	Minimum value (min) Maximum value (max)	Conditions on inputs: 0 < min < max. pdf: $f(x) = \dfrac{1}{x(\ln \max - \ln \min)}$.
Uniform*	Number of subintervals (Nint) Limits of subintervals (Li) i = 0 to Nint Number of observations in subinterval (Oi)	This is a collection of adjacent uniform distributions. Conditions on inputs: Nint > 1, Li–1 < Li, Oi > 0, $N_{obs} = \sum_{i=1}^{N_{int}} \mathrm{O}_i$. pdf: $f_i(x) = \dfrac{1}{L_i - L_{i-1}} \dfrac{O_i}{N_{obs}}$.

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Loguniform*	Number of subintervals (Nint) Limits of subintervals (Li) i = 0 to Nint Number of observations in subinterval (Oi)	This is a collection of adjacent loguniform distributions. Conditions on inputs: Nint > 1, 0 < L0, Li–1 < Li, Oi > 0, $N_{obs} = \sum_{i=1}^{N_{int}} O_i$. pdf: $f_i(x) = \frac{1}{x\ (\ln L_i - \ln L_{i-1})} \frac{O_i}{N_{obs}}$.
Continuous Linear	Number of points (Npts) Values of points (Vi) i = 1 to Npts cdf of points (cdfi) i = 1 to Npts	The cumulative distribution function (cdf) of a number of points is specified, and the cdf of intermediate points is obtained by linear interpolation. Conditions on inputs: Npts > 2, Vi < Vi + 1, cdf1 = 0, cdfN_{pts} = 1. pdf: $f_i(x) = \frac{cdf_i - cdf_{i-1}}{V_i - V_{i-1}}$.

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Continuous Frequency	Number of points (Npts) Values of points (Vi) i = 1 to Npts Frequency of points (fi) i = 1 to Npts	The cdf of a number of points is first computed from the user-specified frequencies. Then the cdf of intermediate points is obtained by linear interpolation. The cdf is computed from the frequencies as follows: cdf1 = 0. $cdf_i = cdf_{i-1} + \frac{f_{i-1} + f_i}{2} \div \sum_{i=2}^{N_{pts}} \frac{f_{i-1} + f_i}{2}.$ Conditions on inputs: Npts > 2, Vi < Vi+1, fi > 0. pdf: $f_i(x) = \frac{cdf_i - cdf_{i-1}}{V_i - V_{i-1}}$
Continuous Logarithmic	Number of points (Npts) Values of points (Vi) i = 1 to Npts cdf of points (cdfi) i = 1 to Npts	The cdf of a number of points is specified, and the cdf of intermediate points is obtained by logarithmic interpolation. Conditions on inputs: $N_{pts} > 2$, $0 < V_1$, $V_i < V_{i+1}$, $cdf_1 = 0$, $cdf_{N_{pts}} = 1$. pdf: $f_i(x) = \frac{cdf_i - cdf_{i-1}}{x(\ln V_i - \ln V_{i-1})}$

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Triangular	Minimum (min) Mode or most likely (mod) Maximum (max)	Conditions on inputs: min < mod < max, min < max. pdf: $f(x) = \frac{2}{\max - \min} \frac{x - \min}{\text{mod} - \min}$ when $x \leq \text{mod}$. $f(x) = \frac{2}{\max - \min} \frac{\max - x}{\max - \text{mod}}$ when $x \geq \text{mod}$.
Pareto	Alpha (α) Beta (β)	Make sure that the values entered for α and β correspond to the definition used for the pdf below. Conditions on inputs: $\alpha < 2$, $\beta > 0$. pdf: $f(x) = \frac{\alpha\beta^{\alpha}}{x^{\alpha+1}}$ when $x > \beta$.
Exponential		
Exponential	Lambda (λ)	Conditions on inputs: $\lambda < 0$. pdf: $f(x) = \lambda \exp(-\lambda x)$.

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Bounded Exponential	Lambda (λ) Minimum value (min) Maximum value (max)	Three parameters specify an exponential distribution with the two parameters defining the cut off. The lower cut-off is the minimum value or the lower quantile, and the upper cut-off is the maximum value of the upper quantile, which are related by 1 – exp(–λmin) = VLq and 1 – exp(–λmax) = Vuq.
Truncated Exponential	Lambda (λ) Lower quantile (Lq) Upper quantile (Uq)	Conditions on inputs: min < max, Lq < Uq. pdf: $f(x) = \frac{\lambda\, exp(-\lambda x)}{Uq - Lq}$.
Weibull	Alpha (α) Beta (β)	Make sure that the values entered for α and β correspond to the definition used for the pdf below. Conditions on inputs: α > 0, β > 0. pdf: $f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\frac{x}{\beta}\right)^{a}$.

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Inverse Gaussian	Mean (μ) Lambda (λ)	Conditions on inputs: $\mu > 0$, $\lambda > 0$. pdf: $f(x) = \sqrt{\frac{\lambda}{2\pi x^3}} \exp\left[-\frac{\lambda}{2\mu^2 x}(x-\mu)^2\right].$
Gamma	Alpha (α) Beta (β)	Make sure that the values entered for α and β correspond to the definition used for the pdf below. Conditions on inputs: $\alpha > 0$, $\beta > 0$. pdf: $f(x) = \frac{\beta(\beta x)^{\alpha-1}\exp(-\beta x)}{\Gamma(\alpha)}.$
Beta	P Q Minimum value (min) Maximum value (max)	Conditions on inputs: min < max, 0.001 < P < 107, 0.001 < Q < 107. pdf: $f(x) = \frac{(P+Q-1)!(x-\min)^{P-1}(\max-x)^{Q-1}}{(P-1)!(Q-1)!(\max-\min)^{P+Q-1}}.$

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Massa Function
Poisson	Mean (λ)	Conditions on inputs: $\lambda > 0$. Probability mass function (pmf): $p(n) = \frac{\lambda^n \exp(-\lambda)}{n!}$, where n = 0, 1, 2, ... 4.
Geometric	Probability of success (p)	Conditions on inputs: $0 < p < 1$. pmf: $p(n) = (1-p)^{n-1} p$, where n = 0, 1, 2, ... 4.
Binomial	Probability of success (p) Number of trials (N)	Conditions on inputs: $0 < p < 1$, $N > 1$. pmf: $p(n) = \frac{N!\,p^n (1-p)^{N-n}}{n!(N-n)!}$, where n = 0, 1, 2, ... N.

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Massa Function
Negative Binomial	Probability of success (p) Number of successes sought (N)	Conditions on inputs: $0 < p < 1, N > 1.$ pmf: $p(n) = \frac{(n-1)!\,p^N (1-p)^{n-N}}{(N-1)!(n-N)!}$, where n = N, N+1, ... 4.
Hypergeometric	Size of population (Npop) Sample size (Nsamp) Successes in population (Nsucc)	The second input has to be the smaller of Nsamp, Nsucc. The third input is the larger of the two. Conditions on inputs: Npop > Nsamp > 0, Npop > Nsucc > 0. pmf: $p(n) = \frac{\binom{N_{succ}}{n}\binom{N_{pop} - N_{succ}}{N_{samp} - n}}{\binom{N_{pop}}{N_{samp}}}$, where $\binom{M}{m} = \frac{M!}{m!(M-m)!}$ and n = max(0, Nsucc + Nsamp – Npop), ... min(Nsucc, Nsamp)

Table H-1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Massa Function
Discrete Cumulative	Number of points (Npts) Values of points (Vi) i = 1 to Npts cdf of points (cdfi) i = 1 to Npts	Conditions on inputs: Npts > 2, Vi < Vi + 1, cdf1 > 0, $cdfN_{pts}$ = 1. pmf: p(n) = cdfn – cdfn–1.
Discrete Histogram	Number of points (Npts) Values of points (Vi) i = 1 to Npts Frequency of points (fi) i = 1 to Npts	$cdf_i = f_i / \sum_{i=1}^{N_{pts}} f_i$. Conditions on inputs: Npts > 2, Vi < Vi + 1, fi > 0. pmf: p(n) = cdfn – cdfn–1.

[a] Probability density function is for continuous distributions; probability mass function is for discrete distributions.

H.4 REFERENCES

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APPENDIX I:

PARAMETER DESCRIPTIONS

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APPENDIX I:

PARAMETER DESCRIPTIONS

I.1 TIME PARAMETERS

I.1.1 Exposure Duration

Definition: The exposure duration is the total length of time considered in the dose calculations, including intervals during which receptors would not be in the contaminated building (see Section I.1.2 on the indoor fraction) or a contaminated indoor location (see Section I.3.4 on the receptor time fraction). The exposure duration is used in conjunction with the indoor fraction and the time fraction at the receptor location to compute the time spent at each receptor location as follows:

Time Spent at the Receptor Location = Exposure Duration × Indoor Fraction × Time Fraction at the Receptor Location

Parameter Name: TTIME Units: Days (d) Range: > 0

Deterministic Analysis Default Value: 365

Probabilistic Analysis Default Distribution: None assigned

Input Form: Time Parameters

Discussion: The total dose depends on the scenario considered. For chronic scenarios such as building occupancy, a period of 365 days typically would be selected to assess an annual dose. Total doses over periods exceeding 1 year may be calculated by entering a longer exposure duration. For example, if an exposed individual would spend 8 hours a day, 5 days a week inside a contaminated building over a period of 2 years, the exposure duration should be 730 days. For short-term exposures, such as building renovations, the estimated time in days from the beginning to end of the exposure should be entered. If site-specific time estimates for building renovation are not available, a value of 90 days may be used (Kennedy and Strenge 1992).

I.1.2 Indoor Fraction

Definition: The indoor fraction is the fraction of the exposure duration (see Section I.1.1 on exposure duration) spent by the receptors inside the building. The indoor fraction is used in the exposure calculations to calculate the amount of time spent at each receptor location, as in the following equation:

Time Spent at the Receptor Location = Exposure Duration × Indoor Fraction × Time Fraction at the Receptor Location

This parameter applies to all indoor receptor locations.

Parameter Name: FTIN Units: Unitless Range: ≥ 0 and ≤ 1

Deterministic Analysis Default Value: 0.5

Probabilistic Analysis Default Distribution: User-defined continuous with linear interpolation. See Table I-1 for the input values.

Figure I-1 shows the cumulative distribution function in graphic.

Input Form: Time Parameters

Discussion: The fraction of time a receptor spends inside a building may range from 0 to 1. This number will depend on the anticipated occupancy of the building. This parameter should take into account anticipated occupancy rates based on current practices. For example, an office worker may be assumed to spend 2,000 hours per year working inside the building, with these hours distributed uniformly throughout the year. The resulting indoor fraction is the ratio of 2,000 hours to 8,760 hours in one year (365 days × 24 hours/day), or 0.23. A different exposure duration may be used for a renovation scenario, for example, 90 days; however, this difference in exposure duration would not affect the indoor time fraction if, like the office worker, the renovation worker works 8 hours per day during weekdays. Residential occupancy scenarios might result in higher indoor fractions than would occupational scenarios.

The U.S. Environmental Protection Agency's (EPA's) Exposure Factors Handbook (EPA 2011) contains a comprehensive review of human activity patterns, including time spent at work, which can be referenced to determine an input value for this parameter. The data collection handbook for RESRAD applications (Yu et al. 2015) summarizes the information in the EPA Exposure Factors Handbook in Section 9.5.

Table I-1 Default Cumulative Distribution Function for the Indoor Fraction

Cumulative Probability	Default Occupational Distribution
0	0.003
0.05	0.0347
0.25	0.306
0.50	0.365
0.75	0.403
0.90	0.469
0.95	0.500
0.98	0.542
0.99	0.594
1.0	0.692

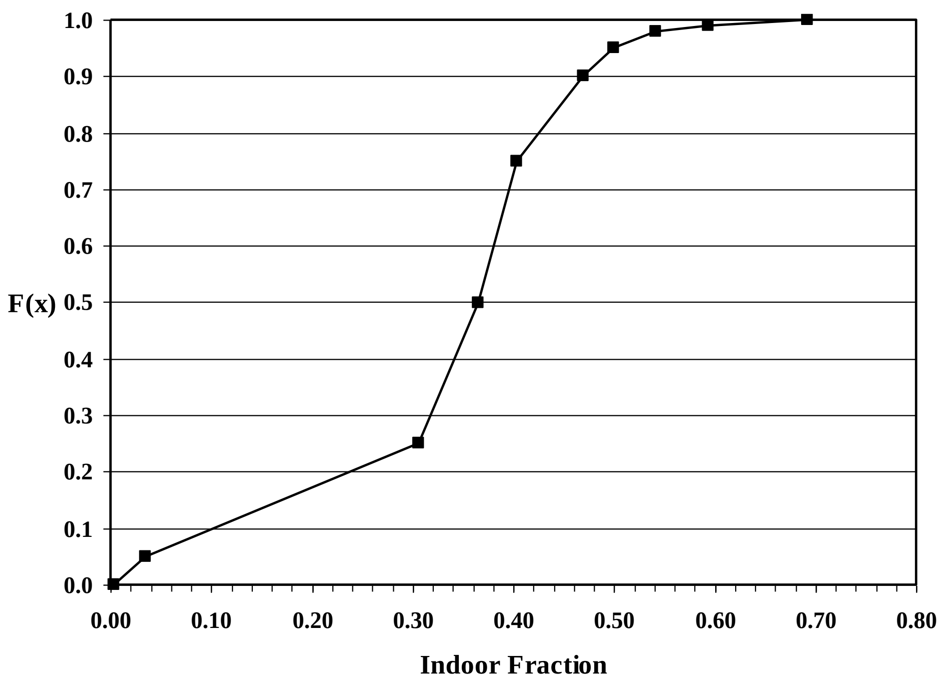

Figure I-1 Default Indoor Fraction Cumulative Distribution Function for an Occupational Setting

I.1.3 Number of Times for Calculation

Definition: This parameter represents the number of user-defined discrete exposure periods for which the dose calculations are performed. The parameter allows the user to assess the dose over the exposure period (or exposure duration) starting at different times (years) to evaluate any time-dependent effects, such as source removal or erosion and radioactive decay and ingrowth (see Sections I.1.1 and I.1.4 on exposure duration and time, respectively). The exposure period starting at the initial time (Time = 0) is automatically calculated and reported.

Parameter Name: NTIME Units: Unitless Range: 1 to 10

Default Value: 1

Input Form: Time Parameters → Evaluation Times

Discussion: The use of this parameter is the same whether the analysis being performed is deterministic or probabilistic. The value for the number of times for calculation entered by the user is an integer ranging from 1 to 10. For simple problems in which ingrowth and decay or source loss during the assessment time frame is not a factor, setting the number of times for calculation to 1 may be sufficient. The number of times for calculation should be based on estimated or actual exposure durations for the selected scenario. The run time of the code is directly proportional to the selected number of times for calculation.

I.1.4 Time

Definition: This parameter refers to the beginning time(s) of the exposure period (duration) for which dose calculations are performed.

Parameter Name: DOSE_TIME Units: Years Range: ≥ 0 to 100,000

Default Value: 1

Input Form: Time Parameters → Evaluation Times

Discussion: The use of this parameter is the same whether the analysis being performed is deterministic or probabilistic. Up to nine user-specified times (in years) may be selected as starting points for the exposure period (duration) for dose calculations. The code will always calculate the dose at time zero. These times can be integer years or fractions of years. The dose/risk is calculated over the specified exposure duration (see Section I.1.1 on exposure duration) in days following each evaluation time entered. For example, if the exposure duration time is 365 days and the user selects times 1 and 10 years, the code will calculate doses/risks incurred during the first (time zero is always calculated), second, and eleventh year. For short-lived radionuclides, or when significant ingrowth would occur, or when erosion would change the nuclide inventory in the source notably during the exposure period, the user may choose to use more time integration points (see Section I.1.5) for dose calculations.

The times for dose calculations should be selected considering the exposure duration for the scenario. For example, if the scenario is building occupancy, the selected times should not go beyond the time at which the source may undergo significant changes (such as during building renovation) and certainly not beyond the anticipated lifetime of the building.

I.1.5 Maximum Time Integration Points

Definition: This parameter refers to the maximum number of points used in numerically integrating the dose/risk rate over the exposure duration.

Parameter Name: POINT Units: Unitless

Range: 1, 2, 3, 5, 9, 17, 33, 65, 129, 257 (Traditional Interface)

1, 2, 3, 5, 9, 17, 33, 65, 129, 257, 513, 1025, 2049 (New Interface)

Default Value: 257 (Traditional Interface) or 2049 (New Interface)

Input Form: Time Parameters → Evaluation Times

Discussion: The dose/risk reported at any evaluation time is obtained by integrating the dose/risk rate over the exposure duration at each receptor location. Time integration of the dose/risk rate may be performed analytically or numerically (see descriptions in Appendix B). When the time integration is performed numerically, the code uses the convergence criterion and the maximum number of time integration points to determine how many time points to use to perform the time integration. The code will use as many time integration points as is necessary to achieve the convergence criterion, subject to the limit specified as the maximum number of time integration points.

The user can select 1, 2, 3, 5, 9, 17, 33, 65, 129, or 257 as the maximum number of time integration points to numerically calculate the time-integrated dose/risk, when the Traditional Interface is used for input data entry. The Traditional Interface limits the number of rooms in the building to 3. If the New Interface is used for input data entry, which limits the number of rooms in the building to 9, then three additional numbers, 513, 1025, or 2049, can be selected as the maximum number of time integration points.

If the user selects 1 as the maximum number of time integration points, then the instantaneous dose/risk at each user-specified time is calculated by assuming the dose/risk rate would be the same throughout the exposure duration.

I.1.6 Convergence Criterion

Definition: This parameter refers to the acceptable fractional difference between successive estimates of the time integrated values via numerical analysis.

Parameter Name: CONVCRIT Units: Unitless Range: 0 to 0.1

Default Value: 0.001

Input Form: Time Parameters → Evaluation Times

Discussion: When the time integration is performed numerically, the code uses the convergence criterion and the maximum number of time integration points to determine how many time points to use to perform the time integration. When the fractional difference between successive estimates of the time-integrated values is less than the convergence criterion, the precision of the integrated values is considered acceptable; therefore, further increment in the number of time points to estimate the time integrated values is not necessary. The code will use as many time integration points as is necessary to achieve the convergence criterion, subject to the limit specified for the maximum number of time integration points. The final integrated values will be used even though the convergence criterion is not met.

The convergence criterion is user changeable in the New Interface, while it is fixed at 0.001 and is not shown in the Traditional Interface.

Time integration is performed numerically in the following cases/situations:

1. Calculation of direct external exposure from volume sources in which the thicknesses of the contaminated and shielding regions change over the exposure duration.
2. Calculation of exposure from inhalation of and external radiation from suspended particulates and gases in the air, and from external exposure from and ingestion of particulates deposited on floors, when the concentrations of suspended and deposited particulates are computed numerically.
3. Calculation of exposure from the release of tritiated water vapor.
4. Calculation of exposure from the release of radon gas: ^{222}Rn, ^{220}Rn.

The “maximum number of points for time integration” and the “conversion criterion for time integration” have no effect when the time integration is preformed analytically. Time integration is performed analytically in the following cases/situations:

1. Calculation of direct ingestion of the source.
2. Calculation of direct external exposure from point, line and surfaces sources.
3. Calculation of direct external exposure from volume sources in which the thicknesses of the contaminated and shielding regions do not change over the exposure duration.
4. Calculation of exposure from inhalation of and external radiation from suspended particulates in the air, and from external exposure from and ingestion of particulates deposited on floors, when the concentrations of suspended and deposited particulates are computed analytically.

I.1.7 References

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I.2 BUILDING PARAMETERS

I.2.1 Number of Rooms

Definition: The number of rooms is the number of distinct airflow regions in the part of the building being modeled. This parameter could represent the number of rooms, the number of levels, or the number of parts of a space where air is hindered from being quickly mixed. This parameter affects only the pathways that depend on airflow. It does not influence the external pathway. In fact, many more rooms can be modeled in the external pathway by appropriate use of locations and shielding.

Parameter Name: NROOM Units: Unitless Range: 1-3 (Traditional Interface) or 1-9 (New Interface)

Default Value: 1

Input Form: Building Parameters

Discussion: Probabilistic input is not available for this parameter. The number of rooms can be set from 1 to 3 in the Traditional Interface or from 1 to 9 in the New Interface. In each room, the air is considered to completely mix instantaneously within its volume. The more rooms there are in a building, the more complicated the airflow specification will be (see Sections J.2.6, I.2.7, and I.2.8 for input requirements).

Figure I-2 shows various room configuration examples that can be considered with the Traditional Interface for a building with 1, 2, or 3 rooms. There is no air exchange between Room 1 and Room 3. This restriction does not apply in the New Interface, in which the rooms considered can be in any configuration, and there can be air flow between every pair of rooms.

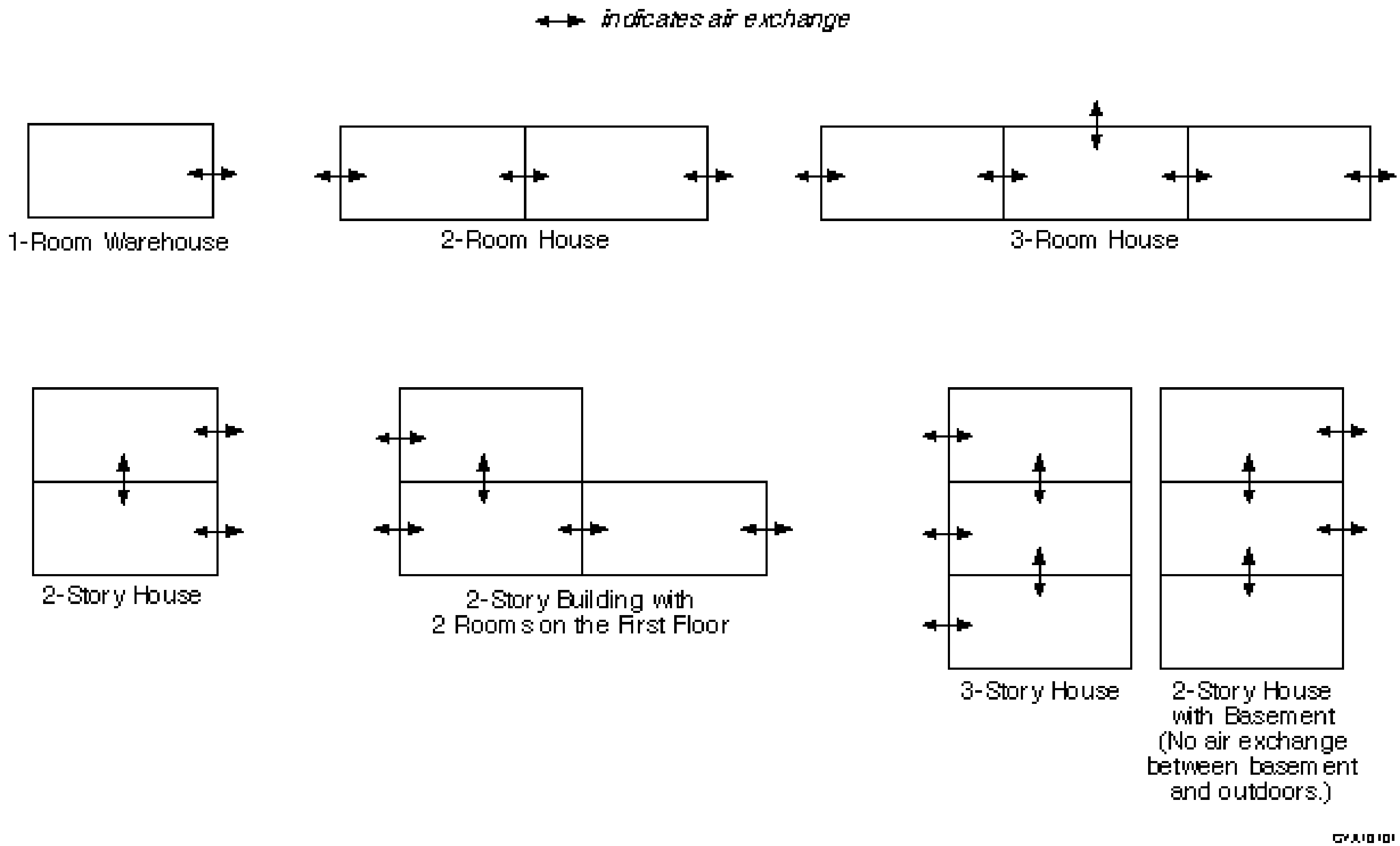

Figure I-2 Examples of Potential Discrete Airflow Regimes in a Building with One, Two, or Three Rooms

I.2.2 Deposition Velocity

Definition: This parameter represents the indoor deposition velocity of contaminant particles in the building air.

Parameter Name: UD Units: m/s Range: ≥ 0

Deterministic Analysis Default Value: 3.9×10^{-4} (Mean of uncertainty distribution)

Probabilistic Analysis Default Distribution: Loguniform

Defining Values for Distribution: Minimum: 2.7×10^{-6} Maximum: 2.7×10^{-3}

Input Form: Building Parameters

Discussion: The buildup of radionuclides on surfaces as a result of deposition of airborne particles containing radionuclides is an important process in several exposure pathways. Deposited beta- and gamma-emitting radionuclides contribute to exposure from external radiation. Deposited particles containing radionuclides also can become airborne because of mechanical disturbances or airflow (see Section I.2.3 on resuspension rate), contributing to inhalation exposure. The same deposition velocity is used for all particles containing radionuclides in the calculations. If this assumption violates the conditions being modeled, e.g., if some nuclides are in the form of particulates and others are in the form of vapor, two different cases should be analyzed, one for particulates and the other for the vapor. The appropriate deposition velocity should be specified for each case.

For the default value, a literature review of deposition velocity of 1micron particulates was conducted (Figure I-3 and Table I-2). This particulate size is consistent with the choice for the dose coefficient values (which are also size-dependent). Many processes determine the deposition rate. These include Brownian diffusion, interception, impaction, turbulent impaction, and sedimentation. For all particle sizes less than a few microns, often the Brownian diffusion and interception are the major processes. The deposition velocity is minimal at a particle size below one micron. (Šíp and Beneš 2017)

The deposition velocity, considering these processes, is about 4E-4 m/s at one micron. Since this is close to the mean value of uncertainty distribution, the mean (3.9E-4 m/s) is set as the default deposition velocity in RESRAD-BUILD. A larger the deposition velocity will reduce the initial air concentration of particulates including attached radon progeny. After the resuspension of the deposited contamination matches the deposition rate, there is no dependence of the equilibrium air concentration on the deposition velocity.

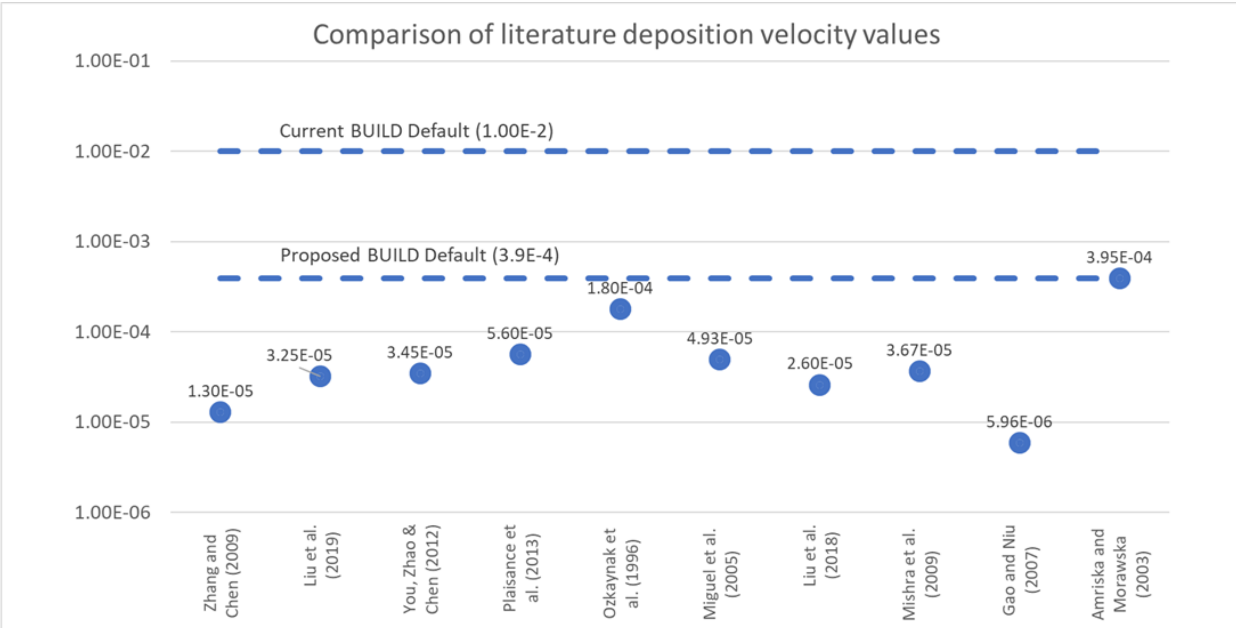

Figure I-3 Literature Indoor Deposition Velocity Values for 1 Micron Particles

Table I-2 Literature Review Used in Determining Default Deposition Velocity

Paper	Methodology and Variables
Zhang and Chen (2009)	Numerical: CFD with Lagrangian on interior walls and ceiling
Liu et al. (2019)	Numerical; by room shape, air exchange rate, and particle size
You, Zhao & Chen (2012)	Empirical; indoor inclined surfaces by friction velocity (dependent on particle size)
Plaisance et al. (2013)	Field investigation; comparison of formaldehyde deposition velocity with other chemicals and particulates
Ozkaynak et al. (1996)	Riverside Field study of residential air quality as analyzed by INDAIR
Miguel et al. (2005)	Experimental; indoor deposition velocity by particle size, relative humidity, and air flow
Liu et al. (2018)	Field study; $PM_{2.5}$ by air exchange in classrooms
Mishra et al. (2009)	Measurement; radon progeny compared with models by surface orientation and particle size
Gao and Niu (2007)	Drift Flux model; different sizes, ventilation type
Jamriska and Morawska (2003)	Measurement; effect of coagulation of aerosols

NUREG/CR-7267 Section C.4.7 (Kamboj et al. 2018) details the review of literature data on deposition velocity as it relates to particle size. Because the deposition velocity input in RESRAD-BUILD is used for all particle sizes and species under a potential range of airflow conditions, a loguniform distribution is selected as the default distribution function for this parameter, with minimum and maximum values of 2.7×10^{-6} m/s and 2.7×10^{-3} m/s, respectively. The density function of this default distribution is shown in Figure I-4.

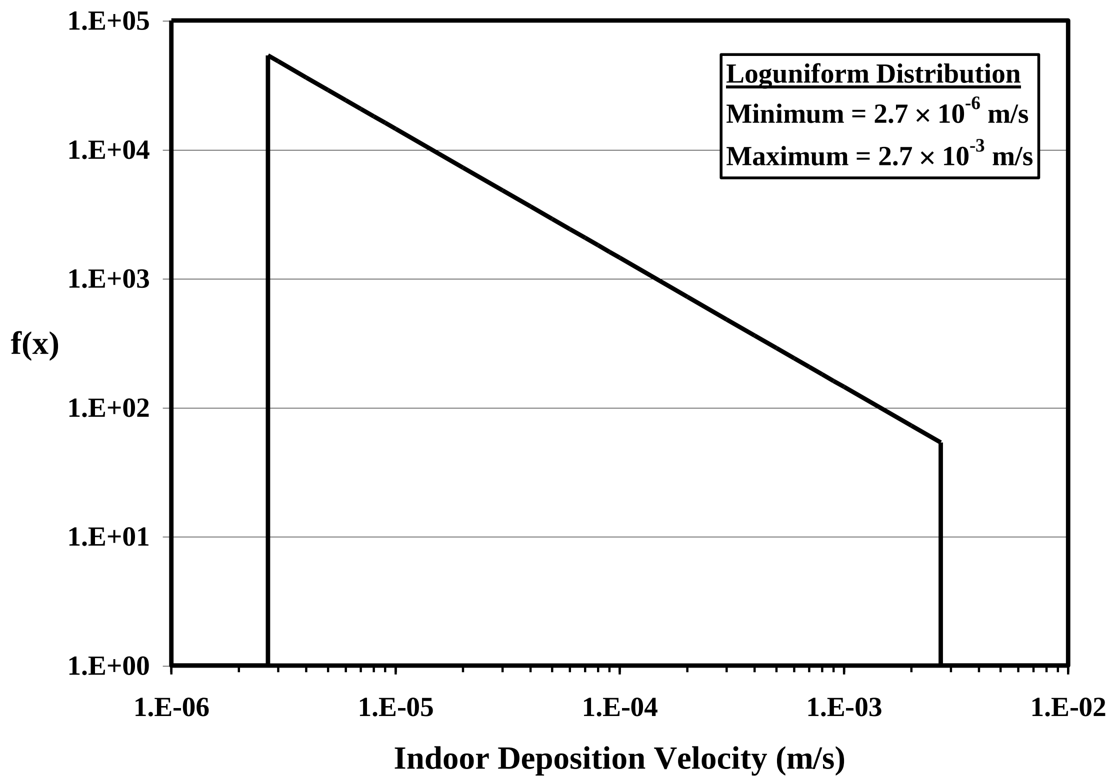

Figure I-4 Indoor Deposition Velocity Probability Density Function

I.2.3 Resuspension Rate

Definition: The resuspension rate (indoor) represents the rate at which particles deposited on interior surfaces are resuspended into the indoor air per unit time. Resuspension is the result of airflow or a mechanical disturbance, such as walking across a surface or sweeping.

Parameter Name: DKSUS   Units: s^{-1} Range: ≥ 0

Deterministic Analysis Default Value: 5×10^{-7}

Probabilistic Analysis Default Distribution: Loguniform

Defining Values for Distribution: Minimum: 2.5×10^{-11} Maximum: 1.3×10^{-5}

Input Form: Building Parameters or Building Parameters → Room Air Flow and Particulates

Discussion: Indoor resuspension of contaminated particles deposited on interior surfaces can lead to external exposure and internal exposure via inhalation. The resuspension rate is the fraction of deposited particles resuspended per unit time. Factors that can affect resuspension include the type of disturbance (airflow vs. mechanical), the intensity of the disturbance, the type of surface, particle size distribution, and physical and chemical characteristics of the particles.

This input parameter appears in the Building Parameters input form with the Traditional Interface; the input value applies to all the rooms in the building. With the New Interface, it appears in the Room Air Flow and Particulates input form, which is associated with the Air Flow tab in the Building Parameters input form. With the New Interface, each room in the building can be specified a resuspension rate and the values can be different for different rooms.

NUREG/CR-7267 Section C.7.2 (Kamboj et al. 2018) discusses the correlation between resuspension rate and resuspension factor and reviews literature data estimated for different conditions. A loguniform distribution is selected as the default distribution function for the resuspension rate parameter, because of the limited but wide-ranged estimated values from literature. The lowest (2.5×10^{-11} s^{-1}) and the largest (1.3×10^{-5} s^{-1}) estimated values are selected as the minimum and maximum value, respectively, for the distribution. Figure I-5 shows the probability density function for the distribution.

The default lowest (2.5×10^{-11} s^{-1}) and largest (1.3×10^{-5} s^{-1}) values selected for Version 4.0 of the code are different from the defaults (2.8×10^{-10} s^{-1} and 1.4×10^{-5} s^{-1}) set in earlier versions of the code. The changes were made to be consistent with NUREG/CR-7267, in which more recent literature data were reviewed to determine the default values.

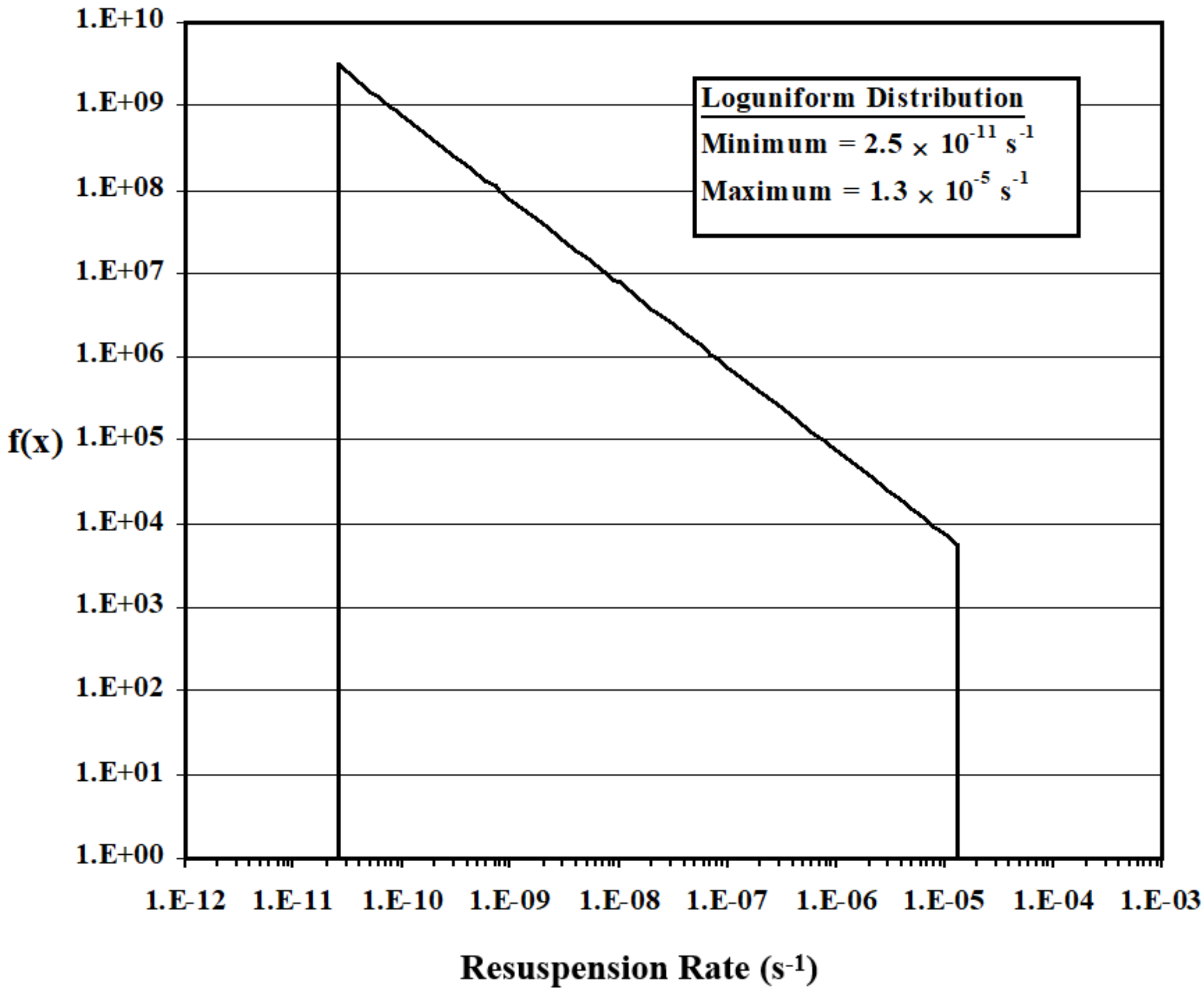

Figure I-5 Indoor Resuspension Rate Probability Density Function

I.2.4 Room Height

Definition: The room height is the distance between the floor and the ceiling of a specific room in the building.

Parameter Name: H Units: m Range: > 0

Deterministic Analysis Default Value: 2.5

Input Form: Building Parameters → Room Details

Discussion: The room height is an input parameter in the Traditional Interface. In the New Interface, it is replaced with the room volume parameter. The room height is used with the room area to determine the mixing volume of each room (distinct airflow volume). By its nature, the airflow volume could be the space within a crawl space under a house (about 1 m in height) or the stairwell in a multistory building (e.g., 3 m height per floor). The volume of the rooms and the airflow rates between rooms and between rooms and the outside are used to compute the building air exchange rate and the room air exchange rate. The height is set for each defined room in the analysis and should be consistent with the definition of that room. To ensure the physical validity of the air ventilation conditions and because both the room height and room area are independent input parameters that are linked to the air flow rates, which are also input parameters, the room area, room height, and air flow rate parameters are excluded from an uncertainty analysis in the Traditional Interface.

For one-story houses without a basement, the values for the building room height typically lie within the range of 2.2–3.0 m. A value of 2.5 m is selected as the default value.

I.2.5 Room Area

Definition: This parameter represents the floor area of a specific room in the building.

Parameter Name: AREA Units: m^2 Range: > 0

Deterministic Analysis Default Value: 36

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 3 Maximum: 900 Most likely: 36

Input Form: Building Parameters → Room Details or Room Air Flow and Particulates

Discussion: The room area is used with the room height to determine the mixing volume of each room (distinct airflow compartment) in the Traditional Interface. In the New Interface, the room volume is an input parameter, replacing the room height parameter. The room area is also used in the equilibrium expression of resuspension and deposition. The area is set for each defined room in the analysis and should be consistent with the definition of that room. This room area parameter can be selected and included in an uncertainty analysis with the New Interface. However, in the Traditional Interface, the room area, room height, and air flow rate parameters are excluded from an uncertainty analysis to ensure the physical validity of the air ventilation conditions. This is because the room height and room area are independent input parameters that are linked to the air flow rates and the air exchange rate, which are also input parameters.

Studies concerning room size distribution are not available. An arbitrary distribution has been selected as a default for use in application of RESRAD-BUILD to commercial buildings. Site-specific distributions or deterministic values should be used, if available. A triangular distribution is used to represent the room area. A minimum value of 3 m^2 (approximate room dimensions of 1.5×2 m) was chosen to represent such areas as utility rooms or storage closets in a commercial environment. A maximum value of 900 m^2 (slightly less than 10,000 ft^2) was chosen to represent larger areas that would correspond to the area of rooms housing such functions as light industrial assembly lines, small to intermediate warehouse operations, or large assembly halls. However, office space is generally required in support of such larger operations. Such a requirement skews the room size distribution toward smaller room area, which suggests that a uniform distribution between the minimum and maximum areas is not appropriate. The choice of a most likely value for a triangular distribution was arbitrary and attempted to account for this observation. A most likely value of 36 m^2 (390 ft^2) was chosen. This value lies above what might be expected for the area for a single-occupant office room (approximately 12 m^2, 3 m $\times$ 4 m) and is in the range of what might be expected for a multi-occupant office room. Figure I-6 presents the probability density function suggested for the room area.

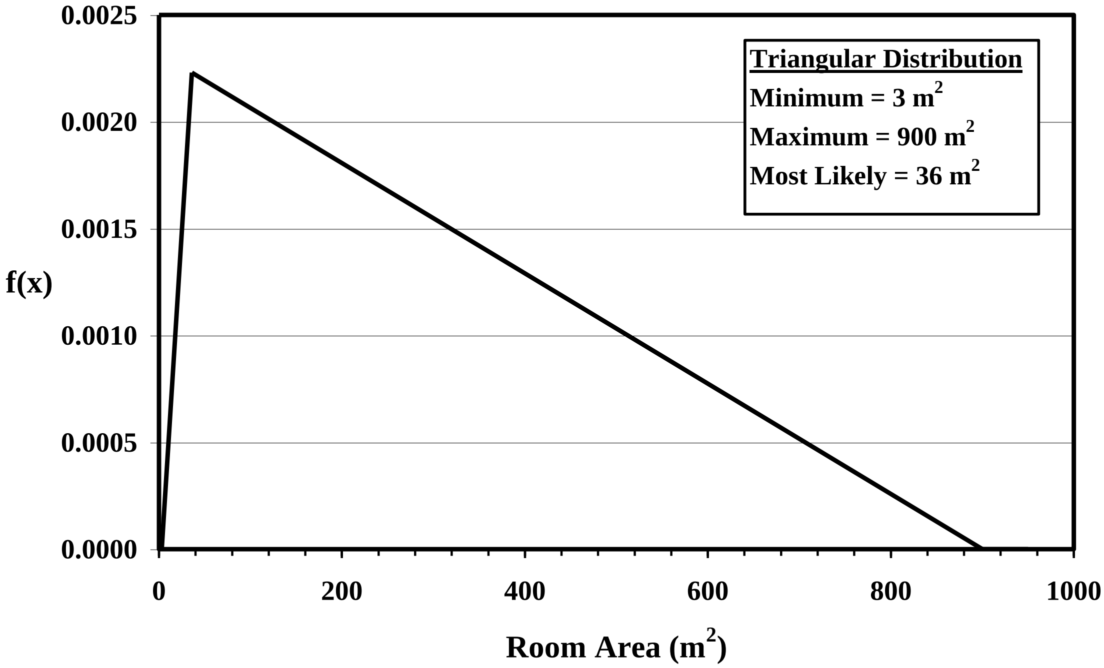

Figure I-6 Room Area Probability Density Function

I.2.6 Room Volume

Definition: The room volume is the airflow volume in each room (distinct airflow compartment) in which instantaneous mixing would occur to achieve homogeneity, as is assumed in the air ventilation modeling.

Parameter Name: VOLUME Units: m^3 Range: > 0

Deterministic Analysis Default Value: 90

Input Form: Building Parameters → Room Air Flow and Particulates

Discussion: The room volume is an input parameter in the New Interface. It replaces the room height parameter as seen in the Traditional Interface. With the input of room volume, the height of a room is calculated by dividing the room volume with the room area. This provides a means to ensure physical validity of the ventilation conditions defined by the room volumes and air flow rates; both are input parameters. The air exchange rates are not included in the New Interface because they are not needed in the ventilation modeling. Both the room volume and room area parameters can be included in an uncertainty analysis in the New Interface. The volume is set for each defined room (distinct airflow compartment) in the analysis and should be consistent with the definition of that room.

The default value for room volume is 90 m^3, which is the product of 36 m^2 (the default room area) and 2.5 m (the default room height). No default distribution function was selected. Because this parameter is strongly correlated with the room area, the input value (distribution function) for the room area should be factored into account when determining the value (distribution function) for the room volume.

I.2.7 Air Exchange Rate

Definition: The air exchange (or ventilation) rate for a building or a room is the fraction of total volume of air in the building or room replaced by air from the outside and from other room(s) per unit of time. For example, a building (or room) with an air exchange rate of 1 per hour (1/h) has its air replaced once every hour on average.

Parameter Name: LAMBDAT (building); LINPUT (room) Units: 1/h Range: > 0

Deterministic Analysis Default Value: 0.8/h (building air exchange rate for one-room model)

Probabilistic Analysis Default Distribution: truncated lognormal-n (probabilistic input is only available for LAMBDAT, the building air exchange rate, for a one-room building)

Defining Values for Distribution:

Mean of underlying normal:	0.4187	Lower quantile value:	0.001
Standard deviation of underlying normal:	0.88	Upper quantile value:	0.999

Input Form: Building Parameters → Room Details

Discussion: The air exchange rates appear only in the Traditional Interface. Only the air exchange rate for a one-room building is input by the user. The room air exchange rate(s) and the building air exchange rate for a two- or three-room building are calculated with the input air flow rates, the room area(s), and the room height(s) by the RESRAD-BUILD code. In the Traditional Interface, the building is conceptualized as a structure composed of up to three rooms. Air exchange is assumed between Rooms 1 and 2 and Rooms 2 and 3 but not between Rooms 1 and 3. All rooms can exchange air with the outdoor atmosphere. The room air exchange rate strongly depends on the number of rooms, inflow, outflow, and net flow within the rooms. The full flow of air can be calculated only if the parameters satisfy certain conditions that guarantee a positive exchange of air between the rooms.

Air exchange involves three processes: (1) infiltration, which is air leakage through random cracks, interstices, and other unintentional openings in the building; (2) natural ventilation, which is airflow through open windows, doors, and other designed openings in the building; and (3) forced, or mechanical, ventilation, which is controlled air movement driven by fans. A single building can have a wide range of air exchange rates both in the short- and long-term, depending on environmental conditions at a particular time (e.g., seasonal/diurnal temperature, pressure, and ambient wind speed and direction); other factors include opening and closing of doors and windows, building type, construction, age, and ventilation system. The U.S. Environmental Protection Agency's (EPA's) Exposure Factors Handbook (EPA 2011) contains a comprehensive review of literature data on air exchange rates. The data collection handbook for RESRAD applications (Yu et al. 2015) summarizes the information in the EPA Exposure Factors Handbook in Section 5.1.

While the air exchange rate data for commercial buildings are less than for residential structures, the distribution of air exchange rates is expected, in part because of human comfort considerations, to be similar to that of residential structures when averaged over the United

States for all four seasons of the year. Thus, a generic lognormal distribution has been assigned to the building exchange rate to represent the average over all conditions. The mean and standard deviation of the distribution are those obtained by Turk et al. (1987), 1.52 h^{-1} and 0.88, respectively. The mean falls within the average mean found by different residential studies and is consistent with other commercial building studies. The standard deviation is the same as observed by Murray and Burmaster (1995). Because of the limited dataset and variations across different industries, climates, and seasons, this distribution is only an approximation to potential building air exchange rates for light industry. Figure I-7 displays the probability density function for the building air exchange rate.

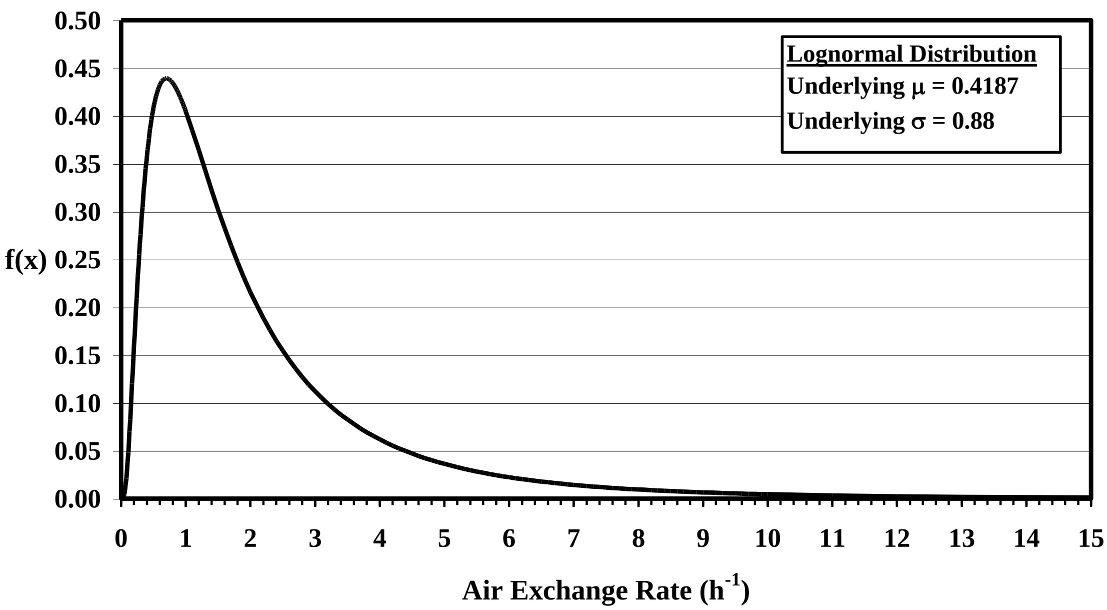

Figure I-7 Building Air Exchange Rate Probability Density Function

I.2.8 Flow Rate between Rooms

Definition: These are the rates at which air flows in each direction between adjacent rooms. Different rates may be specified for the flows in the opposite directions. This parameter does not apply to a one-room building in the Traditional Interface, for which the building air exchange rate is specified.

Parameter Name: QAIR(m,n) (m denotes the room from which air flows out, and n denotes the room to which air flows in)

Units: m^3/h Range: ≥ 0

Default Value: For one-room buildings, not applicable; for two-room buildings, QAIR(1,2) and QAIR(2,1) = 30 m^3/h; for three-room buildings, QAIR(1,2) = 0, QAIR(2,1) = 0, QAIR(2,3) = 30, and QAIR(3,2) = 30 m^3/h; for buildings with 4-9 rooms, QAIR(1,2) = 0, QAIR(1,3) = 0, QAIR(2,1) = 0, QAIR(2,3) = 30, QAIR(3,1) = 0, QAIR(3,2) = 30, and QAIR(m,n) = 72 m^3/h (when m > 3 or n > 3)

Input Form: Building Parameters → Room Details or Room Air Flow and Particulates

Discussion: This parameter is not eligible for probabilistic input in the Traditional Interface. It is eligible for probabilistic input in the New Interface. There is no default distribution for this parameter, because the distribution is considered to be strongly building-specific.

The flow rate between rooms depends strongly on other building-specific parameters, such as the number of rooms, dimensions of rooms, and the air exchange rate. In the Traditional Interface, for one-room buildings, this parameter is not required, and for three-room buildings, no air exchange is allowed between Rooms 1 and 3; therefore, the airflow rate from Room 1 to Room 3 or from Room 3 to Room 1 is not required. In the New Interface, such restrictions are removed, so input of air flows between any pair of rooms are required.

The net flow rate between two rooms may be positive, zero, or negative. The measurement of the net flow between two rooms may be estimated based on building specifications for the ventilation system.

I.2.9 Flow Rate between Room and the Outside

Definition: These are the rates at which air flows between the room and the exterior of the building. In a one-room building, the rate at which the outdoor air flows into the room will be equal to the rate at which the air flows from the room to the exterior. These rates are not necessarily equal in multi-room buildings; they will be equal only if there is no net air flow between the adjoining rooms.

Parameter Name: QAIR(m,0) (from room m to exterior), QAIR(0,m) (from exterior to room m)

Units: m^3/h Range: unlimited

Default Value: For one-room buildings, QAIR(1,0) = QAIR(0,1) = 72 m^3/h; for two-room buildings, QAIR(1,0) = QAIR(0,1) = 84 m^3/h and QAIR(2,0) = QAIR(0,2) = 60 m^3/h; for three-room buildings, QAIR(1,0) = QAIR(0,1) = 96 m^3/h and QAIR(2,0) = QAIR(0,2) = QAIR(3,0) = QAIR(0,3) = 60 m^3/h; for buildings with 4-9 rooms, QAIR(1,0) = QAIR(0,1) = 96 m^3/h, QAIR(2,0) = QAIR(0,2) = 60 m^3/h, QAIR(3,0) = QAIR(0,3) = 60 m^3/h, and QAIR(m,0) = QAIR(0,m) = 72 m^3/h (m = 4 to 9)

Input Form: Building Parameters $\rightarrow$ Room Details or Room Air Flow and Particulate

Discussion: This parameter is not eligible for probabilistic input. The outdoor air inflow and outflow rates strongly depend on other building-specific parameters, such as the number of rooms, room dimensions, and air flow rates between rooms. The net outdoor flow rate (inflow-outflow), like the net flow rate between rooms, may be positive, zero, or negative. The net flow between two rooms may be estimated based on building specifications for the ventilation system.

I.2.10 Efficiency of Vacuuming

Definition: This parameter is the fraction of particulates deposited on the floor that are removed from the building after each vacuuming/cleaning event.

Parameter Name: VACEFF Units: None Range: 0–1

Default Value: 0

Input Form: Building Parameters → Room Air Flow and Particulate

Discussion: This parameter appears only in the New Interface. It is included in the Room Air Flow and Particulates input form associated with the Air Flow button in the Building Parameters input form. The default value is set to 0 to be consistent with the setup in the Traditional Interface, in which vacuuming/cleaning of the deposited particulates is not considered. A value of 0 for this parameter indicates the vacuuming will not remove any of the deposited particulates on the floor. A value of 1, on the other hand, indicates all the deposited particulates will be removed after vacuuming. This parameter is used with the frequency of vacuuming parameter to evaluate the influence of vacuuming on the amount of particulates deposited on the floor over time. These two parameters apply to all the rooms in the building, thereby affecting the amount of deposited particulates (and radionuclides) on the floor in each room discretely.

I.2.11 Frequency of Vacuuming

Definition: The frequency of vacuuming is expressed as the number of days between two successive vacuuming events.

Parameter Name: VACUUMINTERVAL Units: d Range: ≥ 0

Default Value: 7

Input Form: Building Parameters → Room Air Flow and Particulate

Discussion: This parameter appears only in the New Interface. It is included in the Room Air Flow and Particulates input form associated with the Air Flow button in the Building Parameters input form. The default is set to 7 days, assuming vacuuming will be conducted once every week. This parameter is used with the efficiency of vacuuming parameter to evaluate the influence of vacuuming on the amount of particulates deposited on the floor over time. These two parameters apply to all the rooms in the building, thereby affecting the amount of deposited particulates (and radionuclides) on the floor in each room discretely.

I.2.12 Maximum Time Step

Definition: This is the upper bound to the time step used in the numerical solution of the dynamic ventilation model that characterizes the particulate concentration in the air and on the floor in each room over time.

Parameter Name: MAXTSTEP Units: d Range: ≥ 0

Default Value: 0.08911

Input Form: Building Parameters → Room Air Flow and Particulate

Discussion: This parameter is not eligible for probabilistic input. It appears only in the New Interface and is only used in the numerical solution of the dynamic ventilation model. Where appropriate, the RESRAD-BUILD code determines the time step based on the following three constraints:

1. The time step cannot exceed the maximum time step input value.
2. The number of time steps in an exposure duration cannot be less than the maximum number of points for time integration input value. This is to ensure that the same two concentrations, calculated by the numerical solution algorithm, are not used to interpolate for the concentration at more than one time integration time.
3. The time step cannot exceed the reciprocal of the composite removal rate coefficient of the source material from the air in the room where the source material is release into. This is to prevent wide oscillations in the numerically computed concentrations.

These conditions can be represented by the following equations:

$$t_{step} \le t_{step}^{maximum} \tag{I-1}$$

$$t_{step} \le \frac{V_s}{\left(A_s v_d + \sum_{j=0,j\neq i}^{n} q_{i,j}\right) \times 86400} \tag{I-2}$$

$$t_{step} \le \frac{t_{ed}}{n_{TI}^{max}} \tag{I-3}$$

where:

t_{step} = time step used in the numerical integration of dose and risk (d),

$t_{step}^{maximum}$ = maximum time step specified (d),

V_s = volume of the room in which the source is located (m^3),

A_s = area of the room in which the source is located (m^2),

v_d = deposition velocity of the particulates in air (m/s),

$\sum_{j=0,j\neq i}^{n} q_{i,j}$ = sum of the air flows out of the room in which the source is located (m^3/s),

86,400 = unit conversion factor (s/d),

t_{ed} = exposure duration (d), and

n_{TI}^{max} = maximum number of time points to be used for time integration.

I.2.13 Analytical Solution When Possible

Definition: When the check box associated with this input option is checked, the RESRAD-BUILD code will use the analytical solutions to obtain time-integrated dose/risk results whenever possible.

Parameter Name: DONUMERICAL

Default Value: .True.

Input Form: Building Parameters → Room Air Flow and Particulate

Discussion: This parameter appears only in the New Interface. It is included in the Room Air Flow and Particulates input form associated with the Air Flow button in the Building Parameters input form. The default is set to True, meaning the code will use analytical solutions to obtain time-integrated dose/risk results whenever possible before switching to numerical solutions.

The ventilation modeling involves solving the mathematical equations concerning the transient concentrations of the particulates (and the radionuclides contained in the particulates) suspended in the air and deposited on the floor. The transient concentrations as well as the time integration of the transient concentrations can be calculated using analytical solutions or numerical solutions as described in Appendix B of the User's Manual.

The analytical solutions can be used to model releases of particulates or H_2O moisture at a constant rate over a release interval, in buildings with up to 3 rooms, with one known exception. As detailed in Appendix B, it cannot be used in a three-room building where two of the rooms are identical with respect to the properties specified in the Room Air Flow and Particulates input form and there is a source in the third room.

The numerical solutions can be used to model release of particulates and H_2O moisture at both constant and variable rates, in buildings with up to 9 rooms.

Radon and its three short-lived progenies are analyzed using the pseudo-steady-state assumption (Appendix E). The time-integrated air concentration and deposition concentration for the short-lived progenies are always calculated numerically.

The “Analytical Solution When Possible” option is not available in the Traditional Interface. If the Traditional Interface is used to specify air flow parameters, the code will, in general, use the analytical transient solution, if possible. It will use the numerical solution if the user had previously unchecked this option while in the New Interface to modify the current input file and then switched to the Traditional Interface, or if it cannot use the analytical solution as described above.

I.2.14 Write Intermediate Output

Definition: When the check box associated with this input option is checked, the RESRAD-BUILD code will output intermediate results to several files for users to view and use.

Parameter Name: WRITEINTERMEDIATE

Default Value: .True.

Input Form: Building Parameters → Room Air Flow and Particulate

Discussion: This option can be checked via the Advanced menu, or if the New input forms are used for data entry, via the detailed input form, Room Air Flow and Particulates, that is associated with the Air Flow button in the Building Parameters input form. The default is set to True, meaning the code will write intermediate results to numerous output files.

I.2.15 References

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I.3 RECEPTOR PARAMETERS

I.3.1 Number of Receptors

Definition: This parameter represents the number of receptor locations where radiation dose and risk will be evaluated over the exposure duration.

Parameter Name: ND **Units:** Unitless **Range:** Integer values from 1 to 10, inclusive

Default Value: 1

Input Form: Receptor Parameters

Discussion: This parameter is not eligible for probabilistic input. In RESRAD-BUILD, each receptor is specified at a fixed location within the contaminated building where he/she is assumed to spend a specified fraction of time over the exposure duration and incurred radiation exposure. The number of receptors is equivalent to the number of receptor locations. In reality, an individual may spend different amounts of time at different locations within the building. Therefore, the number of receptors may or may not represent the actual number of exposed individuals. An exposed individual maybe represented by several receptors, so his/her radiation exposure is the sum of the exposures of different receptors.

One to 10 receptors may be defined, each with associated parameters, including the location within a building (coordinates relative to a selected origin point), the room within the building, time fraction at that location/room, and inhalation/ingestion rates at that location/room. Different receptors may be assigned the same location and room, only with different time fractions, inhalation rates, and/or ingestion rates. The number of receptors required for each RESRAD-BUILD analysis may be determined on the basis of anticipated occupancy patterns such as those found in time-motion studies.

I.3.2 Receptor Room

Definition: This parameter specifies the room in which a receptor is located.

Parameter Name: DLVL Units: Unitless Range: Integer value of 1, 2, 3 (Traditional Interface) or 1, 2, 3, 4, 5, 6, 7, 8, 9 (New Interface)

Default Value: 1

Input Form: Receptor Parameters

Discussion: This parameter is not eligible for probabilistic input. Each receptor must be located in one of up to a maximum of three rooms (Traditional Interface) or nine rooms (New Interface) allowed by the RESRAD-BUILD code. The identification of the room in which a receptor is located affects dose/risk calculations for all pathways, except for the direct external radiation pathway. The number of rooms must first be defined (see Section I.2.1 on the number of rooms) before a receptor may be located in one of them.

If a scenario was originally set up for a building with multiple rooms and is modified to consider a building with a lesser number of rooms, the receptor(s) that was placed in a room that is no longer valid, i.e., the original room number is greater than the revised number of rooms, the receptor is automatically relocated to Room 1; however, his/her spatial coordinates are not changed. The user is advised to reevaluate the number of receptors, receptor rooms, and receptor locations before running the code to analyze the modified scenario.

I.3.3 Receptor Location

Definition: This parameter specifies the spatial coordinates of the point (x, y, z Cartesian coordinate system) occupied by a receptor.

Parameter Name: DX Units: Meters (m) Range: Unlimited

Default Value: 1,1,1

Input Form: Receptor Parameters

Discussion: This parameter is not eligible for probabilistic input. The receptor location in the room is specified with the x, y, and z coordinates relative to the origin. The user must specify the coordinates of the locations of the receptor(s) and source(s) in relation to a common origin in the building. The coordinates are used to determine the distance between the receptor and each of the radiation sources for the calculation of the direct external radiation dose received by the receptor from each source. The coordinates are not used to calculate radiation dose from the inhalation, ingestion, or external radiation from deposited materials, for which the receptor room information is used.

RESRAD-BUILD accepts positive values, negative values, or 0 for the receptor coordinates. However, the receptor coordinates may not be the same as the coordinates of any of the sources. The receptor location should not be in contact with nor within a source or building structure. For volume and area sources, the receptor coordinates may not be located on the same plane as the source surface. For line sources, the receptor coordinates may not be located on the same line as the source. The spatial coordinates should be within the designated room of the receptor. Typically, direct external dose is estimated at 1 meter above the floor over which the receptor is located. However, different geometrical considerations may reduce or increase this distance (e.g., if the receptor is working at heights or sleeping).

The average of several points within a room may be used to establish the receptor location, considering the receptor would not stay fixed at a certain point. However, if the direct external radiation varies significantly among the different points, a more precise estimate of external dose can be obtained by using more than one receptor to represent the same exposed individual, with receptor time fractions adjusted accordingly.

I.3.4 Receptor Time Fraction

Definition: This parameter specifies the fraction of time spent by one or more receptors at a given location while inside the building.

Parameter Name: TWGHT Units: UnitlessRange: ≥ 0 and ≤ 1

Default Value: 1

Input Form: Receptor Parameters

Distribution: This parameter is not eligible for probabilistic input. If an exposed individual is represented by a single receptor, the time fraction spent by the receptor at any location inside the building may be any number greater than zero but less than or equal to 1. If multiple receptors at different locations are used to represent an exposed individual, the sum of the time fractions at the different locations should not exceed 1. If a receptor is used to represent multiple exposed individuals at the same location, the receptor time fraction may exceed 1. In that case, the sum of time fractions spent by each exposed individual at that location can be used as the receptor time fraction; the resulting dose calculated for the receptor will be the collective dose incurred by the exposed individuals. The user must ensure that the sum of receptor time fractions over all the receptor locations does not exceed the number of building occupants, i.e., the exposed individuals, considered in the analysis.

The receptor time fraction may be estimated on the basis of anticipated occupancy patterns. For example, if an exposed individual would spend 3 hours at a receptor location for every 8 hours spent inside the building, the time fraction at that receptor location would be 0.375 (= 3/8). The time fraction at the receptor location is used in conjunction with the exposure duration and the indoor time fraction to compute the time spent at the receptor location as:

Time Spent at Receptor Location = Exposure Duration × Indoor Time Fraction × Time Fraction at the Receptor Location.

I.3.5 Receptor Breathing/Inhalation Rate

Definition: This parameter reflects the rate at which an individual inhales air at the receptor location.

Parameter Name: BRTRATE Units: m^3/d Range: ≥ 0

Deterministic Analysis Default Value: 18

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 12 Maximum: 46 Most likely: 33.6

Input Form: Receptor Parameters

Discussion: A breathing/inhalation rate is specified for each receptor location. The input value can be set to zero to suppress the exposure from the inhalation pathway. The U.S. Environmental Protection Agency's (EPA's) Exposure Factors Handbook (EPA 2011) contains a comprehensive review of inhalation rates for different activities, age groups, and genders from different studies. The data collection handbook for RESRAD applications (Yu et al. 2015) summarizes the information in the EPA Exposure Factors Handbook in Section 7.2.

A triangular distribution is used as the default function for the inhalation rate in RESRAD-BUILD. The most likely inhalation rate value was taken to be 33.6 m^3/d (1.4 m^3/h), as recommended in Beyeler et al. (1998), which is also the average of the inhalation rates for adult males and females under light exercise conditions (Table I.10, ICRP 2002). The minimum value of 12 m^3/d (0.5 m^3/h) was selected on the basis of recommendations for sedentary adult activities, and a maximum value of 46 m^3/d (1.9 m^3/h) was selected because it represented the highest average value reported in Beyeler et al. (1998) for workers in light industry. The maximum value also falls between the inhalation rates for adults under light and heavy exercise conditions (Table I.10, ICRP 2002). Figure I-8 presents the probability density function for the default inhalation rate distribution.

The breathing rates of individuals are a well-measured parameter that require no additional site-specific measurements unless the receptors considered in the RESRAD-BUILD analysis are significantly different from average. On the basis of the exposure scenario and anticipated activity profile, the average breathing rate at a receptor location may be set to the time-weighted inhalation rate calculated with the inhalation rates for different receptor types and activity levels as listed in Table I-3. The default deterministic value for this parameter is 18 m^3/d.

Table I-3 Reference Values for Inhalation Rates (m^3/h) at Different Physical Activity Levels

Age Group	Resting (Sleeping)	Sitting Awake	Light Exercise	Heavy Exercise
3 months	0.1	NA[a]	0.2	NA
1 year	0.2	0.2	0.4	NA
5 years	0.2	0.3	0.6	NA
10 years, male	0.3	0.4	1.1	2.2
10 years, female	0.3	0.4	1.1	1.8
15 years, male	0.4	0.5	1.4	2.9
15 years, female	0.4	0.4	1.3	2.6
Adult, male	0.5	0.5	1.5	3.0
Adult, female	0.3	0.4	1.3	2.7

[a] NA = Not available.

Source: ICRP (2002).

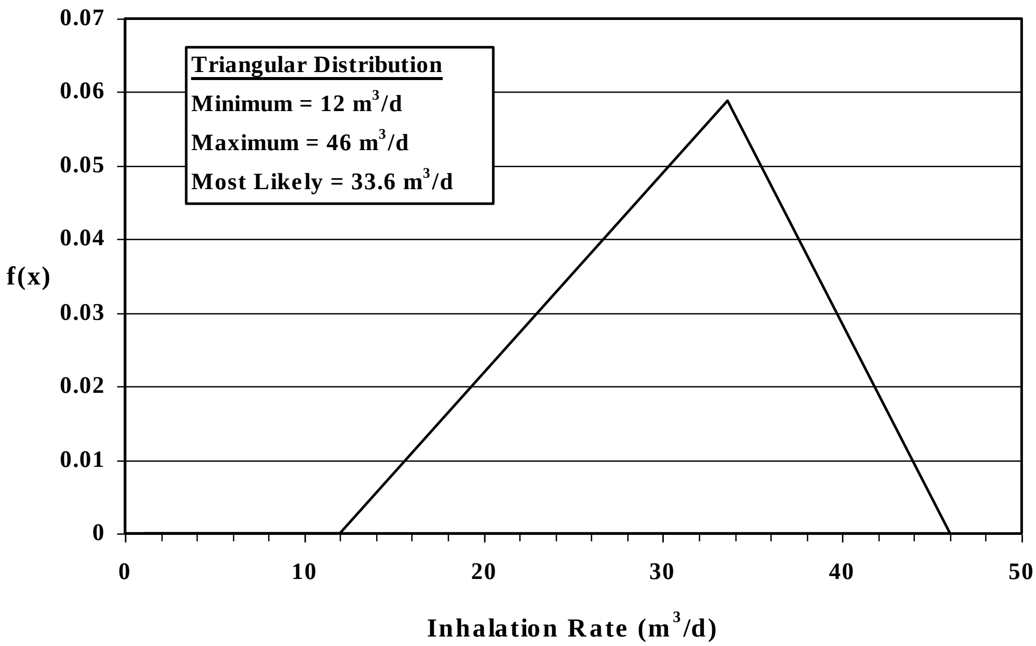

Figure I-8 Inhalation Rate Probability Density Function

I.3.6 Indirect/Secondary Ingestion Rate

Definition: This parameter represents the ingestion rate of deposited material for a receptor in the specified room where he is located. This rate represents the transfer of deposited contamination from building surfaces to the mouth via contact with hands, food, or other objects. The indirect ingestion rate is expressed as the surface area contacted per unit time. This rate is different from the direct ingestion rate, since an individual does not need to be in the same room as the source to be exposed via this pathway.

Parameter Name: INGE2 Units: m^2/h Range: ≥ 0

Deterministic Analysis Default Value: 0.0001

Probabilistic Analysis Default Distribution: Loguniform

Defining Values for Distribution: Minimum: 2.8×10^{-5} Maximum: 2.9×10^{-4}

Window: Receptor Parameters

Discussion: Limited information is available on the values for this parameter. Beyeler et al. (1998) contains eight data references. However, half of them concerned intake by children, not adults in an occupational setting. A larger, secondary set of data from soil ingestion studies is available (see Section I.4.8); however, the primary emphasis is also on soil ingestion rates of children, out of concern over elevated exposures from intensive mouthing behavior in this age group. Only two studies (Calabrese et al. 1990; Stanek et al. 1997) have provided empirical data for soil ingestion by adults. Comprehensive reviews of soil ingestion by humans can be found in EPA (2011).

Because the indirect ingestion rate is specified as the surface area contacted per unit time in RESRAD-BUILD, estimates of the daily ingested amount were converted to the proper unit by using estimates for deposited contaminant concentrations on surfaces (soil) and soil loadings on hand (Beyeler et al. 1998). However, this approach would result in large uncertainty for the indirect ingestion rate derived; in fact, the uncertainty is larger than the anticipated variability across sites (Beyeler et al. 1998). For this reason, Beyeler et al. (1998) proposed an alternative procedure to derive distributions for an effective ingestion rate. The procedure involves the number of hand-to-mouth events per day and transfer efficiencies from surface to hand and from hand to mouth, the factors not explicitly accounted for in the previous approach.

The proposed alternative procedure was on the basis of mean ingestion rates of 0.5 and 50 mg/d, which fall within the range of 0 to 70 mg/d for mean ingestion rates thought to be consistent with the empirical data (Calabrese et al. 1990; Calabrese and Stanek 1995; Stanek et al. 1997). The minimum and maximum ingestion rates with the empirical data were 0 and 200 mg/d, respectively. In the most comprehensive study, 10 subjects were followed for 28 days, yielding an average ingestion rate of 10 mg soil/d, with a 95^{th}-percentile value of 331 mg soil/d (Stanek et al. 1997). Dust loadings were assumed to range from 10 mg/m^2, taken to be the lower limit in a residential setting, to 5,000 mg/m^2, taken to correspond to heavily soiled hands.

The resulting indirect ingestion rate out of the alternative procedure (Table I-4) ranged from 4.4×10^{-4} to 4.6×10^{-3} m^2/d, with a mean of 1.8×10^{-3} m^2/d, and from 5.1×10^{-2} to

4.3×10^{-1} m^2/d, with a mean of 1.8×10^{-1} m^2/d. For use in RESRAD-BUILD, the above derived ingestion rate was assumed for an exposure of 16-hour per day; after normalization, distributions with a mean of 1.1×10^{-4} and 1.1×10^{-2} m^2/h as the low and high average of the ingestion rate were obtained (Table I-4). As discussed in Beyeler et al. (1998), an ingestion rate corresponding to 1×10^{-2} m^2/h implies mouthing an area equivalent to the inner surface of the hand once each hour. Such an ingestion rate appears to be an upper bound for a commercial environment. Because the ingestion rates for adults can approach zero (the lower bound), the lower ingestion rate distribution based on the alternative procedure was selected as the default for use in RESRAD-BUILD. Figure I-9 presents the probability density function.

The code requires that an average indirect ingestion rate in m^2/h be specified for each receptor location. The default deterministic value of 0.0001 m^2/h corresponds to the mean value of the default distribution. Setting this parameter to zero effectively suppresses the exposure from the indirect ingestion pathway.

Table I-4 Indirect Ingestion Rates

Parameter	Mean	Lower Limit	Upper Limit
From Beyeler et al. 1998			
Dust loading (mg/m^2)	320	10	5,000
Low ingestion rate input (mg/d)	0.50	0	200
High ingestion rate input (mg/d)	50	0	200
Low ingestion rate estimate (m^2/d)	1.8×10^{-3}	4.4×10^{-4}	4.6×10^{-3}
High ingestion rate estimate (m^2/d)	1.8×10^{-1}	5.1×10^{-2}	4.3×10^{-1}
RESRAD-BUILD Input[a]			
Low ingestion rate estimate (m^2/h)	1.1×10^{-4}	2.8×10^{-5}	2.9×10^{-4}
High ingestion rate estimate (m^2/h)	1.1×10^{-2}	3.2×10^{-3}	2.7×10^{-2}

[a] Obtained by assuming a 16-hour day for the results from Beyeler et al. (1998).

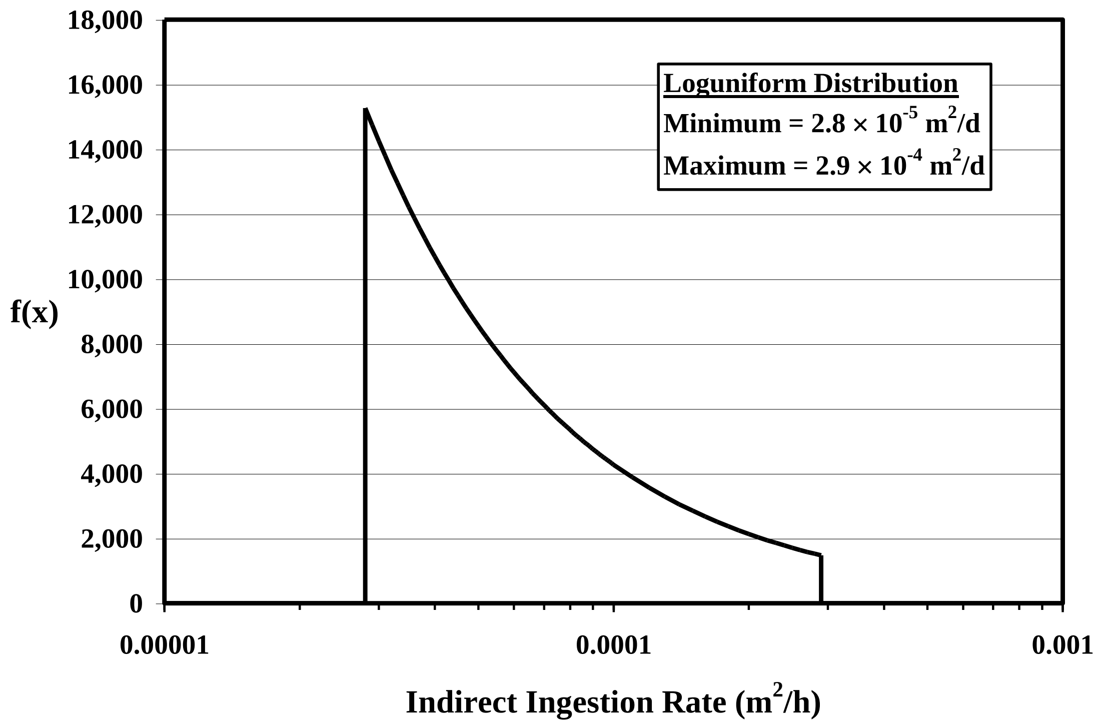

Figure I-9 Indirect Ingestion Rate Probability Density Function

I.3.7 References

Beyeler, W.E., et al., 1998, "Review of Parameter Data for the NUREG/CR-5512 Building Occupancy Scenario and Probability Distributions for the DandD Parameter Analysis," letter report prepared by Sandia National Laboratories, Albuquerque, NM, for U.S. Nuclear Regulatory Commission, WA, Jan.

Calabrese, E.J., and E.J. Stanek, 1995, "Resolving Intertracer Inconsistencies in Soil Ingestion Estimation." *Environmental Health Perspectives* 103(5):454–57.

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Stanek, E.J., et al., 1997, "Soil Ingestion in Adults—Results of a Second Pilot-Study." *Ecotoxicology and Environmental Safety* 36:249–257.

Yu, C., S. Kamboj, C. Wang, and J.-J. Cheng, 2015, *Data Collection Handbook to Support Modeling Impacts of Radioactive Materials in Soil and Building Structure*s, ANL/EVS/TM-14/4, Environmental Science Division, Argonne National Laboratory, Argonne, IL, September.

I.4 SOURCE PARAMETERS

I.4.1 Number of Sources

Definition: The number of sources specifies the number of radioactive sources as well as source locations to be considered in the dose assessment.

Parameter Name: NS Units: Unitless Range: Integer between 1 to 10, inclusive

Default Value: 1

Input Form: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. One to 10 sources may be defined, each at a specific location (x, y, and z coordinates) and with its own properties, such as building room number, geometric type and direction, and radionuclide contained within, etc.

The number of sources to be specified in a RESRAD-BUILD analysis depends on the actual number of independent radioactive sources present in the building and how they will be characterized in the analysis. A single source may be broken down into two or more components on the basis of geometric considerations. For example, a single contaminated pipe that makes a 90-degree bend may be modeled as two line sources. A volume source in a wall with the two exposed surfaces releasing radioactive materials into two different rooms may be modeled as two volume sources with shorter lengths located in two different rooms. Another reason to divide a source into two or more components is if it has a heterogeneous distribution of radionuclides. For example, a source may be volumetrically contaminated with certain radionuclides but may also be contaminated with other radionuclides on a surface. The code requires at least one source (with associated geometrical, physical, and radiological characteristics) be specified in each analysis.

I.4.2 Source Room

Definition: The source room is the room number containing a particular source.

Parameter Name: SLVL Units: Unitless Range: 1, 2, or 3 (Traditional Interface) or 1, 2, 3, 4, 5, 6, 7, 8, or 9 (New Interface)

Default Value: 1

Input Form: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. Each source must be assigned a room in which it resides. The input of the room in which a source resides affects the radiation doses that the receptor(s) will incur from the air-related pathways and the direct ingestion pathway but not the direct external radiation pathway.

The specification of a source room depends on site-specific and scenario-specific assumptions. A source may form part of the boundary between two rooms, such as a wall, floor, or ceiling. In such cases, the room assigned to the source will be the room receiving the radioactive materials released directly from the source. To obtain more precise dose/risk results, the source may be divided into two volume sources, both equal in thickness to the original source. Each volume source would be composed of two layers, one contaminated and one uncontaminated, and each source would be assigned to a separate room. Care must be taken to define each layer of the volume source correctly (see Sections I.4.13 and I.4.14 on number of regions in volume source and contaminated region, respectively).

The number of rooms must first be defined (see Section I.2.1 on the number of rooms) before a source may be located in one of them. If a building was originally set up to consist of more rooms and the number of rooms is modified and reduced, any sources previously located in a room with a number greater than the new number of rooms are automatically relocated to Room 1; however, their spatial coordinates are not changed. The user is advised to reevaluate the number of sources, source rooms, and source locations before running RESRAD-BUILD to analyze the modified problem.

I.4.3 Source Type

Definition: The source type specifies the geometrical representation of the distribution of radioactive material within a source. One of four source types, volume, area, line, or point, with uniform distributions of radionuclides within it, may be selected to represent a source for modeling purposes.

Parameter Name: STYPE Units: Unitless Range: Volume, area, line, or point

Default Value: Volume

Input Form: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. The assumptions for the four different types of sources are described below:

- *Volume source:* The source is assumed to have a cylindrical or parallelogram geometry, with two circular/rectangular areas and some finite thickness perpendicular to the areas (the axial direction). The receptor(s) considered in the analysis are assumed to face one of the circular/rectangular areas and receive(s) external radiation emitted from the source. The source may constitute up to five different regions along the thickness of the source. One of the regions is contaminated, with radionuclides distributed evenly over the volume of the region.

- *Area source:* The source is assumed to have a circular/rectangular area with no thickness. Radionuclides are assumed to distribute evenly over the entire area.

- *Line source:* The source has a finite length, but no width and thickness. Radionuclides are assumed to distribute evenly over the entire length.

- *Point source:* The source does not have dimensional or directional characteristics. All radionuclides are assumed to concentrate in a point.

Given equal amounts of radionuclide inventory, the external radiation (dose) emitted from different types of sources or the same type of sources but with different dimensions are different. The erosion rate of source material is calculated with respective source characterization parameters, which is used in the ventilation model to project the air and surface deposition concentrations of source particles and then concentrations of radionuclides (which are assumed to attach to the source particles) in the air and in building surfaces in each room. Radionuclides that can be released from the source without erosion, namely radon and H-3 as HTO, are handled differently with special models.

It may be possible to model a source in more than one way. The determination of which source type to use depends, in part, on engineering judgment. For example, a small area of surface or volume contamination may be represented as a point source, if the largest dimension of the source is at least three times smaller than the distance between the source and receptor. Similarly, a volumetrically contaminated surface may be treated as an area source, if the thickness of the contamination is small relative to the attenuation properties of the source material. A source whose length is at least three times larger than its width or depth may be treated as a line source.

The RESRAD-BUILD code requires the designation of type to represent each source. Up to 10 sources can be represented with same/different types in each analysis. For the modeling of external radiation dose/risk, the code treats area sources as volume sources with a small thickness of 0.01 cm.

I.4.4 Source Direction

Definition: The source direction indicates the direction of a source relative to the three Cartesian coordinate axes. It applies to line, area, and volume source types. For a line source, the source direction is defined as the axis parallel to the line. For area and volume sources, the source direction is defined as the axis normal to the surface of the source.

Parameter Name: SDIR   Units: Unitless   Range: x, y, or z axis

Default Value: x axis

Input Form: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. A source must have a direction that is parallel to one of three main coordinate axes: x, y, or z. In most cases (e.g., buildings with rooms that can be modeled as boxes), a coordinate system can be defined so that line sources within these rooms will run parallel to the major axes and area and volume sources will have surfaces that lie on orthogonal planes. If the source is curved or at an angle relative to the major coordinate axes, the user must judge whether to model it as an equivalent orthogonal source or rotate the axes to match the direction of the source.

A line source requires a source direction closest to the axis parallel to the line. Area and volume sources require source directions representing a line drawn normal to the surface of the source and parallel to the x, y, or z axis. Figure I-10 provides examples of source direction for line, area, and volume sources.

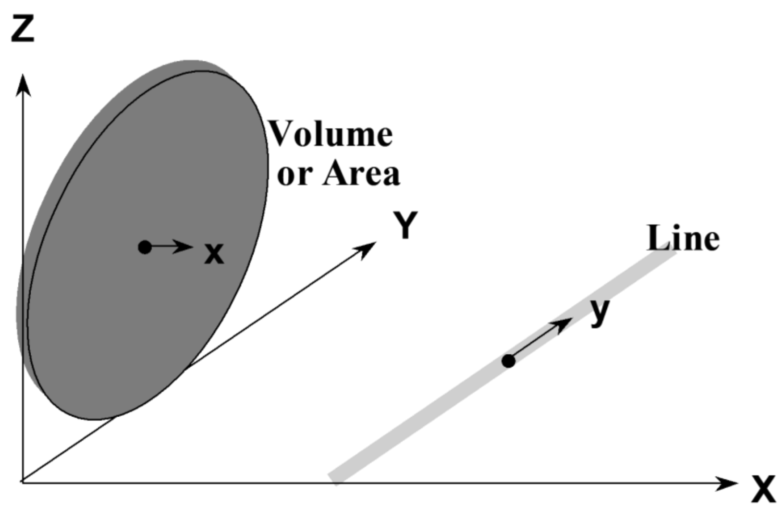

Figure I-10 Source Direction for Line, Area, and Volume Sources

I.4.5 Source Location

Definition: The source location specifies the spatial position of the source in three-dimensional space relative to the origin, which is also used to specify the locations of the receptors. Depending on the source type, additional parameters may be required to define the extent and direction of the source.

Parameter Name: SX   Units: Meters (m)   Range: Unlimited

Default Value: 0,0,0

Input Form: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. The spatial coordinates (x, y, and z) of the source location represent the distance to the selected origin in meters in three different directions. The source may be anywhere inside or outside the building. The user must ensure that the source location is consistent with additional geometrical parameters that may be required to define the source. The coordinates of the source location are used only to calculate direct external exposure.

For a point source, the coordinates of the point are specified. For a line or area source, the coordinates of the center point are specified. For a volume source, the coordinates of the center point of the contaminated region are specified (see Sections I.4.13 and I.4.14 for regions in a volume source). For example, if a volume source has three regions with the middle region contaminated, then the center point of the middle region should be used (and its coordinates specified) to represent the location of the volume source.

For all source types, a source may not be located at the same coordinates as those occupied by a receptor. For volume and area sources, the receptor coordinates may not be located on the same plane as the source surface. For line sources, the receptor coordinates may not be located on the same line as is the source.

I.4.6 Source Length/Area

Definition: This parameter specifies the extent of contamination of a source. For an area or volume source, it is the area of the exposed surface, if the surface is circular, or the length of the two adjacent sides of the exposed surface, if it is rectangular. For a line source, the extent of contamination is characterized by its length. This parameter is not applicable to point sources.

Parameter Name: SAREA Units: m^2 (volume or area source), m (line source) Range: > 0

Deterministic Analysis Default Value: 36 (line, area, and volume sources)

Probabilistic Analysis Default Distribution: None assigned

Input Form: Source Parameters → Details for Source

Discussion: This input parameter appears in the Details for Source input form, which is associated with the Details button in the Source Parameters input form. For the calculation of the direct external radiation dose/risk, the extent of a source may be greater than the dimensions of the room where the source is assigned to be located. For example, a contaminated floor may extend to multiple rooms. However, for all the other pathways, the extent of a source should be limited to the dimensions of the room because, in the RESRAD-BUILD modeling, radionuclides in the source can only be released to that room.

It is assumed contamination distributes uniformly within the specified dimension(s) of the source. If the contamination distribution departs greatly from this assumption, multiple homogeneous sources maybe used to represent the actual source. Sources whose geometries depart significantly from the idealized geometries used in the code may also be broken down into smaller sources (see Section I.4.1 on the number of sources).

I.4.7 Air Release Fraction/Release as a Fraction of Removed

Definition: The air release fraction/release as a fraction of removed is the fraction of the contaminated material removed from the source that is released into the air in the respirable particulate range.

Parameter Name: AIRFR Units: Unitless Range: 0 to 1

Deterministic Analysis Default Value: 0.1

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 1×10^{-6} Maximum: 1 Most likely: 0.07

Input Form: Source Parameters → Details for Source

Discussion: When source materials are eroded and leave the original location, a fraction of the materials could be released to the air (characterized by this parameter); the balance fraction of the eroded materials, 1 AIRFR, is assumed to drop to the floor and be instantaneously removed from the room. The value of this parameter can range from 0 (all eroded materials are removed instantaneously from the room) to 1 (all eroded materials are released to the air, in respirable particulate size). The term “Air fraction” is used in the Traditional Interface. In the New Interface, which is available only for non-volume sources, the term “Release as a fraction of removed” is used. Only the “Air fraction” in the Traditional Interface can be selected for sensitivity and uncertainty (probabilistic) analysis.

This parameter depends strongly on the erosion process. Mechanical disturbances, such as sanding, scraping, or chipping, result in a high contaminant removal rate but usually generate a relatively small fraction of particulates released to air. Most of the eroded material tends to fall to the floor and is removed from the room by housekeeping activities. Dusting results in low erosion rates, but a relatively high fraction of removed material may become suspended in air. Vacuuming, on the other hand, may result in higher erosion rates than would dusting, but a smaller fraction would become airborne; a significant fraction would be trapped in the vacuum.

The RESRAD-BUILD code requires an air release fraction input for each source. Entering a value of 0 would suppress the dose/risk contributions from deposition, immersion, dust inhalation, and indirect ingestion associated with the source. Entering a value of 1 is very conservative because it will maximize the dose/risk contributions from these pathways. If either the removable fraction/fraction removed (Section I.4.9) or erosion rate (Section I.4.17) is 0, the dose/risk contributions from these pathways will be suppressed, no matter what value is input for the air release fraction parameter.

The default distributions selected for this input parameter is based on review of the DOE handbook on airborne release fractions (ARFs) and respirable fractions (RFs)[2] (DOE 1994a) as

[2] The airborne release fraction is the amount of radioactive material that can be suspended in air and made available for airborne transport. The respirable fraction is the fraction of airborne radionuclides as particulates that can be transported through air and inhaled into the human respiratory system. This fraction is commonly assumed to include particles of 10-µm aerodynamic equivalent diameter and less.

documented in NUREG/CR-7267 (Kamboj et al. 2018). Figure I-11 shows the probability density function of the default distributions.

For volume sources containing tritium, in addition to being released as attaching to particulate matters, the tritium is also assumed to be vaporizable (HTO) and can be released as gas, which is modeled differently from the release of particulate matters. The input of air release fraction applies to the tritium released as attaching to particulate matters, which can be eroded and released to the air like other radionuclides.

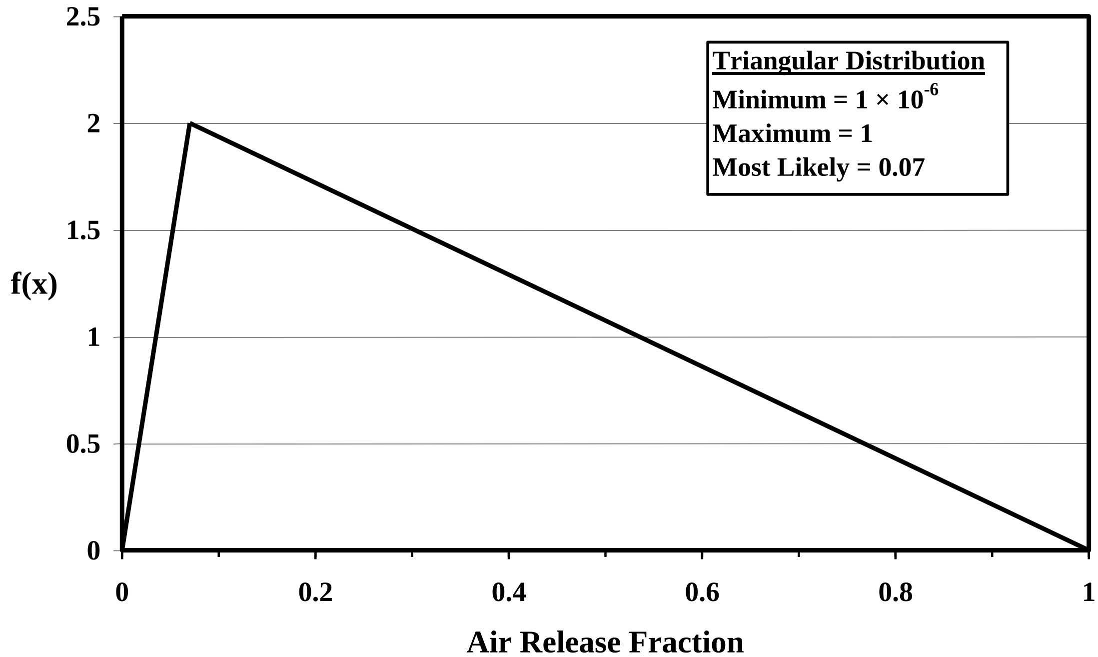

Figure I-11 Air Release Fraction Probability Density Function

I.4.8 Direct Ingestion Rate

Definition: The direct ingestion rate refers to the incidental ingestion rate of contaminated material directly from the source.

Parameter Name: INGE1   Units: g/h for volume sources; 1/h for point, line, and area sources

Range: ≥ 0

Deterministic Analysis Default Value: 0

Probabilistic Analysis Default Distribution: None assigned

Input Form: Source Parameters → Details for Source

Discussion: This is the rate at which the contamination (for non-volume sources) or the source material (for volume sources) is ingested by each receptor who is in the same room. For non-volume sources, the ingestion rate is expressed as the fraction of the contamination per unit time, 1/h. For volume sources, the ingestion rate is expressed as the amount of source material per unit time, g/h. The same direct ingestion rate applies to each receptor in the room.

Only removable contamination or source materials can be ingested; it is modeled as being ingested as it is removed. Therefore, the direct ingestion rate of the source by each receptor is limited by the rate of removal of the source, the number of receptors in the room, and the time fractions of those receptors in the room. In the event that the removal (erosion) rate of the source is not sufficient to satisfy the specified direct ingestion rate at the specified time fractions, the source being removed per unit time is apportioned among the receptors in proportion to their time fractions in the room. Therefore, when limited, the direct ingestion rate of a radionuclide by each receptor at any time is determined by the product of the apportioned direct ingestion rate and the source activity (for non-volume sources) or activity concentration (for volume sources) at that time.

It is considered unlikely for direct ingestion of a source to occur under normal building occupancy conditions; therefore, the direct ingestion rate is normally set to 0 for most calculations. During building maintenance or renovation, physical contact with the source could occur, resulting in direct ingestion of source.

I.4.9 Removable Fraction/Fraction Removed

Definition: The removable fraction is the fraction of a point, line, or area source that can be removed. The balance of the source is assumed to remain fixed.

Parameter Name: RMVFR Units: Unitless Range: 0 to 1

Deterministic Analysis Default Value: 0.5

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 0.0 Maximum: 1.0 Most likely: 0.1

Input Form: Source Parameters → Details for Source

Discussion: The removable fraction or fraction removed is used for non-volume sources. It can account for various events that reduce the amount of source activity over time.

With the Traditional Interface, the removal of the source is considered to proceed with a constant rate over a fixed period of time, the lifetime (see Section I.4.10). The "removable fraction" is the fraction of the source that is removed linearly within the lifetime. If the source is fixed and nothing will be eroded, enter 0 for the removable fraction. RESRAD-BUILD accepts a value in the range 0 to 1 inclusive for this input. The "removable fraction" is eligible for sensitivity and uncertainty (probabilistic) analysis.

With the New Interface, the removal of the source can be considered to proceed with different rates over up to 10 different time periods. The "fraction removed" is the fraction of the source that will be removed linearly within each time period. The length of each time period is characterized by a "start time" and an "end time." Any lapse in time between two successive time periods, i.e., if the "start time" of a time period is greater than the "end time" of the previous time period, is treated automatically as a period without erosion, i.e., the "fraction removed" is 0 during the lapsed time. The sum of the specified "fractions removed" should not be greater than 1. The "fraction removed" is not eligible for sensitivity or uncertainty (probabilistic) analysis.

Source activity may be reduced or removed completely over a period of time as a result of such events as surface washing (chemical and mechanical action) or foot or equipment traffic (mechanical action), if the source is on the floor. On the other hand, source activity could remain unchanged on a wall over a long period of time. Therefore, a triangular distribution is selected as the default distribution for the removable fraction/fraction removed parameter, ranging from 0 to 1. The most likely value is selected to be 0.1, which is the maximum removable fraction acceptable by NRC (2000) after decommissioning. The maximum allowable removable fraction for surface contamination in the DOE *Radiological Control Manual* (DOE 1994b) is 0.2. The NUREG/CR-7267 Section C.8 (Kamboj et al. 2018) details the review of literature data on this parameter. Figure I-12 displays the probability density function for the default distribution function.

A default value of 0.5 is used for deterministic analysis, to result in higher radiation dose associated with the released source particles, through the inhalation, air submersion, direct external from deposition, and indirect ingestion pathways.

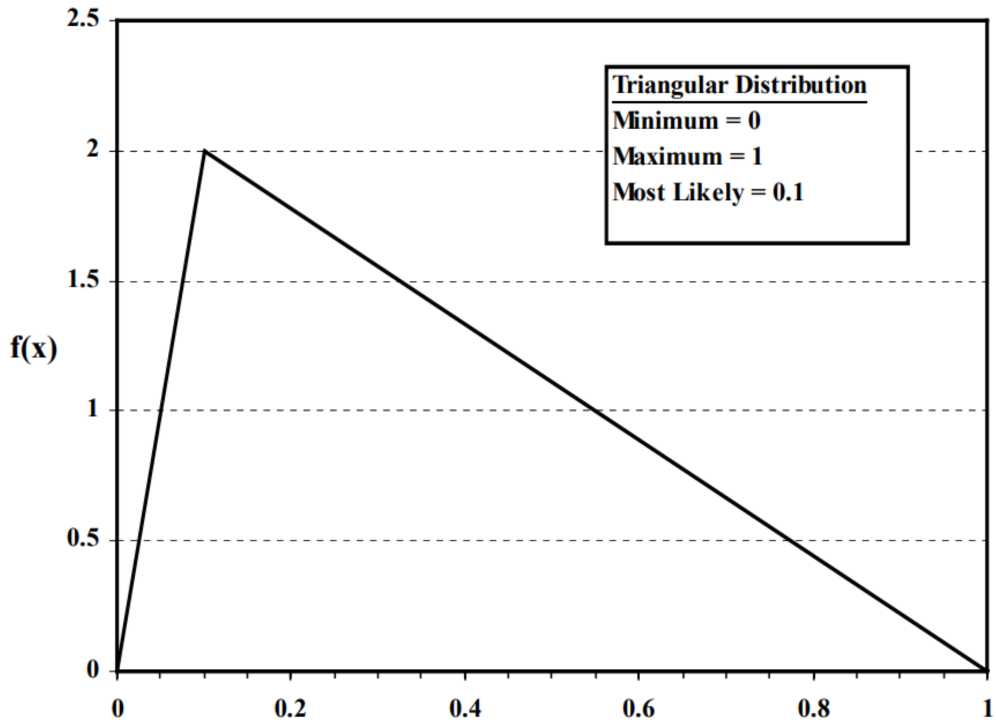

Figure I-12 Removable Fraction Probability Density Function

I.4.10 Lifetime/Start Time/End Time

Definition: In the Traditional Interface, the parameter "lifetime" is used. The lifetime represents the time over which the specified removable part of the source is linearly eroded. The parameter is used in conjunction with the removable fraction of source material parameter (Section I.4.9), the air release fraction parameter (Section I.4.7), and the radionuclide inventory in the source to obtain the emission (injection) rate of radionuclides into the indoor air.

In the New Interface, the parameters "start time" and "end time" are used. The interval between the start time and end time represents the time over which the specified removable part of the source is linearly eroded. The parameter is used in conjunction with the fraction removed of source material parameter (Section I.4.9), the released as a fraction of removed parameter (Section I.4.7), and the radionuclide inventory in the source to obtain the emission (injection) rate of radionuclides into the indoor air.

Parameter Name: RF0 (Traditional Interface) or RELTIME (New Interface)

Units: Days (d) Range: > 0

Deterministic Analysis Default Value: 365 (Traditional Interface) or 0, 365 (New Interface)

Probabilistic Analysis Default Distribution: Triangular (for RF0), no default for RELTIME

Defining Values for Distribution: Minimum: 1,000 Maximum: 100,000 Most likely: 10,000 (27.4 yr)

Input Form: Source Parameters → Details for Source

Discussion: These parameters are used for non-volume sources. The RESRAD-BUILD model considers the potential emission (injection) of loose contamination from a contaminated surface to the indoor atmosphere. With the Traditional Interface, the emission of the loose source material is considered to proceed with a constant rate over the lifetime of the source. If the source materials are fixed, i.e., with no loose material, nothing will be eroded, then enter 0 for the removable fraction and a nonzero value for lifetime. With the New Interface, the removal of the loose source material can be considered to proceed with different rates over up to ten different time periods. The length of each time period is characterized by a "start time" and an "end time." The "end time" of a time period should be no less than the "start time." Any lapse in time between two successive time periods, i.e., if the "start time" of a time period is greater than the "end time" of the previous time period, the lapse is treated automatically as a period without erosion, i.e., the "fraction removed" is zero during the lapsed time. Only "Lifetime" in the Traditional Interface can be selected for sensitivity and uncertainty (probabilistic) analysis.

Different mechanisms can result in the emission of loose surface particles to the atmosphere. Mechanical abrasion during renovation activities would result in the highest emission rate in the shortest period of time. However, for normal building occupancy conditions, renovation activities were excluded from consideration. Information on the lifetime or the time for source removal parameter is not directly available from the open literature; therefore, the potential range of this parameter was inferred on the basis of information on other, related parameters. A triangular distribution was selected as the default distribution function for this parameter. The probability density function is shown in Figure I-13.

According to the American Nuclear Society (ANS), an air release rate of 4×10^{-5}/h is a conservative value for use in estimating the potential exposure resulting from the release of solid powders piled up on a heterogeneous surface under the condition of normal building ventilation flow (ANS 1998). That rate is equivalent to a lifetime of approximately 1,040 days (or 2.85 years). Although the loose particles on the contaminated source are not exactly the same as a pile of solid powders, the value for the free solid powders can be used to derive a lower bounding lifetime value for the loose materials.

Another suggestion by the ANS is an air release rate of 4×10^{-6}/h for solid powders that are covered with a substantial layer of debris or are constrained by indoor static conditions (ANS 1998). This rate is equivalent to a lifetime of approximately 10,000 days (27.4 yr). The loose contaminants on a contaminated surface can be considered as being restricted by some weak physical binding force and would, therefore, behave like the constrained solid powders. The lifetime of the constrained solid powders can be used as the most likely value for the loose contaminants.

Erosion of the surface layer from the contaminated material can eventually occur over a long period of time if there is no constant maintenance. Therefore, all the loose contaminants have the opportunity of being released to the environment. To consider this extreme case, a lifetime of 300 years (approximately 100,000 days) was assumed.

Another factor that is frequently used in the literature for estimating air concentrations from surface sources is the resuspension factor. The resuspension factor is not used in the RESRAD-BUILD code, but it is a quantity closely related to the source lifetime for a surface source. The study of the correlation between the source lifetime and the resuspension factor is detailed in Kamboj et al. (2018) Section C.8.7.

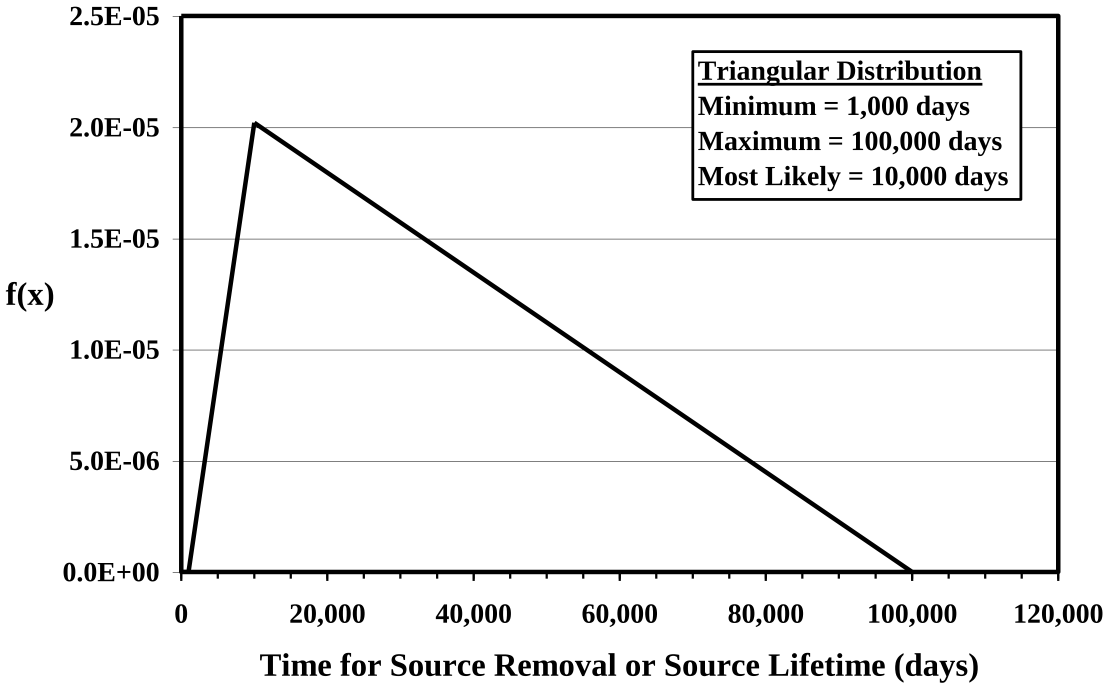

Figure I-13 Time for Source Removal or Source Lifetime Probability Density Function

I.4.11 Radon Release Fraction

Definition: This parameter represents the fraction of the total amount of radon produced by radium decay that escapes the surface of a contaminated material and is released to the air. This parameter applies to point, line, and area sources.

Parameter Name: RRF Units: Unitless Range: 0 to 1

Deterministic Analysis Default Value: 0.2

Probabilistic Analysis Default Distribution: None assigned

Input Form: Source Parameters → Details for Source

Discussion: For non-volume sources, the radon release fraction represents the combined effect of the radon emanation coefficient and the radon diffusion coefficient that apply to volume sources. This parameter is used by RESRAD-BUILD in conjunction with the amount of radium-226 and thorium-228 in a nonvolume source to calculate the release of radon-222 and radon-220, respectively, into the room air. It is applicable only to the radon inhalation pathway. Therefore, it is only required as input when radionuclides that decay to radon are entered as part of an area, line, or point source. It is not required for a volume source. (For volume sources, see Sections I.4.21 and I.4.22 on the radon effective diffusion coefficient and radon emanation coefficient, respectively.)

The radon release fraction is a unitless parameter ranging in value from 0 to 1. Values approaching 0 indicate that the majority of the radon from radium decay is retained in the source material and is not being released to the room air. A release fraction of 1 indicates that all of the radon is being released to the room air. This parameter depends on the combined properties of radon emanation and diffusion through the thin area, line, or point source layer. If the source is sufficiently thin (e.g., area source) and there is no additional layer between the source and the room air, diffusion may be neglected and the release fraction will approach the emanation coefficient. Therefore, the default value for radon release fraction was set to 0.2, same as the default value for radon emanation fraction. If the source is inside a closed, nonporous pipe (line source) or small, sealed container (point source), the radon release fraction should be set to 0. In that case, the radon pathway is literally suppressed.

I.4.12 Radionuclide Concentration/Activity

Definition: This parameter specifies the activity (for a point source) or activity concentration (for volume, area, and line sources) of radionuclides distributed in a source.

Parameter Name: RNUCACT Units: Activity (point source); Activity/m (line source); Activity/m^2 (area source); Activity/g (volume source) Range: > 0

Default Value: 1 pCi/g of Co-60

Input Form: Source Parameters → Details for Source

Discussion: Any of the following four units of radiological activity can be selected: (1) Ci or curie, defined as 3.7×10^{10} disintegrations per second (dps); (2) Bq or becquerel, defined as 1 dps; (3) disintegrations per second (dps); or (4) disintegrations per minute (dpm). Any standard one-character metric prefix can be used with Ci and Bq. This parameter is not eligible for probabilistic input. The activity or concentration is assumed to be distributed homogeneously throughout each source, except volume sources, which may contain up to five distinct layers and only one layer is contaminated.

The total activity or activity concentration in a source may be estimated by performing field measurements or by taking source samples and performing radiological analyses that are appropriate for the radionuclide(s) present in that source. Since the code assumes a uniform distribution of radionuclides within a source, the average concentration should be estimated from several measurements. If individual regions of the source differ significantly from the average (e.g., by a factor of 3 or more above or below this average), the user should consider dividing the source region into smaller subregions with more homogeneous distributions of radionuclides. These subregions, along with their respective radionuclide concentrations, should then be entered as separate sources in the code (see Section I.4.1 on the number of sources).

Up to 10 radionuclides per source may be considered. If more than 10 radionuclides are present in a single source, the user may create two or more sources (as necessary), each with up to 10 radionuclides. These multiple sources should be identical with regard to their geometric and physical characteristics (e.g., type, location, dimension, and removal fraction). The units used to enter radionuclide activity or concentration will depend on the source type, as follows: picocuries (pCi) for point sources, pCi per meter (m) for line sources, pCi per square meter (m^2) for area sources, or pCi per gram (g) for volume sources. The user can also select other radiological activity units as discussed above.

I.4.13 Number of Regions in Volume Source

Definition: This parameter specifies the number of distinct layers in a volume source. It does not apply to area, line, or point sources.

Parameter Name: NREGI0 Units: Unitless Range: Integer value of 1 to 5

Default Value: 1

Input Form: Source Parameters → Details for Source

Discussion: This parameter is not eligible for probabilistic input. The volume source can be split into as many as five regions along its thickness. The number of regions is used to define possible heterogeneities in the physical and radiological characteristics of a volume source. In cases in which the physical characteristics of the source are homogeneous and the contamination is uniformly distributed throughout the entire volume, one region should be selected. The different regions should be numbered sequentially. However, only one region can be specified as contaminated. The coordinates of the source should be defined based on the center point of the contaminated region. The uncontaminated regions will act as a shield for external gamma radiation on the basis of thickness (Section I.4.16) and density (Section I.4.17) and will act as a barrier for the inhalation pathways.

Except for the release of radon, the release of source materials due to erosion is assumed to start from region 1 and move to posterior regions as the anterior regions are removed. This imposes a restriction on the numbering of the regions. Radon is always generated by the decay of its precursor in the contaminated region and then diffuses toward region 1 to be released to the indoor air.

For cases in which heterogeneities arise from the physical properties of the source, the number of regions may be directly measured by taking a core sample of the source. Alternative options are to refer to standard building codes or the building design specifications. For cases in which heterogeneities arise from nonuniform contamination across the depth of the source, the required information can be obtained from a radiological characterization of the core samples.

I.4.14 Contaminated Region (Volume Source)

Definition: This parameter specifies the region number of the contaminated region in a volume source. This parameter does not apply to area, line, or point sources.

Parameter Name: FCONT0 Units: Unitless Range: Integer value of 1 to 5

Default Value: 1

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: This parameter is not eligible for probabilistic input. Only one region (i.e., layer) is allowed to be contaminated per volume source. This region number may be 1, 2, 3, 4, or 5 and is limited by the number of regions that have been defined (see Section I.4.13, Number of Regions in Volume Source). For example, in a volume source with two regions, the user may define the contamination to be in region (or layer) 1 or 2 but is not allowed to define the contamination to be in region 3, 4, or 5. However, multiple layers of contamination may be modeled by creating multiple volume sources, each occupying the same physical space. For example, assume a source has three layers of contamination, each with different radionuclide concentrations. The source can then be modeled as three co-located sources, each with three layers. The physical characteristics of the layers within each source would be the same in all three sources. The first contaminated layer would be entered as region 1 of the first source, the second layer as region 2 of the second source, and the third layer as region 3 of the third source.

The code requires that the user identify one of up to five layers as the contaminated layer in each volume source. The user does not enter a number but actually selects the contaminated region. If the number of regions is then reduced to fewer than the number of regions containing the contamination, the user must reselect the correct region or layer; otherwise, the code assumes the source is one layer when it runs.

I.4.15 Material Type for Source

Definition: This parameter specifies the material that composes the volume source.

Parameter Name: MTLS Units: Unitless Range: Concrete, water, aluminum, iron, copper, tungsten, lead, or uranium

Default Value: concrete

Input Form: Source Parameters → Details for Source

Discussion: The source material determines the attenuation cross section used in calculating the external dose. This parameter is required only for a volume source and is not eligible for probabilistic input.

The user can select among eight options of source material: (1) concrete, (2) water, (3) aluminum, (4) iron, (5) copper, (6) tungsten, (7) lead, and (8) uranium. The type of source material can be determined from direct inspection, standard building codes, and/or building design specifications.

I.4.16 Source Region Thickness (Volume Source)

Definition: This parameter represents the thickness of each layer in an idealized volume source. This parameter does not apply to area, line, or point sources.

Parameter Name: THICK0 Units: cm Range: > 0

Deterministic Analysis Default Value: 15

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 2.5 Maximum: 30 Most likely: 15

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: RESRAD-BUILD allows consideration of a total of five distinct regions (layers) in a volume source. The contamination is in one of those regions, and the total thickness of the volume source is the sum of the thicknesses of those regions. The code requires input of thickness (in centimeters) for every layer of each volume source. The source thickness depends upon the detail of modeling desired. For example, a wall could be modeled as a single layer or multiple layers (e.g., a sequence of paint, drywall, framing gap, drywall, and paint), with up to five layers per source. It is highly recommended that the source thickness be obtained from direct measurement or be estimated on the basis of the applicable building codes. The contaminated layer thickness and position should be based on site-specific measurement.

With the exception of sources resulting from neutron activation, most volume activity in buildings will be limited to small areas (hot spots) or rather shallow sources. For the case of neutron activation, volume sources could extend deep into the volume of a building structure. The thickness of building structure materials will place a limit on the potential thickness for volume sources. Ayers et al. (1999) noted that the contamination of concrete usually results from spills, contaminated dust, or other surficial deposition. In some instances, the contaminants may migrate into the concrete matrix, particularly over time and under environmental stresses. Cracks and crevices may also provide routes for contaminants to spread deeper into the concrete matrix. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed contamination to a 1-in. (2.5-cm) depth and an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness will approximate an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. RESRAD-BUILD uses 15 cm as the default source thickness for a volume source.

Little information is available for the source thicknesses in actual decommissioning and decontamination situations; therefore, on the basis of the above data, a triangular distribution is assumed for source thickness. The maximum value is assumed to be 30 cm, the minimum value is chosen as 2.5 cm, and the most likely value is 15 cm. Figure I-14 presents the probability density function for the source thickness.

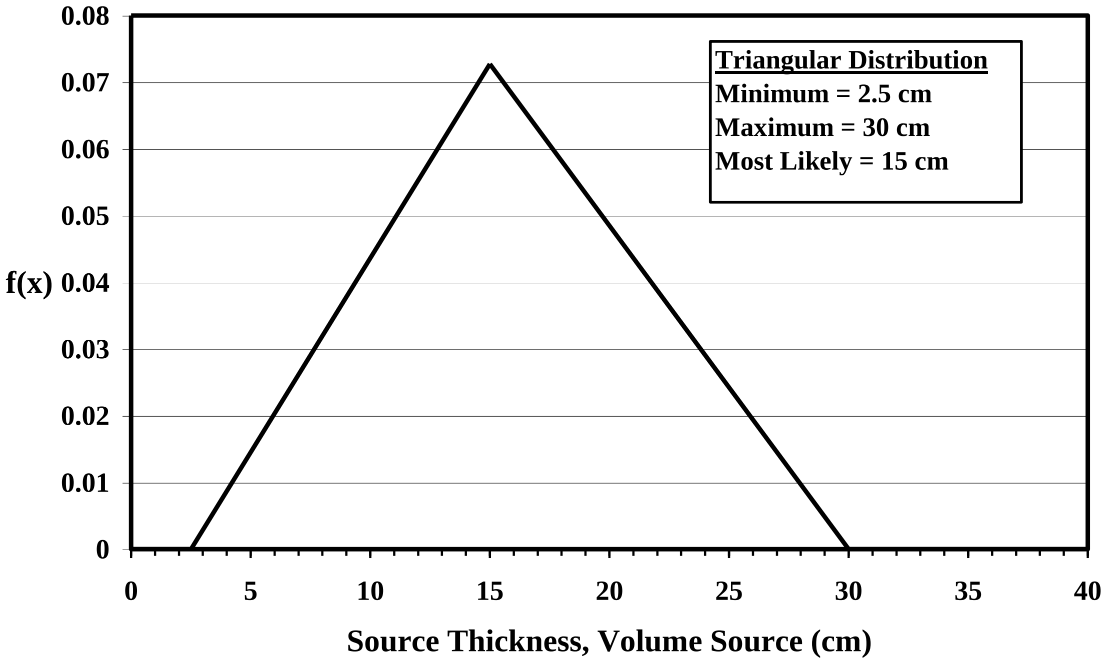

Figure I-14 Source Thickness Probability Density Function

I.4.17 Source Density (Volume Source)

Definition: The source density parameter represents the bulk density of each layer (region) in an idealized volume source. This parameter does not apply to area, line, or point sources.

Parameter Name: DENSI0 Units: g/cm^3 Range: 0–22.5

Deterministic Analysis Default Value: 2.4

Probabilistic Analysis Default Distribution: Uniform (only allowed for concrete)

Defining Values for Distribution: Minimum: 2.2 Maximum: 2.6

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: In the RESRAD-BUILD code, a volume source can be defined with up to five distinct parallel regions (or layers) located along the direction parallel to the partition, each consisting of homogeneous and isotropic materials. For the contaminated region, the source density parameter is used to calculate the total amount of radionuclides in the region; for all regions, it affects the radiation dose of the direct external pathway. RESRAD-BUILD provides the following eight material options to be selected for a specific region: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. In addition to bulk density and material, other parameters to be specified for each source region include thickness, erosion rate, porosity, radon effective diffusion coefficient, and radon emanation fraction; the last three are needed only when a radon precursor exists in the contaminated region.

As is the case for shield density, the source density is limited to less than 22.5 grams per cubic centimeter (g/cm^3). Table I-5 lists the value or range of values of the density for some metals and water from *The Health Physics and Radiological Health Handbook* (Shleien 1992) and the *CRC Handbook of Chemistry and Physics* (Lide 1998) (for cast iron, uranium, and tungsten). Table I-6 provides the concrete density from three different sources: *The Health Physics and Radiological Health Handbook* (Shleien 1992), *Properties of Concrete* (Neville 1996), and *Standard Handbook for Civil Engineers* (Merritt et al. 1995). The default value selected for RESRAD-BUILD corresponds to ordinary concrete. A uniform distribution with the given range listed in Table I-6 may be used as the distribution function for bulk density if a source region is made by a known type of concrete. Figure I-15 shows the probability density function for the default distribution function selected for the bulk density parameter.

Table I-5 Density of Source Materials (except concrete) Allowed in RESRAD-BUILD

Material	Density Range (g/cm^3)	Normal Density (g/cm^3)
Aluminum	-[a]	2.7
Copper	-	8.96
Lead	-	11.35
Steel	-	7.8
Cast iron	7.0–7.4	
Water	-	1.0
Tungsten	-	19.3
Uranium	-	19.1
Iron	-	7.87

[a] A dash indicates that no data were available.

Sources: Shleien (1992); Lide (1998).

Table I-6 Source (Concrete) Density from Various Sources

	Concrete Density (g/cm^3)		
Aggregate	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicaceous) or normal weight	2.2–2.4	2.2–2.6	2.3
Heavy weight	-[a]	-	2.4–6.15
Limonite (goethite, hyd. Fe_2O_3)	2.6–3.7	-	-
Ilmenite (nat. $FeTiO_3$)	2.9–3.9	-	-
Magnetite (nat. Fe_3O_4)	2.9–4.0	-	-
Limonite and magnetite	-	-	3.35–3.59
Iron (shot, punchings, etc.) or steel	4.0–6.0	-	4.0–4.61
Barite	3.0–3.8	-	3.72
Lightweight	-	0.3–1.85	0.55–1.85
Pumice	-	0.8–1.8	1.45–1.6
Scoria	-	1.0–1.85	1.45–1.75
Expanded clay and shale	-	1.4–1.8	-
Vermiculite	-	0.3–0.8	0.55–1.2
Perlite	-	0.4–1.0	0.8–1.3
Clinker	-	1.1–1.4	-
Cinders without sand	-	-	1.36
Cinders with sand	-	-	1.75–1.85
Shale or clay	-	-	1.45–1.75
Cellular	-	0.36–1.55	-
No-fines	-	1.6–2.0	1.68–1.8
No-fines with lightweight aggregate	-	0.64–higher	-
Nailing	-	0.65–1.6	-
Foam	-	-	0.3–1.75

[a] A dash indicates that no data were available.

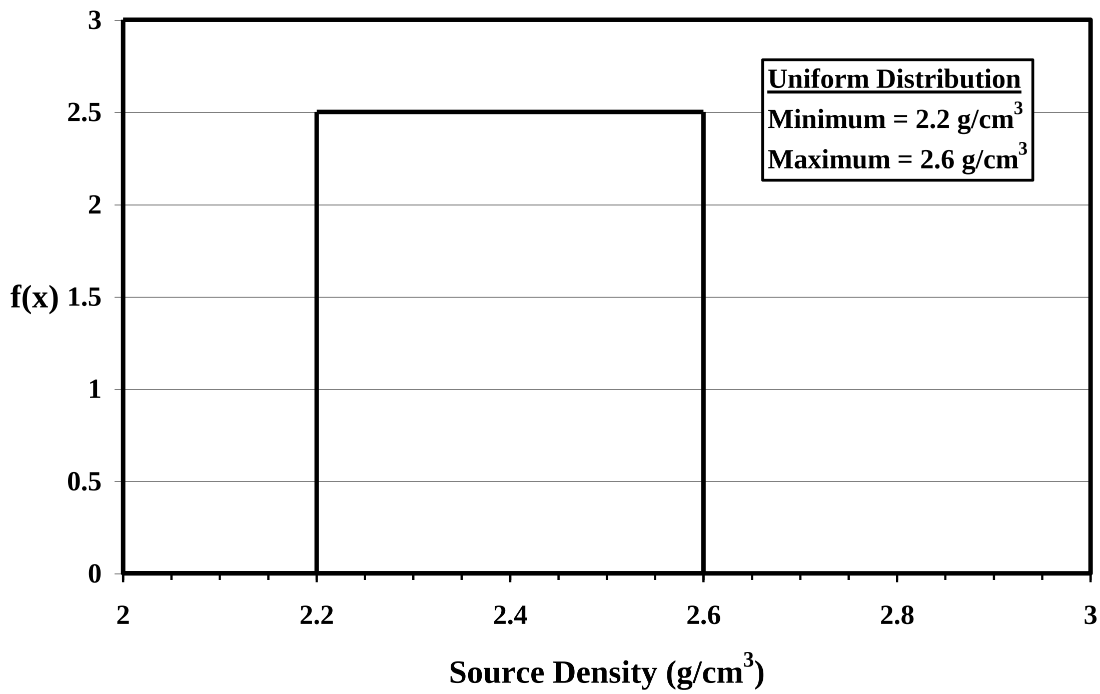

Figure I-15 Source Density Probability Density Function

I.4.18 Source Erosion Rate (Volume Source)

Definition: The source erosion rate parameter represents the amount of contaminated material (expressed as the thickness of the layer [distance perpendicular to the contaminated surface]) removed per unit of time.

Parameter Name: EROS0 Units: cm/d Range: ≥ 0

Deterministic Analysis Default Value: 2.4×10^{-8}

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 0.0 Maximum: 5.6×10^{-7} Most likely: 0.0

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: This parameter does not apply to area, line, or point sources. The source erosion rate is used in determining the amount of the source material removed per unit time, which is then used to calculate the amount of source material released into the air, the amount of source material remaining at the source location to contribute to the direct external exposure, and the remaining thickness of the source regions through which the radon gas must diffuse to get to the indoor air. Based on the erosion rate specified for each source region at each evaluation time, the exposed region can be identified.

The source erosion rate is highly dependent on the source location. In a building occupancy scenario, contamination on walls could remain for a very long period of time, if located in little-used areas not subject to periodic washing or cleaning. The time could stretch even longer, if such residual wall contamination is covered with paint or sealant applied during prior remediation or general maintenance activities. For some floor areas, little or no wear can be expected for the same reasons. The opposite extreme cases are contaminated floors subject to heavy foot traffic or vehicle traffic, such as seen in warehouse operations. However, these areas are usually covered (carpet or tile), sealed, or waxed on a periodic basis, thereby reducing the potential for erosion.

A triangular distribution was selected to represent the source erosion rate. A value of 0 was chosen for both the minimum and most likely values based on consideration of sources located in little-used areas or being covered by paint or sealant even if not in little-used areas. A maximum value of 5.6×10^{-7} cm/d was selected to represent the erosion of sources located in heavy traffic areas. This maximum value was derived assuming airborne particulate (with an average concentration of 100 $\mu g/m^3$) in a room (with a floor area of 36 m^2, a height of 3.7 m, and an air exchange rate of 1.52/h) resulted from erosion of the concrete floor (with a density of 2.4 g/cm^3). Section C.8.2 of Kamboj et al. (2018) provides details of the derivation. Figure I-16 shows the probability density function for the triangular distribution.

In the case of renovation or remedial actions, the source erosion rate can be quite high. For example, thin-volume sources in wood or concrete could be removed in seconds with power sanders or sandblasting techniques. Other examples include the complete removal of wood, carpet, or drywall sections within seconds to minutes. For such a scenario, the user can input values appropriate to the contaminated source and removal technique under consideration.

Because the duration of source erosion is short, it is important to choose appropriate values for the exposure duration, evaluation times, and time integration points to capture changes in the radionuclide inventory in the source, concentration in the air, and concentration in surface deposition during the renovation or remediation process so as to obtain more precise estimates of radiation doses/risks incurred by the workers.

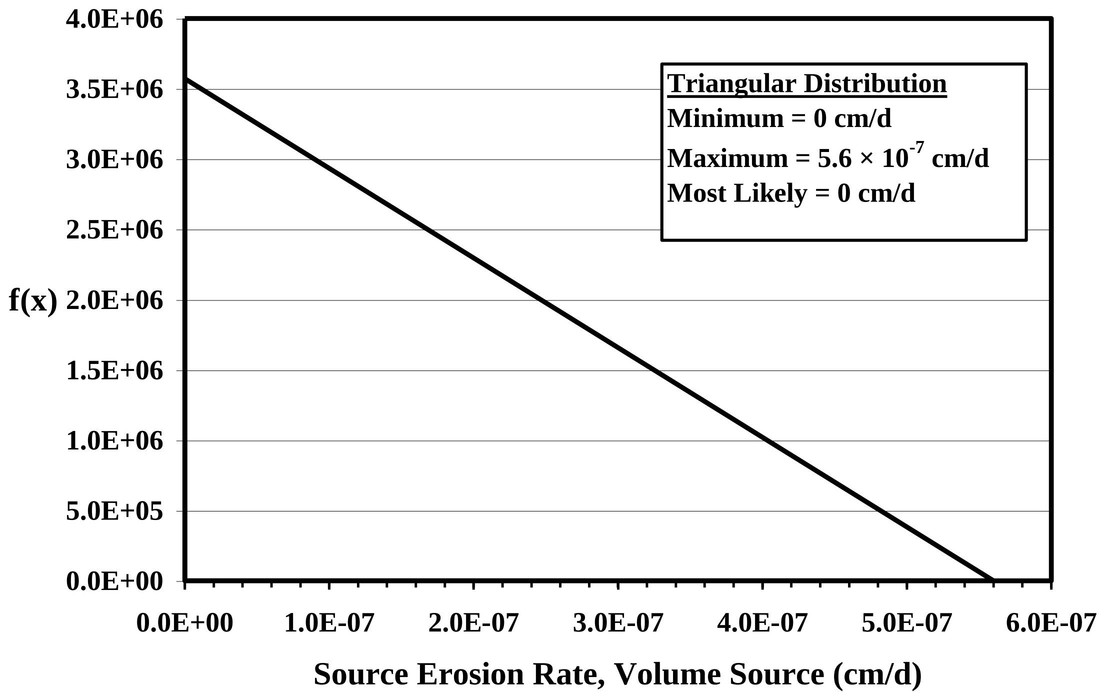

Figure I-16 Source Erosion Rate Probability Density Function

I.4.19 Direction from Interior to Eroding Surface

Definition: This is the direction from the interior of a volume source to the eroding surface, i.e., the exposed surface of region 1, if there are multiple regions in the source. It is the same general direction, x, y, or z, as specified for the volume source, but with "+" or "–" sign to be more specific.

Parameter Name: VOLSRCDIR Units: Unitless

Deterministic Analysis Default Value: 1 ("–" source direction)

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: In RESRAD-BUILD, the erosion of a volume source is considered to occur with only one of the surfaces along the axial direction, i.e., the eroding surface. The direction from the interior to the eroding surface should be specified as "+" or "-" along the source axial direction. If a volume source has multiple regions, this direction is the direction from region 2 to region 1, as region 1 is the region to be eroded first.

This input of direction from the interior to the eroding surface, along with the locations (characterized with x, y, and z coordinates) of the source and the receptor, determine the exposed surface that the receptor is facing, which is critical in the external dose calculations because the attenuation provided by uncontaminated region(s) as well as the remaining contaminated region can be properly accounted for.

I.4.20 Source Porosity

Definition: The source porosity is the ratio of the pore volume to the total volume of a representative sample of the source material.

Parameter Name: POROS0 Units: Unitless Range: > 0 to < 1

Deterministic Analysis Default Value: 0.1

Probabilistic Analysis Default Distribution (only allowed for concrete): uniform

Defining Values for Distribution: Minimum: 0.04 Maximum: 0.25

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: The source porosity parameter is used in RESRAD-BUILD to calculate the diffusion of radon and tritium from a volume source and affects the inhalation dose contributed by tritium and the dose of the radon inhalation pathway. This parameter is only required as input if a tritium volume source is specified or if radon (radon-220 or radon-222) precursors are entered as contaminants in a volume source. It is not required for area, line, or point sources. Precursor radionuclides for radon are listed below:

- Radon-220 precursors: Cf-252, Cm-244, Cm-248, Pu-244, Pu-240, U-236, U-232, Th-232, Th-228, and Ra-228
- Radon-222 precursors: Pu-242, Pu-238, U-238, U-234, Th-230, and Ra-226

The porosity of every layer in each volume source containing one or more radon precursors must be specified.

A value of 0 for this parameter represents a material that is completely solid, without any void spaces. On the other extreme, a porosity approaching 1 represents a material that is made up mostly of void spaces. Building materials such as concrete, brick, or rock typically have porosities up to 0.3. The default uniform distribution for generic probabilistic analyses was selected after a review of literature data (Kamboj et al. 2018). The range of the value, 0.04 to 0.25, is based on suggestions for concrete materials. The probability density function is shown in Figure I-17.

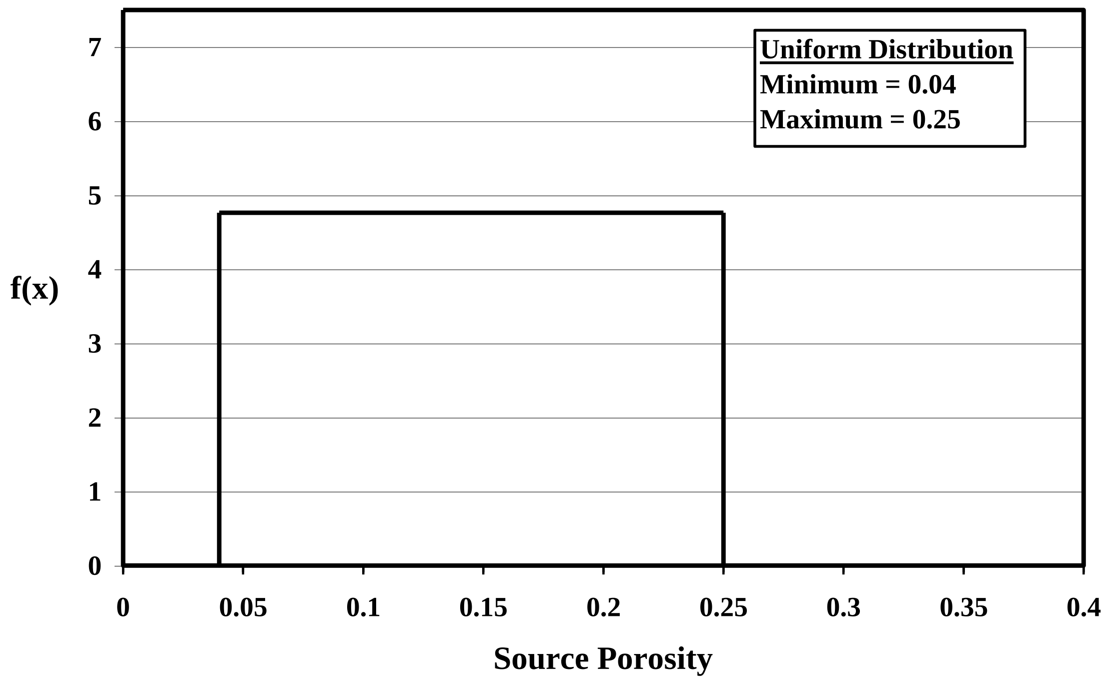

Figure I-17 Source Porosity Probability Density Function

I.4.21 Radon Diffusion Coefficient

Definition: This parameter represents the diffusivity of radon in the pore space of the source materials.

Parameter Name: EFDIF0 Units: m^2/s Range: > 0 to 1.1×10^{-5} m^2/s

Deterministic Analysis Default Value: 2×10^{-5}

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 8×10^{-9} Maximum: 5.2×10^{-7}

Most Likely: 3.7×10^{-7}

Input Form: Source Parameters → Details for Source → Layered Region Parameters

Discussion: RESRAD-BUILD employs a diffusion model to simulate the movement of radon gas within a volume source (from the contaminated inner region, through the pore space of the source materials, to the outer surface of the volume source, i.e., the exposed surface) and the release of the radon gas to the indoor air. When there are multiple regions (layers) in the source, the code calculates radon flux across the two outer surfaces, one each at the two end regions; combines the radon fluxes; and then subjects the total to be released to the room where the volume source is located. Appendix F provides detailed discussions on the radon diffusion model. The input of the radon diffusion coefficient is required only when radon precursor(s) are specified as part of a volume source. It is not required for an area, line, or point source with radon precursor(s), for which the release rate of radon is calculated with the radon release fraction parameter (see Section I.4.11).

The value of radon diffusion coefficient, D, varies over a wide range, depending on the diffusion medium. The upper limit of D is given by the diffusion coefficient in open air, which is about 1.1×10^{-5} m^2/s (Kalkwarf et al. 1982). At the lower extreme, some low-permeability materials may have diffusion coefficients as low as 10^{-10} m^2/s. The diffusion coefficient also decreases with decreasing porosity and with increasing volumetric water content in the porous medium. Its value can also be affected by other factors of the diffusion medium to a lesser degree. Section 4.1 of the RESRAD Data Collection Handbook (Yu et al. 2015) and Section C.8.11 of NUREG/CR-7267 (Kamboj et al. 2018) provide detailed discussions on measurement methods and available literature data.

According to literature data (Yu et al. 2015), the diffusion coefficient is about 6×10^{-10} m^2/s for mud, 8×10^{-7} m^2/s for dry loams, 3×10^{-6} m^2/s for sandy soil, 6.0×10^{-8} to 3.7×10^{-6} m^2/s for clayey soil, 5.4E$\times10^{-6}$ to 7.2×10^{-6} m^2/s for uranium mill tailings, 8×10^{-9} to 5.2×10^{-7} m^2/s for uncracked bricks and concrete, and 1×10^{-6} to 4×10^{-6} m^2/s for gypsum. Based on the data for uncracked bricks and concrete, a triangular distribution with a minimum of 8×10^{-9} m^2/s, a maximum of 5.2×10^{-7} m^2/s, and a most likely value of 3.7×10^{-7} m^2/s was selected as the default distribution function for use in RESRAD-BUILD. The most likely value is consistent with the default value of radon diffusion coefficient for building foundation in RESRAD-ONSITE and RESRAD-OFFSITE. For deterministic analyses, a default value of 2×10^{-5} m^2/s was selected, considering cracks in bricks and concrete.

In RESRAD-BUILD, inputs of a radon diffusion coefficient for every layer in each volume source containing radon precursor(s) are required. Setting the input value to 0 for any uncontaminated layer of a volume source effectively suppresses the flux of radon through that layer until that layer has eroded, thereby rendering the input of other radon-related parameters for that layer inconsequential. The radon diffusion coefficient probability density function is shown in Figure I-18.

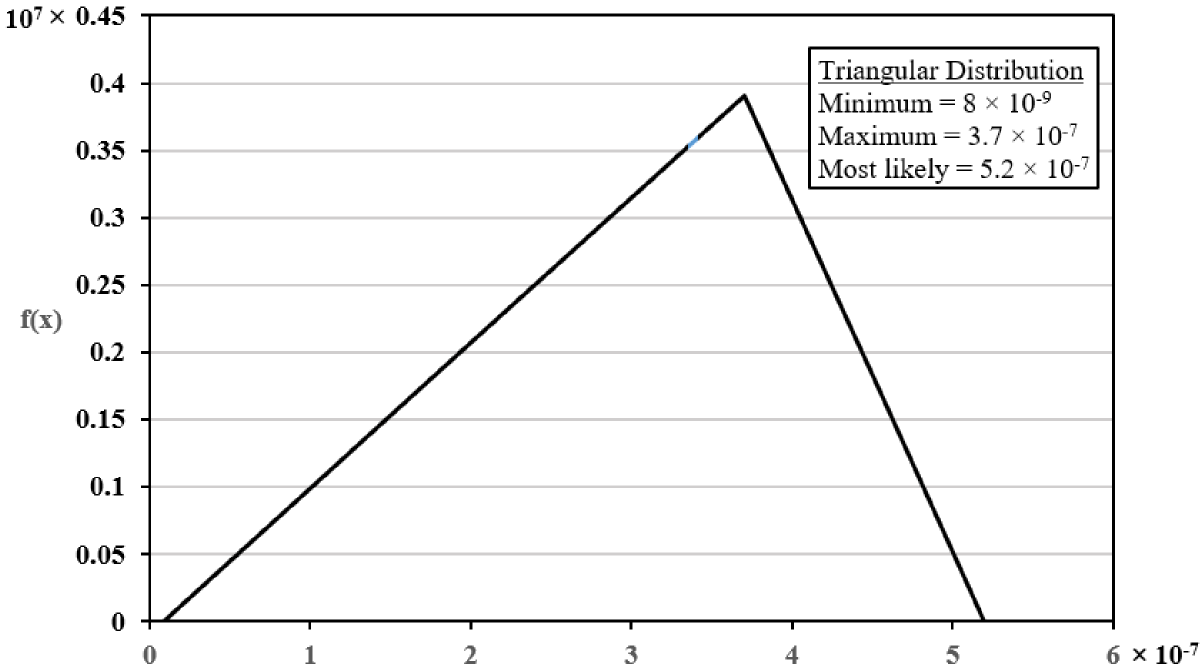

Figure I-18 Radon Diffusion Coefficient Probability Density Function

I.4.22 Radon Emanation Fraction

Definition: This parameter represents the fraction of the total amount of radon produced by radium decay that escapes the matrix of the contaminated material and gets into the pores of the medium.

Parameter Name: EMANA0 Units: unitless Range: 0 to 1

Deterministic Analysis Default Value: 0.13

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 0.005 Maximum: 0.4 Most Likely: 0.13

Input Form: Source Parameters → Details for Source → Layer Region Parameters

Discussion: This parameter is also called the emanating power, emanation coefficient, release ratio, and escape-to-production ratio. The radon emanation fraction is used by RESRAD-BUILD in conjunction with the concentration of radium-226 and thorium-228 to calculate the release of radon-222 and radon-220, respectively, into the pore space of the contaminated layer in a volume source. It is only applicable to the radon inhalation pathway and is only required as input when radionuclides that decay to radon are specified as part of a volume source. It is not required for an area, line, or point source with radon precursor(s), for which the release rate of radon is calculated with the radon release fraction parameter (see Section I.4.11).

The radon emanation fraction is a unitless parameter ranging in value from 0 to 1. Values approaching 0 indicate that the majority of the radon is retained in the matrix of the source material and is not being released to the pore space. An emanation fraction approaching 1 indicates that most of the generated radon is being released to the pore space inside the contaminated material.

The values of the radon emanation fraction have been measured mostly for soils and for Rn-222. Section 4.2 of the RESRAD Data Collection Handbook (Yu et al. 2015) and Section C.8.10 of NUREG/CR-7267 (Kamboj et al. 2018) provide discussions on measurement methods and available literature data. The data show that for Rn-222 in soils, the range is 0.005-0.83, and the mean is 0.2, while in rocks, the range is 0.005-0.4, and the mean is 0.13. The emanation fraction for Rn-220 in rocks has a mean value of 0.11, and the range of the reported means spans from 0.105 to 0.157; in soils, Rn-220 has a mean of 0.14, and the range of the reported means spans from 0.11-0.16. For RESRAD-BUILD, a default triangular distribution was selected for radon (both Rn-220 and Rn-222) emanation fraction, with a minimum of 0.005, a mode of 0.13, and a maximum of 0.4, which were based on data for Rn-222 in rocks. Figure I-19 presents the probability density function for the selected distribution.

Factors affecting the emanation fraction include total porosity, water content in the pore space, grain size of the solid material in the contaminated region, the distribution of the parent radium in the grains, etc.

If a volume source is selected in RESRAD-BUILD and the source contains a radon precursor(s), input for the radon emanation fraction for each layer within the volume source is required.

Different emanation fractions may be specified for radon-222 and radon-220 within the same source. Setting a value of 0 for the radon emanation fraction effectively suppresses the radon pathway, thereby rendering the input of other radon-related parameters inconsequential.

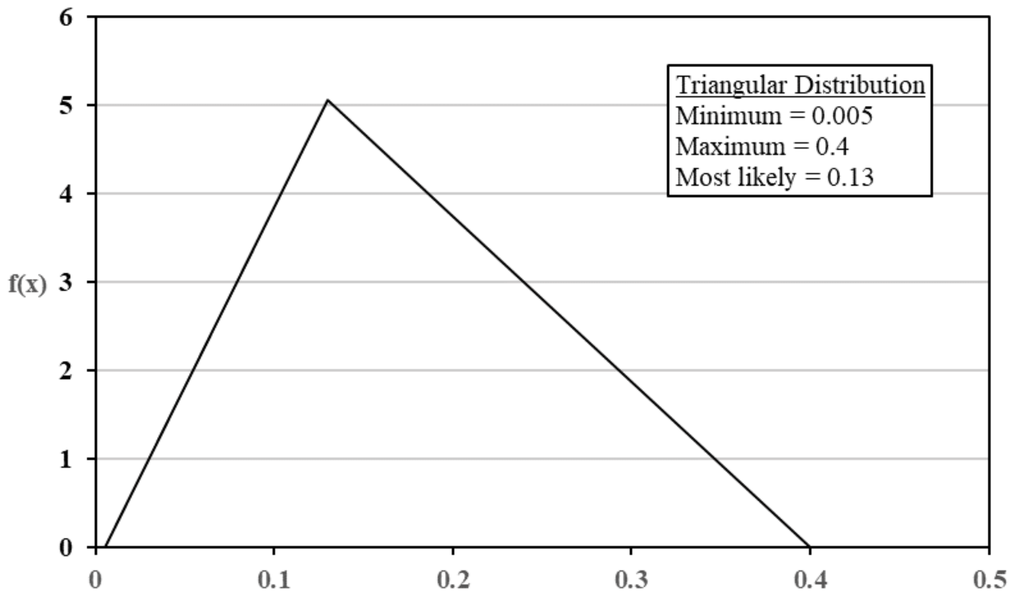

Figure I-19 Radon Emanation Fraction Probability Density Function

I.4.23 References

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I.5 SHIELDING PARAMETERS

I.5.1 (Effective) Shielding Thickness

Definition: This parameter represents the effective thickness of shielding for an object between a source and a receptor.

Parameter Name: DSTH Units: cm Range: ≥ 0

Deterministic Analysis Default Value: 0

Probabilistic Analysis Default Distribution: Triangular

Defining Values for Distribution: Minimum: 0 Maximum: 30 Most likely: 0

Input Form: Shielding Parameters

Discussion: The effective shielding thickness parameter is used in determining the attenuation of direct external radiation from each source to each receptor. It affects only the direct external exposure pathway. For situations in which only air is present between the source and receptor, the effective shielding thickness is 0. The RESRAD-BUILD code requires the specification of an effective shielding thickness for every source-receptor pair (e.g., if there are 4 sources and 6 receptors, the code would require 24 [6 × 4] effective shielding thickness input values).

The shielding effect is modeled simply in RESRAD-BUILD as the attenuation to external radiation using the thickness, density, and the material specified for the shielding. There are no input parameters for further geometrical considerations; therefore, the user must make some approximations. If a shielding wall/block is not perpendicular to the source-receptor line, the projected thickness onto the source-receptor line, not the actual thickness of the wall/block, should be specified as the shielding thickness. This is the effective shielding thickness. In another words, the effective thickness is the thickness of the shielding object that lays on top of the contamination source that provides the same level of attenuation as the shielding object with its actual thickness in its current position. As such, the same shielding object might be assigned different effective shielding thicknesses for different source-receptor pairs. The inclusion of shielding in the external dose calculation should reflect site-specific conditions. For example, to calculate the external dose for a receptor in a different room from the source room, an effective shielding thickness equivalent to the thickness of the wall separating the two rooms should be specified.

Floor and wall thicknesses vary depending on the type of building and type of construction. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness of shielding would reduce the external dose significantly from all radionuclides, including alpha emitters, beta emitters, X-ray or low-energy photon emitters, as well as high-energy gamma emitters. For the default triangular distribution selected for the shielding thickness parameter, the maximum value is set to 30 cm; the minimum and the most likely value is chosen as 0 cm (this selection would yield the most conservative dose/risk results for the direct external exposure pathway). The probability density function for this distribution is shown in Figure I-20.

Because the attenuation provided by materials in a volume source is handled separately, this parameter should account for only the thickness of the shielding material external to the volume source. The user should ensure that the thickness specified does not exceed the distance between the surface of the source facing the receptor and the receptor.

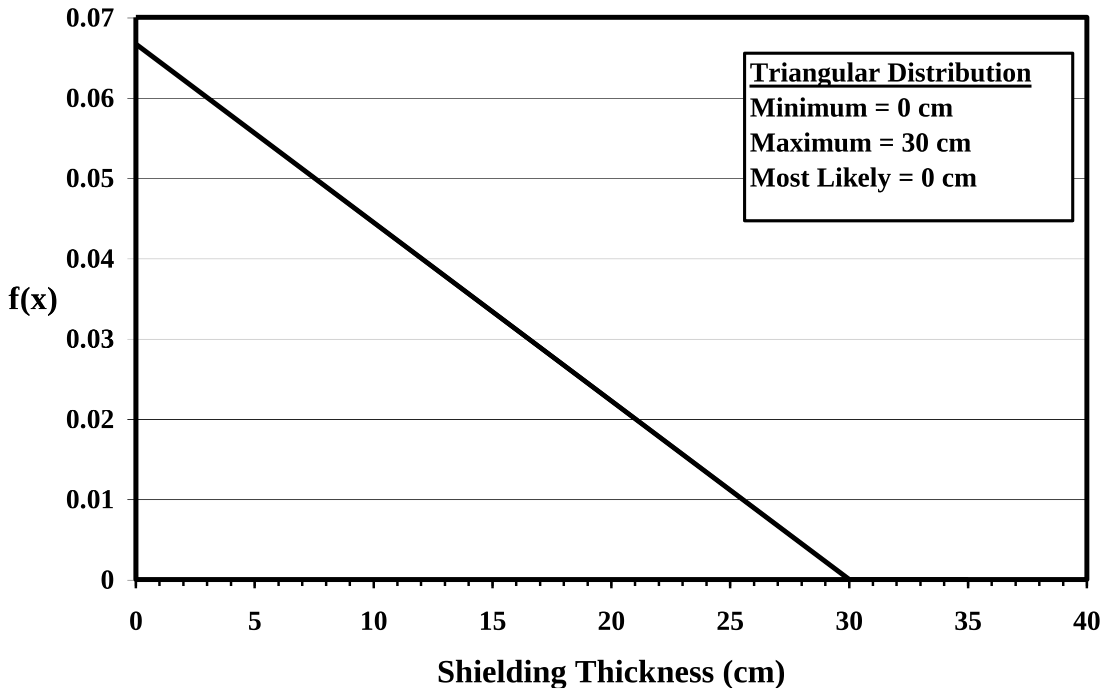

Figure I-20 Shielding Thickness Probability Density Function

I.5.2 Shielding Density

Definition: This parameter represents the effective bulk density of shielding between a receptor and a radiation source.

Parameter Name: DSDEN Units: g/cm^3 Range: 0 to 22.5

Deterministic Analysis Default Value: 2.4

Probabilistic Analysis Default Distribution (allowed only for concrete): Uniform

Defining Values for Distribution: Minimum: 2.2 Maximum: 2.6

Input Form: Shielding Parameters

Discussion: The type of shielding material, along with the shielding thickness and density, determine the attenuation effectiveness of the shield against external radiation. The shielding density parameter affects the radiation dose/risk of the direct external exposure pathway. For situations in which only air is between the source and receptor, the shielding thickness should be set to 0 and the density becomes immaterial. The type of shielding material will often determine the density.

In the RESRAD-BUILD code, the user must input the shielding characteristics for each source-receptor pair (e.g., if there are 4 sources and 6 receptors, the code would require 24 shielding characteristics). As is the case for source density, the shielding density is limited to less than 22.5 grams per cubic centimeter (g/cm^3). The code provides eight types of shielding materials for selection: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. They are the same as the eight types of source material for selection (Section I.4.15). Table I-4 (in Section I.4.17) provides the density value or range for different shielding (or source) materials (except concrete). The values and range are taken from *The Health Physics and Radiological Health Handbook* (Shleien 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide 1998). Table I-5 provides the concrete density from three different sources: *The Health Physics and Radiological Health Handbook* (Shleien 1992), *Properties of Concrete* (Neville 1996), and *Standard Handbook for Civil Engineers* (Merritt et al. 1995). The default shielding density used in the RESRAD-BUILD code is for ordinary concrete, the same as the default source density. A uniform distribution with the given range listed in Table I-5 may be used as the distribution function for shielding density if the shield is made by a known type of concrete. Figure I-21 shows the probability density function for the default distribution function selected for the shielding density parameter.

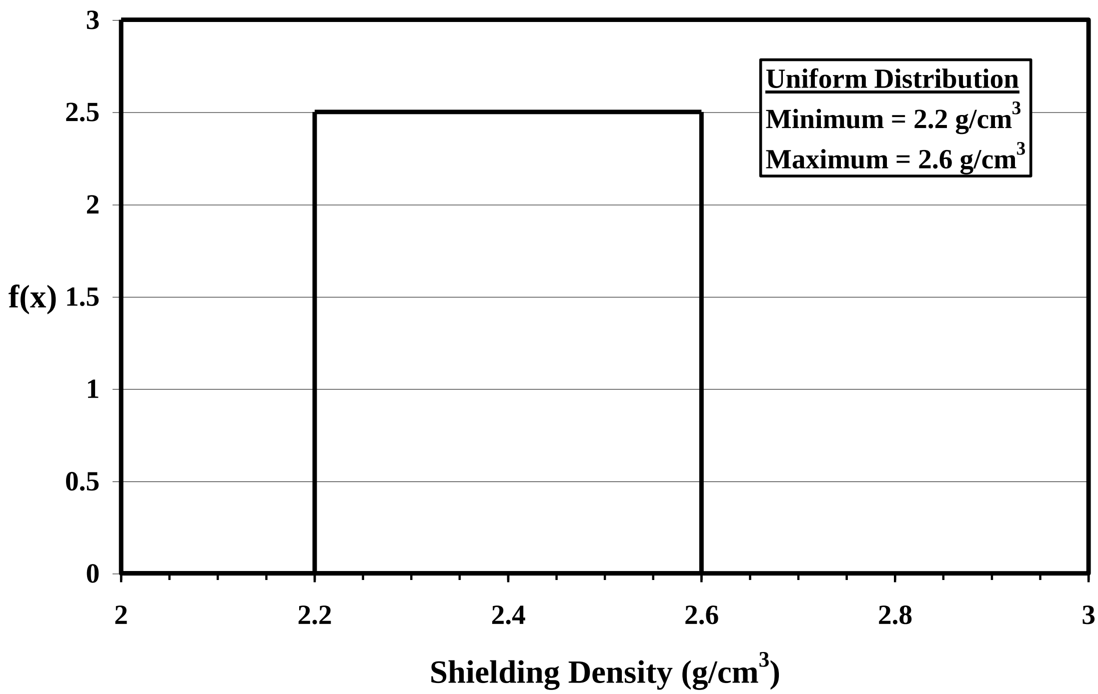

Figure I-21 Shielding Density Probability Density Function

I.5.3 Shielding Material

Definition: This parameter specifies the type of material for the shield between a receptor and a source.

Parameter Name: MTLC Units: Unitless Range: Concrete, water, aluminum, iron, copper, tungsten, lead, or uranium

Default Value: Concrete

Input Form: Shielding Parameters

Discussion: This parameter is not eligible for probabilistic input. If air is the only medium between a source and a receptor, there is no shielding material present. The type of shielding material, along with the shielding thickness and density, determine the attenuation effectiveness of the shield. This parameter affects only the dose/risk of the direct external radiation pathway.

The user can select among eight options of shielding material: concrete, water, aluminum, iron, copper, tungsten, lead, and uranium. The type of shielding material can be determined from direct inspection, standard building codes, and/or building design specifications. When there are many materials in the shield, the input material that most closely approaches the weighted average atomic number of the shield should be chosen.

The code requires the shielding material to be specified for each source-receptor pair. For example, if there are two sources and four receptors, the code requires eight specifications of shielding material. It is up to the user to specify the correct densities for the shielding materials (see Section I.5.2, Shielding Density).

I.5.4 References

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I.6 TRITIUM MODEL PARAMETERS

I.6.1 Dry Zone Thickness

Description: Dry zone thickness is the thickness of the uncontaminated region overlying the tritium contaminated region (wet zone) in a volume source.

Parameter Name: DRYTHICK Units: cm Range: 0–wet + dry zone thickness

Default Value: 0

Input Form: Source Parameters → Details for Source – Tritium Parameters

Discussion: The tritium vaporization model in RESRAD-BUILD considers only a volume source that is situated inside a concrete wall or floor of a contaminated building. The volume source extends to a certain depth from the exposed surface of the concrete wall or floor and constitutes a contaminated region (wet zone) at the bottom and an uncontaminated region (dry zone) at the top. The user can specify the thickness of the dry zone and the thickness of the wet + dry zone at the beginning. The difference between these two thicknesses gives the thickness of the wet, i.e., contaminated, zone. Tritium in a point, line, or area source is assumed to be in a solid form and is released as the source materials are eroded away, by attaching to source particles.

The tritium vaporization model implemented in the RESRAD-BUILD code was adapted from the landfarming model developed by Thibodeaux and Hwang (1982) to consider volatilization of hydrocarbons from contaminated soils. The tritium vaporization model assumes that tritium exists as HTO in a volume source, and the release rate of HTO to the indoor air is controlled by the diffusion rate of water molecules through the pore space of the source materials. The difference between the water vapor concentration in the indoor air and the water vapor concentration in the pore space of the contaminated region is the driving force for the diffusion process. The vaporization of water is assumed to be similar to a peeling process in which, as time goes on, the free water molecules (those that are not fixed to the solid source material) in the wet zone (i.e., the contaminated region) vaporize and diffuse out as if they were peeled off from the wet zone layer by layer. This vaporization process expands (or creates) the dry zone that sees its thickness increase with time until all free water molecules vaporize and leave the contaminated region. As water molecules vaporize, HTO molecules that behave like water molecules also vaporize and are released to the indoor air, resulting in radiation exposure of building occupants. To estimate the release rate of tritium, the values of several additional parameters (see Sections I.6.2 through I.6.5) are required. The RESRAD-BUILD code then uses the values of these parameters to estimate the average tritium release rate over the exposure duration and the integrated radiation dose resulting from exposure to tritium in the indoor air.

I.6.2 Wet + Dry Zone Thickness

Description: This parameter represents the distance from the exposed surface to the bottom surface of a volume source containing tritium. The volume source extends from the surface of a building wall/floor to a certain depth and constitutes an uncontaminated region (dry zone) and a contaminated region (wet zone).

Parameter Name: H3THICK Units: cm Range: ≥ 0

Deterministic Analysis Default Value: 10

Probabilistic Analysis Default Distribution: Uniform (allowed only for volume contamination with tritium)

Defining Values for Distribution: Minimum: 5 Maximum: 30

Input Form: Source Parameters → Details for Source – Tritium Parameters

Discussion: The wet + dry zone thickness parameter is used in RESRAD-BUILD to model the emission rate of tritiated water (HTO) vapor from a contaminated volume source to the indoor atmosphere. In a tritium-handling facility, tritium contamination of the construction material and equipment is recognized as an important source in defining the requirements for atmospheric cleanup and personnel protection. Tritium released during the handling process can quickly sorb to surfaces of the surrounding materials (e.g., concrete walls and floors) and can permeate many of them, resulting in contamination of the bulk as well as of the surface. The tritium that permeates the surrounding materials can then desorb and is released to the indoor air. This sorption/desorption process is generally referred to as the "tritium soaking effect" in tritium-handling facilities.

Tritium released from the tritium-handling facilities can be in different chemical forms; the most common ones are tritium gas (HT) and tritium oxide, or HTO. In general, sorption and desorption of HT occurs faster than that of HTO; however, the total amount sorbed and desorbed is greater for HTO than for HT (Wong et al. 1991; Dickson and Miller 1992). In contrast, HT can easily be converted to HTO in the environment. Experimental data concerning the tritium soaking effect on construction metals also showed that about 90% of the tritium desorbed from metal samples was in the form of HTO, although the samples were exposed to an atmosphere of HT (Dickson and Miller 1992). Because of the conversion from HT to HTO and the potentially longer time required for degassing of HTO (desorption and subsequent release from the contaminated material to the indoor air), the tritium model incorporated into the RESRAD-BUILD code considers only the potential degassing of HTO after the tritium-handling operation has stopped.

Among all the materials that can become contaminated, concrete is of special concern because of its high porosity. The high porosity of concrete materials makes them more vulnerable to the permeation of tritiated water, which can spread inside the concrete matrix after the initial surface absorption/adsorption. In RESRAD-BUILD, the degassing (i.e., the release) of the HTO vapor is assumed to be controlled by the diffusion of free HTO molecules from inside of the concrete matrix to the concrete-atmosphere interface (the "free" molecules are the HTO molecules that are not bound to the concrete matrix and are available for diffusion; see the discussion for the “water fraction available for evaporation” parameter, Section I.6.4).

The diffusion of HTO is assumed to proceed like a peeling process in which the HTO molecules closer to the concrete-atmosphere interface will be released earlier than those farther from the interface. As the release process continues, a region free of free HTO molecules (i.e., the dry zone) will be formed, and its thickness will increase over time. The dry zone thickness then represents the path length for the subsequent diffusion. The region inside the concrete where the free HTO molecules are distributed is called the wet zone. As the dry zone becomes thicker, the thickness of the wet zone decreases accordingly. In fact, the sum of the dry zone thickness and the wet zone thickness is assumed to remain the same throughout the diffusion process.

Although diffusion (permeation) of the HTO vapor to the bulk of concrete materials in a tritium handling facility is recognized (Wong et al. 1991), direct detection of the extent of spreading into the bulk (i.e., dry + wet zone thickness) is not possible because of the short range of the beta radiation (DOE 1991). However, judging by the high porosity of concrete materials, spreading of the HTO vapor throughout the entire thickness is possible if the exposure is of sufficient duration. Therefore, the thickness of the concrete wall is assumed for the “dry + wet zone thickness” parameter in the default case, which, on the basis of engineering judgments, can be as much as 30 cm. A low bound of 5 cm is selected because bulk contamination will not be extensive for a short exposure period. The probability density function is shown in Figure I-22.

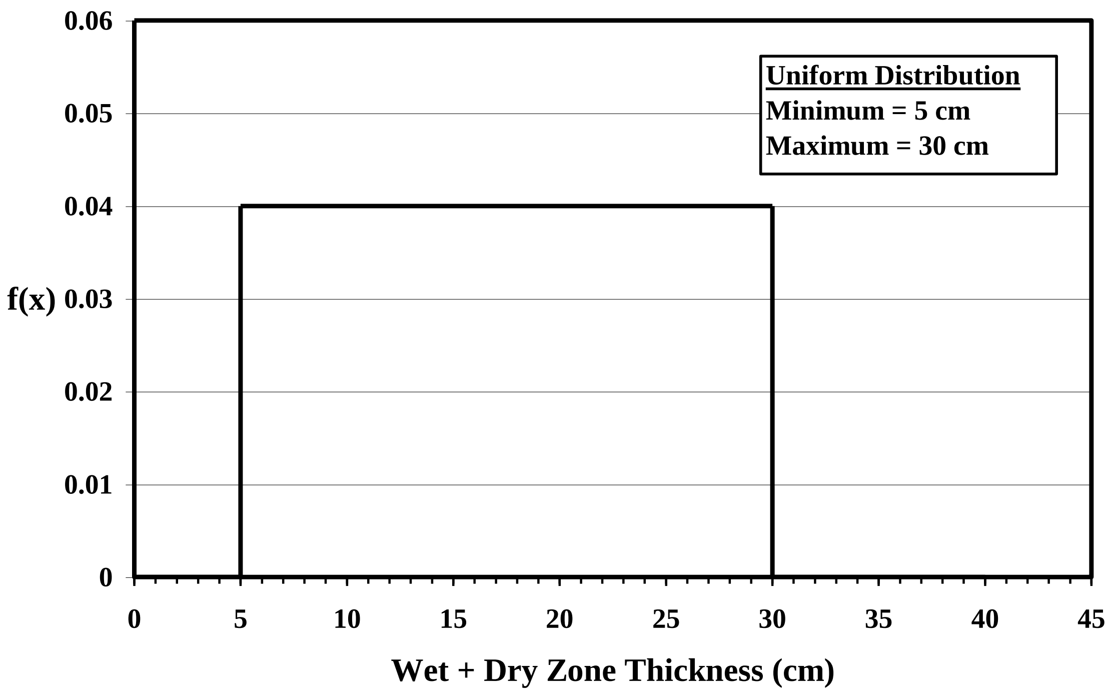

Figure I-22 Wet + Dry Zone Thickness Probability Density Function

I.6.3 Volumetric Water Content

Description: The volumetric water content is the volume of water per unit volume of the porous source material.

Parameter Name: H3VOLFRACT Units: Unitless Range: > 0 to 1

Deterministic Analysis Default Value: 0.03

Probabilistic Analysis Default Distribution: Uniform (allowed only for volume contamination with tritium)

Defining Values for Distribution: Minimum: 0.04 Maximum: 0.25

Input Form: Source Parameters → Details for Source – Tritium Parameters

Discussion: The volumetric water content is used in RESRAD-BUILD in the tritium vaporization model to evaluate the radiation doses/risks associated with a volume source contaminated with tritium. The assumption is made that any tritium in the volume source is present as tritiated water (HTO). Because the contaminated medium is assumed to be concrete, the amount of water in the volume source is expected to be within the range of the concrete's total porosity. Therefore, the default distribution function for the volumetric water content is expected to be the same as that for the source porosity (Section I.4.20). In any case, the maximum value assigned to the volumetric water content should not be greater than the maximum of the source porosity.

I.6.4 Water Fraction Available for Vaporization

Description: This parameter is used in estimating the potential release rate of tritiated water (HTO) vapor from a volume contamination source. It is the fraction of the total amount of tritiated water that will vaporize and be released to the indoor air through the diffusion process under room temperature.

Parameter Name: H3RMVFUnits: UnitlessRange: 0 to 1

Deterministic Analysis Default Value: 1

Probabilistic Analysis Default Distribution: Triangular (allowed only for volume contamination with tritium)

Defining Values for Distribution: Minimum: 0.5 Maximum: 1.0 Most likely: 0.75

Input Form: Source Parameters → Details for Source – Tritium Parameters

Discussion: As discussed in Section I.6.2, the tritium that released from tritium-handling facilities is mostly as tritium gas (HT) or tritiated water (HTO). HT can be easily converted to HTO in the environment; therefore, the tritium vaporization model in RESRAD-BUILD focuses on the release of tritium as HTO from a volume source, which is controlled by diffusion through the pore space of the source materials. The diffusion rate is estimated on the basis of the extent of the contamination (thickness of dry zone, thickness of dry zone + wet zone, and area of contamination), characteristics of the source material (porosity and moisture content), tritium inventory (tritium concentration), and indoor humidity. Because not all the tritium in the source material is available for diffusion under ordinary building occupancy conditions, estimation of the release rate has to take into account the fraction of tritiated water available for vaporization and diffusion.

Experimental observations confirmed that water exists in concrete in two states: free water and bound water (Numata and Amano 1988), which was verified by Ono et al. (1992). Kamboj et al. (2018) discusses and summarizes the experimental results and findings. Based on the reported data and the suggestion from DOE (1994), conclusions on the fraction of water in concrete that is available for vaporization and diffusion are: (1) the free fraction of tritiated water in concrete materials used in tritium-handling facilities is greater than the free fraction of ordinary water in the same materials, and (2) the free fraction of tritiated water in the concrete materials can be very high if the exposure duration of the concrete materials to tritiated water was very short. Therefore, a triangular distribution with a minimum of 0.5, a maximum of 1.0, and a most likely value of 0.75 was assumed for the “free water fraction available for evaporation” parameter. The probability density function is shown in Figure I-23.

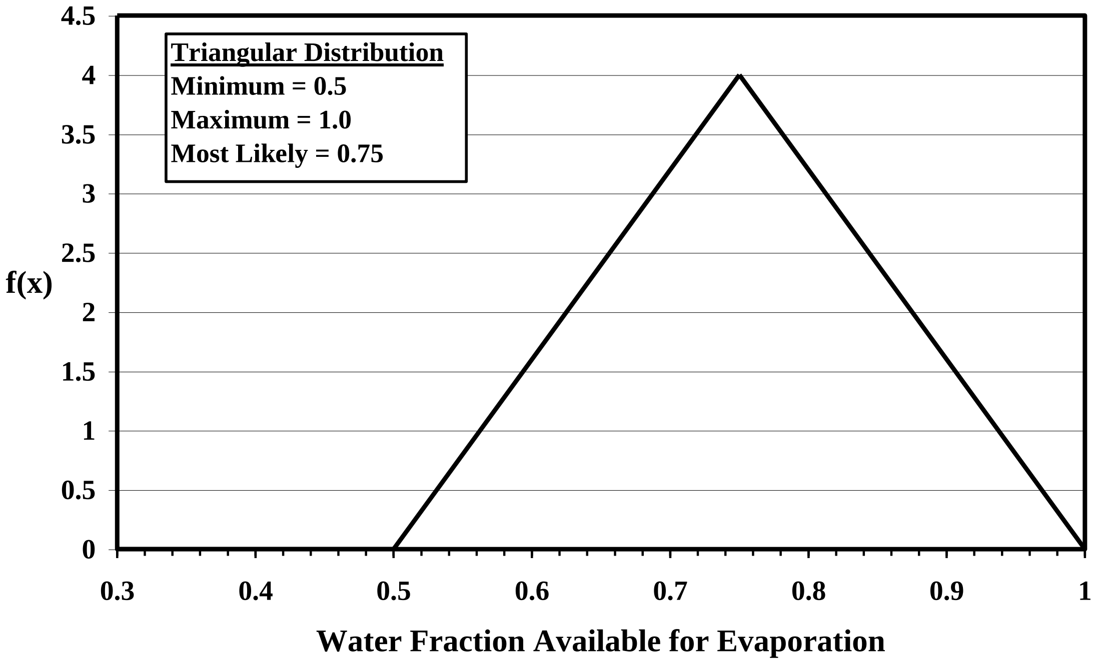

Figure I-23 Water Fraction Available for Evaporation Probability Density Function

I.6.5 Humidity

Description: This parameter represents the average absolute humidity in the building. The absolute humidity is an input used only for the tritium vaporization model concerning a volume source.

Parameter Name: HUMIDITY   Units: g/m^3 Range: 0 to 100

Deterministic Analysis Default Value: 8

Probabilistic Analysis Default Distribution: Uniform (allowed only for volume contamination with tritium)

Defining Values for Distribution: Minimum: 6.5 Maximum: 13.1

Input Form: Source Parameters → Details for Source – Tritium Parameters

Discussion: RESRAD-BUILD requires input for the absolute humidity, the actual concentration of water vapor in the air of the source room. The relevant data available are given in terms of the relative humidity (RH). The RH of a water vapor-air mixture is defined as 100 times the partial pressure of water divided by the saturation vapor pressure of water at the same temperature. For this discussion, RH was converted to absolute humidity by assuming a total pressure of 1 atmosphere in conjunction with a given temperature and partial pressure of water at that temperature. Tabulated values for the partial pressure of water over a range of temperatures were obtained from Dean (1999).

For RESRAD-BUILD, the average humidity in a building depends on the functioning of the heating, ventilation, and air-conditioning (HVAC) systems of the building. At normal room temperatures, the RH in occupied buildings should be between approximately 30 and 60% to help maintain human health and comfort (Sterling et al. 1985). With respect to health, this range in RH minimizes allergic reactions and bacterial and viral growth. Human discomfort is noted at lower and higher humidities. Discomfort at low RH results from the drying of skin, hair, and respiratory membranes.

Because HVAC systems are designed to maintain a healthy environment for building occupants (the 30 to 60% RH range), a uniform distribution for the corresponding absolute humidity range is used as the default distribution in RESRAD-BUILD. The range of 30 to 60% RH corresponds to an absolute humidity range of 6.5 to 13.1 grams of water per cubic meter at 1 atmospheric pressure and 24ºC (75ºF). The probability density function is shown in Figure I-24. However, RH values lower than 30% may occur in buildings that do not have a humidification system, especially during the winter in colder climates. Also, RH values higher than 60% may occur in buildings using natural ventilation in more temperate climates. In such climates where natural ventilation may be employed, the humidity inside the building will be more representative of the outside levels.

For those buildings more dependent on natural ventilation, data from 231 weather stations across the conterminous 48 United States, most with more than 30 years of recorded data, were analyzed to obtain a perspective on ambient outdoor humidity levels. Annual average morning and afternoon RH levels were used in conjunction with annual average temperature readings at these weather stations (NCDC 1999) to estimate absolute humidity levels. The morning and afternoon RH levels were averaged for each station to obtain one value for the annual average RH for use in estimating the absolute humidity.

The resulting absolute humidity probability density function was fit reasonably well to a lognormal distribution by using Bayesian estimation, as shown in Figure I-25. This distribution is only indicative of what might be expected. The sampling is not representative of a uniform grid across the United States, although it is indicative of the larger population centers. When available, site-specific data should be used. For this alternative distribution, the underlying mean and standard deviation for the lognormal fit are 1.98 and 0.334, respectively.

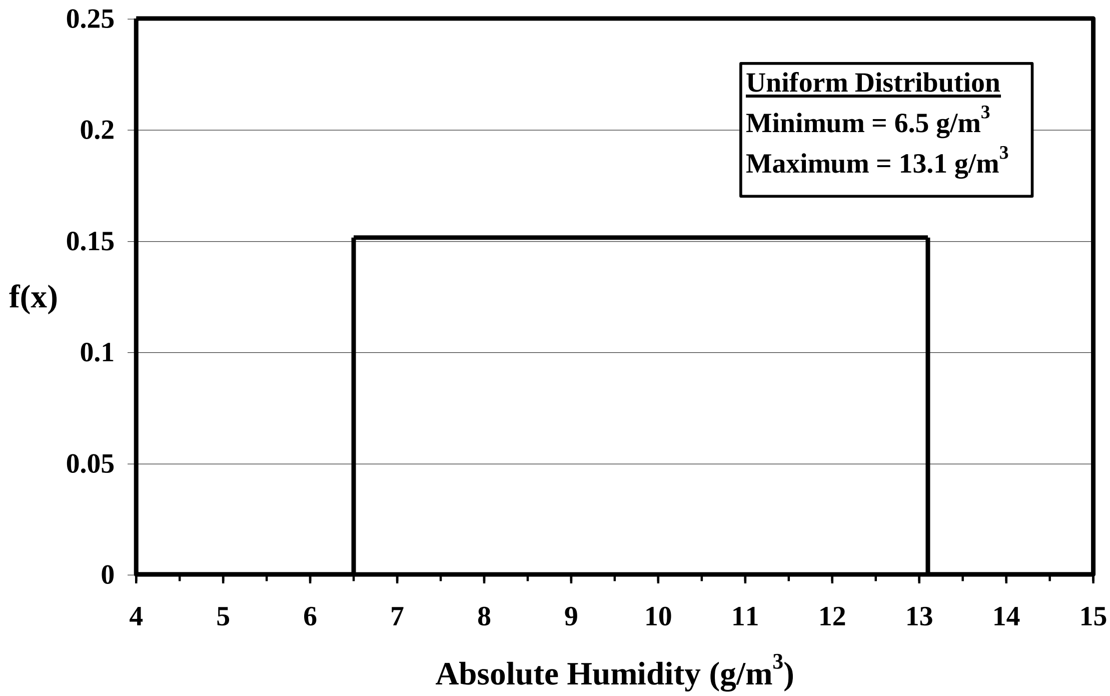

Figure I-24 Default Indoor Absolute Humidity Probability Density Function

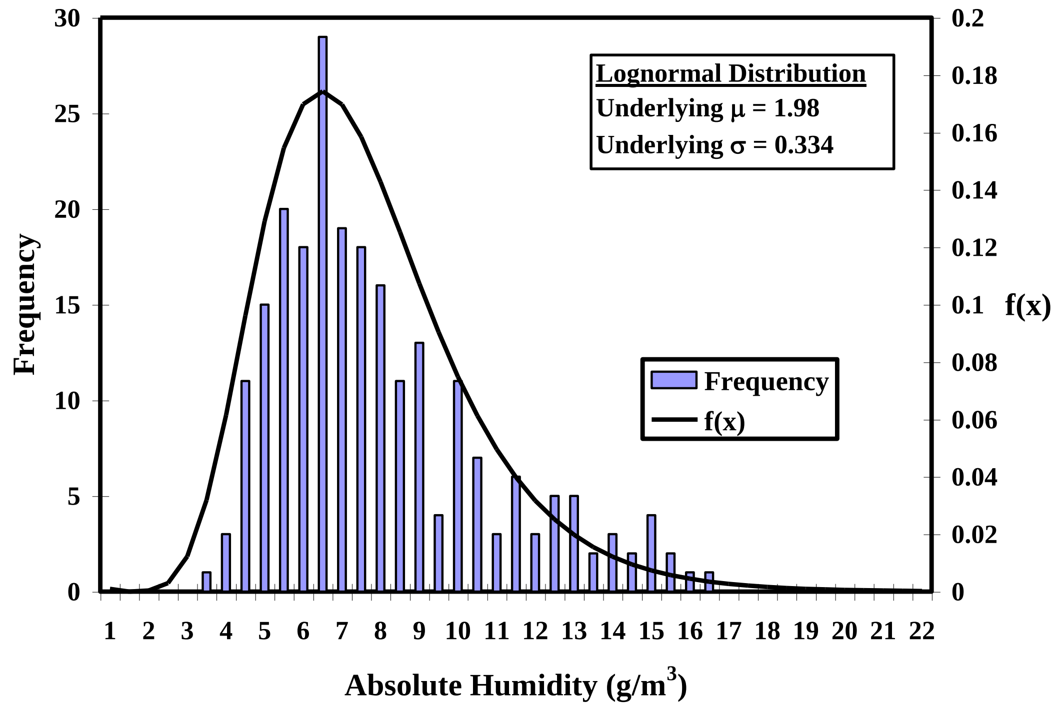

Figure I-25 Representative Probability Density Function for Outdoor Ambient Humidity

I.6.6 References

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I.7 RADIOLOGICAL UNITS

I.7.1 Activity Units

Definition: Any of the following four units of radiological activity can be selected: (1) Ci or curie, defined as 3.7×10^{10} disintegrations per second (dps); (2) Bq or becquerel, defined as 1 dps; (3) dps; (4) disintegrations per minute (dpm). Any standard one-character metric prefix can be used with Ci and Bq. The allowed prefixes are as follows:

E	exa	1×10^{18}
P	peta	1×10^{15}
T	tera	1×10^{12}
G	giga	1×10^{9}
M	mega	1×10^{6}
k	kilo	1×10^{3}
h	hecto	1×10^{2}
	none	1
d	deci	1×10^{-1}
c	centi	1×10^{-2}
m	milli	1×10^{-3}
m	micro	1×10^{-6}
n	nano	1×10^{-9}
p	pico	1×10^{-12}
f	femto	1×10^{-15}
a	atto	1×10^{-18}

Default: pCi (picocurie)

Input Form: Radiological Units

Discussion: The choices for activity include Ci, Bq, dpm, and dps. Both the Ci and Bq settings allow the user to specify a prefix that ranges over 36 orders of magnitude. The activity concentration values in each source are automatically converted to reflect the change in the activity unit.

I.7.2 Dose Units

Definition: The dose equivalent or equivalent dose is the average absorbed dose over a tissue or organ and weighted for the radiation quality that is of interest. The effective dose equivalent or effective dose is the sum of the weighted equivalent doses in all tissues and organs of the body. Either of the two biological radiation dose units, rem or sievert, can be selected. The rem is the conventional unit of dose equivalent, effective dose equivalent, equivalent dose, and effective dose; 1 rem = 0.01 Sv. The sievert (Sv) is the name for the SI unit of dose equivalent, effective dose equivalent, equivalent dose, and effective dose; 1 Sv = 100 rem. Any standard one-character metric prefix can be used with rem or Sv. The allowed prefixes are as follows:

E	exa	1×10^{18}
P	peta	1×10^{15}
T	tera	1×10^{12}
G	giga	1×10^{9}
M	mega	1×10^{6}
k	kilo	1×10^{3}
h	hecto	1×10^{2}
	none	1
d	deci	1×10^{-1}
c	centi	1×10^{-2}
m	milli	1×10^{-3}
m	micro	1×10^{-6}
n	nano	1×10^{-9}
p	pico	1×10^{-12}
f	femto	1×10^{-15}
a	atto	1×10^{-18}

Default: mrem (millirem)

Input Form: Radiological Units

Discussion: The choices for dose include rem and Sv. Both have the prefix option. The dose units are used only for reporting results.

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APPENDIX J:

BENCHMARKING OF RESRAD-BUILD CODE

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APPENDIX J:

BENCHMARKING OF RESRAD-BUILD CODE

This appendix compares the RESRAD-BUILD Version 4.0 dynamic air quality model results with the RESRAD-BUILD Version 3.5 steady-state air quality model. This appendix also compares the risk calculation methodology in RESRAD-BUILD code with the U.S. Environmental Protection Agency's (EPA's) Building Preliminary Remediation Goals (BPRG) indoor worker risk calculations (EPA 2019) and the dose calculation methodology in RESRAD-BUILD code with dose calculations in the Nuclear Regulatory Commission's (NRC's) Decommissioning and Decontamination (DandD) code's building occupancy scenario (McFadden et al. 2001).

The external exposure models in RESRAD-BUILD code are compared with Monte Carlo N-Particle (MCNP) code (Briesmeister 1993) for point, line, area, and volume sources in different receptor configurations.

J.1 COMPARISON OF RESRAD-BUILD CODE VERSION 4.0 AND VERSION 3.5.

The RESRAD-BUILD code is a pathway analysis model for calculating the potential radiological doses and risks to individuals who work or live inside a building that is contaminated with radioactive material. A single run of the RESRAD-BUILD code can model 10 sources and 10 receptors. The code provides four geometries to characterize a radiation source—point, line, area, and volume—in which radionuclides are homogeneously distributed. The code calculates the potential radiation dose and cancer risk incurred by each receptor from seven exposure pathways: (1) external radiation directly from the sources (accounting for shielding), (2) external radiation from radioactive particles deposited on the floors, (3) external radiation from airborne radionuclides, (4) inhalation of airborne radionuclides and tritiated water vapor, (5) inhalation of radon and radon progenies, (6) inadvertent ingestion of radioactive particles directly from the source, and (7) inadvertent ingestion of radioactive particles deposited on the floors. Various exposure scenarios can be modeled with RESRAD-BUILD code, including, but not limited to, office worker, renovation worker, decontamination worker, building visitor, and resident by adjusting input parameter values. Both deterministic and probabilistic analyses can be performed to obtain results in both text reports and graphic displays.

RESRAD-BUILD code uses two direct exposure models based on the source geometry. The first model for area and volume sources is based on a semi-infinite slab source with corrections for geometric factors. The second model for point and line contamination is a point kernel dose integral method (Appendix C). A shielding material can be specified between each source-receptor pair for external gamma dose and risk calculations for external exposure directly from the source. The user can select from eight different shielding material types. The volume source can be composed of up to five layers of different materials, with each layer being homogeneous and isotropic. Shielding from these layers is also modeled for exposure directly from that source, as appropriate.

Version 4.0 of RESRAD-BUILD has many modeling enhancements and new features over the previously released Version 3.5. The major changes are:

- Providing a choice of the International Commission on Radiation Protection Publication 38 (ICRP-38) (ICRP 1989) and Publication 107 (ICRP-107) (ICRP 2008) radiological transformation data;

- Providing compatible choices of internal and external dose libraries and risk libraries for each choice of transformation data;

- Modeling all branches of the transformation chain, and providing an option to specify a cut-off half-life in case it is necessary to reduce run time;

- A transient model to compute the concentration of particulates (and of the radionuclides in those particles) deposited on the floor and suspended in air as a function of time. Modeling the effects of vacuuming at a regular interval of time. Modeling delayed and intermittent releases from point, line and area sources. An analytical solution for most scenarios with up to 3 rooms. A numerical solution for scenarios with up to 9 rooms;

- Expanded versions for several input forms to accommodate additional parameters to activate additional functionality. Retained input forms which are similar as possible to the Version 3.5 input forms for those who prefer simpler ones, at a corresponding reduction in functionality;

- Performing time integration analytically when possible, to reduce execution time. Performing time integration numerically for some exposure pathways, when necessary or when specified, to user-specified convergence criteria using a larger number of time points while still reducing the execution time;

- Limiting direct ingestion of source material to the material removed from the source, less the material released to air;

- Redefining the basis for volume source coordinates and the explicit specification of the orientation of the source;

- Generating reports of intermediate calculation results; and

- Updated DCF Editor includes air submersion dose coefficients and slope factors.

The code calculates time-integrated dose and risk over the exposure duration at up to 9 user-specified times. The time zero calculation is always done, no matter whether time zero is specified by the user or not. The projection of radiation dose and cancer risk at a future time factor into account the presence of progenies of the initial radionuclides due to radiological transformation, thereby including the dose/risk contributions from the progenies. The radionuclide transformation data in ICRP-38 and ICRP-107 can be used to establish the decay chains and to calculate the radioactivity of progenies over time.

RESRAD-BUILD Version 4.0 has all radionuclides from ICRP-38 and ICRP-107. The ICRP-38 database contains radiological transformation data for 838 radionuclides, and ICRP-107 database contains radiological transformation data for 1,252 radionuclides. Any of these radionuclides can be selected for dose/risk calculations in RESRAD-BUILD provided they are in the currently selected transformation database and have a half-life greater than the cut-off half-life.

There are two sets of base dose coefficient libraries developed with the ICRP-38 radionuclide transformation database. One set was developed using the ICRP-26/30 methodology and published in Federal Guidance Reports (FGRs) No. 11 (Eckerman et al. 1988) and No.12 (Eckerman and Ryman 1993). These base libraries only include dose coefficients for adult members of the public. The other set of base libraries was developed using the ICRP-60 (ICRP 1991) methodology and published in the ICRP-72 (ICRP 1996) report. These libraries include dose coefficients for six different age groups (infant, 1, 5, 10, 15, and adult) of the general public. There is one set of the base dose coefficient library developed with the ICRP-107 radionuclide transformation database. This library also includes dose coefficients for six different age groups (infant, 1, 5, 10, 15, and adult) of the general public and for DOE-STD-1196-2011 (Reference Person). The reference person is defined as a hypothetical aggregation of human (male and female) physical and physiological characteristics arrived at by international consensus for standardizing radiation dose calculations. The reference person dose coefficients are derived using age-specific dose coefficients coupled with information on the age and gender structure of the U.S. population in 2000 census data and age- and gender-specific intakes (DOE 2011).

Table J-1 and Figure J-1 compare the concentrations of radionuclides in air and on the floor computed by RESRAD-BUILD Version 4.0 with those computed by the last officially released Version 3.5. The RESRAD-BUILD default volume and line sources are used to compare the air concentration and deposited concentration for one short half-life radionuclide (Co-60) and one long half-life radionuclide (U-238) at different evaluation times. Release of radionuclides occurs over a period of 365 days in the default line source; the default volume source represents a long-term release. The default for the deposition velocity is changed in Version 4.0 to 3.9E-04 m/s compared to Version 3.5 default value of 0.01 m/s. For this comparison the deposition velocity is kept at 0.01 m/s.

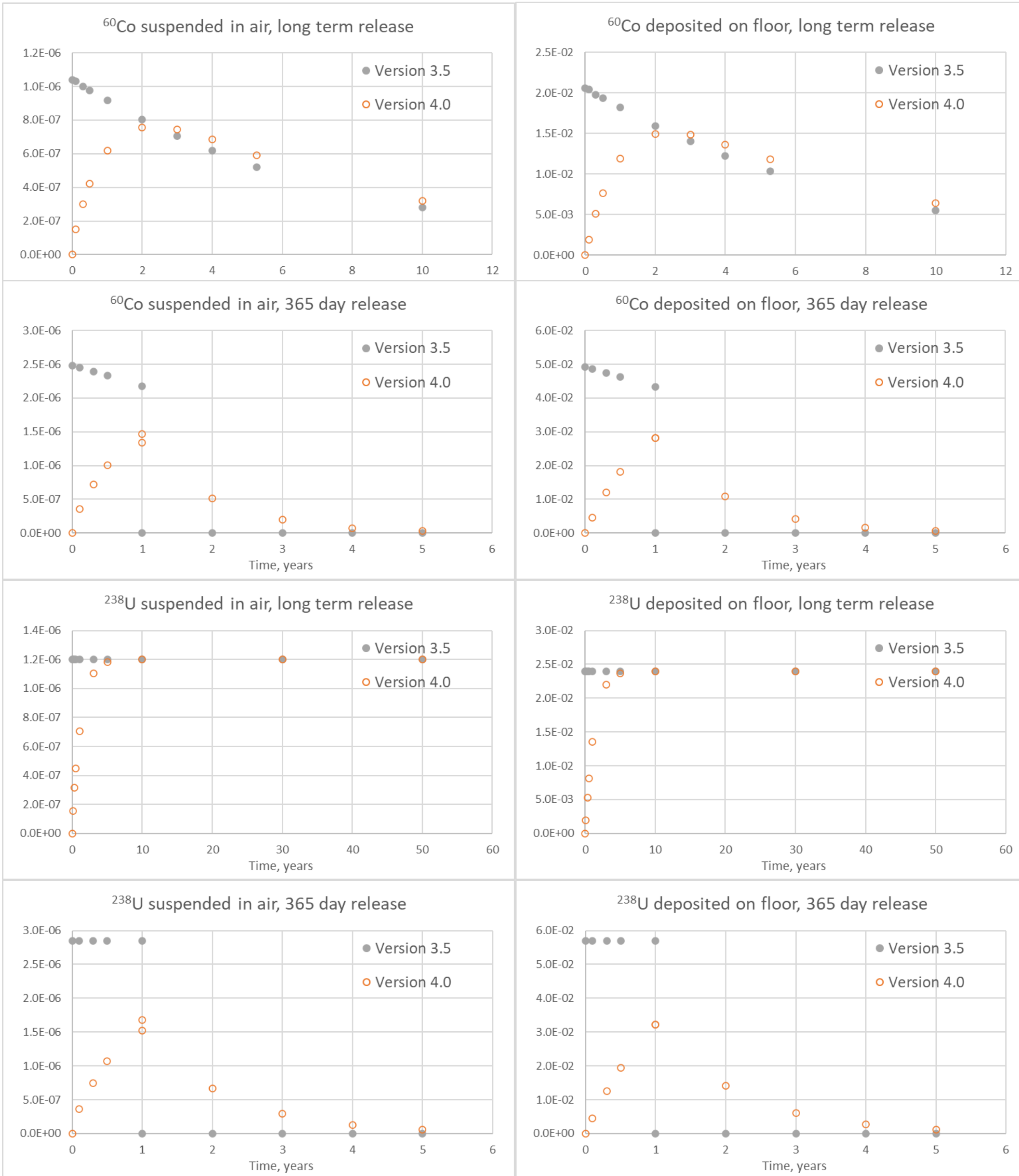

Figure J-1 Temporal Concentration Plots of Radionuclides Suspended in Air and Radionuclides Deposited on the Floor, to Illustrate the Effects of the Half-life of the Radionuclides and the Duration of the Release

For the long-term releases from volume sources with Co-60 and U-238 contamination, the following differences are observed:

- In Version 3.5:
  - There is no change in the U-238 air concentration and deposited concentration on the floor at different evaluation times (evaluation times are much less than the U-238 decay half-life).
  - For Co-60, there is change in air concentration and deposited concentration on the floor at different evaluation times; however, the change in air concentration or deposited concentration at different evaluation times is due only to the effect of radionuclide decay on the rate of release to the air. These are the steady-state concentrations that result from the release of radionuclides at a constant rate over a period of time. The concentration reported for each evaluation time is the steady-state concentration that corresponds to the rate of release at that time.

- In Version 4.0:
  - At earlier evaluation times, the U-238 air concentration and deposited concentration are much less than the values in Version 3.5. The Version 4.0 concentrations increase with time and reach the steady-state value of Version 3.5.
  - At earlier evaluation times, air concentration and deposited concentration of Co-60 are much less than the values in Version 3.5. The concentrations increase with time, reach a peak value, and then gradually decrease with time. The Version 4.0 values exceed the values computed by Version 3.5 beginning shortly after the time of the peak.

For the shorter duration release from the line sources with Co-60 and U-238 contamination, the following differences are observed:

- In Version 3.5:
  - There is no change in U-238 air concentration and deposited concentration on the floor at evaluation times less than the source lifetime. At evaluation times greater than the source lifetime, the air concentrations and deposited concentrations are zero.
  - For Co-60, there are changes in the air concentration and deposited concentration on the floor at evaluation times less than the source lifetime due to radionuclide decay. At evaluation times greater than the source lifetime, the air concentrations and deposited concentrations are zero.

- In Version 4.0:

  – At earlier evaluation times less than the source lifetime, U-238 air concentration and deposited concentration are less than the values in Version 3.5. Values in Version 4.0 increase with time; the values decrease at evaluation times greater than the source lifetime but are non-zero.
  – For Co-60 at earlier evaluation times less than the source lifetime, air concentrations and deposited concentrations are less than the values in Version 3.5. Values in Version 4.0 increase with time; the values decrease at evaluation times greater than the source lifetime but are non-zero.

Table J-1 Comparison of Air Concentration and Deposited Concentration for Different Release Durations and Half-lives

Evaluation time (yr)	Version 4.0		Version 3.5	
	Air Concentration (pCi/m^3)	Deposited Concentration (pCi/m^2)	Air Concentration (pCi/m^3)	Deposited Concentration (pCi/m^2)
Long-term release of a short-lived radionuclide Co-60 Volume Source @ 1 pCi/g with all RESRAD-BUILD Version 3.5 defaults				
0	0.00E+00	0.00E+00	1.04E-06	2.06E-02
0.1	1.52E-07	1.89E-03	1.03E-06	2.04E-02
0.3	3.02E-07	5.09E-03	1.00E-06	1.98E-02
0.5	4.21E-07	7.64E-03	9.78E-07	1.94E-02
1	6.18E-07	1.19E-02	9.16E-07	1.82E-02
2	7.56E-07	1.49E-02	8.03E-07	1.59E-02
3	7.45E-07	1.48E-02	7.04E-07	1.40E-02
4	6.85E-07	1.37E-02	6.17E-07	1.22E-02
5.271	5.93E-07	1.18E-02	5.22E-07	1.04E-02
10	3.22E-07	6.44E-03	2.80E-07	5.55E-03
365-day release of a short-lived radionuclide Co-60 Line Source @ 1 pCi/m with all RESRAD-BUILD Version 3.5 defaults				
0	0.00E+00	0.00E+00	2.48E-06	4.92E-02
0.1	3.61E-07	4.49E-03	2.45E-06	4.86E-02
0.3	7.17E-07	1.21E-02	2.39E-06	4.74E-02
0.5	1.00E-06	1.82E-02	2.33E-06	4.62E-02
0.999	1.47E-06	2.82E-02	2.18E-06	4.32E-02
1	1.34E-06	2.82E-02	0.00E+00	0.00E+00
2	5.11E-07	1.08E-02	0.00E+00	0.00E+00
3	1.95E-07	4.12E-03	0.00E+00	0.00E+00
4	7.46E-08	1.57E-03	0.00E+00	0.00E+00
5	2.85E-08	6.02E-04	0.00E+00	0.00E+00

Table J-1 (Cont.)

Evaluation time (yr)	Version 4.0 Air Concentration (pCi/m^3)	Version 4.0 Deposited Concentration (pCi/m^2)	Version 3.5 Air Concentration (pCi/m^3)	Version 3.5 Deposited Concentration (pCi/m^2)
Long-term release of a long-lived radionuclide U-238 Volume Source @ 1 pCi/g with all RESRAD-BUILD Version 3.5 defaults				
0	0.00E+00	0.00E+00	1.20E-06	2.40E-02
0.1	1.54E-07	1.91E-03	1.20E-06	2.40E-02
0.3	3.14E-07	5.29E-03	1.20E-06	2.40E-02
0.5	4.49E-07	8.15E-03	1.20E-06	2.40E-02
1	7.04E-07	1.35E-02	1.20E-06	2.40E-02
3	1.11E-06	2.20E-02	1.20E-06	2.40E-02
5	1.18E-06	2.36E-02	1.20E-06	2.40E-02
10	1.20E-06	2.40E-02	1.20E-06	2.40E-02
30	1.20E-06	2.40E-02	1.20E-06	2.40E-02
50	1.20E-06	2.40E-02	1.20E-06	2.40E-02
365-day release of a long-lived radionuclide U-238 Line Source @ 1 pCi/m with all RESRAD-BUILD Version 3.5 defaults				
0	0.00E+00	0.00E+00	2.85E-06	5.70E-02
0.1	3.66E-07	4.55E-03	2.85E-06	5.70E-02
0.3	7.46E-07	1.26E-02	2.85E-06	5.70E-02
0.5	1.07E-06	1.94E-02	2.85E-06	5.70E-02
0.999	1.67E-06	3.22E-02	2.85E-06	5.70E-02
1	1.52E-06	3.22E-02	0.00E+00	0.00E+00
2	6.64E-07	1.40E-02	0.00E+00	0.00E+00
3	2.89E-07	6.11E-03	0.00E+00	0.00E+00
4	1.26E-07	2.66E-03	0.00E+00	0.00E+00
5	5.50E-08	1.16E-03	0.00E+00	0.00E+00

Note: Only parent radionuclide information is listed. Air concentrations and deposited concentrations are taken from intermediate results in Version 4.0. Air concentration in Version 3.5 is taken from Version 3.5 results listed in the detailed report, and deposited concentration is calculated using Equation B.3 in the RESRAD-BUILD Version 3 Manual (Yu et. al. 2003).

J.2 BPRG CALCULATOR AND DANDD CODE COMPARISON WITH RESRAD-BUILD VERSION 4.0

J.2.1 EPA BPRG Calculator

The BPRG Calculator developed by EPA (EPA 2019) is used to calculate preliminary remediation goals for radionuclides in buildings (BPRG) for resident and indoor worker exposure. The BPRGs are reasonable maximum exposure (RME) risk concentrations derived from standardized equations that use exposure parameters and slope factors. The Calculator is based on the Risk Assessment Guidance for Superfund: Volume 1, Human Health Evaluation Manual (EPA 1989). The BPRG calculator estimates radionuclide concentrations in dust settled on surfaces, radionuclide concentrations in air inside the building, and direct external exposure from radionuclide concentrations on six surfaces/inside walls of different room sizes that are protective of humans over a lifetime for a selected risk level. The Calculator does not consider any relationship between the concentration on surfaces with air concentration inside the building or on the settled dust or vice versa (i.e., no Air Model or Deposition Model). The calculator has three options for calculating BPRGs: 1) assumes secular equilibrium throughout the chain (no decay) (default assumption); 2) does not assume secular equilibrium, but rather provides results for progeny throughout the chain (with decay); and 3) does not assume secular equilibrium, with no progeny included. Similar equations are used for both resident and indoor worker exposure, the only difference is in the parameters used. If media concentrations are input in the BPRG Calculator for dust, air, soil, and ground plane, it also calculates risk from dust settled on surfaces, ambient air concentration, and direct external exposure.

For estimating radionuclide concentrations in dust settled on surfaces at target risk, the BPRG Calculator considers external exposure and dust ingestion pathways. The slope factors used in the BPRG Calculator are taken from an Oak Ridge National Laboratory (ORNL) report (ORNL 2014). For estimating radionuclide concentrations in air inside the building at target risk level, the BPRG Calculator considers two exposure routes: inhalation and air submersion.

For estimating radionuclide surface or volumetric concentrations inside the building at target risk level, the BPRG Calculator considers direct external exposure from surface or volumetric contamination. It assumes all inside six sides of the building (walls, floor, and ceiling) are uniformly contaminated. The room surface factor accounts for the exposure to multiple contaminated surfaces of different finite sizes (length, width, depth, material) compared to infinite size based on Finklea (2015).

J.2.2 NRC DandD Code

The DandD code developed by Sandia National Laboratories for the NRC converts contamination levels at a site to annual dose for building occupancy and residential scenarios (MacFadden et al. 2001). The building occupancy scenario computes yearly average dose from surface contamination in buildings for light industrial use. The exposure starts immediately after release of the building. The building occupancy scenario considers direct external exposure from surface sources, exposure by breathing indoor air contaminated by resuspension of radionuclides from surface contamination, and inadvertent ingestion of surface contamination.

DandD code provides the capability to conduct sensitivity and probabilistic analysis to identify parameters that have the greatest impact on the dose distribution. DandD calculates air concentration as the product of resuspension factor (units of m^{-1}) and the removable activity per unit area in units of Activity/m^2.

J.2.3 Comparison of Main Features in RESRAD-BUILD, BPRG Calculator, and DandD Code

Table J-2 compares the main features and options in RESRAD-BUILD Version 4.0 code with the EPA BPRG Calculator’s Indoor Worker Scenario and DandD code’s (Version 2.4.0) Building Occupancy Scenario.

Table J-2 Comparison of Features and Options in RESRAD-BUILD Code (Version 4.0) with BPRG Calculator's Indoor Worker Scenario and DandD Code's (Version 2.4.0) Building Occupancy Scenario

Feature	RESRAD-BUILD Code	EPA BPRG Calculator	NRC DandD Code
Dose-risk calculations	RESRAD-BUILD can model scenarios related to occupancy and remediation of building structures. The code calculates time-variant dose and risk from each source to the receptor. In a single run, 10 sources and 10 receptors can be specified. BPRGs are not calculated; however, they can be derived from the calculated risk results.	Derives BPRGs (preliminary remediation goals for buildings) based on a target risk level. Also calculates cancer risks based on the input concentration of radionuclide in settled dust on surfaces, in ambient air inside the building, and surface or volumetric contamination on room surfaces; these risks are not functions of time.	The code calculates dose received over one year for building occupant. It includes direct external exposure from an infinite area source. The code assumes a static relationship between the amount of loose surface contamination and the airborne concentration. BPRGs are not calculated.
Sensitivity and probabilistic analysis	Allows sensitivity and probabilistic analysis on certain parameters.	Not included in the calculator.	Allows sensitivity and probabilistic analysis on certain parameters.
Basis/source of dose coefficients and/or slope factors	RESRAD-BUILD code has three dose coefficient libraries, two for the ICRP-38 decay scheme library and the other for the ICRP-107 radionuclide library. For the ICRP-38 decay scheme, for one library the inhalation and ingestion dose coefficients are from FGR 11 and for the other library the ICRP-72 age-dependent coefficients and external dose coefficients are from FGR 12. For the ICRP-107 decay scheme, the inhalation and ingestion dose coefficients are taken from DCFPAK3.02, and external dose coefficients are also taken from DCFPAK3.02 that are derived based on the ICRP-60 methodology. RESRAD-BUILD code has morbidity and mortality slope factors from FGR 13 (Eckerman et al. 1999) and DCFPAK3.02. The users also have the option to create their own library by modifying dose and risk coefficients.	Either the user inputs values or the defaults are used in the calculations. Defaults are morbidity slope factors from the ORNL report (ORNL 2014).	For inhalation and ingestion pathways, dose coefficients from FGR 11 are used, while for external exposure, dose coefficients from FGR12 are used.

Table J-2 (Cont.)

Feature	RESRAD-BUILD Code	EPA BPRG Calculator	NRC DandD Code
Radionuclide decay and ingrowth	Considers ingrowth of progenies over time as the parent nuclide decays in an environmental medium. Includes associated radionuclides (progeny radionuclides with half-life less than the selected cut-off half-life in equilibrium with the parent radionuclide) for the calculation of dose and risk from short-lived progenies.	Three options exist for progenies: (1) assume secular equilibrium throughout the entire decay chain; (2) do not assume secular equilibrium, but provide results for progenies throughout the chain (with decay); (3) do not assume secular equilibrium, providing results for selected isotopes only.	Considers ingrowth of progenies over time as the parent nuclide decays in an environmental medium. Includes "+C" radionuclides. A "+C" suffix denotes the equilibrium assumption for the radionuclide. The code has two options for "+C" radionuclides: 1) distribute initial activity and 2) do not distribute. In the first option, the entered activity is the combined activity of all equilibrium progeny, and in the second option, the entered activity is for the parent radionuclide, and all other progenies are assigned the same activity as the parent radionuclide.
Radionuclides	All 838 radionuclides in ICRP-38 and 1,252 radionuclides in ICRP-107. Radionuclide decay and ingrowth based on ICRP- 38 or ICRP-107, depending on which radionuclide transformation database is used (ICRP-38 or ICRP-107).	All 1,252 radionuclides in ICRP-107. Radionuclide decay based on ICRP-107 radionuclide database.	208 radionuclides, 14 "+C" radionuclides, U_nat and Th_nat. Radionuclide decay and ingrowth based on ICRP-38.
Source	Four source types: point, line, area, and volume. The sources are defined by multiple input parameters depending on the source type such as source location, area, thickness, material type, etc. In a single run, 10 sources can be input.	Settled dust on surfaces inside a room, ambient air in a room, contamination on building surfaces.	Surface contamination inside the building.
Receptor	In a single run, 10 receptors can be input. Receptor is defined by its location (in x, y, z coordinates relative to origin selected for the source and receptors), room, time fraction spent, inhalation rate, and indirect ingestion rate.	For direct external exposure from volumetric contamination on surfaces inside a room, there are three receptors: one at the center (center), one 30 cm away from the center of one wall (center wall), and one 30 cm away from two walls (corner).	Receptor is located in the center of a large, contaminated plane source in a room at 1 m height.

Table J-2 (Cont.)

Feature	RESRAD-BUILD Code	EPA BPRG Calculator	NRC DandD Code
Air concentration inside a room	The code uses the dynamic air quality mode that allows consideration of up to nine rooms inside a building with air exchange and air flow between those rooms, resuspension of deposited contamination, periodic vacuuming to remove part of deposited concentration. The air concentration inside a room is calculated in the code using multiple user input parameters in the source and air flow model (room size, air exchange rate, air flow between rooms, air release fraction, removable fraction, source lifetime, erosion rate, etc.).	User input.	The air concentration is calculated from the resuspension rate and the user-specified surface concentration.
Deposited secondary concentration on surfaces	Calculated in the code using multiple input parameters such as for air concentration inside a room.	Not required nor modeled.	Not required nor modeled.
Ingestion rate	Direct and indirect ingestion rates are specified by user. However, the direct ingestion from sources has an upper bound that depends on mass balance of the source removal and air fraction. The default indirect ingestion rate = 1.0E-04 m^2/h and the default direct ingestion rate = 0.	Ingestion occurs when hands contact contamination on a surface and then come in contact with the mouth. Transfer from surface to mouth depends on the type of surface (hard or soft). The ingestion rate is calculated from the number of times the receptor comes in contact with the contaminated surface and the surface area of the receptor's fingers. The default for indoor worker = 176.4 cm^2/day.	Calculated by the user-specified receptor's loose ingestion rate and loose fraction of contamination. The default is 1.1E-05 m^2/h.
Pathways	Direct external exposure from source, external exposure from deposited contamination on surfaces, inhalation, radon inhalation, air submersion, direct ingestion from source, and ingestion from deposited contamination on building surfaces.	Dust ingestion and direct external exposure from settled dust on surfaces, inhalation and air submersion from given ambient air concentration, direct external exposure from surface or volumetric contamination on six building surfaces.	Direct external exposure, inhalation, and secondary ingestion.

Table J-2 (Cont.)

Feature	RESRAD-BUILD Code	EPA BPRG Calculator	NRC DandD Code
Direct external exposure pathway	Two direct exposure models based on the geometrical type of sources are used. The model for the point and line contamination is a point kernel dose integral method. The model for area and volume sources is based on a semi-infinite slab source, with corrections for geometrical factors considering varying thicknesses of cover and depth, different wall materials, and location (offset) of receptors.	For settled dust, the direct external exposure pathway risk is calculated by assuming an infinite ground plane (surface source) is contaminated and receptor is located in the center of the plane at 1 m height. For 3-D exposure, the direct external pathway dose is calculated as in RESRAD code for volume and area sources using the depth and cover factor, area and material factor, and off-set factor. However, BPRG does not provide depth and cover factor, area factor, or material factor. For few receptor locations, building sizes, building material types, and fixed source thicknesses (ground plane, 1 cm, 5 cm, 15 cm, and infinite), it uses precalculated parameter values in calculating risk.	The direct external exposure pathway risk is calculated by assuming an infinite ground plane (surface source) is contaminated and receptor is located in the center of the plane at 1 m height.
External exposure from deposited material	The external exposure from the material deposited on the floor is estimated by treating the floor as an area source with the receptor located at 1 m above the center of the floor. The correction for size is applied to account for the finite dimensions of the floor.	Not considered.	Not considered.
Inhalation pathway	Inhalation pathway exposure (dose or risk) is calculated from the calculated average air concentration over the exposure duration in the code, inhalation rate, time spent indoor, and inhalation dose/risk coefficients.	Inhalation pathway risk is calculated from the ambient air concentration input in the code corrected for decay over the exposure duration, inhalation rate, and time spent indoor in the contaminated room.	Inhalation pathway dose is calculated from the calculated average air concentration in the code over the exposure duration, inhalation rate, time spent indoor, and inhalation dose coefficients.
Air submersion pathway	Air submersion pathway exposure (dose or risk) is calculated from the calculated average air concentration over the exposure duration in the code, time spent indoor, and air submersion dose/risk coefficients.	Air submersion pathway risk is calculated from the ambient air concentration input in the code corrected for decay over the exposure duration, time spent indoor in the contaminated room, and the air submersion slope factors.	Not considered.

Table J-2 (Cont.)

Feature	RESRAD-BUILD Code	EPA BPRG Calculator	NRC DandD Code
Radon inhalation pathway	Radon inhalation pathway exposure (dose or risk) is calculated from the calculated average air concentration over the exposure duration in the code. A radon diffusion model with radon parent (Ra-226, etc.) source term model is used to model radon generation and diffusion in the indoor environment.	Not considered.	Not considered.
Ingestion pathway	For direct ingestion pathway, dose/risk is calculated from the calculated average source concentration in the code over the exposure duration, ingestion rate, time spent indoor, and ingestion dose/risk coefficients. For the ingestion dose/risk calculation from deposited contamination on building surfaces, the calculated average deposited contamination on the room floor and indirect ingestion rates are used.	Ingestion pathway risk is calculated using the ingestion rate, settled dust concentration adjusted for radionuclide decay over the exposure duration and adjusted for dissipation over the exposure duration (change in dust concentration on surfaces over the exposure duration due to dissipation), if needed, exposure duration, time spent indoor, and dust ingestion slope factors.	Ingestion pathway dose is calculated from the calculated average source concentration in the code over the exposure duration, ingestion rate, time spent indoor, and ingestion dose coefficients.

J.3 RESRAD-BUILD VERSION 4 EXTERNAL EXPOSURE MODEL BENCHMARKING WITH MCNP CODE

In the RESRAD-BUILD code, two direct exposure models based on the source geometry are used. The model for area and volume sources is based on a semi-infinite slab source with corrections for geometric factors. The model for point and line contamination is a point kernel dose integral method (Appendix C).

The external exposure models in RESRAD-BUILD code Version 3 were previously benchmarked with the MCNP transport code (Kamboj et al. 2001; Yu et al. 2003). The comparisons were performed at different source-receptor configurations for Co-60, Mn-54, and Au-195. Good agreement (within 5%) was observed.

No major changes in the external exposure models are made in RESRAD-BUILD Version 4. RESRAD-BUILD Version 4.0 results are compared with MCNP code for point, line, area, and volume sources in different source receptor configurations. The results are summarized in Sections 3.1 and 3.2.

J.3.1 Point, Line, Area, and Volume Source Dose Comparison without Shielding

For comparing point, line, area, and volume source dose calculations at T = 0 years, it is assumed the indoor fraction is 1; the removable fraction is 0 in point, line, and area sources; and there is no erosion in volume sources. These assumptions will result in only the direct external pathway dose. The other parameters are kept at RESRAD-BUILD defaults except for the receptor distance and source dimensions.

The point source doses are compared at three receptor distances (15, 100, and 1,000 cm from the source) for three radionuclides: Co-60 (1.25 MeV, gamma abundance 200%), Mn-54 (836 keV, gamma abundance 100%), and Au-195 (71.6 keV, gamma abundance 110%) to cover different energy sources.

Table J-3 compares the point source average dose between RESRAD-BUILD Version 4.0 and MCNP. All results are within 7% of each other.

Table J-3 Point Source Average Dose [(mrem/yr)/pCi] Comparison between RESRAD-BUILD Version 4.0 and MCNP

Radionuclide	Receptor Distances in cm					
	15		100		1,000	
	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP
Au-195	7.19E-06	6.77E-06	1.62E-07	1.55E-07	1.94E-09	1.82E-09
Mn-54	9.00E-05	9.09E-05	2.02E-06	2.04E-06	2.00E-08	2.00E-08
Co-60	3.49E-04	3.49E-04	7.85E-06	7.83E-06	7.74E-08	7.66E-08

The line source average doses are compared at three receptor distances (10, 100, and 1,000 cm) for the same three radionuclides as were used for the point source comparison. The comparison was performed for line sources of four different lengths (1, 10, 100, and 1,000 cm). Table J-4 presents the comparison of the RESRAD-BUILD calculated results with the MCNP calculations. All results are within 7% of each other.

Table J-4 Line Source Average Dose [(mrem/yr)/(pCi/m)] Comparison between RESRAD-BUILD Version 4.0 and MCNP

	Receptor Distance in cm					
	10		100		1,000	
Radionuclide	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP
Line source length = 1 cm						
Au-195	1.62E-07	1.51E-07	1.62E-09	1.55E-09	1.94E-11	1.82E-11
Mn-54	2.02E-06	2.04E-06	2.02E-08	2.08E-08	2.00E-10	2.00E-10
Co-60	7.85E-06	7.84E-06	7.85E-08	7.82E-08	7.74E-10	7.67E-10
Line source length = 10 cm						
Au-195	1.50E-06	1.41E-06	1.61E-08	1.55E-08	1.94E-10	1.82E-10
Mn-54	1.88E-05	1.89E-05	2.02E-07	2.04E-07	2.00E-09	2.00E-09
Co-60	7.29E-05	7.28E-05	7.84E-07	7.82E-07	7.74E-09	7.67E-09
Line source length = 100 cm						
Au-195	4.43E-06	4.17E-06	1.50E-07	1.44E-07	1.94E-09	1.81E-09
Mn-54	5.56E-05	5.59E-05	1.87E-06	1.89E-06	1.99E-08	2.00E-08
Co-60	2.16E-04	2.15E-04	7.27E-06	7.26E-06	7.74E-08	7.67E-08
Line source length = 1,000 cm						
Au-195	4.98E-06	4.71E-06	4.34E-07	4.31E-06	1.78E-08	1.71E-08
Mn-54	6.28E-05	6.31E-05	5.52E-06	5.59E-06	1.84E-07	1.86E-07
Co-60	2.44E-04	2.42E-04	2.15E-05	2.14E-05	7.16E-07	7.13E-07

The area source doses are compared at three receptor distances (15, 100, and 1,000 cm) for the same three radionuclides as were used for the point source comparison. The comparison was performed for a source area of 3.2 m^2. Table J-5 presents the comparison of the RESRAD-BUILD code results with the MCNP calculations. All results are within 25% of each other; for high-energy gamma emitters (Mn-54 and Co-60), results are within 6%.

Table J-5 Area Source Average Dose [(mrem/yr)/(pCi/m^2)] Comparison between RESRAD-BUILD Version 4.0 and MCNP

	Receptor Distances in cm					
	15		100		1,000	
Radionuclide	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP
Au-195	1.43E-06	1.84E-06	2.63E-07	3.37E-07	4.57E-09	5.68E-09
Mn-54	2.32E-05	2.46E-05	4.25E-06	4.45E-06	6.05E-08	6.34E-08
Co-60	9.20E-05	9.47E-05	1.68E-05	1.71E-05	2.40E-07	2.40E-07

The volume source doses are compared at three receptor distances (15, 100, and 1,000 cm) for Au-195, Mn-54, and Co-60. The comparison was performed for a source density of 2.4 g/cm^3, an area of 3.2 m^2, and three thicknesses (1, 10, and 50 cm). Table J-6 presents the comparison of the RESRAD-BUILD code results with the MCNP calculations with agreement within 22%. The comparison includes the area and material factor, off-set factor, and depth-and-cover factor.

Table J-6 Volume Source Average Dose [(mrem/yr)/(pCi/g)] Comparison between RESRAD-BUILD Version 4.0 and MCNP

	Receptor Distances in cm					
	15		100		1,000	
Radionuclide	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP
Source thickness = 1 cm						
Au-195	3.89E-02	3.73E-02	8.51E-03	9.61E-03	1.22E-04	1.56E-04
Mn-54	5.27E-01	5.84E-01	1.01E-01	1.19E-01	1.44E-03	1.72E-03
Co-60	2.01E+00	2.23E+00	3.84E-01	4.43E-01	5.50E-03	6.31E-03
Source thickness = 10 cm						
Au-195	7.55E-02	7.75E-02	2.58E-02	2.76E-02	4.07E-04	4.88E-04
Mn-54	2578E+00	2.46E+00	7.09E-01	7.58E-01	1.11E-02	1.23E-02
Co-60	1.06E+01	1.02E+01	2.82E+00	3.00E+00	4.40E-02	4.78E-02
Source thickness = 50 cm						
Au-195	7.41E-02	7.97E-02	2.55E-02	2.82E-02	4.03E-04	4.99E-04
Mn-54	2.77E+00	2.95E+00	8.99E-01	9.99E-01	1.58E-02	1.75E-02
Co-60	1.17E+01	1.28E+01	3.76E+00	4.25E+00	6.67E-02	7.53E-02

The external exposure model was also compared with MCNP calculations for RESRAD-BUILD Version 4.0 default parameter values (except for erosion rate and air fraction [erosion = 0 and air fraction = 0] in volume source, air fraction, release rate, and source lifetime in area, line, and point sources [air fraction = 0, removable fraction = 0], and source lifetime = 36,500 d) for point, line, surface, and volume sources. The radionuclides used in this comparison were the same as before (Au-195, Mn-54, and Co-60) to cover a wide energy range. Table J-7 presents the comparison of the values from RESRAD-BUILD code output and MCNP code calculations. The results match within 3% for point sources, within 2% for line sources, within 25% for area sources, and within 6% for volume source for all radionuclides. For higher energy radionuclides, Mn-54 and Co-60, the results agree within 6%.

Table J-7 Direct External Exposure Pathway Average Dose (mrem/yr) Comparison between RESRAD-BUILD Version 4.0 and MCNP Using Default Parameters

	Point		Line		Area		Volume	
Radionuclide	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP	BUILD	MCNP
Au-195	2.71E-08	2.62E-08	1.66E-07	1.69E-07	4.51E-07	5.90E-07	3.05E-02	3.25E-02
Mn-54	3.36E-07	3.40E-07	2.11E-06	2.14E-06	7.17E-06	7.58E-06	1.14E+00	1.10E+00
Co-60	1.31E-06	1.30E-06	8.20E-06	8.20E-06	2.84E-05	2.91E-05	4.78E+00	4.59E+00

J.3.2 Co-60 and Mn-54 External Dose Comparison with and without Shielding

For higher energy radionuclides, Mn-54 and Co-60, the comparison between RESRAD-BUILD Version 4.0 and MCNP was also done for different source receptor configurations with and without (thicknesses used were 1, 5, and 15 cm) concrete shielding (density = 2.4 g/cm^3). There was no release of contaminants in the air, and the receptor spent 100% time inside the contaminated building (indoor fraction = 1). Tables J-8 and J-9 present the comparison for Co-60 and Mn-54, respectively.

For Co-60 (see Table J-8) without shielding, point and line source results were within 1% and area and volume source results were within 10%. With 1 cm concrete shielding, point and line source results were within 5% and area and volume source results were within 12%. With 5 cm concrete shielding, point and volume source results were within 11% and line and area source results were within 30%. With 15 cm concrete shielding, area and volume source results were within 33% and point source results were within 21%. For line sources, large differences were observed because of the difference in the modeling geometry. RESRAD-BUILD code assumes a constant shielding thickness of 15 cm between a line source and the receptor (Appendix C), whereas in MCNP code, a plane of 15 cm concrete shielding was assumed between the source and receptor that in effect changes the effective shielding thickness between line sources and the receptor.

For Mn-54 (see Table J-9) without shielding, point and line source results were within 1% and area and volume source results were within 10%. With 1 cm concrete shielding, point and line source results were within 7% and area and volume source results were within 12%. With 5 cm concrete shielding, point and volume source results were within 17% and line and area source results were within 32%. With 15 cm concrete shielding, area and volume source results were within 28% and point source results were within 36%. For line sources, large differences were observed because of the difference in the modeling geometry. RESRAD-BUILD code assumes a constant shielding thickness of 15 cm between a line source and the receptor (Appendix C), whereas in MCNP code, a plane of 15 cm concrete shielding was assumed between the source and receptor that in effect changes the effective shielding thickness between line sources and the receptor.

Table J-8 Direct External Exposure Pathway Average Dose (mrem/yr) Comparison for Co-60 between RESRAD-BUILD Version 4.0 and MCNP for Different Source Receptor Configurations

		RESRAD-BUILD Dose Rate (mrem/yr)			MCNP Dose Rate (mrem/yr)		
Co-60 Source	Source Strength	Receptor (0,0,30)	Receptor (0,0,100)	Receptor (0,0,400)	Receptor (0,0,30)	Receptor (0,0,100)	Receptor (0,0,400)
Without any shielding							
Point (0,0,0)	1 mCi	8.73E+04	7.85E+03	488	8.71E+04	7.83E+03	4.87E+02
Line (0,0,0), Length = 1 m	1 mCi/m	5.39E+04	7.27E+03	486	5.38E+04	7.26E+03	4.84E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	1.16E+05	6.01E+04	1.28E+04	1.18E+05	6.13E+04	1.31E+04
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	1.17E+10	8.49E+09	2.25E+09	1.15E+10	8.74E+09	2.50E+09
1 cm Concrete shield							
Point (0,0,0)	1 mCi	8.42E+04	7.57E+03	471	8.21E+04	7.47E+03	4.70E+02
Line (0,0,0), Length = 1 m	1 mCi/m	5.20E+04	7.02E+03	468	4.97E+04	6.90E+03	4.67E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	8.60E+04	4.98E+04	1.10E+04	8.34E+04	5.37E+04	1.25E+04
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	9.88E+09	7.66E+09	2.14E+09	8.97E+09	7.46E+09	2.29E+09
5 cm Concrete shield							
Point (0,0,0)	1 mCi	7.02E+04	6.30E+03	391	6.34E+04	5.87E+03	3.73E+02
Line (0,0,0), Length = 1 m	1 mCi/m	4.33E+04	5.84E+03	388	3.52E+04	5.35E+03	3.70E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	4.34E+04	3.70E+04	1.02E+04	3.37E+04	2.94E+04	9.35E+03
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	4.72E+09	4.41E+09	1.53E+09	4.43E+09	3.98E+09	1.55E+09
15 cm Concrete shield							
Point (0,0,0)	1 mCi	3.42E+04	3.07E+03	189	2.85E+04	2.54E+03	1.57E+02
Line (0,0,0), Length = 1 m	1 mCi/m	2.11E+04	2.85E+03	188	1.31E+04	2.22E+03	1.55E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	6.76E+03	6.71E+03	3.17E+03	7.76E+03	7.12E+03	3.35E+03
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	7.38E+08	7.34E+08	3.92E+08	1.08E+09	9.63E+08	4.91E+08

Table J-9 Direct External Exposure Pathway Average Dose (mrem/yr) Comparison for Mn-54 between RESRAD-BUILD Version 4.0 and MCNP for Different Source Receptor Configurations

		RESRAD-BUILD Dose Rate (mrem/yr)			MCNP Dose Rate (mrem/yr)		
Mn-54 Source	Source Strength	Receptor (0,0,30)	Receptor (0,0,100)	Receptor (0,0,400)	Receptor (0,0,30)	Receptor (0,0,100)	Receptor (0,0,400)
Without any shielding							
Point (0,0,0)	1 mCi	2.25E+04	2.02E+03	126	2.24E+04	2.01E+03	1.25E+02
Line (0,0,0), Length = 1 m	1 mCi/m	1.39E+04	1.87E+03	125	1.38E+04	1.87E+03	1.25E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	2.92E+04	1.51E+04	3.22E+03	3.05E+04	1.58E+04	3.38E+03
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	2.84E+09	2.09E+09	5.65E+08	2.72E+09	2.10E+09	6.29E+08
1 cm Concrete shield							
Point (0,0,0)	1 mCi	2.18E+04	1.96E+03	122	2.10E+04	1.92E+03	1.21E+02
Line (0,0,0), Length = 1 m	1 mCi/m	1.35E+04	1.81E+03	121	1.26E+04	1.77E+03	1.20E+02
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	2.24E+04	1.31E+04	2.88E+03	2.03E+04	1.35E+04	3.21E+03
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	2.29E+09	1.83E+09	5.25E+08	2.05E+09	1.75E+09	5.67E+08
5 cm Concrete shield							
Point (0,0,0)	1 mCi	1.81E+04	1.62E+03	100	1.55E+04	1.44E+03	9.17E+01
Line (0,0,0), Length = 1 m	1 mCi/m	1.12E+04	1.50E+03	99.9	8.45E+03	1.31E+03	9.12E+01
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	9.94E+03	8.78E+03	2.52E+03	7.67E+03	6.67E+03	2.25E+03
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	9.96E+08	9.47E+08	3.50E+08	9.34E+08	8.56E+08	3.48E+08
15 cm Concrete shield							
Point (0,0,0)	1 mCi	7.76E+03	6.96E+02	42.8	5.96E+03	5.18E+02	3.15E+01
Line (0,0,0), Length = 1 m	1 mCi/m	4.79E+03	6.45E+02	42.6	2.61E+03	4.49E+02	3.10E+01
Area (0,0,0), Length = 6 m, Width = 6 m	1 mCi/m^2	1.22E+03	1.21E+03	6.25E+02	1.41E+03	1.34E+03	6.45E+02
Volume (0,0,0), Length = 6 m, Width = 6 m, Thickness = 10 cm, Density = 2.4 g/cm^3	1 mCi/g	1.22E+08	1.22E+08	7.07E+07	1.63E+08	1.68E+08	8.67E+07

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