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User’s Manual for RESRAD-BUILD Version 3

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User's Manual for RESRAD-BUILD Version 3

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PREFACE

In 1994, a manual was released on using the RESRAD-BUILD code to analyze the radiological doses resulting from human activities at buildings contaminated with radioactive material. Since then, the manual and code have been used widely by the U.S. Department of Energy and its contractors, the U.S. Nuclear Regulatory Commission, and many other government agencies and institutions. New features, some in response to comments received from users, have been incorporated into the code to form RESRAD-BUILD Version 3. These improvements have increased RESRAD-BUILD's capabilities and flexibility and enabled users to interact with the code more easily. RESRAD-BUILD Version 3 represents the third major version of the code since it was first released in 1994.

The RESRAD-BUILD code can now perform uncertainty/probabilistic analysis with an improved probabilistic interface.[1] It uses a preprocessor and a postprocessor to perform probabilistic dose analysis.[2] It incorporates default parameter distributions (based on national average data) for the selected parameters. The code can provide analysis results as text reports, interactive output, and graphic output. The results of an uncertainty analysis can be used as a basis for determining the cost-effectiveness of obtaining additional information or data on input parameters (variables).[3]

The RESRAD-BUILD code now allows users to calculate the time-integrated dose over the exposure duration at user-specified times. The instantaneous dose over the exposure duration can be calculated by setting the time integration point to one. The other major changes in the code are the new external exposure model for volume and area sources and a new tritium model for volume sources. In addition, the RESRAD-BUILD database has been updated. It now includes inhalation and ingestion dose conversion factors from U.S. Environmental Protection Agency Federal Guidance Report No. 11 (FGR-11),[4] direct external exposure and air submersion

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[1] Yu, C., et al., 2000, *Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes,* ANL/EAD/TM-98, NUREG/CR-6697, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C., Dec.

[2] LePoire, D., et al., 2000, *Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes, User Guide,* ANL/EAD/TM-91, NUREG/CR-6692, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C., Nov.

[3] Kamboj, S., et al., 2000, *Probabilistic Dose Analysis Using Parameter Distribution Developed for RESRAD and RESRAD-BUILD Codes,* ANL/EAD/TM-89, NUREG/CR-6676, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C., July.

[4] Eckerman, K.F., et al., 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,* EPA-520/1-88-020, Federal Guidance Report No. 11, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C.

dose conversion factors from FGR-12,[5] and radionuclide half-lives from International Commission on Radiological Protection Publication 38.[6]

RESRAD-BUILD Version 3 incorporates many improvements made since the code was first released in 1994. A table for easier input and review of source/receptor shielding properties has been added. The code now has an improved 3-D display to illustrate source-receptor locations. Users can now input radionuclide activity in SI units, and the resultant dose can also be reported in SI units. The help file in the code and the table of contents of the text report have been improved and are now much easier to use and navigate. This latest version of the RESRAD-BUILD code can be run only on computers with Windows operating systems (Windows 95, 98, NT, XP, and 2000). The DOS version of RESRAD-BUILD is no longer supported. Furthermore, to take advantage of the latest computer technology, the RESRAD-BUILD FORTRAN programs are now being compiled with the FORTRAN 95 (LAHEY/FUJITSU LF95) compiler. Also, the Windows interface, which was initially developed in 16-bit Visual Basic 4.0, has been upgraded to 32-bit Visual Basic 6.0.

The RESRAD-BUILD code is part of the RESRAD family of codes, which now has its own Web site (http://www.ead.anl.gov/resrad). The site has information on updates to the codes, and users can download the most recent release of the code of interest. The site also contains information on upcoming training workshops and links to many documents relevant to application of the particular code. Users can get technical assistance via e-mail (resrad@anl.gov). User's manuals for several of the RESRAD family of codes, including RESRAD-BUILD Version 3, can also be found on the RESRAD Web site in Adobe pdf format. A CD-ROM containing the RESRAD family of codes and supporting documents is available upon request.

This manual is a user's guide for operating RESRAD-BUILD Version 3 and a reference manual on the algorithms and formulas used in RESRAD-BUILD. Because this version reflects a number of changes in the RESRAD-BUILD code, it is very different from previous versions. Many parts were added (e.g., Section 5 on verification and Appendixes G, H, I, and J on the tritium model for volume sources, calculating time-integrated doses, uncertainty analysis, and parameter descriptions). Other parts were extensively modified (e.g., the Section 4 user's guide and Appendix F on external radiation exposure). The Section 3 discussion on exposure scenarios was expanded to include default data template files for building occupancy and building renovation scenarios.

The RESRAD-BUILD code is continuously being updated and improved. Some planned improvements include risk calculations, graphic output, and addition of radionuclides. These improvements are not included in this manual. Users are encouraged to visit the RESRAD Web site for the most recent improvements to the code.

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[5] Eckerman, K.F., and J.C. Ryman, 1993, *External Exposure to Radionuclides in Air, Water, and Soil, Exposure to Dose Coefficients for General Application*, based on the 1987 Federal Radiation Protection Guidance, EPA 402-R-93-081, Federal Guidance Report No. 12, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Washington, D.C.

[6] International Commission on Radiological Protection, 1993, *Radionuclide Transformations: Energy and Intensity Emissions,* ICRP Publication 38, Annals of the ICRP, Vols. 11–13, Pergamon Press, New York, N.Y.

ACKNOWLEDGMENTS

The RESRAD-BUILD code and the user's manual were first published in November 1994. Since then, the code has undergone various modifications and enhancements, resulting in the release of Version 3. Although Version 3 includes new, improved models, many of the models used in previous releases have been retained.

Numerous individuals who contributed to the previous versions of the code and manual have not been listed as coauthors of the current manual. The authors would like to thank the following individuals for their past contributions and continued interest in the development and improvement of RESRAD-BUILD: Celso Loureiro, Lynn Jones, Inseok Baek, and Tim Klett. The authors would like to thank Tony Dvorak, Director of Argonne National Laboratory's Environmental Assessment Division, and Shih-Yew Chen, Strategic Area Manager of Risk and Waste Management for the Division, for their continued support. The authors would like to thank Don Mackenzie and the late John Russell, who made important and useful contributions to RESRAD-BUILD development. The authors would also like to thank Tin Mo and his colleagues at the U.S. Nuclear Regulatory Commission for their support for the improvement of the probabilistic modules.

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DOE FOREWORD

RESRAD-BUILD is a computer code designed to evaluate the radiation doses from RESidual RADioactivity in BUILDings. This version of RESRAD-BUILD is the third major revision of the code. The RESRAD-BUILD code was developed by Argonne National Laboratory under sponsorship of the U.S. Department of Energy (DOE) and other federal agencies.

The first version of RESRAD-BUILD was released in 1994 for a DOS computer platform. The second version was released in 1996 and used a Windows platform. Version 3 has been prepared with extensive improvements in both the computational and user modules. This version of RESRAD-BUILD supercedes the previous versions, and the sponsors believe it will be useful in demonstrating compliance with the radiation protection requirements of DOE and other federal and state agencies.

The RESRAD activities at Argonne National Laboratory are sponsored by the DOE Office of Environmental Policy and Assistance and the DOE Office of Environmental Management. Other federal agencies have made noteworthy contributions; in particular, substantial improvements in the uncertainty modules were made under the sponsorship of the U.S. Nuclear Regulatory Commission, with Dr. Tin Mo as the project manager.

RESRAD-BUILD may be used to demonstrate compliance with dose-based decommissioning requirements for structures and for evaluating radiation exposures within structures. Because of the intended regulatory use, the source code for RESRAD-BUILD is not provided without written direction by DOE. Persons wishing to obtain the source code (for scientific review, possible modification, or translation into other languages) should request the source code from the DOE sponsors with a written justification. The justification should specify in detail the intended work, the modifications under consideration, the use of the code output, and the use of any new code segments. This degree of control over the source code is considered necessary by DOE to control the configuration of RESRAD-BUILD and to ensure compliance with regulatory requirements.

NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

AMAD	activity median aerodynamic diameter
ANS	American Nuclear Society
AP	anterior-posterior
ARF	airborne release fraction
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BLS	Bureau of Labor Statistics
BNL	Brookhaven National Laboratory
CDF	cumulative distribution function
CEDE	committed effective dose equivalent
CG	correlated/uncorrelated grouping
DCF	dose conversion factor
DOE	U.S. Department of Energy
EF	error factor
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
GI	gastrointestinal
G-P	geometric progression
HT	tritium gas
HTO	tritiated water (tritium oxide)
HVAC	heating, ventilation, and air-conditioning
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISO	International Organization for Standardization
LHS	Latin hypercube sampling
MCNP	Monte Carlo N-particle
NAHB	National Association of Home Builders
NBS	National Bureau of Standards
NCDC	National Climatic Data Center
NRC	U.S. Nuclear Regulatory Commission
PA	posterior-anterior
PCC	partial correlation coefficient
pdf	probability density function
PFT	perfluorocarbon tracer
pmf	probability mass function
PRCC	partial rank correlation coefficient
RAM	random access memory

R_f	resuspension factor
RF	respirable fraction
RG	random grouping
RH	relative humidity
SF_6	sulfur hexafluoride
SRC	standardized partial regression coefficient
SRRC	standardized partial rank regression coefficient
SRS	simple random sampling
TEDE	total effective dose equivalent
3-D	three-dimensional

UNITS OF MEASURE

atm	atmosphere(s)
Bq	becquerel(s)
°C	degree(s) Celsius
cm	centimeter(s)
cm^2	square centimeter(s)
cm^3	cubic centimeter(s)
Ci	curie(s)
d	day(s)
°F	degree(s) Fahrenheit
ft	foot (feet)
ft^2	square foot (feet)
g	gram(s)
h	hour(s)
in.	inch(es)
K	kelvin(s)
kg	kilogram(s)
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
MB	megabyte(s)
MeV	megaelectron volt(s)
mg	milligram(s)
min	minute(s)
mol	mole(s)
mrem	millirem(s)
MW	molecular weight
pCi	picocurie(s)
s	second(s)
WL	working level(s)
WLM	working level month(s)
yr	year(s)
µg	microgram(s)
µm	micrometer(s)

USER'S MANUAL FOR RESRAD-BUILD VERSION 3

by

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ABSTRACT

The RESRAD-BUILD computer code is a pathway analysis model designed to evaluate the potential radiological dose incurred by an individual who works or lives in a building contaminated with radioactive material. The transport of radioactive material within the building from one compartment to another is calculated with an indoor air quality model. The air quality model considers the transport of radioactive dust particulates and radon progeny due to air exchange, deposition and resuspension, and radioactive decay and ingrowth. A single run of the RESRAD-BUILD code can model a building with up to three compartments, four source geometries (point, line, area, and volume), 10 distinct source locations, and 10 receptor locations. The volume source can be composed of up to five layers of different materials, with each layer being homogeneous and isotropic. A shielding material can be specified between each source-receptor pair for external gamma dose calculations. The user can select shielding material from eight different material types. Seven exposure pathways are considered in the RESRAD-BUILD code: (1) external exposure directly from the source, (2) external exposure to materials deposited on the floor, (3) external exposure due to air submersion, (4) inhalation of airborne radioactive particulates, (5) inhalation of aerosol indoor radon progeny and tritiated water vapor, (6) inadvertent ingestion of radioactive material directly from the source, and (7) ingestion of materials deposited on the surfaces of the building compartments. Various exposure scenarios may be modeled with the RESRAD-BUILD code. These include, but are not limited to, office worker, renovation worker, decontamination worker, building visitor, and residency scenarios. Both deterministic and probabilistic dose analyses can be performed with RESRAD-BUILD, and the results can be shown in both text and graphic reports.

1 INTRODUCTION

Argonne National Laboratory has developed the computer code RESRAD for the U.S. Department of Energy (DOE) to evaluate residual radioactive material in soil (Yu et al. 1993, 2001). The RESRAD code implements the DOE requirements described in Chapter 4 of DOE Order 5400.5 (DOE 1990). Many sites that are contaminated with radioactive material in soil also have contamination inside the buildings on the site. DOE Order 5400.5 provides generic surface contamination guidelines that are applicable to building structures and equipment. Those generic contamination guidelines, in general, are not dose-based. Argonne National Laboratory, sponsored by the DOE, has developed a methodology for assessing radiological doses resulting from the reuse of surface-contaminated material and equipment (Cheng et al. 2000). This methodology has been coded in a computer program called RESRAD-RECYCLE. To evaluate indoor building surface contamination, a detailed modeling of the release mechanisms and transport of contaminants in the indoor environment is needed. Such modeling would be especially useful because buildings (like soil) vary from site to site; the building structural materials may be different; the size and air exchange rate of the buildings and rooms within them may be different; and the contamination inside the buildings may vary in size, thickness, and shape. The RESRAD-BUILD computer code was developed on the basis of these factors, and it considers all the potential exposure pathways to an individual in a contaminated building.

The RESRAD-BUILD computer code is a pathway analysis model developed to evaluate the potential radiological dose incurred by an individual who works or lives in a building contaminated with radioactive material. The radioactive material in the building structure can be released into the indoor air by mechanisms such as diffusion (radon gas and tritiated water), mechanical removal (decontamination activities), or erosion (removable surface contamination). The transport of radioactive material within the building from one compartment to another is calculated with an indoor air quality model (see Appendix A). The air quality model evaluates the transport of radioactive dust particulates and radon progeny due to (1) air exchange between compartments and with outdoor air, (2) the deposition and resuspension of particulates, and (3) radioactive decay and ingrowth. RESRAD-BUILD can model up to three compartments in a building, thereby making it possible to evaluate situations ranging from a one-room warehouse to a three-story house, for example.

The design of RESRAD-BUILD is similar to that of the RESRAD code: the user can construct the exposure scenario by adjusting the input parameters. Typical building exposure scenarios include long-term occupancy (resident and office worker) and short-term occupancy (renovation worker and visitor). The long-term occupancy scenarios are usually low release scenarios, whereas short-term occupancy scenarios may involve a high release of contaminants in a short time period. Up to 10 receptor locations and 10 distinct source locations can be input into the RESRAD-BUILD code to calculate dose in a single run of the code. The calculated dose can be the total (individual) dose to a single receptor spending time at various locations or the total (collective) dose to a workforce decontaminating the building. If a building is demolished, the RESRAD computer code may be used to evaluate the potential dose from the buried material.

The RESRAD-BUILD code considers seven exposure pathways: (1) external exposure directly from the source, (2) external exposure to materials deposited on the floor, (3) external exposure due to air submersion, (4) inhalation of airborne radioactive particulates, (5) inhalation of aerosol indoor radon progeny (in the case of the presence of radon predecessors) and tritiated water vapor, (6) inadvertent ingestion of radioactive material directly from the source, and (7) ingestion of materials deposited on the surfaces of the building compartments. A detailed discussion of exposure scenarios and pathways is presented in Section 3.

The RESRAD-BUILD code can compute the attenuation due to a shielding material between each source-receptor combination when calculating the external dose. The user can select the shielding material from eight material types and input the thickness and density of the shielding material. The user may also define the source as a point, line, area, or volume source. Volume sources can be composed of up to five layers of different materials, with each layer being homogeneous and isotropic.

The radionuclides included in the RESRAD-BUILD code are similar to those included in the RESRAD code. Currently, the RESRAD-BUILD database contains 67 radionuclides, and additional radionuclides are being added. All these radionuclides have a half-life of six months or longer, and they are referred to as principal radionuclides. It is assumed that the short-lived decay products with half-lives of six months or less, referred to as the associated radionuclides, are in secular equilibrium with their parent (principal) radionuclides. For the 67 principal radionuclides in the current RESRAD-BUILD database, there are 53 associated radionuclides. Therefore, a total of 120 radionuclides are available in RESRAD-BUILD Version 3. A detailed list of these radionuclides can be found in Table 3.1 of the RESRAD User’s Manual (Yu et al. 2001).

The information presented in this manual is organized as follows:

- Descriptions of buildings, sources of contamination, and receptors exposed to radiation — Section 2;
- Exposure pathways and scenarios for building contamination — Section 3;
- Description of the RESRAD-BUILD code and instructions for its use — Section 4;
- Verification of the RESRAD-BUILD code — Section 5;
- Models, formulas, and the database used in RESRAD-BUILD code — Appendixes A through H;
- Uncertainty analysis — Appendix I; and
- Detailed discussion of parameters used in the RESRAD-BUILD code — Appendix J.

2 DESCRIPTIONS 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 surface of the floors, walls, or ceiling; (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 can model up to three 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 on the basis of the user input for shielding material type, thickness, and density. Internal (inhalation and ingestion) exposures are calculated on the basis of 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 subsections.

2.1 BUILDING DESCRIPTION

In the RESRAD-BUILD model, the building is conceptualized as a structure composed of up to three compartments. It can be a one-room warehouse, a two-room house or apartment, a three-room ranch house, a three-story office building, or a two-story house with a basement. Air exchange is assumed between compartments 1 and 2 and compartments 2 and 3 but not between compartments 1 and 3. All compartments can exchange air with the outdoor atmosphere. It is also possible to set air exchange between a compartment and the outdoor atmosphere to zero, for example in a case of 2-story house with a basement when there is no air exchange between the basement and the outdoors. 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 A.

Typical building geometries that can be modeled by the RESRAD-BUILD code are illustrated in Figure 2.1. A coordinate system is used in RESRAD-BUILD to define the location of the sources and receptor points inside the building. The origin and axes of the coordinate system can be at any location and 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 compartment (see Figure 2.2); the y-axis being perpendicular into the building; and the z-axis measuring the vertical distance and coinciding with the left edge of the building.

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

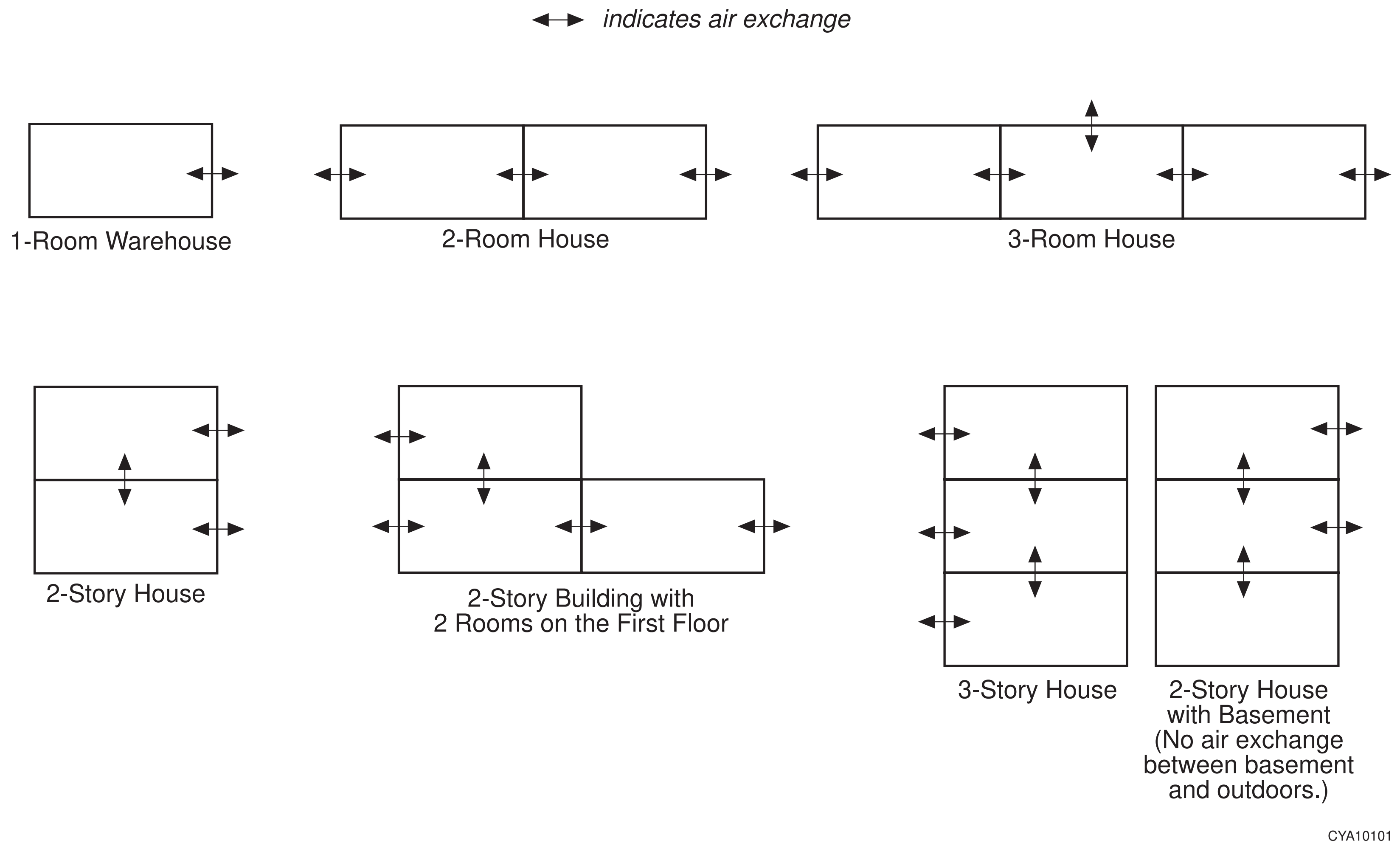


FIGURE 2.1 Vertical View of Possible Building Geometries for the RESRAD-BUILD Code

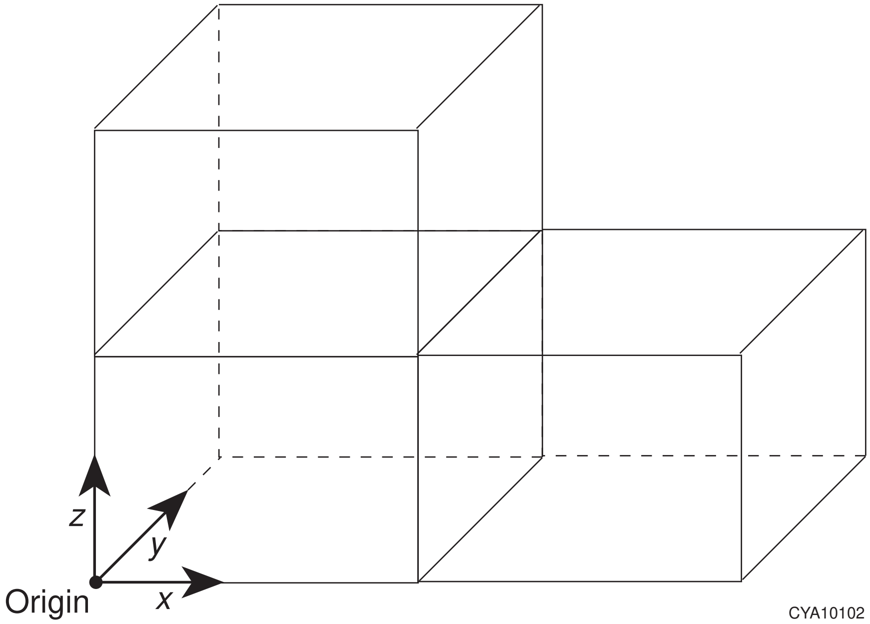


FIGURE 2.2 Example of a Coordinate System Used in the RESRAD-BUILD Code

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 DESCRIPTIONS

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 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, according to the system of coordinates used for the building compartments (see Figure 2.2). The number of different radionuclides and their initial concentrations are also defined for each source. Depending on the type of the source, two other geometric parameters may also be defined: the area/length and the direction of the source. For either a volume or a surface source, the area is defined as the surface area of the source facing the open air; the area is assumed to be circular. 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, will 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 the 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 wall in the building, contaminated with radioactive materials, is an example of a possible volume source. The volume source could be located entirely within one compartment, such as in an external wall, or it could be located at the boundaries of the compartment, such as in the floor/ceiling or in the wall separating two compartments. If the volume source is located at the boundary between two compartments, it could have two faces, one exposed to the open air of each compartment. In this case, the volume source could release radon and tritiated water to both compartments but release contaminated particulates to the primary side only. Currently, the releases of tritiated water are estimated for the primary side only. 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 effective diffusion coefficient, radon emanation fraction, erosion rate (of the surface closest to the origin), and concentration of radioactive contaminants. The definition of a volume source must also identify to which compartments the faces of the source are exposed. Finally, the rate of inadvertent ingestion of loose materials directly from the source must be defined.

Definition of a surface source is considered in 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 removable fraction, a time for source removal (source lifetime), a release fraction of material to the indoor air (air release fraction), and a 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. Parameters used to characterize the line source are similar to those for the area 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. Parameters used to characterize point sources are similar to those for the area and line sources. The unit for point sources is pCi or Bq.

2.3 RECEPTOR DESCRIPTIONS

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 DESCRIPTIONS 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, conditions, 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 and 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 amount and rate of contaminants released into the air and selects appropriate pathways, RESRAD-BUILD can model all scenarios. Input template files for the building occupancy and building renovation scenarios 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 computer code (Yu et al. 2001) 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

The exposure pathways considered include external and internal exposure. Figure 3.1 illustrates all the pathways considered in the RESRAD-BUILD code:

1. External exposure to penetrating radiation emitted directly from the source,

2. External exposure to penetrating radiation emitted from radioactive particulates deposited on the floors of the compartments,

3. External exposure to penetrating radiation due to submersion in airborne radioactive particulates,

4. Inhalation of airborne radioactive particulates,

5. Inhalation of aerosol indoor radon decay products and tritiated water vapor,

6. Inadvertent ingestion of radioactive material contained in removable material directly from the source, and

7. Inadvertent ingestion of airborne radioactive particulates deposited on the surfaces of the building.

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. In RESRAD-BUILD, the external radiation doses are evaluated as the effective dose equivalent, and the internal exposure is evaluated as the committed effective dose equivalent (CEDE). The total radiation dose, which is the sum of the external and internal doses, is expressed as the total effective dose equivalent (TEDE). The DCFs used for inhalation, ingestion, and external exposures are discussed in detail in Appendixes D, E, and F, respectively.

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 conversion factor by 50%.

3.3 INPUT DATA TEMPLATES

For both the building occupancy and building renovation scenarios, the external, inhalation, ingestion, and air submersion dose conversion factors are radionuclide specific. The values are taken from the Federal Guidance Reports (FGR) 11 and 12 (Eckerman et al. 1988;

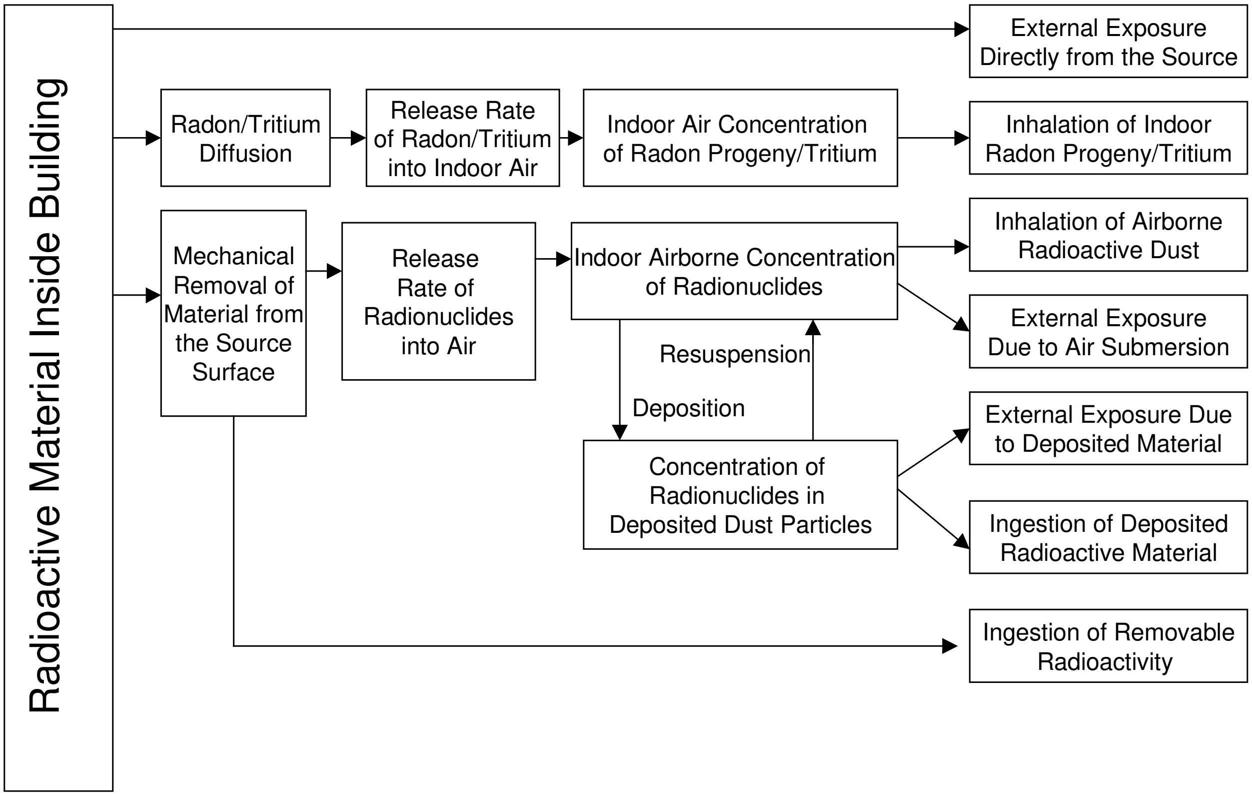


FIGURE 3.1 Exposure Pathways Incorporated into the RESRAD-BUILD Code

Eckerman and Ryman 1993). The dose is calculated for one receptor only. The receptor is at the center of the floor at a height of 1 m. The critical group receptor occupies a room with contaminated sources. For a site-specific analysis, the total number of sources, source types, source locations, room area, and room height should be site specific. Table 3.1 lists the key parameters used in the building occupancy and building renovation scenarios. Only those parameters that would be different are listed, the other parameters are site specific or are kept at RESRAD-BUILD defaults. It is assumed that for the building occupancy scenario, contamination is only on the surface, while for the renovation scenario, contamination is volumetric. Detailed descriptions of parameters and their distributions are given in Appendix J. The technical basis for calculating radiation doses for the building occupancy scenario and the related parameter distributions are provided in Biwer et al. (2002).

TABLE 3.1 Key Parameters Used in the Building Occupancy and Building Renovation Scenarios

		Parameter Values		
Parameter	Unit	Building Occupancy[a]	Building Renovation[b]	Remarks
Exposure duration	days (d)	365.25	179.00	To match the occupancy period of 365.25 days in NUREG/ CR-5512 building occupancy scenario (Beyeler et al. 1999) and renovation period of 179 days in NUREG/CR-5512 building renovation scenario (Wernig et al. 1999).
Indoor fraction	–[c]	0.267	0.351	To match the 97.5 d/yr time in building in NUREG/CR-5512 building occupancy scenario (Beyeler et al. 1999) and 62.83 days spent in the building during renovation period in NUREG/CR-5512 building renovation scenario (Wernig et al. 1999).
Receptor location	m	0, 0, 1	0, 0, 1	At 1-m from the center of the source.
Receptor inhalation rate	m^3/d	33.6	38.4	For building occupancy scenario it matches with 1.4 m^3/h breathing rates in NUREG/CR-5512 (Beyeler et al. 1999) and for building renovation scenario it matches with 1.6 m^3/h breathing rate of moderate activity given in the EPA Exposure Factor Handbook (EPA 1997).
Receptor indirect ingestion rate	m^2/h	1.12×10^{-4}	0	Value for the building occupancy scenario is the mean value from the distribution and for the building renovation scenario it is assumed the ingestion is only from the direct contact with the source.
Source type	–	Area	Volume	For building occupancy scenario it is assumed that contamination is only on the surfaces, whereas for the building renovation scenario contamination is volumetric.

TABLE 3.1 (Cont.)

		Parameter Values		
Parameter	Unit	Building Occupancy[a]	Building Renovation[b]	Remarks
Direct ingestion rate	1/h (area)g/h (volume)	3.06×10^{-6}	0.052	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). The effective transfer rate from NUREG/CR-5512 building renovation scenario for ingestion of loose dust to the hands and mouth during building renovation (Wernig et al. 1999).
Air release fraction	–	0.357	0.1	For the building occupancy scenario, it is the mean value from the parameter distribution (Appendix J). For the building renovation scenario, a smaller fraction is respirable.
Removable fraction	–	0.1	NR[d]	10% of the contamination is removable (NUREG/CR-5512 building occupancy scenario default). The parameter is not required for the volume source.
Time for source removal or source lifetime	d	10,000	NR	Value for the building occupancy scenario is the most likely value from the parameter distribution (Appendix J). The parameter is not required for the volume source.
Source erosion rate	cm/d	NR	4.1×10^{-4}	For the building renovation scenario, it is assumed that the total source thickness of 15 cm can be removed in 100 years of building life.

[a] Parameter values used in the building occupancy scenario.

[b] Parameter values used in the building renovation scenario.

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

[d] NR = parameter not required for the analysis.

4 USER'S GUIDE

The RESRAD-BUILD computer code is designed to assess the radiological doses to individuals who live or work in a building contaminated with radioactive material. The conceptual model, with its underlying assumptions, and descriptions of the building, sources, and receptors are presented in Section 2. Section 3 describes exposure scenarios and pathways. A more specific and detailed description of the model used in RESRAD-BUILD is presented in the appendixes. This section describes the use of RESRAD-BUILD as follows:

- Section 4.1, Installation: Lists requirements and installation procedures for various distribution media.
- Section 4.2, Navigation and File Management: Describes how to move around the interface to accomplish tasks and how to save input and output results.
- Section 4.3, Input Windows: Provides a closer look at the parameters on the input windows.
- Section 4.4, Results Windows: Discusses how to find results in the textual and graphical output.

4.1 INSTALLATION

Requirements for installation are as follows:

- Windows 95, 98, NT, XP, 2000, or later versions;
- Pentium-compatible processor;
- 16 MB of random access memory (RAM); and
- 16 MB of disk space.
- A printer driver must be installed, although a physical printer need not be attached.

To install from CD-ROM:

- Insert the CD-ROM into the CD-ROM drive.
- Click Install Product.
- Click Install RESRAD-BUILD.

- Enter the information requested by the standard installation program.
- After installation, a new RESRAD-BUILD icon will be placed in the RESRAD group. Double-clicking on this icon will start RESRAD-BUILD.

To install from the Web site:

- Register at the RESRAD Web site: web.ead.anl.gov/resrad/register.
- Download the latest RESRAD-BUILD self-extracting executable to your computer.
- Run this executable.
- Enter the information requested by the standard installation program.
- After installation, a new RESRAD-BUILD icon will be placed in the RESRAD group. Double-clicking on this icon will start RESRAD-BUILD.

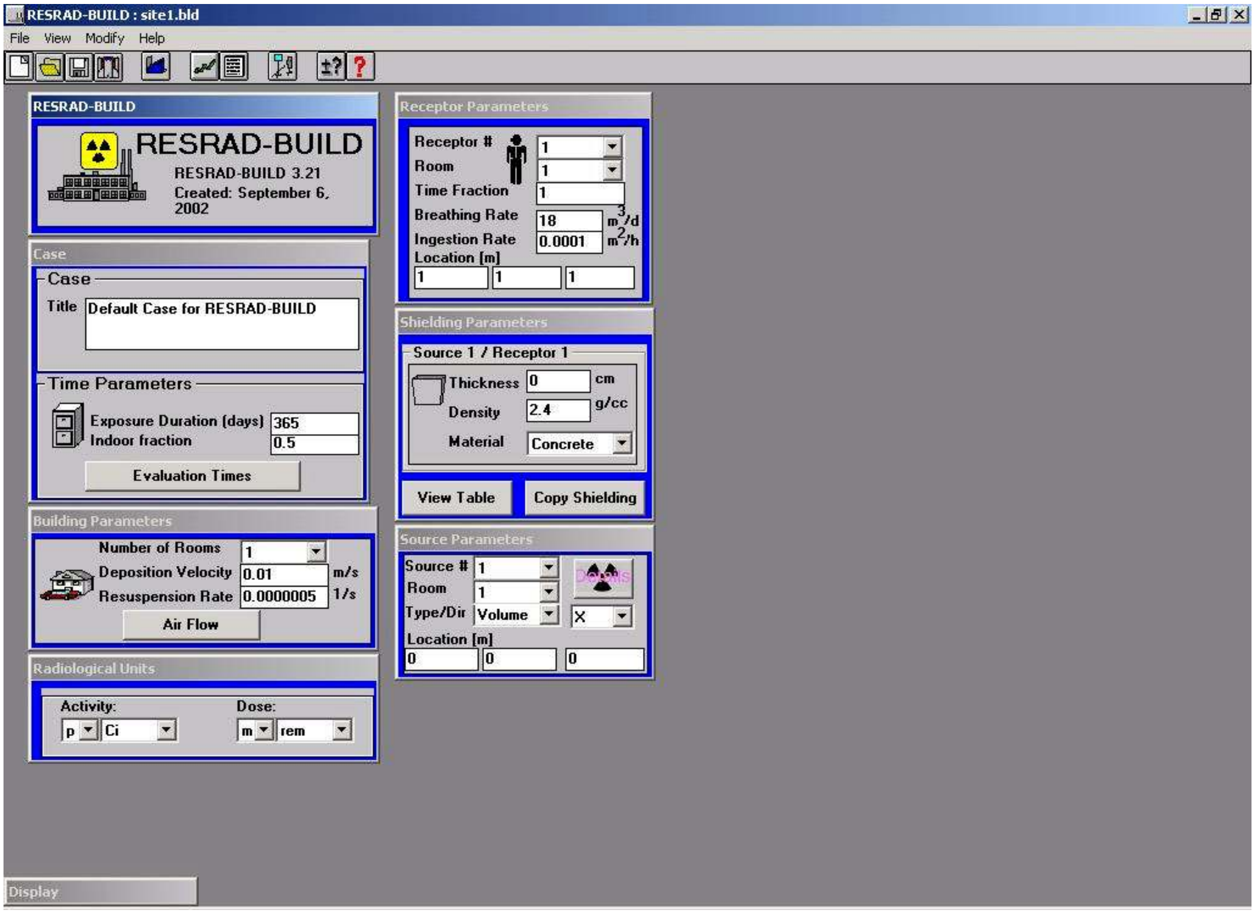
To uninstall RESRAD-BUILD:

- Click on Start.
- Click on Control Panel.
- Click on Add/Remove Programs.
- Click on RESRAD-BUILD 3.X for Windows.
- Click on Change/Remove.
- Complete uninstall process.

4.2 NAVIGATION AND FILE MANAGEMENT

The main window that appears when RESRAD-BUILD is started is shown in Figure 4.1. This window contains six input “subwindows”: Case, Building Parameters, Radiological Units, Receptor Parameters, Shielding Parameters, and Source Parameters. These six windows show some of the major input parameters necessary for RESRAD-BUILD. Three of the windows (Case, Building, and Source Parameters) contain buttons to access more detailed input windows. The Shielding Parameters window contains buttons to facilitate specification of multiple shields.

The main window contains a menu and toolbar. The File menu option contains the standard functions for file management, which pertain to the input file only. The output files are



RESRAD-BUILD : site1.bld

RESRAD-BUILD
RESRAD-BUILD 3.21
Created: September 6, 2002

Case
Title: Default Case for RESRAD-BUILD

Time Parameters
Exposure Duration (days): 365
Indoor fraction: 0.5

Number of Rooms: 1
Deposition Velocity: 0.01 m/s
Resuspension Rate: 0.0000005 1/s

Activity: p Ci
Dose: m rem

Receptor #: 1
Room: 1
Time Fraction: 1
Breathing Rate: 18 m^3/d
Ingestion Rate: 0.0001 m^2/h
Location [m]: 1 1 1

Source 1 / Receptor 1
Thickness: 0 cm
Density: 2.4 g/cc
Material: Concrete

Source #: 1
Room: 1
Type/Dir: Volume X
Location [m]: 0 0 0

FIGURE 4.1 Main Menu

saved under a standard name for each run and are automatically overwritten unless they are explicitly saved by using the Save All command in the Output Report Viewer. The File menu also includes a Run option, which starts the calculations after all the parameters have been specified. These functions are also available by activating the first four toolbar buttons.

Users can also open previously saved input files with the File/Open command. The RESRAD-BULD input files have a .BLD file extension by default. To share files, for deterministic cases, the .BLD file is all that is required. For probabilistic cases, an additional file with an .LHS file extension is automatically saved whenever the .BLD file is saved.

The View menu option allows the user to toggle the visibility of certain windows, including the output windows, graphic output windows, three-dimensional (3-D) display, and uncertainty window. These functions are also available by activating the next four toolbar buttons.

The Modify menu option allows the user to add and delete receptors and sources. Shortcut keys are defined for these functions, but no toolbar buttons are defined.

Context-specific help can be viewed by clicking on the Help menu or the last toolbar button on the right, or by pressing the F2 key while highlighting an input textbox (Figure 4.1).

Template files can also be saved with a .TEM extension. Template files are useful when saving a particular scenario class, such as a building renovation scenario. Two template files for building occupancy and building renovation scenarios are distributed with the RESRAD-BUILD code.

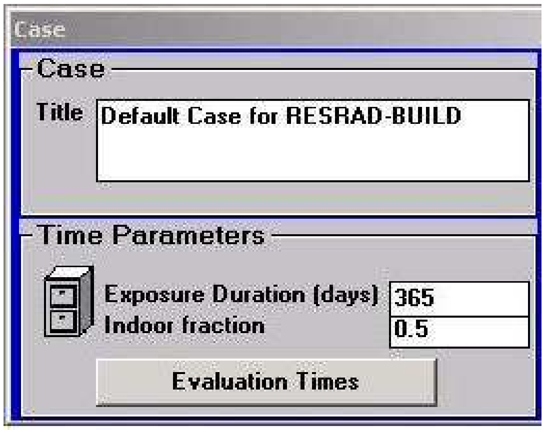
4.3 INPUT WINDOWS

4.3.1 Case Window

The Case Window (Figure 4.2) allows for a user-specified title that is placed at the top of all output report pages. Two of the three exposure time parameters appear in the Case window. Exposure Duration is the period of time over which the exposure takes place. The dose will be integrated over this time period. Discussion on the integrated dose is provided in Appendix H. Indoor fraction specifies the fraction of the exposure duration that a receptor is inside the building. The third time parameter, Time Fraction, appears in the Receptor Parameters window (Figure 4.8, which appears later in Section 4.3.3). This allows receptor-specific time fractions to be entered. The time a receptor spends at a given location is the product of these three exposure time parameters.

The total time spent on site is specified in days. The calculated radiological dose represents the total dose received during the exposure time. RESRAD-BUILD also calculates a dose rate in terms of dose per year.

RESRAD-BUILD follows the decay, ingrowth, and erosion of the contaminated material over time. The user can select up to 10 times to be evaluated. The model estimates doses for the



Title: Default Case for RESRAD-BUILD

Exposure Duration (days): 365

Indoor fraction: 0.5

FIGURE 4.2 Case Window

user-specified scenario for each time by calculating the time-integrated dose of the source starting from the specified evaluation time for the exposure duration. This allows the user to determine the estimated dose at the initial characterization and at later times (e.g., at loss of institutional control or expected demise of the building).

By pressing the Evaluation Times button, the user can specify the times in the Evaluation Times window (Figure 4.3) by either entering the times in the text boxes or by moving the clock icons. The estimate for the initial time, time zero, is automatically included. The user can select either 1, 2, 3, 5, 9, 17, 33, 65, 129, or 257 as the number of points to calculate the time-integrated dose. If the user selects 1, the instantaneous dose at the user-specified time is calculated. The use of integration points is further discussed in Appendix H.

4.3.2 Building Parameters

The second input form in the modify data series represents the characteristics of the building (Figure 4.4). The conceptual building model consists of one to three rooms. The user must enter the area and the ceiling height of each room. These parameters are used in the air quality model. To solve the air quality model, the user must enter the average building air-exchange rate for the one-room model. For the two- and three-room models, the user must enter additional parameters for each additional room: the outdoor inflow rates for the rooms, the flow between adjacent rooms 1 and 2, and the flow between adjacent rooms 2 and 3. It is assumed that no direct airflow occurs between rooms 1 and 3. To solve the deposition model, a deposition velocity and resuspension rate are required, which are assumed to be the same in each room.

4.3.2.1 Room Details for One-Room Model

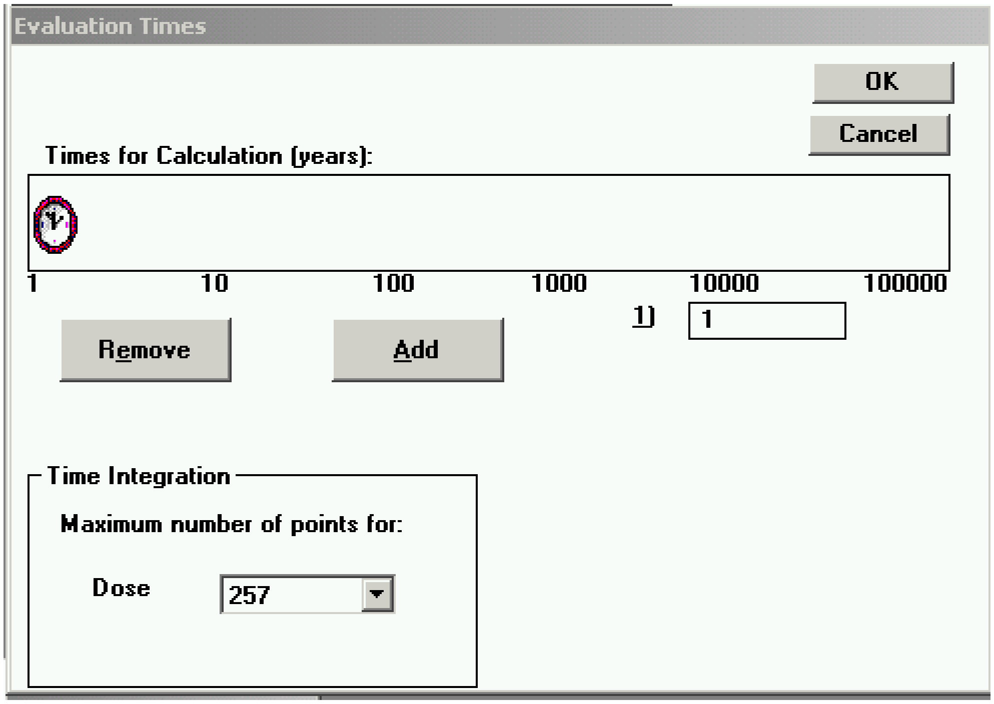
For the one-room model (Figure 4.5), the only airflow parameter necessary is the total air exchange rate.

4.3.2.2 Room Details for Two-Room Model

For the two-room model (Figure 4.6) the airflow parameters necessary are the outdoor inflow in both rooms and the flow between the two rooms. The full airflow then can be solved if the parameters entered satisfy certain conditions that guarantee a positive exchange of air between the rooms. These conditions are discussed in the air quality model in Appendix A.

4.3.2.3 Room Details for Three-Room Model

For a three-room model (Figure 4.7), the airflow parameters necessary are the outdoor inflow in all rooms and the flow between the adjacent rooms. It is assumed that there is no direct



Times for Calculation (years):

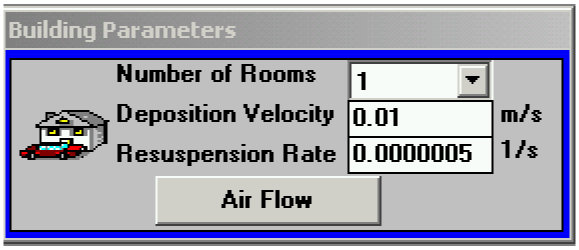
1) 1

Time Integration

Maximum number of points for:

Dose 257

FIGURE 4.3 Evaluation Times Window

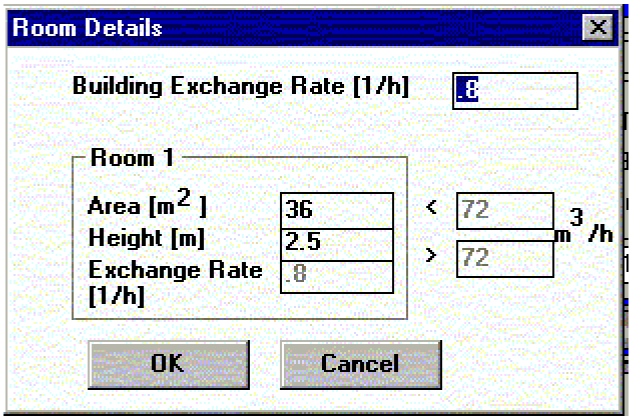


Number of Rooms 1

Deposition Velocity 0.01 m/s

Resuspension Rate 0.0000005 1/s

FIGURE 4.4 Building Parameters Window



Building Exchange Rate [1/h] .8

Room 1

Area [m^2] 36

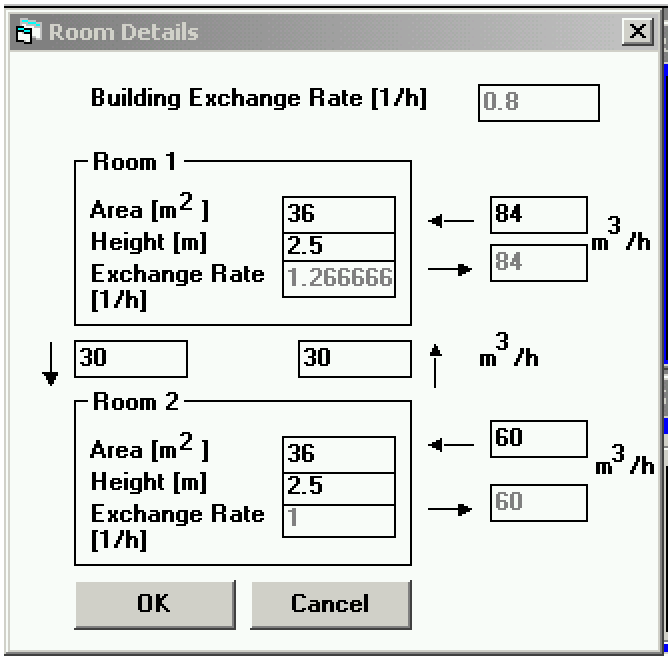
Height [m] 2.5

Exchange Rate [1/h] .8

< 72 m^3/h

> 72

FIGURE 4.5 Room Details for One-Room Model



Room Details

Building Exchange Rate [1/h] 0.8

Room 1

Area [m^2] 36

Height [m] 2.5

Exchange Rate [1/h] 1.266666

84 m^3/h

84

30 30 m^3/h

Room 2

Area [m^2] 36

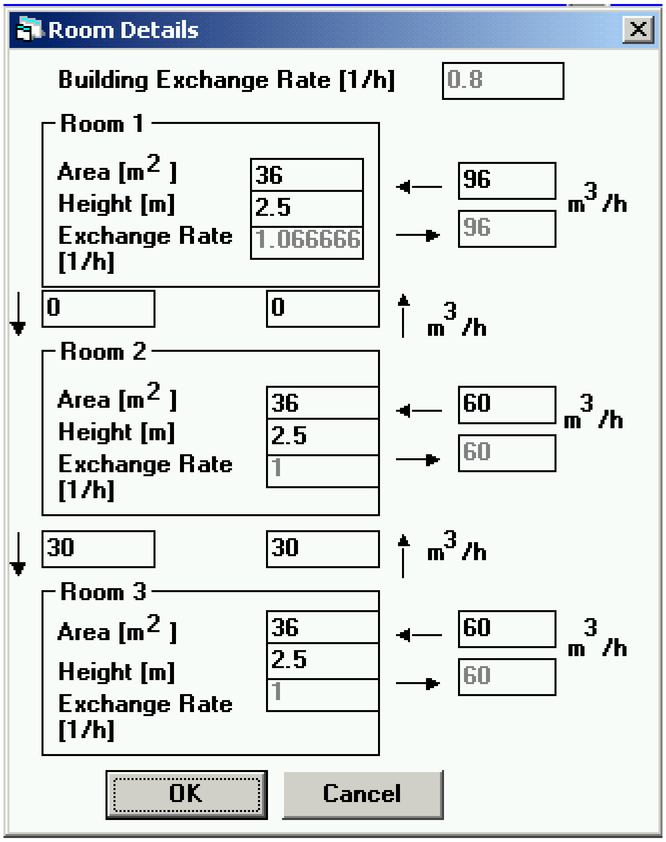
Height [m] 2.5

Exchange Rate [1/h] 1

60 m^3/h

60

FIGURE 4.6 Room Details for Two-Room Model



Room Details

Building Exchange Rate [1/h] 0.8

Room 1

Area [m^2] 36

Height [m] 2.5

Exchange Rate [1/h] 1.066666

96 m^3/h

96

0 0 m^3/h

Room 2

Area [m^2] 36

Height [m] 2.5

Exchange Rate [1/h] 1

60 m^3/h

60

30 30 m^3/h

Room 3

Area [m^2] 36

Height [m] 2.5

Exchange Rate [1/h] 1

60 m^3/h

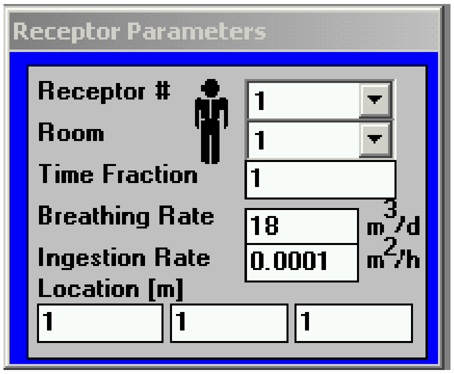
60

FIGURE 4.7 Room Details for Three-Room Model inflow between room 1 and room 3. The full airflow then can be solved if the parameters entered satisfy certain conditions that guarantee a positive exchange of air between the rooms. These conditions are discussed in the air quality model in Appendix A.

4.3.3 Receptor Parameters

The Receptor Parameters window (Figure 4.8) allows the user to specify the exposure characteristics of an individual. Although multiple receptors can be specified, the Receptor Parameters window shows input only for the individual specified by the Receptor #. Multiple receptors could be interpreted as many different individuals in a room or as one individual who spends time at many different locations. The total time an individual spends at a particular location is the product of the exposure duration, indoor fraction, and the time fraction. Each receptor point is specified by the room, location, and fraction of the time that an individual spends at each location. The ingestion rate applies to the ingestion pathway of incidental dust ingestion. The breathing rate must also be specified.

The location of the receptor is the absolute coordinate of the receptor midpoint location according to some origin chosen by the user. The same reference origin is used for all receptors and sources. For example, the receptor location should be 1 m above the absolute location on the floor where the receptor is standing. This information is important for the direct external exposure pathway only. The other pathways only require the room locations of the receptor and the source.



Receptor # 1
Room 1
Time Fraction 1
Breathing Rate 18 m^3/d
Ingestion Rate 0.0001 m^2/h
Location [m] 1 1 1

FIGURE 4.8 Receptor Parameters Window

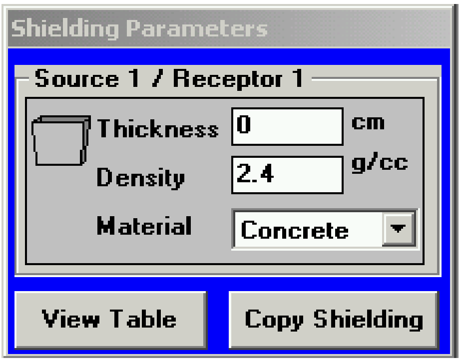
4.3.4 Shielding Parameters

Although the locations of the source and receptor points are known, the external pathway also requires information about the shielding between them. This information is gathered in the Shielding Parameters window (Figure 4.9). The RESRAD-BUILD model is simplified so that the user specifies just one average shield between each source-receptor point pair. This shielding is characterized by a material type, thickness, and density. The possible material types include concrete, water, aluminum, iron, copper, tungsten, lead, and uranium. The View Table button on this window opens a screen that allows the user to view and modify the shielding between each receptor and source (Figure 4.10). The Shielding Parameters window always displays the shielding parameters for the receptor and source that are being viewed in their respective windows. The Copy Shielding button in this window opens a screen that allows the user to copy the current shielding properties of a receptor or a source to multiple receptors and sources (Figure 4.11).

4.3.5 Source Parameters

The Source Parameters window collects data on the source type and location (Figure 4.12). The location of the source includes the room and the coordinates of the center point of the source. The location of the source center point is the absolute coordinate according to some origin chosen by the user. This reference origin must be used to specify the receptor locations also. This information is important for the direct external-exposure pathway only. The other pathways require only the room location of the receptor and the source.

The source details are specified in one of the secondary windows (input forms) by pressing the button with the radiation symbol in the main menu. The secondary forms (Figures 4.13 through 4.16) request information about radon release (if applicable), size, removable fraction, air release fraction, and radionuclide contamination of the source. For external dose calculations, the volume and area sources are assumed to be circular. For nonvolume sources with a radon source present, the radon release fraction is required.



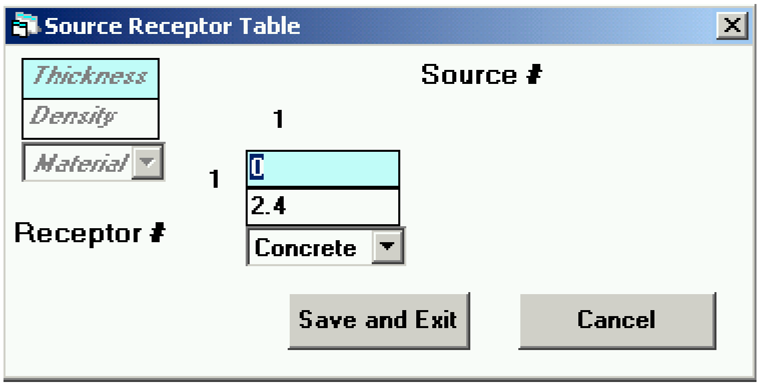
Source 1 / Receptor 1

Thickness: 0 cm

Density: 2.4 g/cc

Material: Concrete

FIGURE 4.9 Shielding Parameters Window

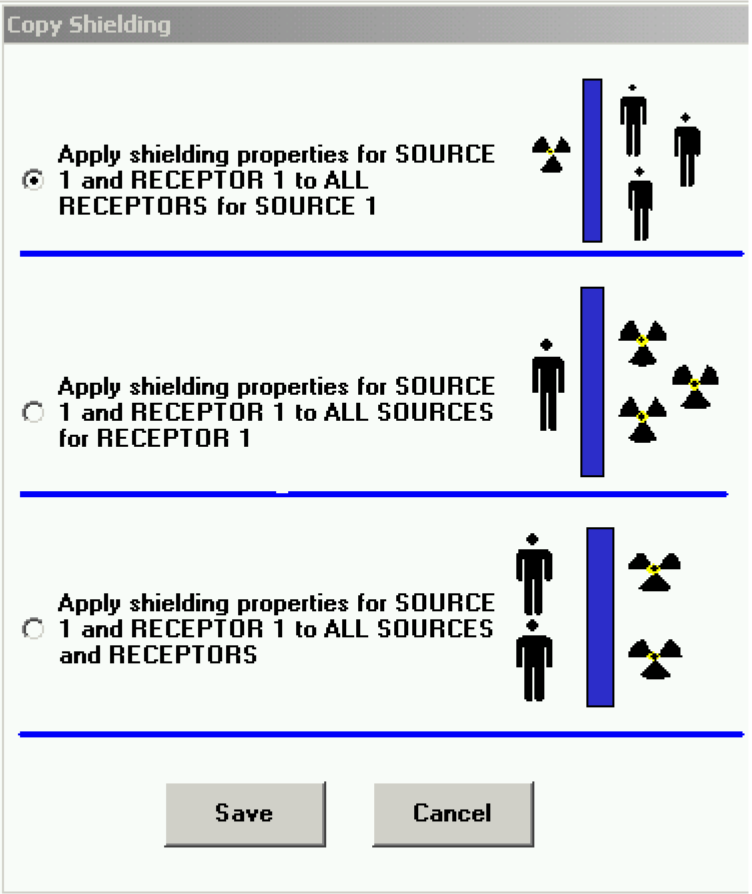


0

2.4

Concrete

FIGURE 4.10 Source-Receptor Table Window

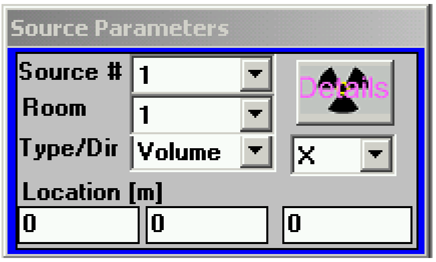


● Apply shielding properties for SOURCE 1 and RECEPTOR 1 to ALL RECEPTORS for SOURCE 1

○ Apply shielding properties for SOURCE 1 and RECEPTOR 1 to ALL SOURCES for RECEPTOR 1

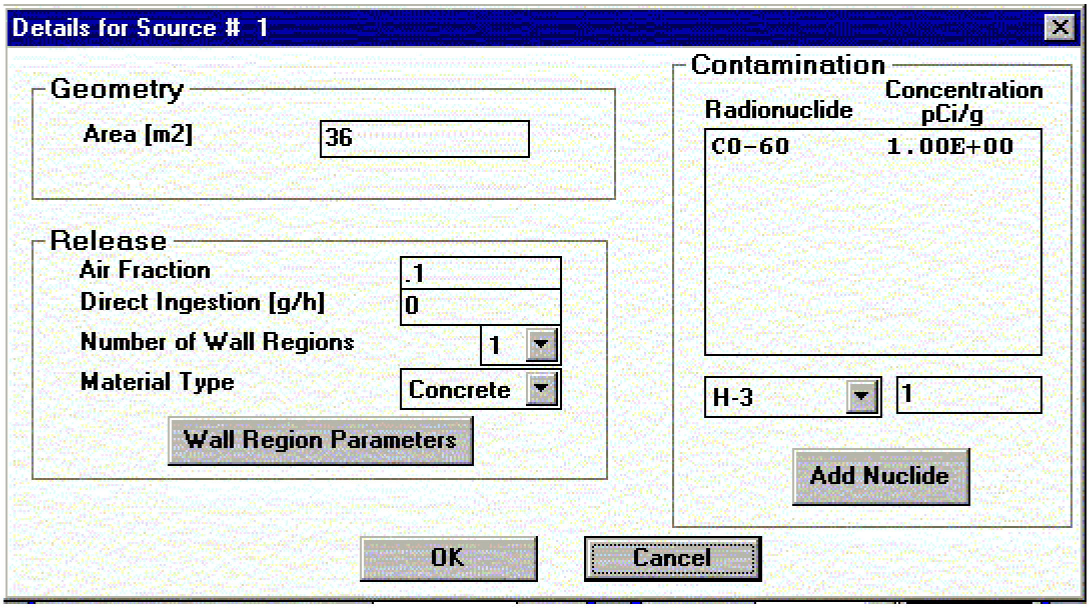
○ Apply shielding properties for SOURCE 1 and RECEPTOR 1 to ALL SOURCES and RECEPTORS

FIGURE 4.11 Copy Shielding Window



Source # 1
Room 1
Type/Dir Volume X
Location [m] 0 0 0

FIGURE 4.12 Source Parameters Window



Area [m2] 36

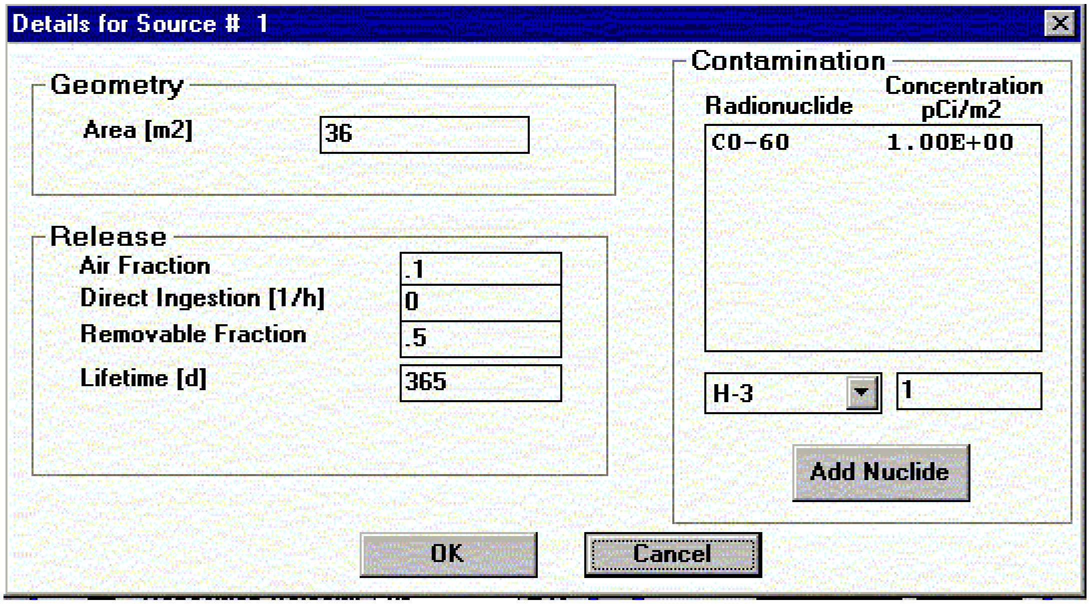
Air Fraction .1
Direct Ingestion [g/h] 0
Number of Wall Regions 1
Material Type Concrete

Radionuclide	Concentration pCi/g
CO-60	1.00E+00
H-3	1

FIGURE 4.13 Volume Source Detail Window

For the volume sources, an additional form on the properties of the source (Figure 4.17) needs to be completed. The source is modeled as a number of distinct regions. The properties of each region include density, porosity, radon emanation fraction, radon diffusion coefficient, thickness, and the erosion rate in the region. If there is more then one region, Region 1 is defined as the region closest to the origin. For the tritium volume source, a separate source needs to be entered, with tritium as the only contaminant. The property window for a tritium source is shown in Figure 4.18.

A 3-D display of source and receptor objects (Figure 4.19) can be viewed and manipulated by selecting the 3-D View option through the View/3-D Display menu options or the 3-D Display toolbar button. Each type of object is represented by a different icon: gray person for a receptor, square for a volume source, circle for an area source, line for a line source, and ball for a point source. Each object is displayed in the 3-D x, y, and z coordinate space. The



Details for Source # 1

Geometry

Area [m2] 36

Release

Air Fraction .1

Direct Ingestion [1/h] 0

Removable Fraction .5

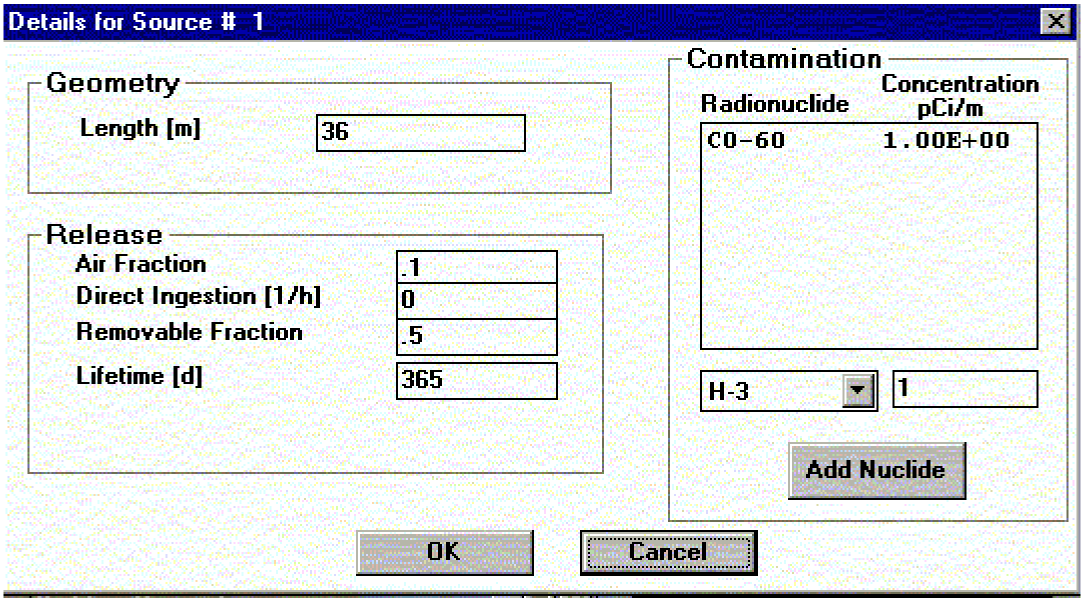
Lifetime [d] 365

Contamination

Radionuclide	Concentration pCi/m2
CO-60	1.00E+00

H-3 1

FIGURE 4.14 Area Source Detail Window



Details for Source # 1

Geometry

Length [m] 36

Release

Air Fraction .1

Direct Ingestion [1/h] 0

Removable Fraction .5

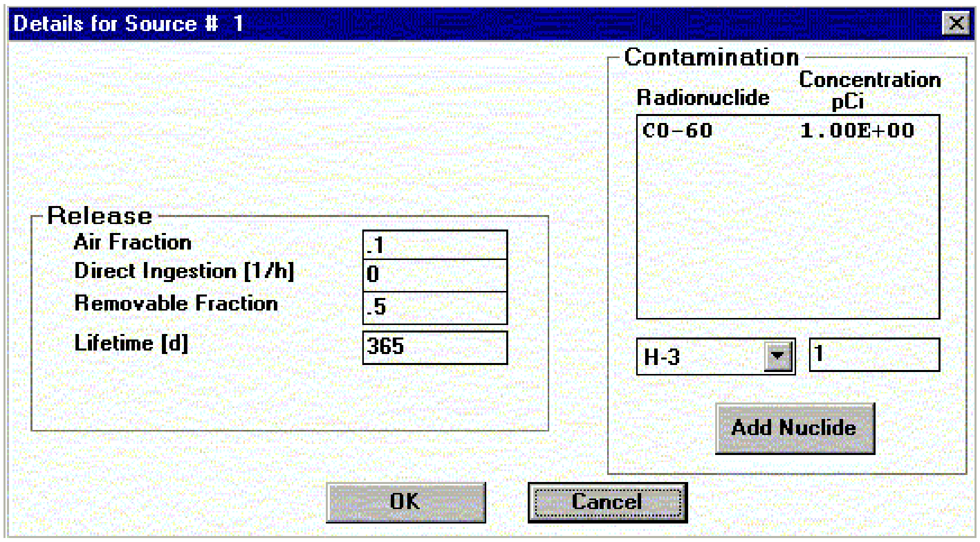
Lifetime [d] 365

Contamination

Radionuclide	Concentration pCi/m
CO-60	1.00E+00

H-3 1

FIGURE 4.15 Line Source Detail Window



Release

Air Fraction: .1

Direct Ingestion [1/h]: 0

Removable Fraction: .5

Lifetime [d]: 365

Contamination

Radionuclide	Concentration pCi
CO-60	1.00E+00

H-3: 1

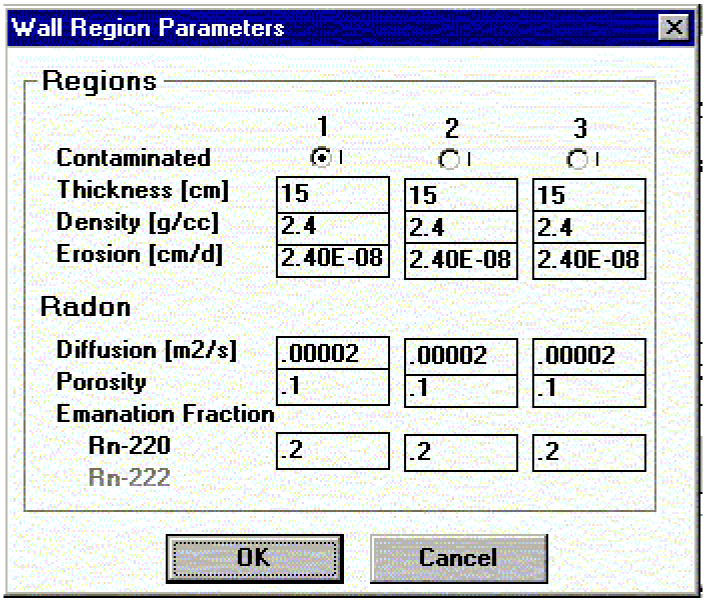
FIGURE 4.16 Point Source Detail Window

projection on the x-y plane is indicated by an oblique crosshair (pedestal). The height (z dimension) is represented as a column from the pedestal. The scale (in meters) of each of the axes is given by the number above the Reset Scale button. To change the scale, the user enters a new number in the box and presses the Reset Scale button. The objects can also be manipulated in 3-D by clicking on the pedestal or object and then dragging. Dragging the pedestal changes the x and y coordinates. Dragging the object changes the z coordinate. The object number is also directly displayed on the object (e.g., the second receptor is indicated by the number 2 in the middle of the gray bubble person icon). The room assignment can also be determined by the color (red, green, or blue) of the number.

4.3.6 Radiological Units

Users are able to specify the units they wish to input into the activity concentration and view the resultant dose equivalent (Figure 4.20). The primary units for activity concentration include Ci (curies) Bq (becquerels), dpm (disintegrations per minute), and dps (disintegrations per second), while the primary units for dose equivalent include rem and Sv (sievert). In addition, users can select any metric prefix to be used for Ci, Bq, rem, and Sv. The allowed prefixes are as follows:

E	exa	1×10^{18}	d	deci	1×10^{-1}
P	peta	1×10^{15}	c	centi	1×10^{-2}
T	tera	1×10^{12}	m	mili	1×10^{-3}
G	giga	1×10^{9}	μ	micro	1×10^{-6}
M	mega	1×10^{6}	n	nano	1×10^{-9}
k	kilo	1×10^{3}	p	pico	1×10^{-2}
h	hecto	1×10^{2}	f	femto	1×10^{-15}
	none	1	a	atto	1×10^{-18}



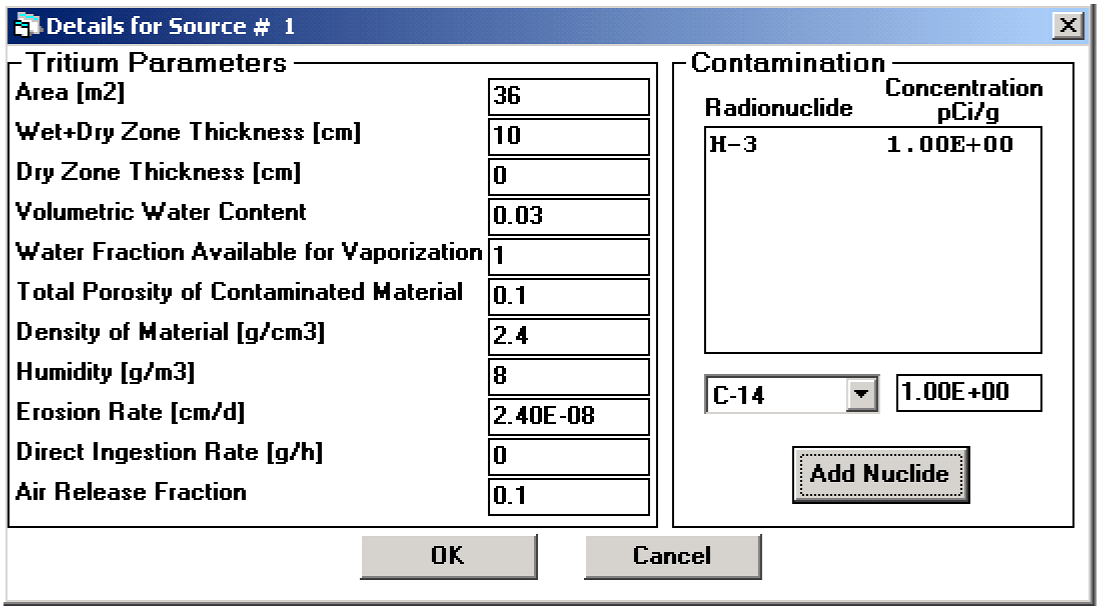
Regions

	1	2	3
Contaminated	●	○	○
Thickness [cm]	15	15	15
Density [g/cc]	2.4	2.4	2.4
Erosion [cm/d]	2.40E-08	2.40E-08	2.40E-08

Radon

	1	2	3
Diffusion [m2/s]	.00002	.00002	.00002
Porosity	.1	.1	.1
Emanation Fraction			
Rn-220	.2	.2	.2
Rn-222			

FIGURE 4.17 Nontritium Volume Source Wall Regions Window



Tritium Parameters

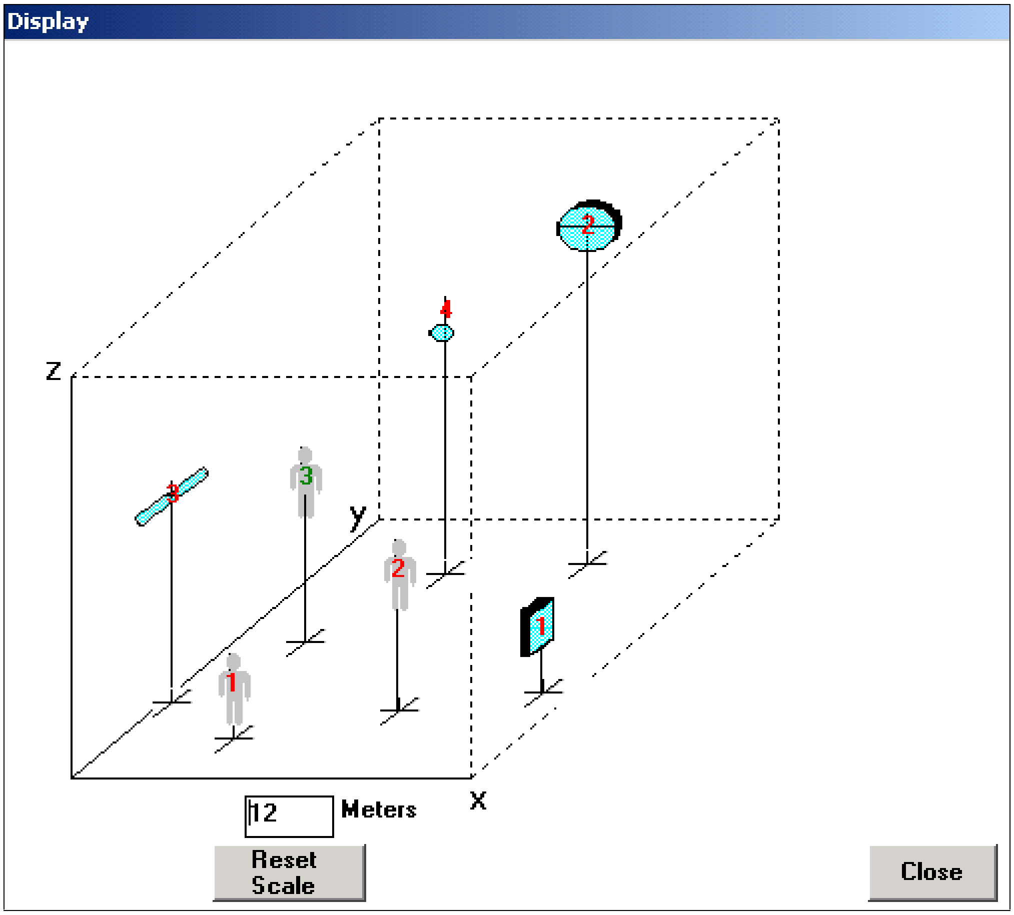
Area [m2]	36
Wet+Dry Zone Thickness [cm]	10
Dry Zone Thickness [cm]	0
Volumetric Water Content	0.03
Water Fraction Available for Vaporization	1
Total Porosity of Contaminated Material	0.1
Density of Material [g/cm3]	2.4
Humidity [g/m3]	8
Erosion Rate [cm/d]	2.40E-08
Direct Ingestion Rate [g/h]	0
Air Release Fraction	0.1

Contamination

Radionuclide	Concentration pCi/g
H-3	1.00E+00

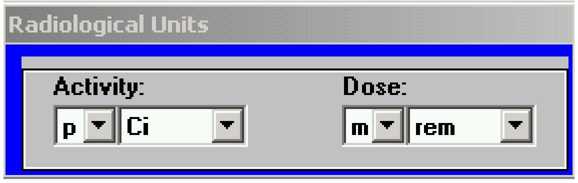
C-14 ▼ 1.00E+00

FIGURE 4.18 Tritium Volume Source Parameters Window



12 Meters

FIGURE 4.19 Interactive 3-D Display Window



Activity: p Ci

Dose: m rem

FIGURE 4.20 Radiological Units Window

Previously entered concentrations are automatically adjusted when the activity units are changed. The dose units in the report are fixed when the case is run.

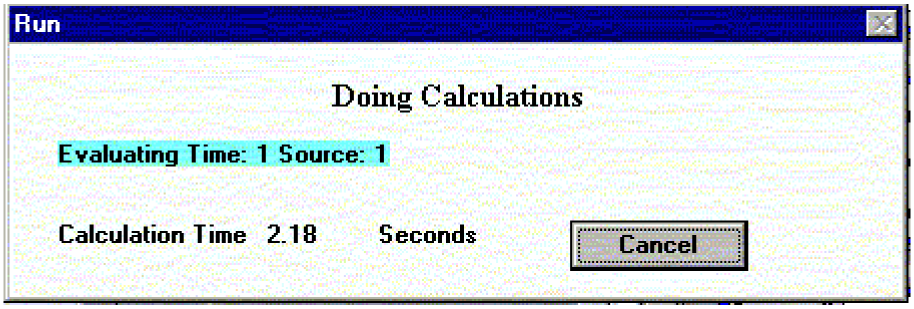
4.4 RESULTS WINDOWS

The user must select the Run option from the File menu (or use the toolbar button that looks like the space shuttle) to calculate the dose estimate for the case that has been set up. While the calculations are taking place for the deterministic analysis, the Run window (Figure 4.21) is displayed. This window contains (1) a short feedback line, (2) the amount of time spent so far on the calculation, and (3) a button to cancel the current calculation and return to the main user interface. After the calculation is complete, the report file is automatically opened in the report viewer. (Note: RESRAD-BUILD can also be run from a DOS prompt or in batch mode. To do this, create an input file, filename.BLD, and then issue the DOS command RESBMAIN.EXE filename.BLD.)

4.4.1 Text Output

A report file named RESRADB.RPT (Figure 4.22) is generated each time RESRAD-BUILD is executed. This contains a complete input table and dose estimates for each time, broken into details by pathway, nuclide, source, and receptor. The Report Viewer may be accessed at any time from the menu and toolbar. To move between reports, select File/Open from the main menu. To move within a page, use the scroll bars. There are many ways to move from page to page within the report:

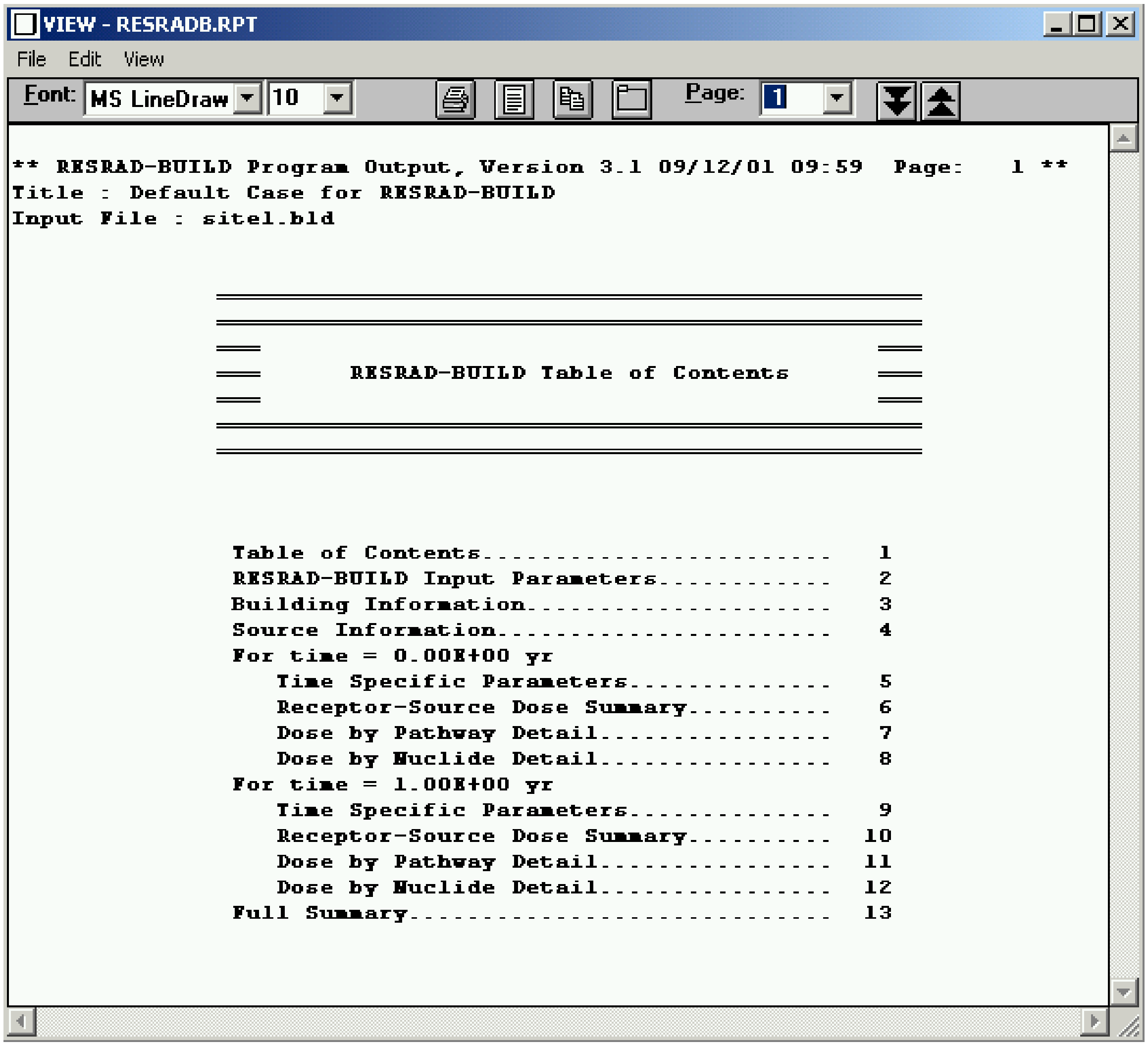
- Enter the page number in the page text box and press return.
- Pull down the page list and click on the desired page.
- Advance a page by pressing the Page Down key or by clicking on the double down arrows.
- Go back a page by pressing the Page Up key or by clicking on the double up arrows.



Evaluating Time: 1 Source: 1

Calculation Time 2.18 Seconds

FIGURE 4.21 Window Displayed during Calculations



```
** RESRAD-BUILD Program Output, Version 3.1 09/12/01 09:59   Page:    1 **
Title : Default Case for RESRAD-BUILD
Input File : sitel.bld


                ════════════════════════════════════════════════
                ════════════════════════════════════════════════
                ═══                                          ═══
                ═══        RESRAD-BUILD Table of Contents    ═══
                ═══                                          ═══
                ════════════════════════════════════════════════
                ════════════════════════════════════════════════


                 Table of Contents.........................    1
                 RESRAD-BUILD Input Parameters............    2
                 Building Information.....................    3
                 Source Information.......................    4
                 For time = 0.00E+00 yr
                    Time Specific Parameters..............    5
                    Receptor-Source Dose Summary..........    6
                    Dose by Pathway Detail................    7
                    Dose by Nuclide Detail................    8
                 For time = 1.00E+00 yr
                    Time Specific Parameters..............    9
                    Receptor-Source Dose Summary..........   10
                    Dose by Pathway Detail................   11
                    Dose by Nuclide Detail................   12
                 Full Summary.............................   13
```

FIGURE 4.22 Output Report

Two other text files also contain calculation results. The file named Diag.out contains some intermediate calculation results, such as the airflow matrix and air concentrations from each source for each time. The file named resradb.grf contains a comma-delimited set of dose estimate details by source, parent radionuclide, progeny radionuclide, receptor, time, and pathway. These data can be copied into a spreadsheet or database for further analysis.

Every time a calculation is run, the previous reports and graphics files are overwritten. The results can be saved under different names, thus allowing for later retrieval.

- To save all files: Select File/Save All under the View menu. This option saves all textual reports to files. If the input filename is xxxx.BLD, the report is saved as xxxx.rpt.

- To save the open report: Select File/Save under the View menu. This option prompts the user for a name under which to save the currently displayed report.

Printing is done in the standard way:

- To set up the printer: RESRAD-BUILD uses the standard Windows printer. The setup for the printer can be accessed through the File/Printer/Setup menu option. Options to be selected include the printer, paper size, and paper orientation.

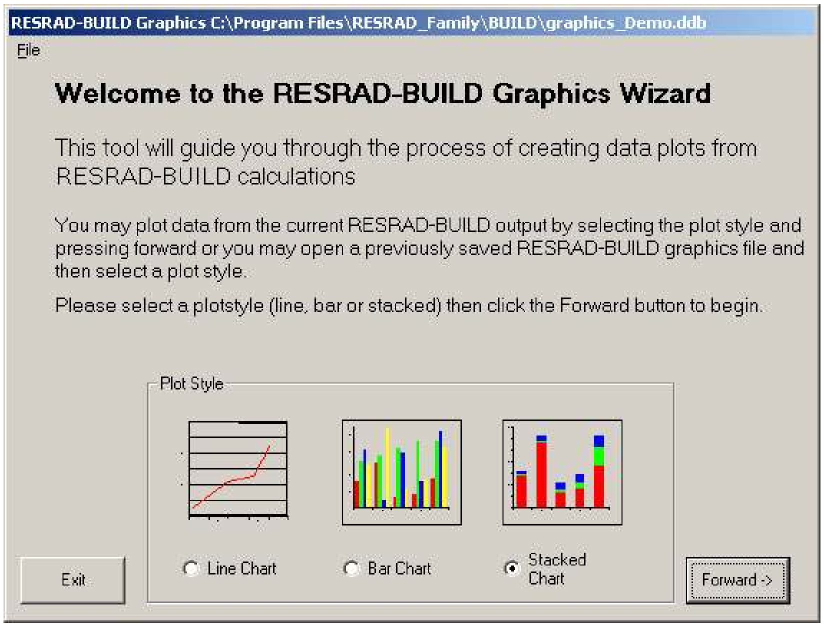
- To print: Select the File/Print menu option or press the printer icon button. A dialogue box lets you print the whole report, sets of pages, or the current highlighted text.

4.4.2 Graphic Output

The user may view results of RESRAD-BUILD output graphically by creating charts with the RESRAD-BUILD Graphics Wizard, as shown in Figure 4.23. Enter the graphics wizard program either by clicking Standard Graphics from the View menu or by pressing the green-colored graph icon located on the toolbar.

Once the graphics wizard opens, the user can create a new graph from one of three chart types: line, bar, or stacked. Line charts are most informative when one wishes to view results over many user-specified times. Bar and stacked charts are similar except stacked charts are useful to display the total dose for a specific set of groupings. Bar charts provide an excellent way to display dose subtotals for specific groupings. After selecting the chart style, the user must press the Next button to display the selected chart.

When bar and stacked charts are selected, the user can select up to two categories for the x-axis (primary and secondary axis). For example, a user may wish to view the dose to each receptor for every pathway for a specific radionuclide and a specific source. In this case, the two categories on the x-axis would be receptor (primary axis) and pathway (secondary axis). Figure 4.24 illustrates such a case. By selecting different primary and secondary axes, the user can plot the results from many different points of view. For example, a user may want to determine which nuclide-pathway combination contributes the most dose to a particular receptor at a given time. In this case, the primary axis would be radionuclide and the secondary axis would be pathway. Figure 4.25 illustrates such a graph. This flexibility allows users to analyze the results from a RESRAD-BUILD calculation in much greater detail than what is possible with the text-based report alone. All charts can be printed with the File/Print menu option or by pressing the printer icon button. As an added feature, results from the RESRAD-BUILD Graphics Wizard can be exported to Microsoft Excel for further analysis.



Welcome to the RESRAD-BUILD Graphics Wizard

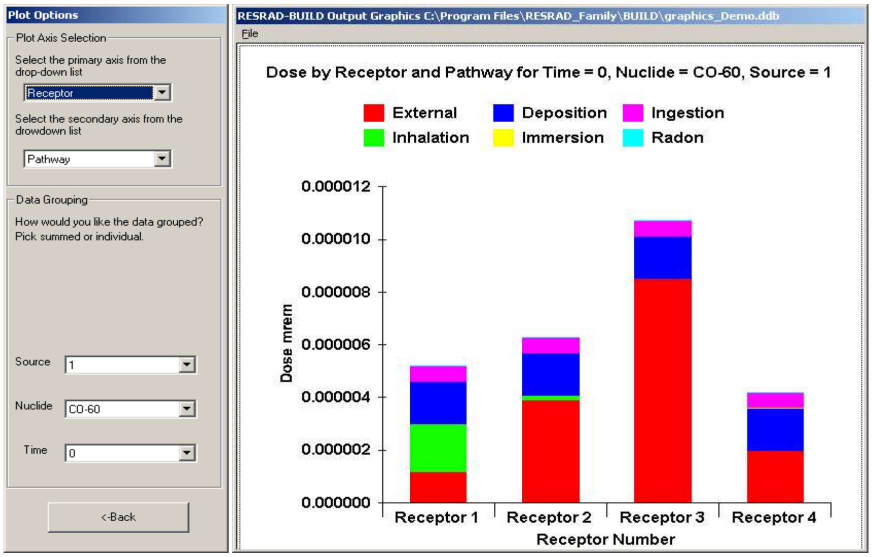
This tool will guide you through the process of creating data plots from RESRAD-BUILD calculations

You may plot data from the current RESRAD-BUILD output by selecting the plot style and pressing forward or you may open a previously saved RESRAD-BUILD graphics file and then select a plot style.

Please select a plotstyle (line, bar or stacked) then click the Forward button to begin.

○ Line Chart ○ Bar Chart ● Stacked Chart

FIGURE 4.23 RESRAD-BUILD Graphics Wizard Window



Select the primary axis from the drop-down list: Receptor

Select the secondary axis from the drowdown list: Pathway

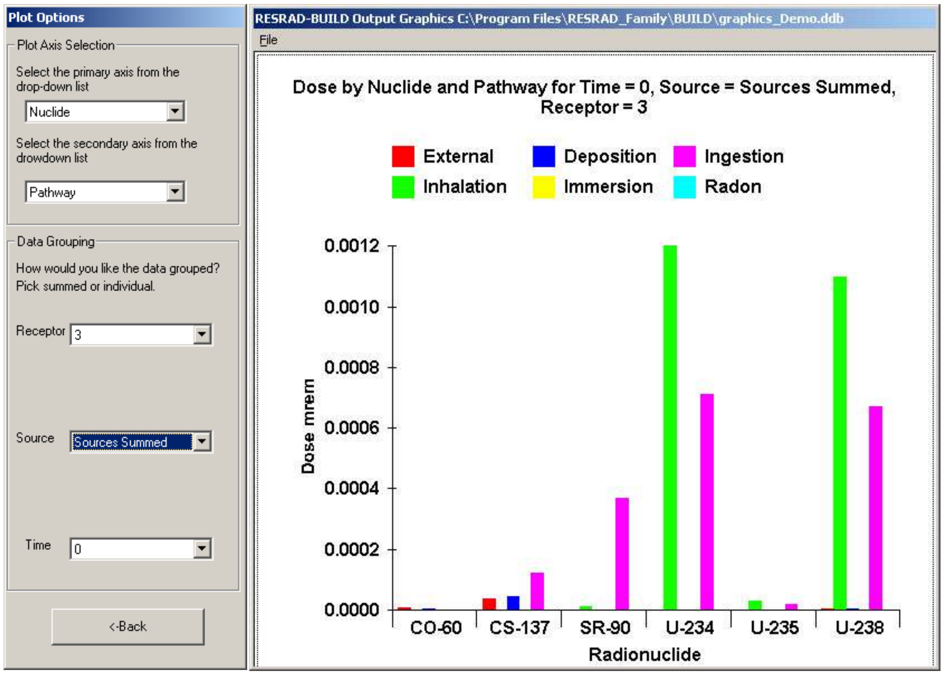
How would you like the data grouped? Pick summed or individual.

Source: 1

Nuclide: CO-60

Time: 0

FIGURE 4.24 Stacked Chart Showing the Dose to Each Receptor for Each Pathway for Source 1



Plot Options

Plot Axis Selection

Select the primary axis from the drop-down list: Nuclide

Select the secondary axis from the drowdown list: Pathway

Data Grouping

How would you like the data grouped? Pick summed or individual.

Receptor: 3

Source: Sources Summed

Time: 0

RESRAD-BUILD Output Graphics C:\Program Files\RESRAD_Family\BUILD\graphics_Demo.ddb

FIGURE 4.25 Bar Chart of Dose to Receptor 3 for Each Radionuclide and Pathway Combination

4.5 PROCEDURES FOR USING PROBABILISTIC ANALYSIS

The procedures for using probabilistic analysis with the RESRAD-BUILD codes are as follows:

- Run the standard software interface to set deterministic values for all parameters not involved with probabilistic analysis.

- Set the probabilistic analysis by finding parameters in the standard interface and pressing the F8 key. The probabilistic input window with four tab screens then appears. The parameter is automatically added, with its default distribution (if available), to the list of parameters for probabilistic analysis. The default distribution can be replaced with the site-specific distribution.

- Run the case. The standard deterministic calculations are performed first, then the probabilistic calculations begin. The estimated time for completion is continually updated and displayed.

- After the calculations are completed, the interactive output window for creating tables and graphics appears. Access is available to both the textual report and the detailed data dump files containing the results.

The probabilistic modules have been designed to be flexible and quite independent of the original RESRAD-BUILD application, yet easily applied and integrated with the application and able to use previously written software for Latin hypercube sampling (LHS) and correlation analysis.

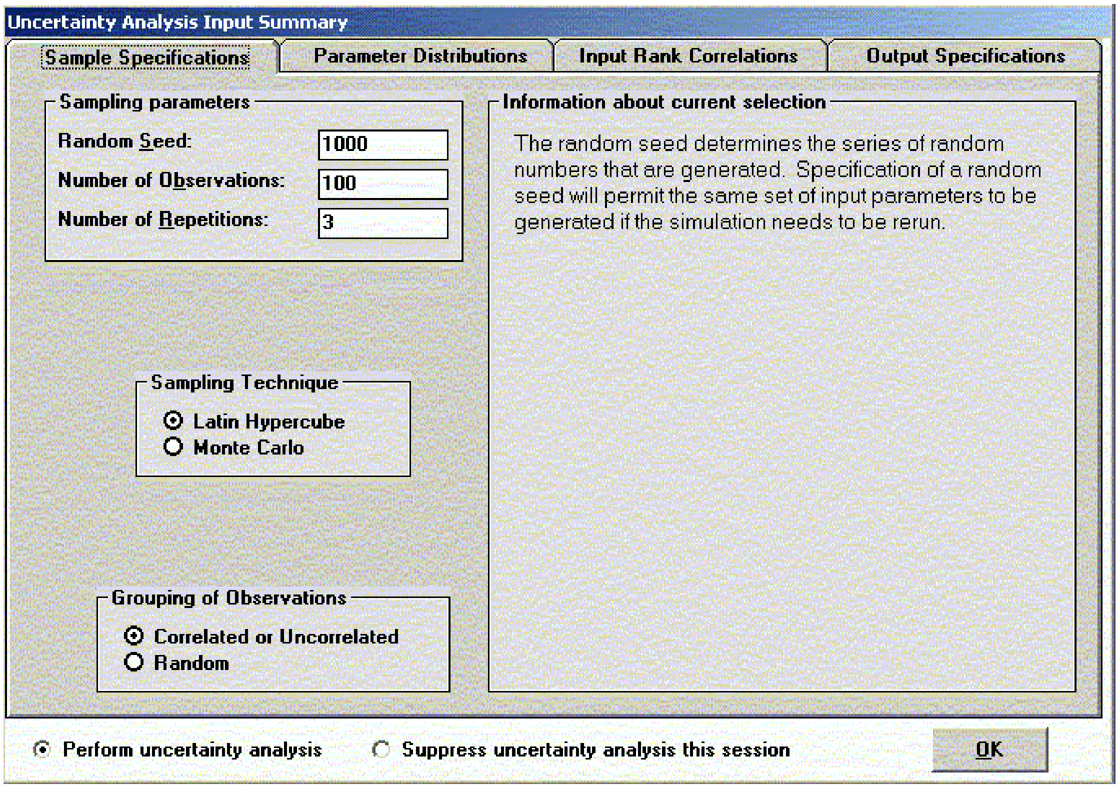
4.5.1 Input Window

The input window has four tabs that cover aspects of the sample specification, parameter distributions, input rank correlations, and output specifications (Figure 4.26). This window is displayed by choosing either to add or modify probabilistic analysis for a parameter or to view the probabilistic input from the View menu on the main menu.

Uncertainty analysis can be turned off while yet preserving other settings by selecting the "Suppress uncertainty analysis this session" option at the bottom of this window.

4.5.1.1 Sample Specifications

The general sampling requirements, including the number of samples and the technique used to generate and correlate samples, are specified in the Sample Specifications tab



Sampling parameters
Random Seed: 1000
Number of Observations: 100
Number of Repetitions: 3

Sampling Technique
● Latin Hypercube
○ Monte Carlo

Grouping of Observations
● Correlated or Uncorrelated
○ Random

Information about current selection

The random seed determines the series of random numbers that are generated. Specification of a random seed will permit the same set of input parameters to be generated if the simulation needs to be rerun.

● Perform uncertainty analysis ○ Suppress uncertainty analysis this session

FIGURE 4.26 Sample Specifications Tab Screen

(Figure 4.26). Information about the possible selections are shown in the right frame of the tab. Up to 2,000 observations can be specified. There is no software limit on the number of repetitions, although the memory available on the computer determines an effective limit.

- Sampling Technique: The Latin hypercube option splits the distribution to be sampled into a number of equally probable distribution segments (the number is equal to the desired number of observations) and obtains one sample at random from within each segment. This process ensures that the samples cover the entire range of the distribution. The Monte Carlo option obtains the specified number of samples randomly from within the whole distribution.

- Grouping of Observations: The Correlated or Uncorrelated option orders the samples for each variable so that (1) the correlations between the specified variables are as close as possible to the specified input correlations and (2) the correlation between the variables that are not specified to be correlated are as close to zero as possible. The Random option groups the variables in the order that they were obtained. It is possible that some of the variables so sampled will be correlated just by chance.

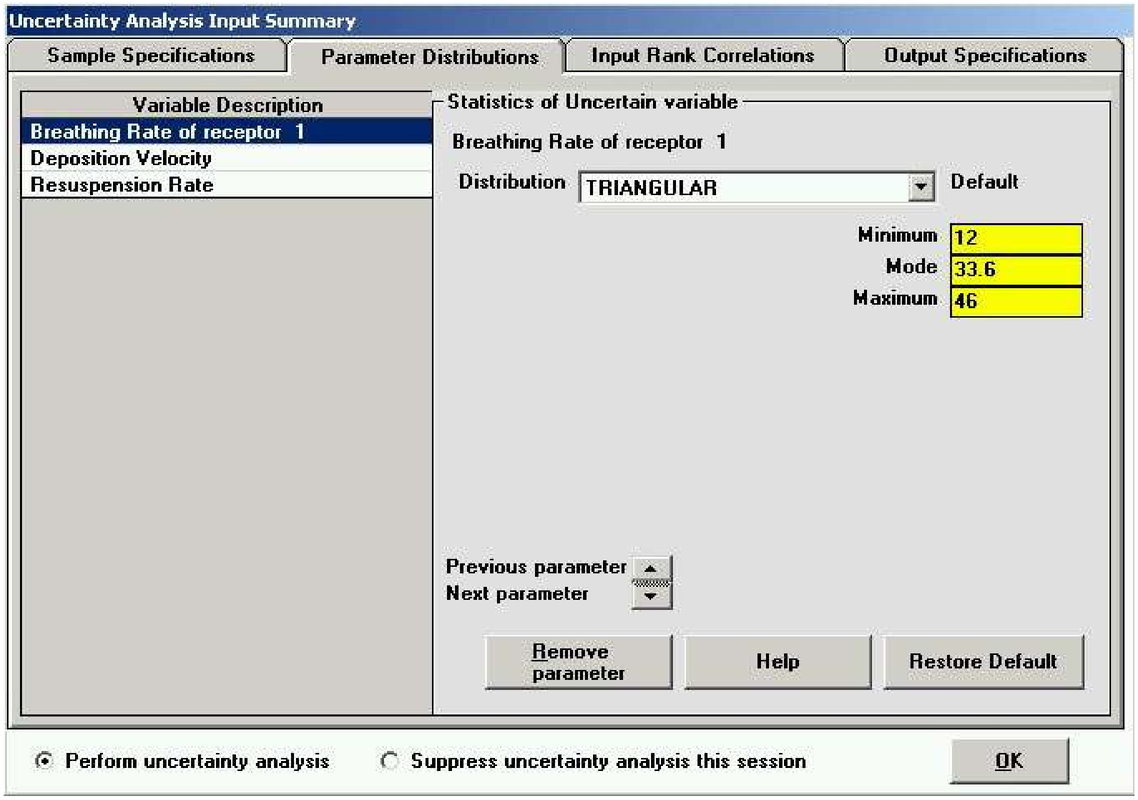
4.5.1.2 Parameter Distributions

The Parameter Distributions tab screen (Figure 4.27) allows the user to view and edit all currently specified parameter distributions for probabilistic analysis. The parameters are listed in the left frame. The detailed distribution properties are shown in the right frame.

- Navigation: Navigation to other parameter distributions is achieved by either clicking on the parameter in the left frame or using the Up-Down arrow button in the right frame.

- Variable Description List for Probabilistic Analysis: The list of the currently chosen parameters (variables) is shown in the left frame. Clicking on one of the variables shown under the Variable Description heading causes the complete distribution properties for that variable to appear for review and editing on the right. Up to 250 variables can be chosen for probabilistic analysis.

- Statistics of Uncertain Variable: The properties displayed are the distribution type and the statistical parameters of the specific distribution. In the example shown in Figure 4.27, the statistical parameters are for the triangular distribution, that is, the minimum, mode, and maximum. The changes that the user makes to a distribution are automatically saved. However, if after making changes, the user wishes to restore the default distribution for this parameter, Restore Default can be selected. The user can also remove the parameter from further probabilistic consideration by clicking on the Remove parameter button. A plot of this distribution is created if the “Help” button is pressed.



Breathing Rate of receptor 1

Distribution TRIANGULAR Default

Minimum 12

Mode 33.6

Maximum 46

● Perform uncertainty analysis ○ Suppress uncertainty analysis this session

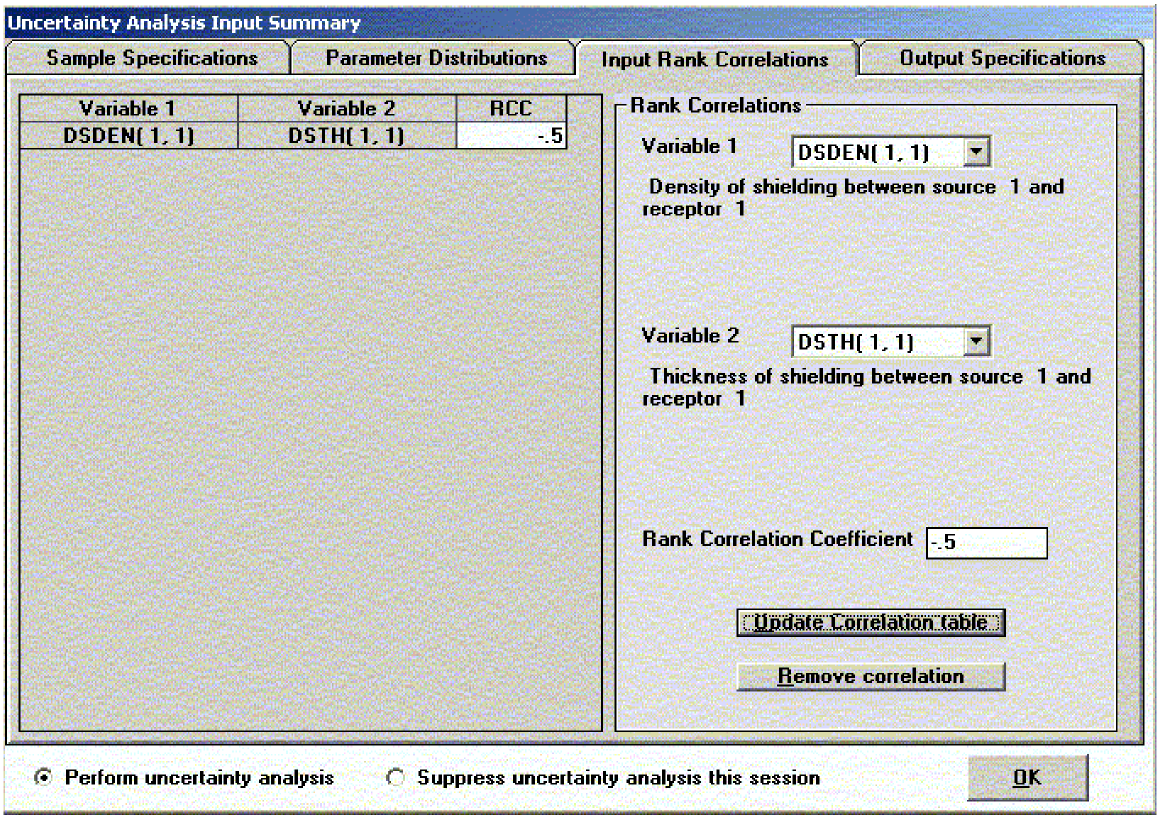
FIGURE 4.27 Parameter Distributions Tab Screen

4.5.1.3 Input Rank Correlations

The Input Rank Correlations tab screen (Figure 4.28) allows the user to view and edit all correlations among input parameters for probabilistic analysis. The paired parameters with nonzero correlations are listed in the left frame. Correlations can be modified, added, or deleted in the right frame.

- Navigation. The user can select an existing correlation pair by clicking on its row in the left frame. New pairs are chosen in the right frame by selecting the two variables. The edits in this frame are incorporated after the user clicks on the Update Correlation table button. The pair is removed by clicking on the Remove correlation button.

- Parameter List for Correlation. The currently chosen pairs of parameters are listed in the left frame in a three-column table that shows the variable names in the code and the correlation coefficients. By clicking on any element in any row of the table, the user can modify or delete the correlation in the right frame. The range of correlation coefficients is from greater than –1.00 to less than 1.00. The correlation for all pairs not specified here is assumed to be 0.0. The user can check the results of the sampling correlation after the run has



Variable 1	Variable 2	RCC
DSDEN(1, 1)	DSTH(1, 1)	-.5

Variable 1 DSDEN(1, 1)

Density of shielding between source 1 and receptor 1

Variable 2 DSTH(1, 1)

Thickness of shielding between source 1 and receptor 1

Rank Correlation Coefficient -.5

● Perform uncertainty analysis ○ Suppress uncertainty analysis this session

FIGURE 4.28 Input Rank Correlation Tab Screen

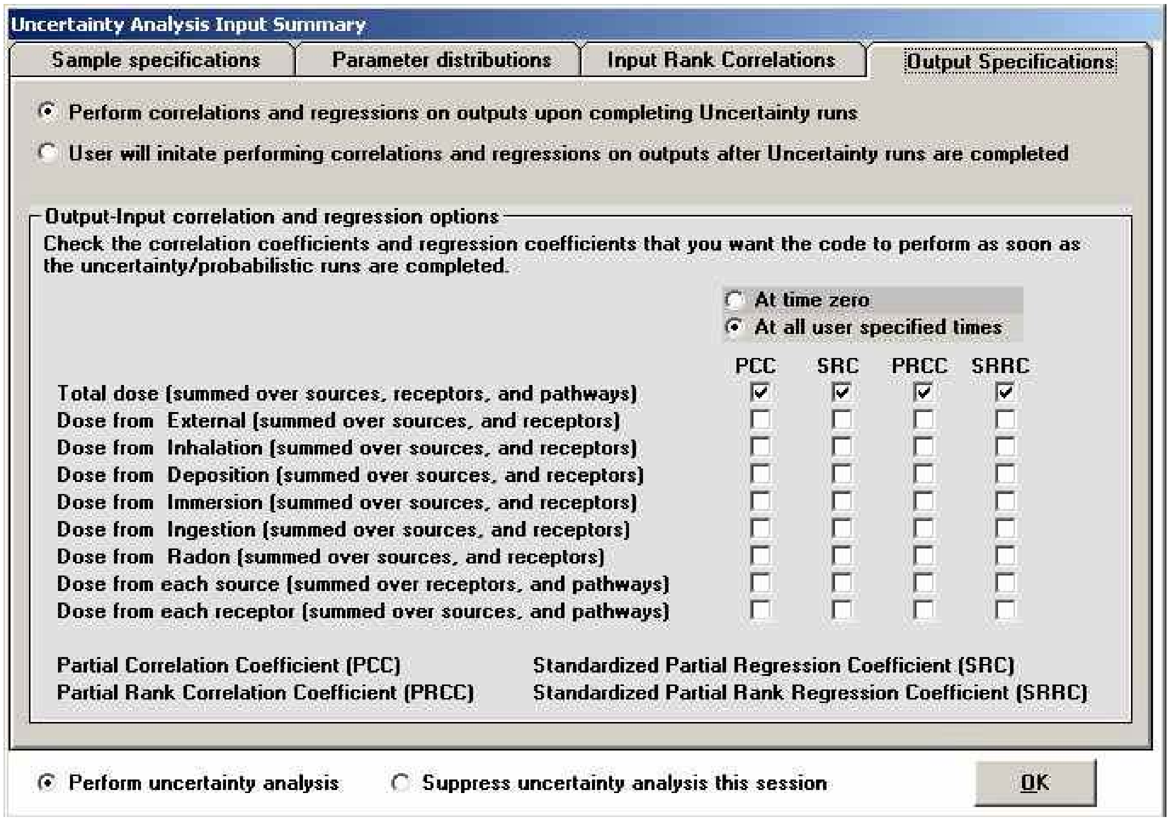
been completed. Full descriptions of the variables can be seen in the right frame. If more parameters are chosen for correlation than fit in the window, the left frame becomes a scrolling table.

- Correlation Edit. The two correlated parameters and the correlation coefficient are shown and editable in the right frame. The user can also remove the correlation from further probabilistic consideration by clicking on the Remove correlation button.

4.5.1.4 Output Specifications

The user selects from output options in the Output Specifications tab screen (Figure 4.29). More detailed output options (e.g., by pathway, nuclide, or user-specified times) take longer to run.

- Navigation. The output options are selected with the check boxes on the right side of the screen. These options are the only inputs on this tab screen. The columns on the right show what output options the user can obtain for each of



● Perform correlations and regressions on outputs upon completing Uncertainty runs

○ User will initate performing correlations and regressions on outputs after Uncertainty runs are completed

Output-Input correlation and regression options

Check the correlation coefficients and regression coefficients that you want the code to perform as soon as the uncertainty/probabilistic runs are completed.

○ At time zero
● At all user specified times

	PCC	SRC	PRCC	SRRC
Total dose (summed over sources, receptors, and pathways)	☑	☑	☑	☑
Dose from External (summed over sources, and receptors)	☐	☐	☐	☐
Dose from Inhalation (summed over sources, and receptors)	☐	☐	☐	☐
Dose from Deposition (summed over sources, and receptors)	☐	☐	☐	☐
Dose from Immersion (summed over sources, and receptors)	☐	☐	☐	☐
Dose from Ingestion (summed over sources, and receptors)	☐	☐	☐	☐
Dose from Radon (summed over sources, and receptors)	☐	☐	☐	☐
Dose from each source (summed over receptors, and pathways)	☐	☐	☐	☐
Dose from each receptor (summed over sources, and pathways)	☐	☐	☐	☐

Partial Correlation Coefficient (PCC)
Standardized Partial Regression Coefficient (SRC)
Partial Rank Correlation Coefficient (PRCC)
Standardized Partial Rank Regression Coefficient (SRRC)

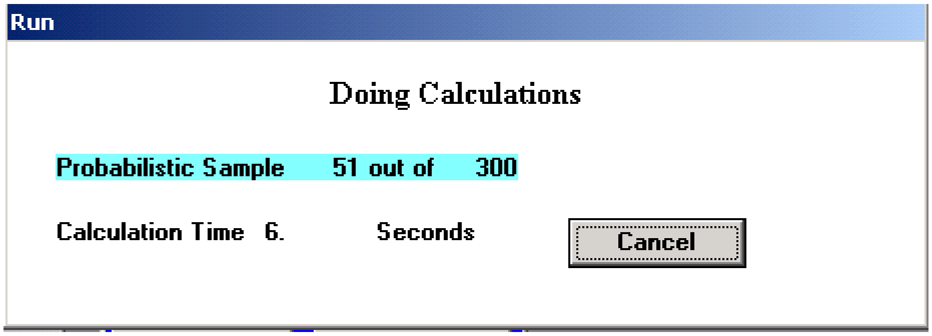
● Perform uncertainty analysis ○ Suppress uncertainty analysis this session

FIGURE 4.29 Output Specifications Tab Screen

the checked options after running RESRAD-BUILD. The user is able to specify and view these options from the interactive table and interactive graphic screens. Various correlation types are available: partial correlation coefficient (PCC), partial rank correlation coefficient (PRCC), standardized partial regression coefficient (SRC), and standardized partial rank regression coefficient (SRRC) (Iman et al. 1985).

4.5.2 Output Results

The case calculations are performed by clicking on the Run button. A pop-up window, shown in Figure 4.30, displays calculation progress feedback. The Cancel button in the lower right of this window allows the user to stop the calculations at any time. When the calculations are complete, the deterministic summary report appears in the viewer window (Figure 4.22). This report contains a complete list of all variables used in the case. This report contains the results from the deterministic calculations, which are therefore not related to the probabilistic analysis. The report can be accessed through the View option on the main menu.



Doing Calculations

Probabilistic Sample 51 out of 300

Calculation Time 6. Seconds

FIGURE 4.30 Window Displayed When Calculations Are Being Performed

The following sections discuss the variety of ways to access results.

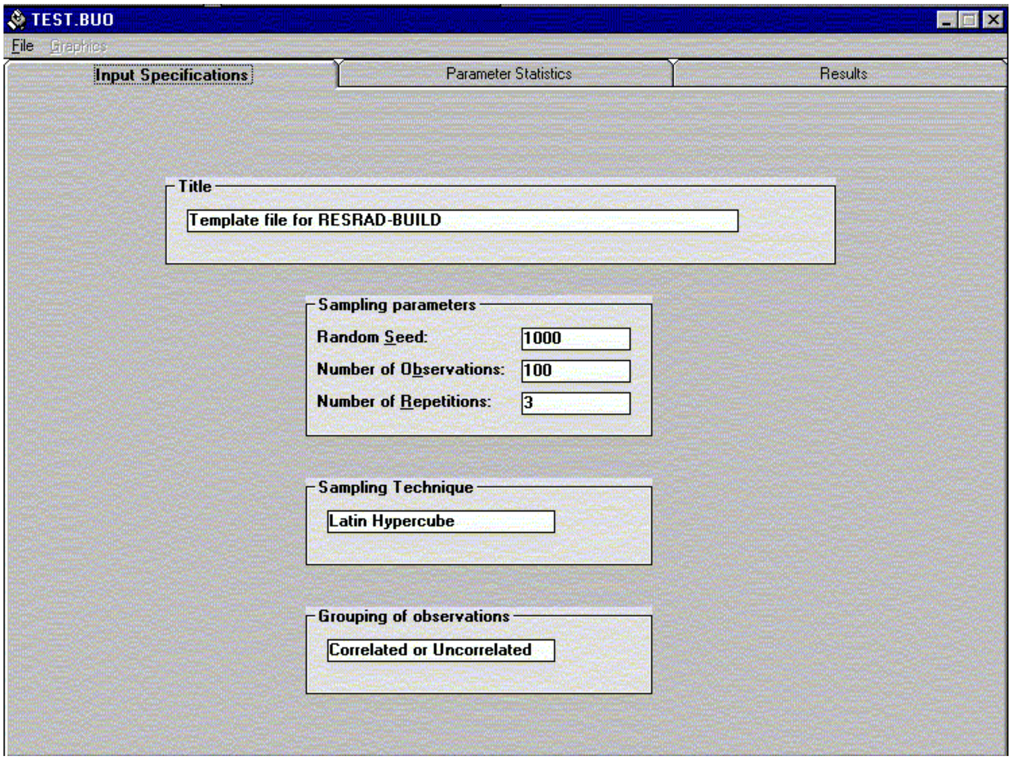
The Interactive Output window contains interactive tabular and graphical results to facilitate quick exploration of the data. The Uncertainty Report specifies the applied input and detailed results. The LHS Report contains details of the sampling. The Correlate Output button in the Navigator window allows the user to specify additional output after the main calculation has been performed. Also, a formatted file (Access database) with the case name but a .BUO extension, gives the user access to the raw input and output data for specific analysis needs.

4.5.2.1 Interactive Output

The user can review the probabilistic inputs, including the Input Specifications tab screen (repetitions, observations, random seed; see Figure 4.31) and the Parameter Statistics tab screen (parameter distributions and input correlations; see Figure 4.32). The user can then select what type of interactive output should be generated.

Results, the third tab screen, allows the user to explore text (Figure 4.33) and graphical results. For each table, the user can select a primary statistical object. The object contains the Dose at User Times. The primary statistical object has a series of secondary statistical objects. The secondary objects for the Dose at User Times contain all pathways, each individual pathway, all sources, each source, each nuclide, all nuclides, and each user time. After selecting the appropriate statistical object, the user must specify the statistical property for analysis. The statistical property options contain either General Statistics or Percentile. The General Statistics Results table provides the minimum, maximum, mean, and standard deviation and the 50th, 90th, and 95th percentile of the statistical object selected. The Percentile Results table provides the 5th through 95th percentile at every 5th percentile for the statistical object selected.

- Navigation. The user selects the type of output in the left frame by specifying the Statistical Object and Statistical Property. The Results table is shown in the right frame. If the output is time-dependent, the user must then select from the previously entered specified times.



Title: Template file for RESRAD-BUILD

Sampling parameters

Random Seed: 1000

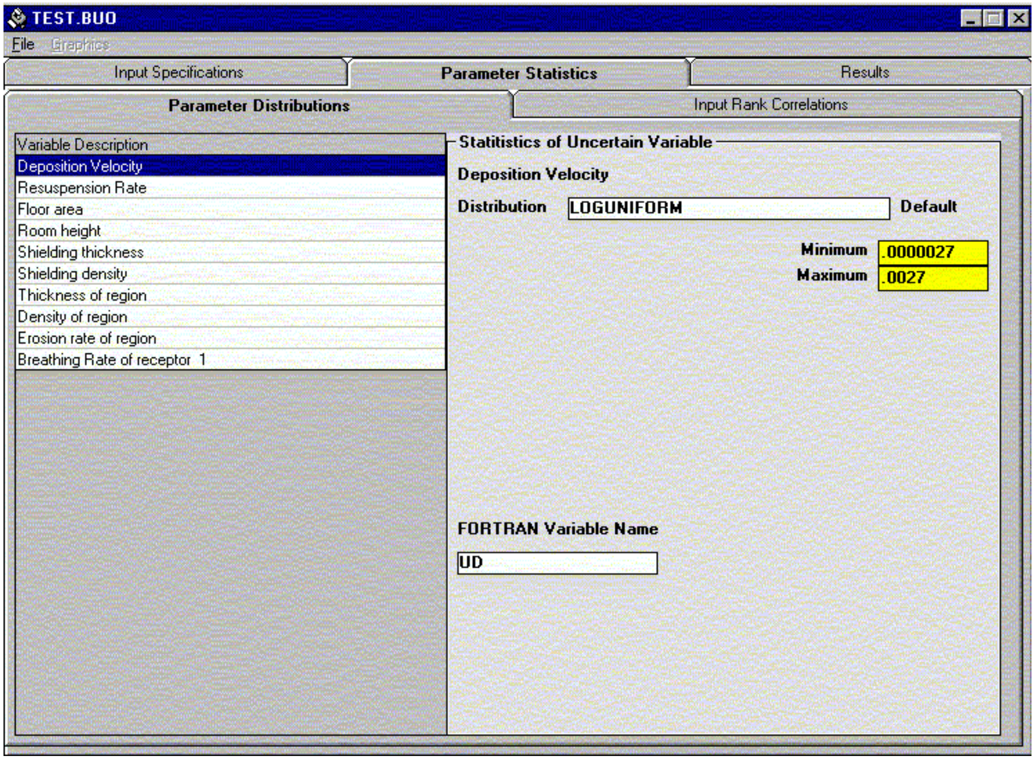
Number of Observations: 100

Number of Repetitions: 3

Sampling Technique: Latin Hypercube

Grouping of observations: Correlated or Uncorrelated

FIGURE 4.31 Input Specifications Tab Screen



Statitistics of Uncertain Variable

Deposition Velocity

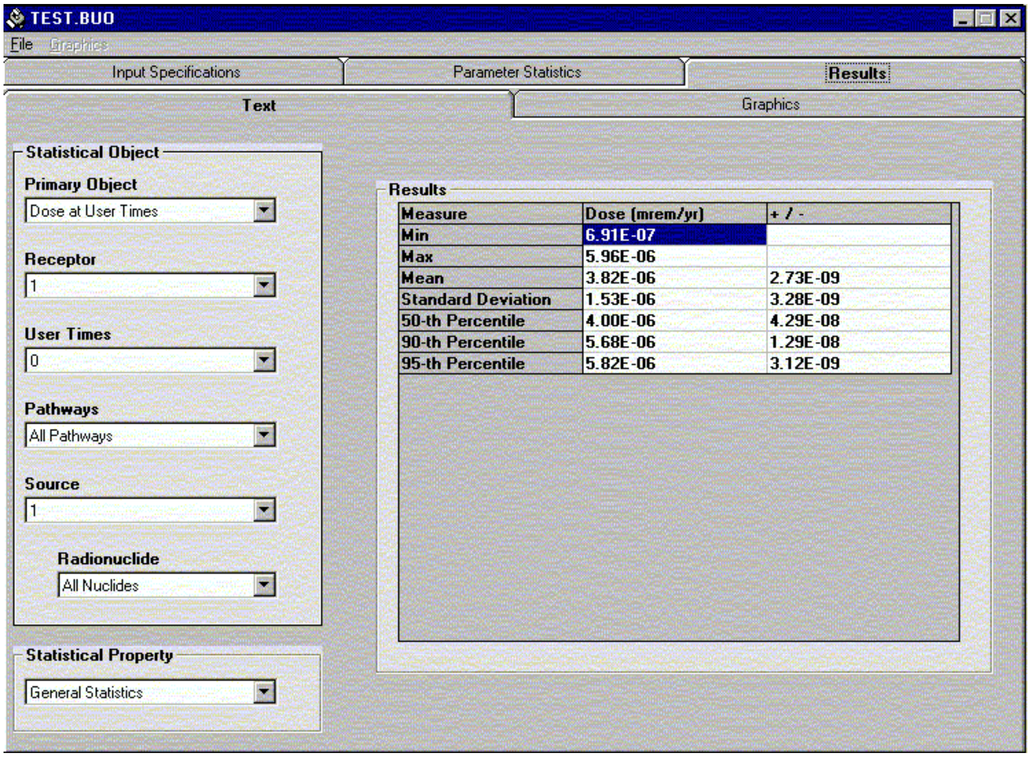
Distribution: LOGUNIFORM

Minimum: .0000027

Maximum: .0027

FORTRAN Variable Name: UD

FIGURE 4.32 Parameter Distributions Tab Screen



Statistical Object

Primary Object: Dose at User Times

Receptor: 1

User Times: 0

Pathways: All Pathways

Source: 1

Radionuclide: All Nuclides

Statistical Property: General Statistics

Results

Measure	Dose (mrem/yr)	+ / -
Min	6.91E-07	
Max	5.96E-06	
Mean	3.82E-06	2.73E-09
Standard Deviation	1.53E-06	3.28E-09
50-th Percentile	4.00E-06	4.29E-08
90-th Percentile	5.68E-06	1.29E-08
95-th Percentile	5.82E-06	3.12E-09

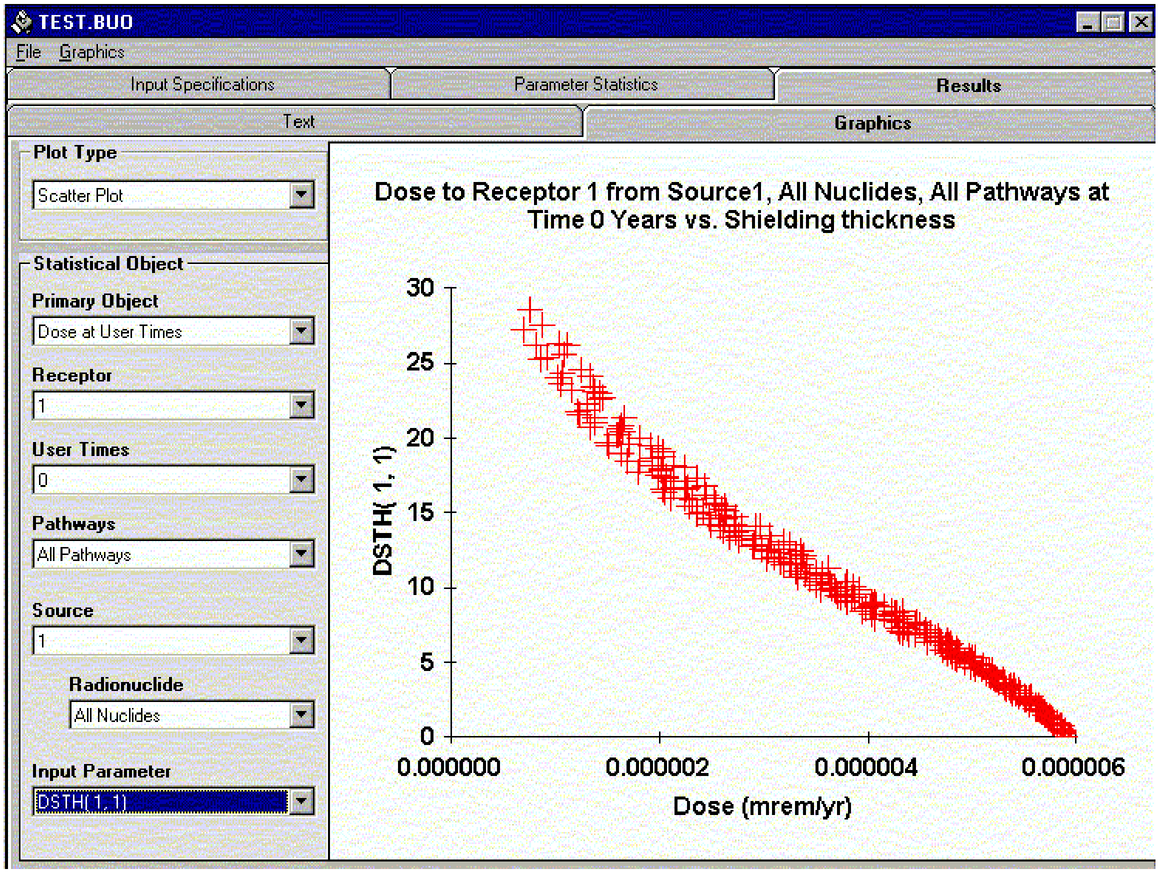
FIGURE 4.33 Text Results Tab Screen

- Statistical Object. The object contains the doses at user-specified times.

- Statistical Properties. The properties contain General Statistics (average, maximum, minimum, standard deviation), and Percentile. The right column of the Results table for these properties contain an estimate of how well these values are known based on the variation within the repetitions. The numbers under the +/- column are the standard deviation of the properties from the repetitions divided by the square root of the number of repetitions. They are measured in the same units as the property.

4.5.2.2 Interactive Graphical Output

RESRAD-BUILD output is also available for viewing in graphical plots (Figure 4.34). The plots include cumulative probability plots and scatter plots. The cumulative probability plots provide a plot of the statistical object selected versus the cumulative probability. The same statistical object available for the tables is available for the cumulative probability plots. The scatter plots provide a plot of the statistical object versus an input vector. Scatter plots should be used in conjunction with the correlation analysis to determine the correlation between the input vector(s) and the output.



Plot Type: Scatter Plot

Primary Object: Dose at User Times

Receptor: 1

User Times: 0

Pathways: All Pathways

Source: 1

Radionuclide: All Nuclides

Input Parameter: DSTH(1, 1)

FIGURE 4.34 Graphics Results Tab Screen

- Navigation. The user selects the type of output in the left frame of the Graphics Results tab screen (Figure 4.34) by specifying the Statistical Object and Plot Type. The resulting graph is shown in the right frame. If the output is time-dependent, the user must then select from the previously entered specified times.

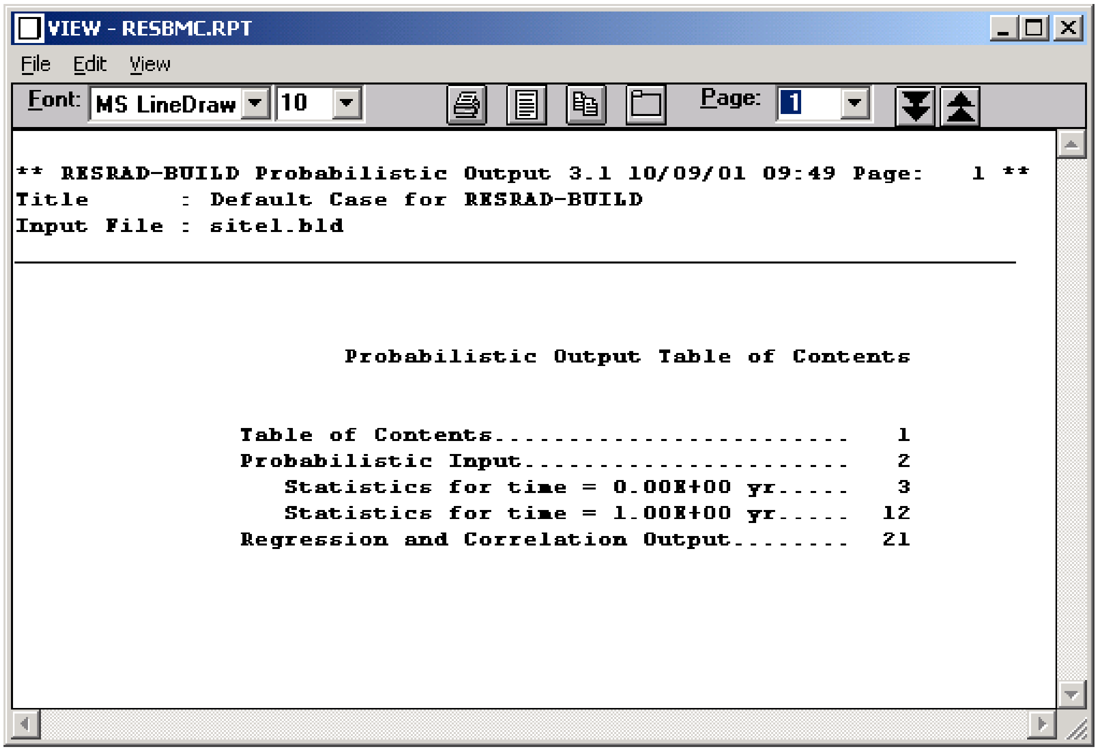
- Statistical Objects. The object contains the doses for individual pathways or for all pathways at user-specified times for different receptors, sources, and radionuclides. The object can also select input parameter.

- Plot Type. The user can select output-input scatter plots and cumulative probability distribution plots.

4.5.2.3 Complete Tabular Report

The RESRAD-BUILD code generates two probabilistic report files. One pertains to the input, and the other pertains to the output, as described below.

- RESRAD-BUILD Input Report File. The Input Report File, EXAMPLE1.UN6, can be accessed via the View, Any file, or under All Files, among other ways. It is generated by the LHS program and is used by RESRAD-BUILD. It includes the following information for each repetition (or replication) requested by the user:
    - The initial random seed.
    - The number of probabilistic variables.
    - The number of observations.
    - The current repetition.
    - A description of each probabilistic variable, the specified distribution, parameters defining the distribution, and the Label (FORTRAN name in RESRAD).
    - The rank correlation matrix, if one was specified by the user.
    - The adjusted rank correlation matrix, if the user-specified rank correlation matrix is not positive definite.
    - A list of all the input samples (or vectors) that were generated.
    - A list of the rank of all the input samples that were generated.
    - A matrix of correlations among the raw values of the variable generated by the sampling program.
    - A matrix of correlations among the rank of values of the variable generated by the sampling program.
- RESRAD-BUILD Output Report File. The Output Report File (Figure 4.35) can be accessed via the View, Last Probabilistic Report, menu option. The report includes the following information:
    - Table of Contents of the report.
    - The number of sample runs, input parameter distributions specified, and the statistical parameter associated with those distributions.



```
** RESRAD-BUILD Probabilistic Output 3.1 10/09/01 09:49 Page:    1 **
Title      : Default Case for RESRAD-BUILD
Input File : site1.bld
____________________________________________________________________


                      Probabilistic Output Table of Contents


               Table of Contents.........................   1
               Probabilistic Input.......................   2
                  Statistics for time = 0.00E+00 yr.....   3
                  Statistics for time = 1.00E+00 yr.....  12
               Regression and Correlation Output........  21
```

FIGURE 4.35 Probabilistic Output Report File

- For each user-specified time:
  - Statistics of the total dose (minimum, maximum, average, and standard deviation) for all pathways and all radionuclides summed for each source and receptor.
  - For each source and receptor, statistics of the dose (minimum, maximum, average, and standard deviation) for each pathway summed over the source radionuclides.
  - For each source and receptor, percentile doses for each pathway starting at the fifth percentile, incrementing every fifth percentile to the one hundredth percentile dose.
  - For each source and receptor, statistics of the dose (minimum, maximum, average, and standard deviation) for each radionuclide summed over the pathways.
  - For each source and receptor, percentile doses for each radionuclide starting at the fifth percentile, incrementing every fifth percentile to the one hundredth percentile dose.

- A table of regression and correlation coefficients between the total dose (summed over nuclides and pathways) and each of the probabilistic inputs for each repetition. The coefficients included are the PCC, SRC, PRCC, and the SRRC. If selected by the user, these coefficients are available for each individual pathway.

4.5.2.4 Complete Formatted Results File

The user has access to a complete formatted set of output results and input sample vectors in Microsoft Access format. Access to this file permits the user to perform any type of analysis or graphing of the data. For example, the user can easily identify and analyze sample vectors that result in output values between certain percentiles.

- Navigation. The user's own spreadsheet, database, or software program must be used to read the specified formatted data and to perform analyses. The database file name is the case base name with a .BUO extension. For example, if the case was saved in siteA.rad, then the database would be saved as siteA.BUO. The format of the file is Microsoft Access Version 2000.

5 VERIFICATION OF THE RESRAD-BUILD COMPUTER CODE

As part of a quality assurance program, RESRAD-BUILD has undergone extensive review, benchmarking, and verification. Many models used in the 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 (Yu et al. 2001). Recently, the NRC compared the DandD code Version 1.0 with the RESRAD Version 5.61 and RESRAD-BUILD Version 1.5 codes (NRC 1999). This section summarizes the most recent verification results using RESRAD-BUILD Version 3.0 and Microsoft Excel spreadsheets (Kamboj et al. 2001). An independent verification of the RESRAD-BUILD models and parameters was also conducted (Tetra Tech NUS, Inc. 2003).

5.1 VERIFICATION PROCEDURE

The results generated by RESRAD-BUILD Version 3.0 were compared with those obtained with hand-held calculators and spreadsheets. The equations and reference data listed in the appendixes of this manual for different pathways were used in the calculations. For verification purposes, several radionuclides — H-3, C-14, Na-22, Al-26, Cl-36, Mn-54, Co-60, Au-195, Ra-226, Ra-228, Th-228, and U-238 — were chosen to effectively test all pathways and models. Tritium, Ra-226, and Th-228 were chosen to test the special models used for tritium and radon in the RESRAD-BUILD code. The other radionuclides were selected to represent a spectrum of radiation types and energies.

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 (Version 7) to verify all the major portions of the code. The verification was conducted on a step-by-step basis and used different test cases as templates, since all possible options could not be considered. The following types of calculations were investigated: (1) source injection rate, (2) air concentration in the room, (3) air particulate deposition, (4) radon pathway model, (5) tritium model for volume source, (6) external exposure model, (7) different pathway doses, and (8) time dependence of dose.

Except for a dose from the direct external exposure pathway, the dose to a receptor in a room depends on the radionuclide concentration in the air of that room. The radionuclide air concentration, in turn, depends on the source injection rate. Therefore, the source injection rate calculations were verified first. Then the air concentrations in one-room and two-room models were verified. Since air deposition depends on the air concentration in the room, air deposition was verified next. The special radon and tritium models in RESRAD-BUILD were then verified. The external exposure models in RESRAD-BUILD were independently benchmarked with the MCNP transport code (Briesmeister 1993). Finally, the total dose for a single receptor calculated by RESRAD-BUILD was compared and verified with the total dose calculated by the Excel spreadsheets. The time-independent part of the code was tested first (instantaneous dose calculations at time zero, without integrating over one year or the exposure duration). Then the time-integrated dose was verified.

The following parameters used in the RESRAD-BUILD code (Version 3.0) were checked and verified for correctness against their original source documents: inhalation, ingestion, air submersion, and external DCFs; external exposure model parameters; and radionuclide half-lives and other decay data. Excel spreadsheets were prepared that calculated the different pathways according to the source receptor configuration. Three spreadsheets were used for all verification runs. The first spreadsheet used all the RESRAD-BUILD default parameters; the second used lower-bound values of the input parameters; and the third used all the upper bound values for the input parameters. The lower and upper bound values of the parameters were taken from Yu et al. (2000). The verification was performed for these three data sets to cover wide variations in input values. Two direct exposure models based on source geometry are used in the RESRAD-BUILD code. The first model for area and volume sources is based on a semi-infinite slab source with corrections for geometric factors (Kamboj et al. 1998). This exposure model uses the external DCFs from Federal Guidance Report No. 12 (Eckerman and Ryman 1993). The methodology described by Kamboj et al. (1998) for corrections due to finite size was extended to include differences due to the source material. The second model for point and line contamination is a simple dose integral method (see Appendix F). The results of the external exposure models (point and line sources and area and volume sources) were also benchmarked with those from the MCNP transport code. For this comparison, MCNP Version 4A was used.

5.2 RESULTS AND DISCUSSION

Detailed results and discussion of the verification exercises are presented in Kamboj et al. (2001). The verification results for different types of calculations are summarized here. Table 5.1 compares pathway doses for different source types calculated by RESRAD-BUILD with those calculated by Excel spreadsheets. For this comparison, all RESRAD-BUILD default parameters except for external exposure pathways were used. For the direct external exposure pathway comparison, a receptor at a height of 1 m from the center of a large source was assumed. For the deposited material exposure pathway, the deposition was assumed to be in a room with a large floor area. For all pathways except the radon inhalation pathway (where the contaminant is Ra-226), the contaminant was assumed to be Na-22 at unit concentration (volume source = 1 Bq g^{-1}, area source = 1 Bq m^{-2}, line source = 1 Bq m^{-1}, and point source = 1 Bq). No inconsistencies between the code output and spreadsheet calculations were found for the following pathways: submersion, direct inadvertent ingestion, inadvertent ingestion of deposited materials, and inhalation of airborne radioactive particulates. For inhalation of aerosol indoor radon progeny, good agreement, to within 0.1%, was obtained. For direct external exposure, good agreement, to within 2%, was obtained; for external exposure to deposited material, agreement within 3% was obtained.

Table 5.2 compares the RESRAD-BUILD calculated doses and MCNP simulated doses for four source types (point, line, area, and volume) and for Au-195, Mn-54, and Co-60 using all

TABLE 5.1 Comparison of RESRAD-BUILD and Spreadsheet Pathway Doses (μSv yr^{-1}) for Different Source Types[a]

Source Type	Direct External	Exposure of Deposited Material	Submersion	Inadvertent Ingestion	Inhalation	Radon Inhalation
RESRAD-BUILD						
Volume	1.77×10^{3}	2.21×10^{-8}	1.57×10^{-6}	2.47×10^{-5}	6.28×10^{-6}	6.13×10^{2}
Area	3.38×10^{-2}	5.26×10^{-8}	3.75×10^{-6}	5.88×10^{-5}	1.49×10^{-5}	8.51×10^{-4}
Line	3.15×10^{-3}	5.26×10^{-8}	3.75×10^{-6}	5.88×10^{-5}	1.49×10^{-5}	8.51×10^{-4}
Point	1.05×10^{-3}	1.46×10^{-9}	1.04×10^{-7}	1.63×10^{-6}	4.15×10^{-7}	2.37×10^{-5}
Spreadsheet						
Volume	1.78×10^{3}	2.17×10^{-8}	1.57×10^{-6}	2.47×10^{-5}	6.28×10^{-6}	6.13×10^{2}
Area	3.32×10^{-2}	5.16×10^{-8}	3.73×10^{-6}	5.88×10^{-5}	1.49×10^{-5}	8.50×10^{-4}
Line	NA	5.16×10^{-8}	3.73×10^{-6}	5.88×10^{-5}	1.49×10^{-5}	8.50×10^{-4}
Point	NA	1.43×10^{-9}	1.04×10^{-7}	1.63×10^{-6}	4.15×10^{-7}	2.36×10^{-5}

[a] The doses for all pathways are the instantaneous doses for unit concentration (volume source = 1 Bq g^{-1}, area source = 1 Bq m^{-2}, line source = 1 Bq m^{-1}, and point source = 1 Bq) of Na-22 except for the radon inhalation pathway, which is for Ra-226 contamination. The direct external exposure pathway dose was compared only for volume and area sources; however, all source type doses were benchmarked with the MCNP code. The comparison was performed with all RESRAD-BUILD default parameters, except for exposure from direct external and deposited material, where the receptor is at a height of 1 m from an infinitely large source area.

TABLE 5.2 Comparison of RESRAD-BUILD[a] and MCNP Dose Values (μSv yr^{-1}) for the Direct External Exposure Pathway

	Point		Line		Area		Volume	
Radionuclide	RESRAD-BUILD	MCNP	RESRAD-BUILD	MCNP	RESRAD-BUILD	MCNP	RESRAD-BUILD	MCNP
Au-195	1.31×10^{-5}	1.30×10^{-5}	7.96×10^{-5}	8.38×10^{-5}	3.08×10^{-4}	2.92×10^{-4}	1.47×10^{1}	1.61×10^{1}
Mn-54	1.33×10^{-4}	1.33×10^{-4}	8.29×10^{-4}	8.38×10^{-4}	2.90×10^{-3}	2.97×10^{-3}	4.36×10^{2}	4.32×10^{2}
Co-60	3.76×10^{-4}	3.76×10^{-4}	2.36×10^{-3}	2.36×10^{-3}	8.27×10^{-3}	8.38×10^{-3}	1.33×10^{3}	1.32×10^{3}

[a] The doses were compared for unit concentration (volume source = 1 Bq g^{-1}, area source = 1 Bq m^{-2}, line source = 1 Bq m^{-1}, and point source = 1 Bq) of source with all RESRAD-BUILD default parameters.

RESRAD-BUILD default parameters to cover a wide energy range. For point sources, good agreement, to within 1%, was obtained; for line, area, and volume sources, agreement within 5% was obtained. The verification results for different types of calculations are discussed below.

Input parameter check. The parameters checked included inhalation, ingestion, air submersion, and external DCFs; external exposure model parameters; and radionuclide half-lives and other decay data.

Source injection rate. Excellent agreement was obtained between the RESRAD-BUILD generated results and spreadsheet calculations.

Air concentration in the room. Air concentrations for four source types were compared for one- and two-room air quality models. Excellent agreement was obtained between the RESRAD-BUILD and spreadsheet calculations.

Air particulate deposition. Air particulate deposition was computed because it is used in two pathways: external exposure due to deposited material and inadvertent ingestion directly from the deposited materials.

Radon pathway model. The radon injection rate and the radon progeny concentration calculations were checked. For the point, line, and area sources, no difference was found in the RESRAD-BUILD and spreadsheet calculations of the source injection rates. However, the volume source injection rates for Rn-222 and Rn-220 were different in two cases. The difference was due to the density used in the calculations. For the spreadsheet calculations, it was assumed that the particle density is input; in RESRAD-BUILD, the source bulk density was assumed. If the same density values are used in RESRAD-BUILD, the results are the same (within round-off errors) as the spreadsheet calculations. No significant differences in the RESRAD-BUILD and spreadsheet calculations were observed in radon progeny concentrations.

Tritium model for volume source. The tritium-transport model used in RESRAD-BUILD for a volume source estimates the injection rate of tritiated water molecules into the indoor air from evaporation. This injection rate is then added to the source injection from erosion to calculate the total source injection. This summed source injection rate is then used to calculate air concentration, air deposition, etc. No inconsistencies between the code output and spreadsheet calculations occurred for the injection rate of tritiated water molecules.

External exposure model. In the RESRAD-BUILD code, two direct exposure models based on the source geometry are used. 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 simple dose integral method. The results of the external models were compared with those from the MCNP transport code. The comparisons were performed at different source-receptor configurations for Co-60, Mn-54, and Au-195. Good agreement (within 5%) was observed.

Different pathway doses. The different pathway doses calculated by the RESRAD-BUILD code were compared with the spreadsheet calculations. No inconsistencies between the code output and spreadsheet calculations were obtained for submersion, direct inadvertent ingestion, inadvertent ingestion of deposited materials, inhalation of airborne radioactive particulates, and tritium volume source. For inhalation of aerosol indoor radon progeny, good agreement, to within 1%, was obtained. For direct external exposure, good agreement to within 2%, was obtained, and for external exposure to deposited material, agreement within 5% was observed. For the total receptor dose, there was no difference between the spreadsheet and code results.

Time dependence in dose calculations. No significant differences in the time-integrated and the average individual pathway dose (obtained by averaging the dose over different time intervals) were obtained.

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APPENDIX A:

INDOOR AIR QUALITY MODEL

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INDOOR AIR QUALITY MODEL

An indoor air quality model has been developed to simulate the transport of radiological contaminants inside a building with air exchange between compartments and with outdoor air. The air quality model assumes that particulates in the indoor air of any compartment are well mixed; therefore, the pollutant concentration is the same for every point in the air within the compartment. The air exchange and ventilation of building compartments are discussed in Section A.1; the models used to calculate the radionuclide concentrations in the indoor air are presented in Section A.2. The adaptation of the air quality model to calculate airborne concentrations of radionuclides, including radon and its progeny, is presented in Section A.3.

A.1 BUILDING VENTILATION AND INFILTRATION

Consider a three-compartment building represented by the schematic configuration shown in Figure A.1. From the principle of conservation of mass, applied at any building compartment i and assuming a steady-state condition, we can write the following general expression:

$$\sum_{\substack{j=0 \\ (j \neq i)}}^{3} Q_{ij} = \sum_{\substack{j=0 \\ (j \neq i)}}^{3} Q_{ji}\,, \tag{A.1}$$

where

Q_{ij} = flow from compartment i to compartment j (m^3/h) and

i or j = compartment index, representing the outdoor air and the first, second, and third compartment for $i = 0$, 1, 2, and 3, respectively.

The net inflow rate, N_{ij}, from compartment i to compartment j is defined as:

$$N_{ij} = Q_{ij} - Q_{ji}\,. \tag{A.2}$$

The value of N_{ij} can be negative, meaning that the net air flow is from compartment j into compartment i.

Now, applying Equation A.1 to compartment number 1 ($i = 1$) yields:

$$Q_{10} + Q_{12} + Q_{13} = Q_{01} + Q_{21} + Q_{31}\,. \tag{A.3}$$

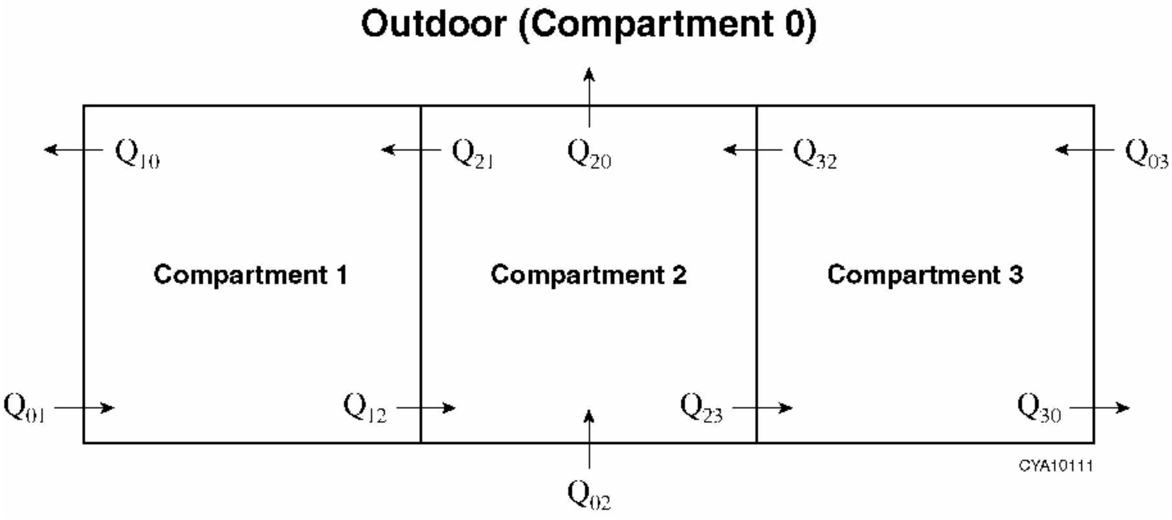

FIGURE A.1 Schematic Representation of the Three-Compartment Building, Showing the Inflow and Outflow of Air in Each Compartment

The RESRAD-BUILD model assumes that compartment 1 is not adjacent to compartment 3 and thus does not communicate directly with compartment 3. Therefore, the following expression applies:

$$Q_{13} = Q_{31} = 0 . \tag{A.4}$$

Equations A.3 and A.4 yield:

$$Q_{10} + Q_{12} = Q_{01} + Q_{21} , \tag{A.5}$$

that is, the total inflow of air to compartment 1 is equal to the total outflow of air from compartment 1.

Similarly, applying Equation A.1 to compartment 2 ($i = 2$) yields:

$$Q_{20} + Q_{21} + Q_{23} = Q_{02} + Q_{12} + Q_{32} . \tag{A.6}$$

Finally, applying Equation A.1 to compartment 3 ($i = 3$) and considering Equation A.4, yields:

$$Q_{30} + Q_{32} = Q_{03} + Q_{23} . \tag{A.7}$$

Note that summing Equations A.5, A.6, and A.7 yields:

$$Q_{10} + Q_{20} + Q_{30} = Q_{01} + Q_{02} + Q_{03} , \tag{A.8}$$

which expresses the fact that the total outflow of air from inside the building is equal to the total inflow of air from outside.

The ventilation (or air exchange) rate of a building (or a compartment) is defined as the number of total volumes of air contained in the building (or the compartment) that is being exchanged with outside air (or air from other compartments) per unit of time. For example, a building with a ventilation rate of 1 h^{-1} has its volume of air replaced once each hour. The air exchange rate λ_i^a for compartment i can be calculated as:

$$\lambda_i^a = \frac{\sum_{\substack{j=0\\(j\neq i)}}^{3} Q_{ji}}{V_i} = \frac{\sum_{\substack{j=0\\(j\neq i)}}^{3} Q_{ij}}{V_i}, \tag{A.9}$$

where V_i is the volume of compartment i.

The building air exchange rate λ_b^a is:

$$\lambda_b^a = \frac{\sum_{i=1}^{3} Q_{i0}}{\sum_{i=1}^{3} V_i} = \frac{\sum_{i=1}^{3} Q_{0i}}{\sum_{i=1}^{3} V_i}. \tag{A.10}$$

The measurement methodology and ranges of air exchange rate are discussed by Yu et al. (1993; 2000) and Nero (1988). A detailed discussion on the air exchange rate for different building types (commercial and residential) and their distributions is given in Appendix J.

A.2 INDOOR AIR CONCENTRATION

Assuming that the pollutant in the indoor air is well mixed within a generic compartment i, the mass balance of a pollutant within the volume V_i, due to the contribution of one specific source, can be expressed as:

$$V_i \frac{d\,C_i^n(t)}{dt} = \lambda_{rn} V_i C_i^{n-1}(t) + \sum_{\substack{j=0\\(j\neq i)}}^{3} \left(Q_{ji} C_j^n(t)\right) - C_i^n(t) \sum_{\substack{j=0\\(j\neq i)}}^{3} Q_{ij} + I_i^n(t) - S_i^n(t), \tag{A.11}$$

where

i = compartment index (i = 0, 1, 2, and 3) representing, respectively, the outdoor air (0th compartment) and the first, second, and third compartments;

$C_i^n(t)$ = concentration at time t of a radionuclide of order n in its radioactive decay series, present in the air of compartment i (pCi/m^3);

λ_{rn} = radioactive decay constant of radionuclide n;

Q_{ij} = flow of air from compartment i to compartment j ($i \neq j$) (m^3/h);

$I_i^n(t)$ = injection rate of radionuclide n into the air of compartment i at time t (pCi/h);

V_i = volume of compartment i (i = 1, 2, and 3) (m^3); and

$S_i^n(t)$ = sink term for radionuclide n in compartment i at time t (pCi/h).

Each term of Equation A.11 represents the variation in time of a part of the mass of the material within the volume V_i due to some specific process. The term at the left side of the equation represents the net change (accumulation or depletion) of the pollutant within volume V_i per unit of time. The first term on the right-hand side of the equation represents the generation of the principal radionuclide of order n due to the radioactive decay of its predecessor of order (n-1). The second term on the right side represents the total contribution due to the inflow of air from the neighbor compartments. The third term represents the loss of material in compartment i due to the total outflow of air into the neighbor compartments. The sink term $S_i^n(t)$ represents the loss of mass of airborne material due to radioactive decay, S_{ri}^n, and deposition, S_{di}^n, and can be expressed as:

$$S_i^n(t) = S_{ri}^n(t) + S_{di}^n(t)\,, \tag{A.12}$$

where

$$S_{ri}^n(t) = \lambda_{rn} V_i C_i^n(t)\,, \tag{A.13}$$

$$S_{di}^n(t) = \lambda_{di} V_i C_i^n(t)\,, \tag{A.14}$$

$$\lambda_{di} = \left(\frac{u_d A_i}{V_i}\right), \tag{A.15}$$

λ_{rn} = radioactive decay constant of radionuclide n (h^{-1}),

λ_{di} = deposition rate (h^{-1}),

u_d = deposition velocity (m/h), and

A_i = horizontal area of compartment i (m^2).

Therefore, from Equations A.12, A.13, and A.14, the sink term S_i^n, can be expressed as:

$$S_i^n(t) = (\lambda_{rn} + \lambda_{di}) V_i C_i^n(t). \tag{A.16}$$

The term $I_i^n(t)$ in Equation A.11 represents the total injection of material (radionuclide n) into the air of compartment i due to the source present within the compartment, I_{Si}^n, and due to resuspension of the material deposited on the floor, I_{Ri}^n. It can be expressed as:

$$I_i^n(t) = I_{Si}^n(t) + I_{Ri}^n(t)\,, \tag{A.17}$$

where $I_{Si}^n(t)$ is the source-dependent term representing the direct injection rate of radioactive material into the indoor air. It depends on the mechanical removal or erosion rate of the source (or on the radon/HTO diffusion process, for the case of radon source or tritium volume source) and must be evaluated specifically for each defined source and operational scenario. The resuspension term, $I_{Ri}^n(t)$, depends on the resuspension rate, λ_R, and the deposition velocity, u_d, and can be expressed as (see Appendix B):

$$I_{Ri}^n(t) = \left(\frac{\lambda_R u_d A_i}{\lambda_{rn} + \lambda_R}\right) C_i^n(t)\,, \tag{A.18}$$

$$I_{Ri}^n(t) = \left(\frac{\lambda_R}{\lambda_{rn} + \lambda_R}\right)\left(\frac{u_d A_i}{V_i}\right) V_i C_i^n(t)\,, \tag{A.19}$$

or

$$I_{Ri}^n(t) = \left(\frac{\lambda_R \lambda_{di}}{\lambda_{rn} + \lambda_R}\right) V_i C_i^n(t)\,. \tag{A.20}$$

Therefore, from Equations A.17 and A.20, the injection rate I_i^n can be expressed as:

$$I_i^n(t) = I_{Si}^n(t) + \left(\frac{\lambda_R \lambda_{di}}{\lambda_{rn} + \lambda_R}\right) V_i C_i^n(t)\,. \tag{A.21}$$

Substituting Equations A.16 and A.21 into Equation A.11 yields the following general mass balance equation:

$$V_i \frac{d\,C_i^n(t)}{dt} = \lambda_{rn} V_i C_i^{(n-1)}(t) + \sum_{\substack{j=0 \\ j\neq i}}^{3} \left(Q_{ji} C_j^n(t)\right) - C_i^n(t) \sum_{\substack{j=0 \\ j\neq i}}^{3} Q_{ij} + I_{Si}^n(t)$$

$$+ \left(\frac{\lambda_R \lambda_{di}}{\lambda_{rn} + \lambda_R}\right) V_i C_i^n(t) - \left(\lambda_{rn} + \lambda_{di}\right) V_i C_i^n(t)\,. \tag{A.22}$$

Now, substituting the steady-state compartment mass balance Equation A.1 into A.22 and assuming steady-state conditions, Equation A.22 becomes (for each compartment *i*):

$$\lambda_{rn} V_i C_i^{(n-1)}(t) + \sum_{\substack{j=0\\ j\neq i}}^{3} \left(Q_{ji} C_j^n(t)\right) - C_i^n(t) \sum_{\substack{j=0\\ j\neq i}}^{3} Q_{ji} + I_{Si}^n(t)$$

$$+\left(\frac{\lambda_R \lambda_{di}}{\lambda_{rn}+\lambda_R}\right) V_i C_i^n(t) - \left(\lambda_{rn}+\lambda_{di}\right) V_i C_i^n(t) = 0, \tag{A.23}$$

$$\left[\left(\lambda_{rn}+\lambda_{di}-\frac{\lambda_R \lambda_{di}}{\lambda_{rn}+\lambda_R}\right) V_i + \sum_{\substack{j=0\\ j\neq i}}^{3} Q_{ji}\right] C_i^n(t) - \sum_{\substack{j=0\\ j\neq i}}^{3} \left(Q_{ji} C_j^n(t)\right)$$

$$= I_{Si}^n(t) + \lambda_{rn} V_i\, C_i^{(n-1)}(t). \tag{A.24}$$

Applying Equation A.24 to all three internal compartments of the building ($i = 1, 2, 3$) generates a system of three equations related to the three unknowns, C_1^n, C_2^n, and C_3^n, which can then be solved.

So, applying Equation A.24 for compartments 1, 2, and 3 yields, respectively:

$$\left[\left(\lambda_{rn}+\lambda_{d1}-\frac{\lambda_R\ \lambda_{d1}}{\lambda_{rn}+\lambda_R}\right) V_1 + \sum_{\substack{j=0\\ j\neq 1}}^{3} Q_{j1}\right] C_1^n(t) - Q_{21} C_2^n(t) - Q_{31} C_3^n(t)$$

$$= I_{S1}^n(t) + Q_{01} C_0^n(t) + \lambda_{rn} V_1 C_1^{(n-1)}(t)\,; \tag{A.25}$$

$$-Q_{12} C_1^n(t) + \left[\left(\lambda_{rn}+\lambda_{d2}-\frac{\lambda_R\ \lambda_{d2}}{\lambda_{rn}+\lambda_R}\right) V_2 + \sum_{\substack{j=0\\ j\neq 2}}^{3} Q_{j2}\right] C_2^n(t) - Q_{32} C_3^n(t)$$

$$= I_{S2}^n(t) + Q_{02} C_0^n(t) + \lambda_{rn} V_2 C_2^{(n-1)}(t)\,; \tag{A.26}$$

$$-Q_{13} C_1^n(t) - Q_{23} C_2^n(t) + \left[\left(\lambda_{rn}+\lambda_{d3}-\frac{\lambda_R \lambda_{d3}}{\lambda_{rn}+\lambda_R}\right) V_3 + \sum_{\substack{j=0\\ j\neq 3}}^{3} Q_{j3}\right] C_3^n(t)$$

$$= I_{S3}^n(t) + Q_{03} C_0^n(t) + \lambda_{rn} V_3 C_3^{(n-1)}(t). \tag{A.27}$$

Using a matrix notation, the system of equations represented by Equations A.25, A.26, and A.27 can be rewritten as:

$$A \times x = b\ , \tag{A.28}$$

where A is a systematic coefficient matrix of order 3 that can be written as:

$$A = \begin{bmatrix} \left(\lambda_{rn}+\lambda_{d1}-\frac{\lambda_R\lambda_{d1}}{\lambda_{rn}+\lambda_R}\right)V_1+\Sigma^3_{\substack{j=0\\ j\neq 1}}Q_{j1} & -Q_{21} & -Q_{31} \\ -Q_{12} & \left(\lambda_{rn}+\lambda_{d2}-\frac{\lambda_R\lambda_{d2}}{\lambda_{rn}+\lambda_R}\right)V_2+\Sigma^3_{\substack{j=0\\ j\neq 2}}Q_{j2} & -Q32 \\ -Q_{13} & -Q_{23} & \left(\lambda_{rn}+\lambda_{d3}-\frac{\lambda_R\lambda_{d3}}{\lambda_{rn}+\lambda_R}\right)V_3+\Sigma^3_{\substack{j=0\\ j\neq 3}}Q_{j3} \end{bmatrix} \tag{A.29}$$

The vectors of the unknown variables and the independent terms, ***x*** and ***b***, are written respectively as:

$$\text{x} = \begin{bmatrix} C^n_1(t) \\ C^n_2(t) \\ C^n_3(t) \end{bmatrix}; \qquad \text{b} = \begin{bmatrix} I^n_{s1}(t)+Q_{01}C^n_0(t)+\lambda_{rn}V_1C^{(n-1)}_1(t) \\ I^n_{s2}(t)+Q_{02}C^n_0(t)+\lambda_{rn}V_2C^{(n-1)}_2(t) \\ I^n_{s3}(t)+Q_{03}C^n_0(t)+\lambda_{rn}V_3C^{(n-1)}_3(t) \end{bmatrix}. \tag{A.30}$$

Equation A.28 is a general expression representing the air quality model. It can be solved for the concentrations $C^n_1(t)$, $C^n_2(t)$, and $C^n_3(t)$ of a radionuclide n. Compartments 1 and 3 are assumed to be separated, and no air flows between them. Therefore, $Q_{13} = Q_{31} = 0$. In the current version of RESRAD-BUILD, the outdoor air concentration $C^n_0(t)$ is assumed to be zero.

A.3 ADAPTATION OF THE AIR QUALITY MODEL

This air quality model can be used to calculate the airborne concentration of a radionuclide of order n at time t in its radioactive decay series or the concentration of radon and its decay progeny in the air of compartments 1, 2, and 3. Use of the model to simulate these cases would require the following adaptation.

Case 1 — Airborne concentration of a radionuclide of order n:

- The injection rate $I^n_{Si}(t)$ is evaluated according to the behavior of the source, such as source erosion rate (see Appendix D).

- The concentration $C^{(n-1)}_i(t)$ is given by the concentration of the predecessor radionuclide in the series. If $n = 1$, then $C^{(n-1)}_i(t)$ is made equal to zero.

Case 2 —Airborne radon concentration:

- The rate of radon injection, $I_{Si}^{n}(t)$, from the source into the indoor air of compartment i is evaluated by solving the radon transport equation within the source (see Appendix C).
- The order number n is made equal to 1.
- The precursor concentration $C_i^0(t)$ is equal to the concentration of radium-226 (for the case of radon-222) or thorium-228 (for the case of radon-220) in the air of compartment i, due to a direct release from the source. $C_i^0(t)$, which will be used for the radon calculations, can be calculated according to Case 1.
- In most cases, the radon calculations could be performed by neglecting the contribution from the indoor air precursor concentration $C_i^0(t)$.
- The deposition velocity for the radon gas is negligible; therefore, $\lambda_{di} = 0$.

Case 3 —Airborne concentration of radon progeny:

- The order number n is made equal to 2, 3, and 4.
- $C_i^1(t) = C_i^{Rn}(t)$ for each i. Note that $C_i^1(t)$ is calculated according to Case 2.
- The concentration of the radon progeny is determined by solving Equation A.28 sequentially with $n = 2$, 3, and 4.
- The injection rate is $I_{Si}^{n}(t) = 0$ for all i and n.
- Specific details are shown in Appendix C.

Case 4 —Airborne concentration of tritium:

- For point, line, or area sources, the injection rate, $I_{Si}^{n}(t)$, is calculated by using the "removable fraction" parameter that describes the behavior of the source material.
- For volume source, the injection rate, $I_{Si}^{n}(t)$, is calculated by considering two mechanisms: the erosion mechanism and the vaporization/diffusion mechanism. Specific discussions on the erosion and the vaporization/diffusion mechanism are provided in Appendixes D and G, respectively.
- The concentration of $C_i^{(n-1)}(t)$ is zero since there is no precursor for tritium.

A.4 REFERENCES

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APPENDIX B:

AIR PARTICULATE DEPOSITION

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The objective of the deposition model is to evaluate the surface concentration, $C_{di}^{n}(t)$, of the principal radionuclide of order *n* in the decay series, at each compartment *i* of the building, as a function of the respective airborne concentration in the indoor air of compartment *i*. For the derivation of the deposition model, consider the schematic representation of a generic compartment *i*, as shown in Figure B.1.

Thus, from a mass balance principle applied to the projected plane surface of compartment *i*, the following expression can be derived:

$$A_i \frac{d\,C_{di}^{n}(t)}{dt} = u_d\, A_i\, C_i^{n}(t) - \lambda_{rn}\, A_i\, C_{di}^{n}(t) - \lambda_R\, A_i\, C_{di}^{n}(t)\,, \tag{B.1}$$

where

$C_{di}^{n}(t)$ = surface concentration at time *t* of principal radionuclide of order *n* in the radioactive decay series, due to deposition at the projected horizontal surface of compartment *i* (pCi/m^2);

$C_i^{n}(t)$ = airborne concentration at time *t* of radionuclide *n*, in the indoor air of compartment *i* (pCi/m^3);

u_d = average deposition velocity of the airborne radioactive dust particulates (m/h);

λ_{rn} = radioactive decay constant of radionuclide *n* (1/h);

λ_R = resuspension rate of deposited dust particulates into the air, or the fraction of the deposited dust particulates that is resuspended into the indoor air per unit of time (1/h); and

A_i = surface area of the floor of compartment *i* (m^2).

Each term in Equation B.1 represents the variation of mass (activity) on the projected plane surface, per unit of time, due to different processes. The term on the left-hand side represents the total accumulation/depletion of mass (activity) on the surface. The first term on the right-hand side represents the addition of mass due to the deposition of dust particulates. The second term represents the loss of mass due to radioactive decay. Finally, the third term represents the loss of mass due to the resuspension of deposited dust particulates back into the indoor air.

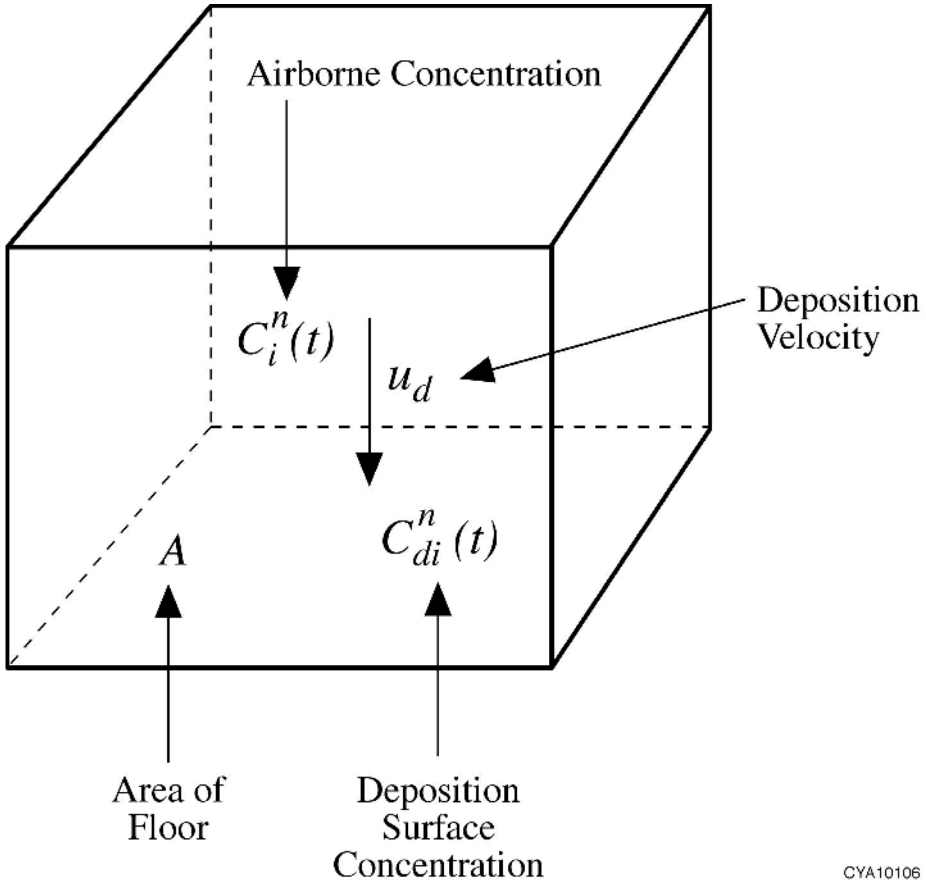

FIGURE B.1 Schematic Representation of a Compartment *i* of the Building, Showing the Deposition of Dust Particulates onto the Projected Horizontal Surface

Assuming a steady-state condition, the mass balance Equation B.1 yields:

$$u_d \; C_i^n(t) - \lambda_{rn} C_{di}^n(t) - \lambda_R C_{di}^n(t) = 0 \,, \qquad \text{(B.2)}$$

or

$$C_{di}^n(t) = \left(\frac{u_d}{\lambda_{rn} + \lambda_R} \right) C_i^n(t) \,. \qquad \text{(B.3)}$$

Equation B.3 is used to calculate $C_{di}^n(t)$, at each compartment *i*, as a function of the respective airborne concentration $C_i^n(t)$. The contribution for the total injection rate at each compartment *i* due to resuspension can be evaluated from the last term of Equation B.1. That is:

$$I_{Ri}^n(t) = \lambda_R \, A_i \, C_{di}^n(t) \,, \qquad \text{(B.4)}$$

where I_{Ri}^{n} is the rate of injection of radionuclide n into the indoor air of compartment i due to resuspension of deposited dust particulates (pCi/h). Substituting Equation B.3 into B.4 yields:

$$I_{Ri}^{n}(t)=\left(\frac{\lambda_R u_d A_i}{\lambda_{rn}+\lambda_R}\right)C_i^n(t). \tag{B.5}$$

Equation B.5 is used in the air quality model (see Appendix A) to represent the component of the injection rate due to resuspension.

APPENDIX C:

RADON AND ITS PROGENY CONCENTRATION

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C.1 RADON FLUX

The airborne radon concentration in the indoor air of compartment *i* is calculated by using the generic air quality model, as described in Appendix A. However, to apply the air quality model, it is necessary to evaluate the radon injection rate $I_{Si}^{Rn}(t)$ directly from the source into the indoor air of compartment *i*. The rate of radon injection into the indoor air depends on the concentration of the radon parent within the source and on the geometric and physical properties of the source. Therefore, $I_{Si}^{Rn}(t)$ is defined for each type of source: surface, line, point, and volume. For surface, line, and point sources, $I_{Si}^{Rn}(t)$ (pCi/s) at time *t* is calculated as:

$$I_{Si}^{Rn}(t) = F^{Rn}\,\lambda\,A_{total}^{p}(t)\,, \tag{C.1}$$

where

F^{Rn} = fraction of radon generated within the source that escapes from the source and is injected into the air (dimensionless),

λ = radon decay constant (s^{-1}), and

$A_{total}^{p}(t)$ = total amount of the radon parent radionuclide present within the source at time *t* (pCi).

For a volume source, the radon injection rate, $I_{Si}^{Rn}(t)$, is evaluated differently, according to the following:

$$I_{Si}^{Rn}(t) = A_s J(t), \tag{C.2}$$

where

A_s = surface area of the face of the volume source that is exposed to the indoor air of compartment *i* (m^2) and

$J(t)$ = flux density of radon activity (or radon flux, for short) through the exposed face of the volume source [pCi/($m^2 \times s$)] at time *t*.

The variables F^{Rn} and $A_{total}^{p}(t)$ are given as input parameters to the model. Therefore, the calculation of $I_{Si}^{Rn}(t)$ for surface, line, and point sources is a straightforward procedure, based directly on Equation C.1. Yet, for volume sources, the radon flux is not given as an input parameter and must be evaluated specifically for each case. Sections C.1.1 to C.1.3 describe the model for calculating the radon flux $J(t)$ for the cases in which the volume sources are defined.

C.1.1 Mathematical Model

Consider an initial three-dimensional configuration of a volume source composed of up to five distinct regions, as shown in Figure C.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 is neglected, the distribution of radon concentration in the lateral (boundary) zones within the source could be assumed invariable. Neglecting the value of J_{lat} increases the calculated values of J_i and J_j, resulting in a conservative estimation of indoor radon concentration. Under these assumptions, the three-dimensional configuration in Figure C.1 can be further simplified and represented by a five-zone, one-dimensional configuration, as shown in Figure C.2.

The general mass balance equation for radon activity in a two-phase porous system composed of solid phase and gas phase (no moisture content) in any region represented in Figure C.2 can be expressed as:

$$\frac{\partial(nC)}{\partial t} = -\vec{\nabla} \times \vec{J} - nR + nS\ , \tag{C.3}$$

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^{-1}),

R = radon sink term (pCi × m^{-3} × s^{-1}),

S = radon source term (pCi × m^{-3} × s^{-1}), and

n = total (volumetric) porosity.

Each term of Equation C.3 expresses the variation of radon activity per unit of total volume and per time. These terms are functions of time and/or space. For simplicity in expression, the time and space dependency is 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:

$$\vec{J} = -nD_e \vec{\nabla} C\ , \tag{C.4}$$

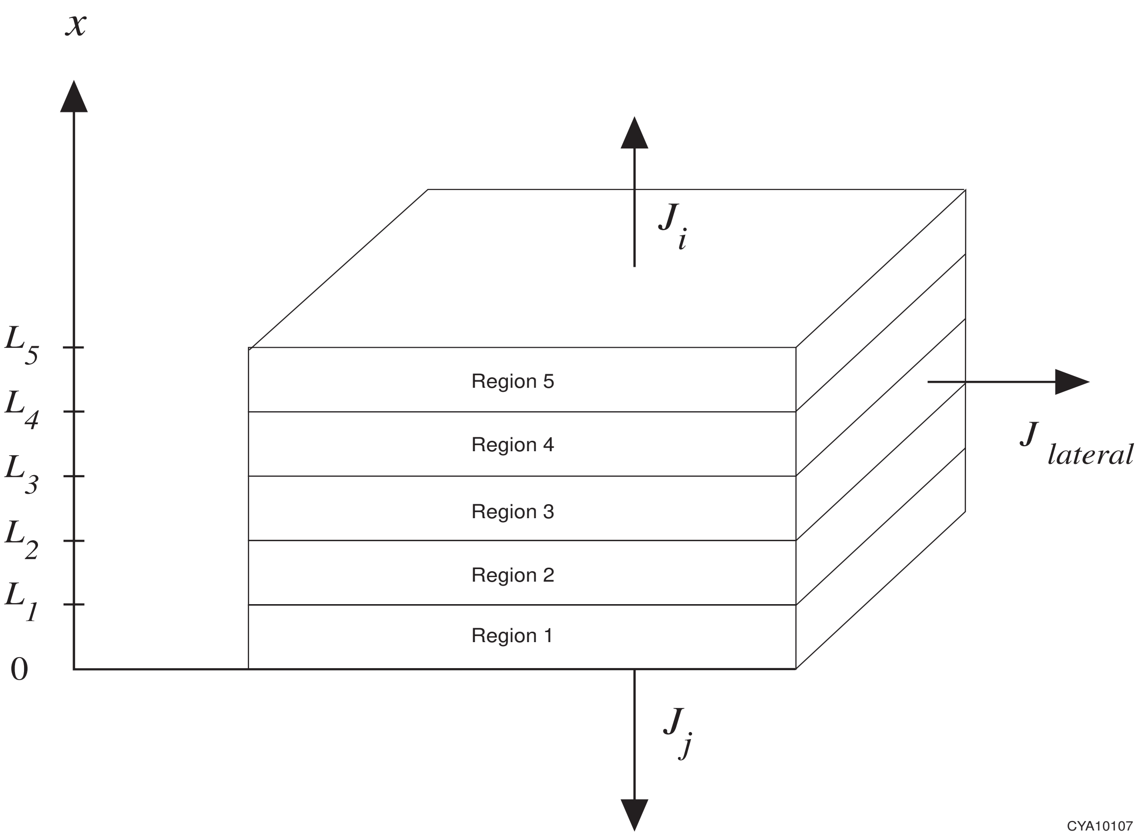

FIGURE C.1 Three-Dimensional Schematic Representation of a Volume Source (showing its five distinct regions and the radon flux densities at the surfaces of the source)

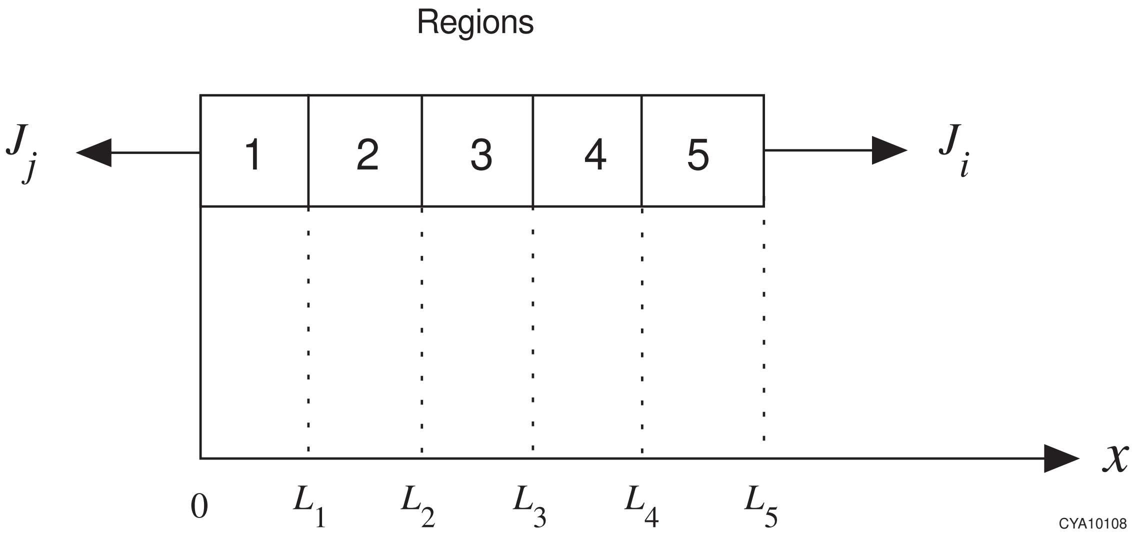

FIGURE C.2 One-Dimensional Schematic Representation of a Volume Source (showing its five distinct regions and radon flux densities at the surfaces of the source)

where D_e is the effective diffusion coefficient of radon in the porous medium ($m^2 \cdot s^{-1}$).

The source of radon activity into the pore volume of the porous medium can be evaluated by the following expression:

$$S = \varepsilon \rho_s C^p \lambda \left(\frac{1-n}{n} \right), \tag{C.5}$$

where

ε = radon emanating factor,

ρ_s = density of solid phase of the porous medium (kg/m^3),

C^p = concentration of the radon parent radionuclide in the solid phase (pCi/kg),

λ = radon decay constant (1/s), and

n = total porosity of the medium.

The decay of radon activity (the sink term) in the pore volume can be expressed as:

$$R = \lambda C. \tag{C.6}$$

Now, considering the steady-state condition in the one-dimensional configuration and the constitutive expressions above, the general mass balance equation for radon becomes:

$$-\frac{d}{dx}\left(n D_e \frac{dC}{dx} \right) + n\lambda C = nS, \tag{C.7a}$$

$$-nD_e \frac{d^2 C}{dx^2} + n\lambda C = nS, \tag{C.7b}$$

or

$$-D_e \frac{d^2 C}{dx^2} + \lambda C = S, \tag{C.7c}$$

where the porosity n and the diffusion coefficient D_e are assumed invariable with distance.

Equation C.7a 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:

$$C = K_1 e^{rx} + K_2 e^{-rx} + \frac{S}{\lambda}, \tag{C.8a}$$

or

$$C = K_1 e^{\frac{x}{L_D}} + K_2 e^{-\frac{x}{L_D}} + \frac{S}{\lambda}, \tag{C.8b}$$

where K_1 and K_2 are linear coefficients to be determined from the boundary conditions, and r represents the inverse of the diffusion length, L_D, and is given by:

$$r = \frac{1}{L_D} = \sqrt{\frac{\lambda}{D_e}}, \tag{C.9}$$

where L_D is the diffusion length (m).

Equation C.8 represents the profile of radon activity concentration, C, within a specific one-dimensional region where all the parameters (such as D_e, 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 C.8 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.

C.1.2 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:

$$C_{(x=0)} = 0 \tag{C.10a}$$

and

$$C_{(x=L_5)} = 0\,. \tag{C.10b}$$

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:

$$C_{(x=x_i-)} = C_{(x=x_i+)} \tag{C.11a}$$

and

$$\left[nD_e\frac{dC}{dx}\right]_{(x=x_i-)} = \left[nD_e\frac{dC}{dx}\right]_{(x=x_i+)}. \tag{C.11b}$$

C.1.3 Analytical Solution: General Multilayer Configuration

The general solution for the one-dimensional radon diffusion equation, Equation C.8, can be applied to represent the profile of radon activity concentration and flux density along a multiregion, 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 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 C.8 into this configuration results in the following system of equations:

$$C(x) = K_{11}e^{r_1x} + K_{12}e^{-r_1x} + \frac{S_1}{\lambda}, \quad 0 \le x \le L_1, \tag{C.12a}$$

$$C(x) = K_{21}e^{r_2x} + K_{22}e^{-r_2x} + \frac{S_2}{\lambda}, \quad L_1 \le x \le L_2, \tag{C.12b}$$

$$C(x) = K_{31}e^{r_3x} + K_{32}e^{-r_3x} + \frac{S_3}{\lambda}, \quad L_2 \le x \le L_3. \tag{C.12c}$$

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 C.11, 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 C.10a or C.10b.

Thus, applying the condition represented by Equation C.10 on the first boundary of the system (at $x = 0$) yields:

$$K_{11} + K_{12} = -\frac{S_1}{\lambda}. \tag{C.13a}$$

Then, applying the condition represented by Equation C.11 on an internal boundary between region i and region $(i + 1)$ at the distance $(x = L_i)$ of the system yields:

$$\left(e^{r_i L_i}\right)K_{i1} + \left(e^{-r_i L_i}\right)K_{i2} + \frac{S_i}{\lambda} = \left(e^{r_{i+1} L_i}\right)K_{(i+1)1} + \left(e^{-r_{i+1} L_i}\right)K_{(i+1)2} + \frac{S_{i+1}}{\lambda}, \tag{C.13b}$$

and

$$\begin{gathered}\left(n_i D_{e_i} r_i e^{r_i L_i}\right)K_{i1} - \left(n_i D_{e_i} r_i e^{-r_i L_i}\right)K_{i2} = \\ \left(n_{i+1} D_{e_{i+1}} r_{i+1} e^{r_{i+1} L_i}\right)K_{(i+1)1} - \left(n_{i+1} D_{e_{i+1}} r_{i+1} e^{-r_{i+1} L_i}\right)K_{(i+1)2}.\end{gathered} \tag{C.13c}$$

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:

$$\left(e^{r_3 L_3}\right)K_{31} + \left(e^{-r_3 L_3}\right)K_{32} = -\frac{S_3}{\lambda}. \tag{C.13d}$$

The system of equations represented by Equations C.13a through C.13d contains six ($2n = 6$) equations related to the six unknowns, K_{ij}. It can be represented by the following matrix equation:

$$A \times k = b, \tag{C.14}$$

where A is a pentadiagonal coefficient matrix that can be written as:

$$A = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ e^{r_1 L_1} & e^{-r_1 L_1} & -e^{r_2 L_1} & -e^{-r_2 L_1} & 0 & 0 \\ D_1 r_1 e^{r_1 L_1} & -D_1 r_1 e^{-r_1 L_1} & -D_2 r_2 e^{r_2 L_1} & D_2 r_2 e^{-r_2 L_1} & 0 & 0 \\ 0 & 0 & e^{r_2 L_2} & e^{-r_2 L_2} & -e^{r_3 L_2} & -e^{-r_3 L_2} \\ 0 & 0 & D_2 r_2 e^{r_2 L_2} & -D_2 r_2 e^{-r_2 L_2} & -D_3 r_3 e^{r_3 L_2} & D_3 r_3 e^{-r_3 L_2} \\ 0 & 0 & 0 & 0 & e^{r_3 L_3} & e^{-r_3 L_3} \end{bmatrix}. \tag{C.15a}$$

To save space in writing the matrix identity above, the product $n_i D_{e_i}$ was substituted by the bulk diffusion coefficient D_i. By definition, the product of porosity times the effective diffusion coefficient is equal to the bulk diffusion coefficient. That is,

$$n_i D_{e_i} = D_i \,. \tag{C.15b}$$

The vectors of the unknown variables and the independent terms *k* and *b* are written, respectively, as:

$$k = \begin{bmatrix} K_{11} \\ K_{12} \\ K_{21} \\ K_{22} \\ K_{31} \\ K_{32} \end{bmatrix} \quad \text{and} \quad b = \begin{bmatrix} -\dfrac{S_1}{\lambda} \\ \left(\dfrac{S_2 - S_1}{\lambda}\right) \\ 0 \\ \left(\dfrac{S_3 - S_2}{\lambda}\right) \\ 0 \\ -\dfrac{S_3}{\lambda} \end{bmatrix} . \tag{C.15c}$$

The solution of Equation C.14 provides the values of the coefficients K_{ij}, which could then be used in Equation C.12 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 C.4 and C.12. Thus, at $x = 0$, the flux $J\ (x = 0)$ is given by:

$$J_{(x=0)} = -n_1 D_{e1} \Delta C_{(x=0)}$$

$$= -n_1 D_{e1} \left(r_1 K_{11} e^{r_1 x} - r_1 K_{12} e^{-r_1 x} \right)_{(x=0)},$$

or

$$J_{(x=0)} = -n_1 D_{e_1} r_1 \left(K_{11} - K_{12} \right). \tag{C.16}$$

Similarly, for $X = L_3$, the flux density $J(x = L_3)$ is given by:

$$J_{(x=L_3)} = -n_3\, D_{e3}\, r_3 \left(K_{31} e^{r_3 L_3} - K_{32} e^{-r_3 L_3}\right). \tag{C.17}$$

Finally, after calculating J_i from Equations C.16 and C.17, the radon injection rate from each face of the volume source into the indoor air of the respective compartment i can be calculated from Equation C.2. This methodology is implemented in the RESRAD-BUILD code for up to five regions of different material.

C.2 RADON PROGENY

The objective of the radon dosimetry model is to evaluate the effective dose equivalent due to inhalation of the airborne radon progeny. The model presented here is an adaptation of the radon dosimetry model currently used in the RESRAD computer code (Yu et al. 2001).

Consider a three-compartment building as shown in Figure C.3. The terms shown in the figure 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 all the time spent inside the building in which the individual stays in the compartment i (with i = 1, 2, 3 for the first, second, and third compartment, respectively) (dimensionless); C_i^n is the indoor air concentration of radon decay products (n = 2, 3, 4) for either radon-222 or radon-220 progeny 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

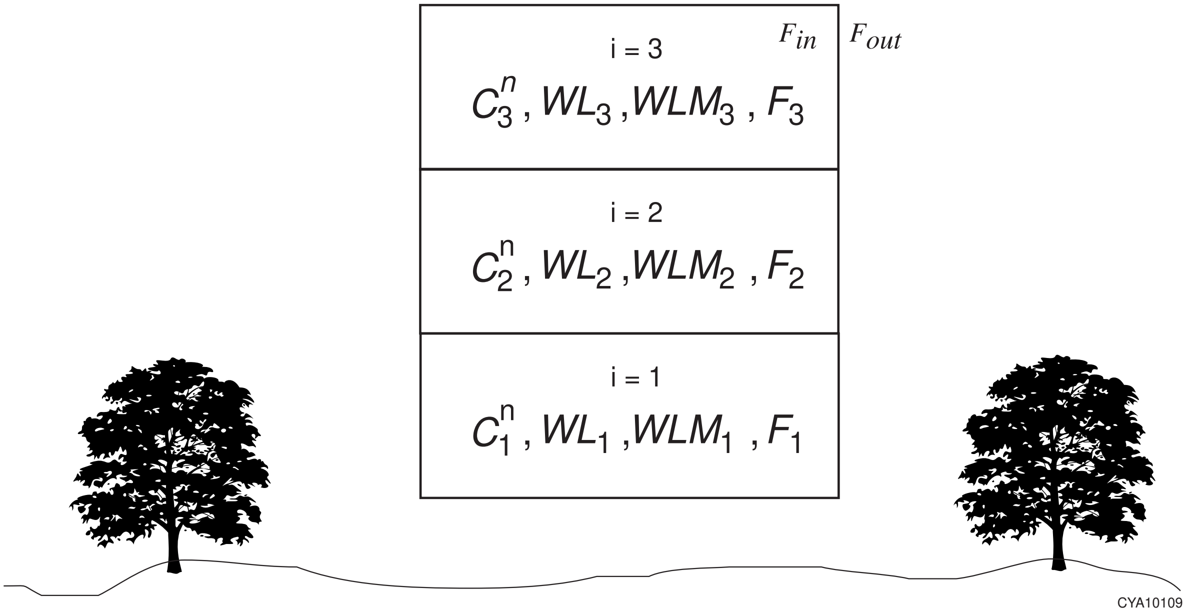

FIGURE C.3 Schematic Representation of the Three-Compartment Building

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 decay products for either radon-222 or radon-220, in the compartment i (i = 1, 2, 3) (in units of working level month [WLM]); and D_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/yr).

The algorithm to calculate the radon decay product dosimetry can be summarized in the following four steps:

1. Calculate C_i^n the indoor air concentration of radon and its decay products (obtained by applying the air quality model, Appendix A).

2. Calculate the WL_i, based on the values of C_i^n.

3. Calculate the exposure (WLM_i) to the radon decay products, based on the WL_i and the exposure time.

4. Calculate the effective dose equivalent D_i^{Rn}, based on the WLM_i and the related dose conversion factors (see Section C.5).

C.2.1 Airborne Radon Progeny Concentration

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 C.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, and po designate, respectively, the free, attached, and plated-out states in which the radon decay products may exist.

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 of Figure C.4. At this free state, the atom of element A

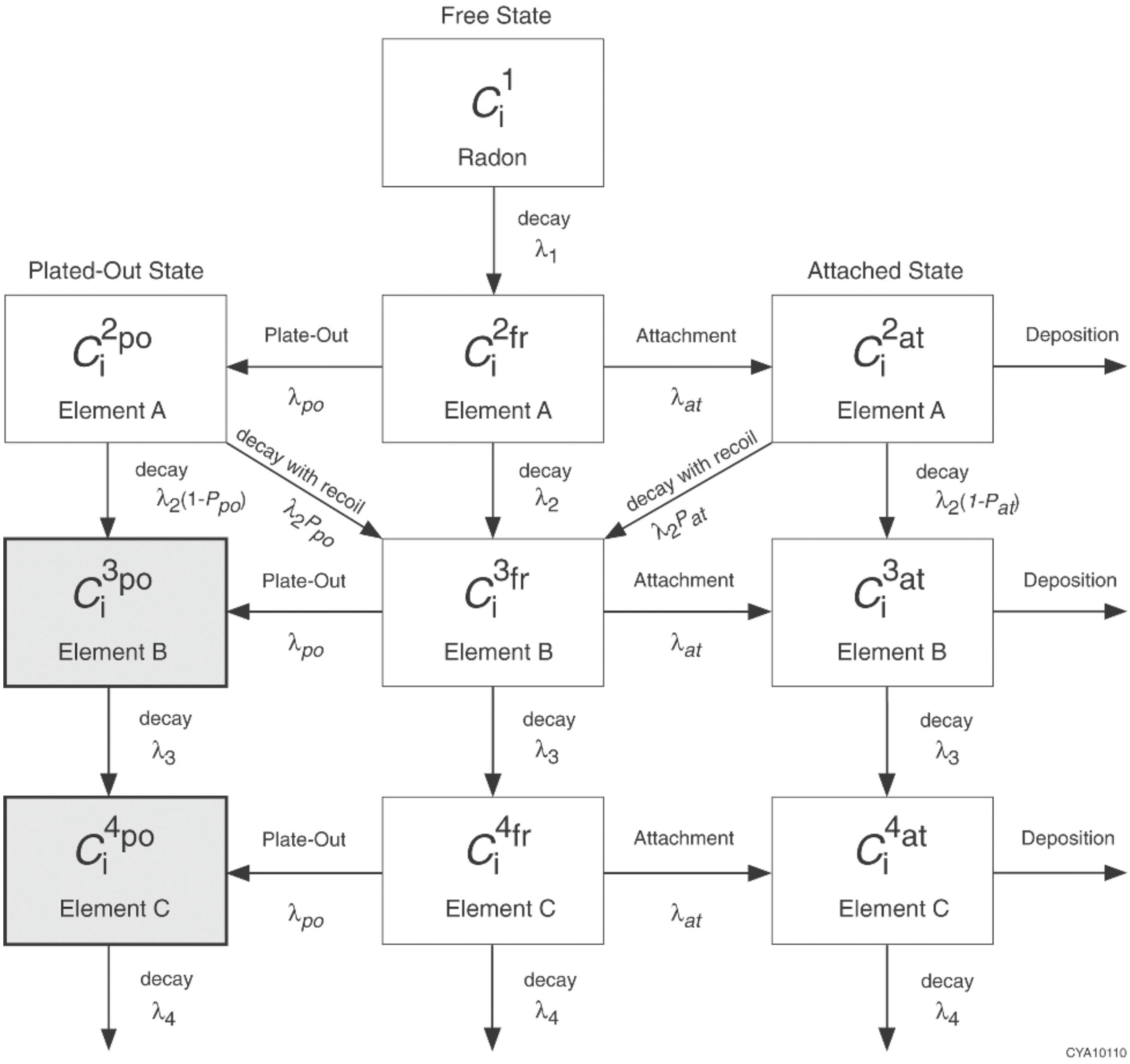

FIGURE C.4 Schematic Representation of the Interrelationships among the Several States of the Short-Lived Radon Decay Products (The superscripts 1, 2, 3, and 4 represent radon and its first three decay products, respectively.)

may follow several possible courses: (1) attach to airborne particulates (one block at right in Figure C.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 C.4); or (4) be ventilated out of compartment *i*.

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, together with the deposition of the air particulates; or (4) be ventilated out of compartment *i*.

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.

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*, either in the attached or plated-out 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} and P_{po} are the probabilities that a free atom of element *B* will be created due to recoil and detachment from attached and plated-out 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 C.1. The default vault 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 (as described in Appendix A) to find the radon concentration first and, then, to each unshaded block of Figure C.4 to find the concentration of the radon progeny at each state. Therefore, in relation to the radon progeny calculations, the air quality model will be applied in eight consecutive steps to calculate (1) the radon concentration; (2) the concentrations of element *A* in the free, attached, and plated-out states; (3) the concentrations of element *B* in the free and attached states; and (4) the concentrations of element *C* in the free and attached 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.

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[1] The recoil process is usually only considered for polonium-218 because of the substantial recoil energy (6 MeV) associated with alpha decay.

TABLE C.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).

C.2.1.1 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 (see Equation A.23 in Appendix A):

$$0 = \lambda_2 V_i C_i^1 + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{2fr} - C_i^{2fr} \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} - \left(\lambda_2 + \lambda_{at} + \lambda_{po}\right) V_i C_i^{2fr} , \tag{C.18}$$

where the terms related to the injection rate and the deposition-resuspension are neglected. Equation C.18 can be rewritten in the appropriate format to be used in the indoor air quality model as:

$$\left[\left(\lambda_2 + \lambda_{at} + \lambda_{po}\right) V_i + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji}\right] C_i^{2fr} - \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{2fr} = \lambda_2 V_i C_i^1 . \tag{C.19}$$

C.2.1.2 Mass Balance of Element *A* — Attached State

A mass balance of element *A* in the attached state within compartment *i* yields:

$$\begin{aligned} 0 = {} & \lambda_{at} V_i C_i^{2fr} + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{2at} - C_i^{2at} \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} - \lambda_2 V_i C_i^{2at} - \lambda_{di} V_i C_i^{2at} \\ & + \left(\frac{\lambda_R \lambda_{di}}{\lambda_2 + \lambda_R}\right) V_i C_i^{2at} , \end{aligned} \tag{C.20}$$

or

$$\left\{\left[\lambda_2 + \lambda_{di}\left(1 - \frac{\lambda_R}{\lambda_2 + \lambda_R}\right)\right] V_i + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji}\right\} C_i^{2at} - \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{2at} = \lambda_{at} V_i C_i^{2fr} . \tag{C.21}$$

C.2.1.3 Mass Balance of Element *A* — Plated-Out State

A mass balance of element *A* in the plated-out state within compartment *i* yields:

$$0 = \lambda_{po} V_i C_i^{2fr} - \lambda_2 V_i C_i^{2po}, \tag{C.22}$$

or

$$C_i^{2po} = \left(\frac{\lambda_{po}}{\lambda_2} \right) C_i^{2fr}. \tag{C.23}$$

C.2.1.4 Mass Balance of Element *B* — Free State

A mass balance of element *B* in the free state within compartment *i* yields:

$$\begin{aligned} 0 = {} & \lambda_3 V_i C_i^{2fr} + P_{at} \lambda_3 V_i C_i^{2at} + P_{po} \lambda_3 V_i C_i^{2po} + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{3fr} \\ & - C_i^{3fr} \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} - \left(\lambda_3 + \lambda_{at} + \lambda_{po} \right) V_i C_i^{3fr}, \end{aligned} \tag{C.24}$$

or

$$\begin{aligned} & \left[\left(\lambda_3 + \lambda_{at} + \lambda_{po} \right) V_i + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} \right] C_i^{3fr} - \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{3fr} \\ & = \lambda_3 V_i C_i^{2fr} + P_{at} \lambda_3 V_i C_i^{2at} + P_{po} \lambda_3 V_i C_i^{2po}. \end{aligned} \tag{C.25}$$

C.2.1.5 Mass Balance of Element *B* — Attached State

A mass balance of element *B* in the attached state within compartment *i* yields:

$$\begin{aligned} 0 = {} & \left(1 - P_{at} \right) \lambda_3 V_i C_i^{2at} + \lambda_{at} V_i C_i^{3fr} + \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} C_j^{3at} - C_i^{3at} \sum_{\substack{j=0 \\ j \neq i}}^{3} Q_{ji} \\ & - \lambda_3 V_i C_i^{3at} - \lambda_{di} V_i C_i^{3at} + \left(\frac{\lambda_R \lambda_{di}}{\lambda_3 + \lambda_R} \right) V_i C_i^{3at}, \end{aligned} \tag{C.26}$$

or

$$\left\{\left[\lambda_3+\lambda_{di}\left(1-\frac{\lambda_R}{\lambda_3+\lambda_R}\right)\right]V_i+\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}\right\}C_i^{3at}-\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}C_j^{3at} = (1-P_{at})\lambda_3V_iC_i^{2at}+\lambda_{at}V_iC_i^{3fr}. \tag{C.27}$$

C.2.1.6 Mass Balance of Element *C* — Free State

A mass balance of element *C* in the free state within compartment *i* yields:

$$0=\lambda_4V_iC_i^{3fr}+\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}C_j^{4fr}-C_i^{4fr}\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}-(\lambda_4+\lambda_{at}+\lambda_{po})V_iC_i^{4fr}, \tag{C.28}$$

or

$$\left[(\lambda_4+\lambda_{at}+\lambda_{po})V_i+\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}\right]C_i^{4fr}-\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}C_j^{4fr}=\lambda_4V_iC_i^{3fr}. \tag{C.29}$$

C.2.1.7 Mass Balance of Element *C* — Attached State

A mass balance of element *C* in the attached state within compartment *i* yields:

$$0=\lambda_4V_iC_i^{3at}+\lambda_{at}V_iC_i^{4fr}+\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}C_j^{4at}-C_i^{4at}\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji} -\lambda_4V_iC_i^{4at}-\lambda_{di}V_iC_i^{4at}+\left(\frac{\lambda_R\lambda_{di}}{\lambda_4+\lambda_R}\right)V_iC_i^{4at}, \tag{C.30}$$

or

$$\left\{\left[\lambda_4+\lambda_{di}\left(1-\frac{\lambda_R}{\lambda_4+\lambda_R}\right)\right]V_i+\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}\right\}C_i^{4at}-\sum_{\substack{j=0\\ j\neq i}}^{3}Q_{ji}C_j^{4at} =\lambda_4V_iC_i^{3at}+\lambda_{at}V_iC_i^{4fr}. \tag{C.31}$$

C.3 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:

$$WL_i^{\text{Rn-222}} = \left(1.03 \times 10^{-6}\right) C_i^2 + \left(5.07 \times 10^{-6}\right) C_i^3 + \left(3.73 \times 10^{-6}\right) C_i^4 \ , \tag{C.32}$$

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). Similarly, for thoron (radon-220), the WL_i value is evaluated as:

$$WL_i^{\text{Rn-220}} = \left(9.48 \times 10^{-10}\right) C_i'^2 + \left(1.23 \times 10^{-4}\right) C_i'^3 + \left(1.17 \times 10^{-5}\right) C_i'^4 \ , \tag{C.33}$$

where $C_i'^2$, $C_i'^3$, and $C_i'^4$ are the concentrations of polonium-216, lead-212, and bismuth-212, respectively, in the indoor air of compartment *i* (pCi/m^3).

C.4 WORKING LEVEL MONTH

The normalized 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:

$$WLM_i = \left(\frac{24 \cdot ED}{170}\right) F_{in} F_i \overline{WL_i} \ , \tag{C.34}$$

where

24 = number of hours per day (h/d),

170 = number of working hours per month (h/mo),

ED = exposure duration (*d*), and

$\overline{WL_i}$ = average working level in compartment *i* for the exposure duration.

The fractions of time in Equation C.34 are defined in Section C.2. The indoor time fraction F_{in} and the outdoor time fraction F_{out} should sum up to 1. That is:

$$F_{in} + F_{out} = 1.0 \ . \tag{C.35}$$

The time fraction in compartment *i*, F_i, can be less than, equal to, or greater than 1 in the RESRAD-BUILD code. When F_i is greater than 1, it can be used to calculate the collective dose.

The total exposure to the indoor airborne radon decay products is then evaluated by summing Equation C.34 from all three compartments. That is:

$$WLM = \sum_{i=1}^{3} WLM_i = \left(\frac{24 \cdot \mathrm{ED}}{170} \right) F_{in} \sum_{i=1}^{3} \left(F_i \overline{WL_i} \right). \tag{C.36}$$

Note that Equations C.34 and C.36 can be used to calculate the *WLM* from exposure to either radon-222 or radon-220 progenies.

C.5 RADON PROGENY DOSIMETRY

The effective dose equivalent due to the exposure to radon decay products in the indoor air of each compartment *i* can be evaluated as:

$$D_i = K\, WLM_i DCF\ , \tag{C.37}$$

where

D_i = effective dose equivalent due to exposure to radon decay products (from either radon-222 or radon-220) in compartment *i* (mrem/yr),

DCF = dose conversion factor for the inhalation of radon decay products (mrem/*WLM*), and

K = multiplication factor to account for the extrapolation of doses from uranium mines to homes.

For the radon-222 decay products, the values of the *DCF* and the *K* factor are equal to 1,000 (mrem/*WLM*) and 0.76 (dimensionless), respectively. Similarly, for the radon-220 decay products, the values of the *DCF* and the *K* factor are equal to 350 (mrem/*WLM*) and 0.42 (dimensionless), respectively.

The total effective dose equivalent resulting from the inhalation of airborne radon decay products is then given by summing the contribution from the occupancy of each compartment of the building. That is:

$$D = \sum_{i=1}^{3} D_i = K\, WLM\ \ DCF\ . \tag{C.38}$$

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 contribution from each decay series. That is:

$$D_{total} = D_{Rn\text{-}222} + D_{Rn\text{-}220}\ . \tag{C.39}$$

C.6 REFERENCES

Bruno, R.C., 1983, "Verifying a Model of Radon Decay Product Behavior Indoors," *Health Physics* 45:471.

Jacobi, W., 1972, "Activity and Potential Alpha Plan Energy of Radon 222 and Radon 220 Daughters in Different Air Atmosphere," *Health Physics* 22:331.

Porstendörfer, J., 1984, "Behavior of Radon Daughter Products in Indoor Air," *Radiation Protection Dosimetry* 7:107.

Yu, C., et al., 2001, *User's Manual for RESRAD Version 6*, ANL/EAD-4, Argonne National Laboratory, Argonne, Ill., Sept.

APPENDIX D:

INHALATION OF AIRBORNE RADIOACTIVE DUST

APPENDIX D:

INHALATION OF AIRBORNE RADIOACTIVE DUST

D.1 DUST RELEASE RATE

The inhalation pathway can be included in the building contamination model by performing three sets of calculations:

- The mechanical removal of material from the source and the rate of release of radionuclides into the indoor air of each compartment,
- The indoor airborne concentration of the radionuclides released into the air (using the indoor air quality model), and
- The inhalation of airborne radioactive dust and the associated effective dose equivalent.

For a volume source, the release rate of a principal radionuclide *n* into compartment *i* is calculated by:

$$I_{si}^{n}(t) = \frac{10{,}000\, f\; E\; A_s\; \rho_{bs}\; C_s^n(t)}{24}, \tag{D.1}$$

where

$I_{si}^{n}(t)$ = injection rate of radionuclide *n* into the indoor air of compartment *i* at time *t* (pCi/h),

f = fraction of mechanically removed or eroded material that becomes airborne (air release fraction),

E = source removal or erosion rate (cm/d),

A_s = effective surface area of the source (m^2),

ρ_{bs} = bulk density of the source material (g/cm^3),

$C_s^n(t)$ = radionuclide concentration in the source material (pCi/g) at time *t*,

24 = time conversion factor (number of hours per day) (h/d), and

10,000 = area conversion factor (cm^2/m^2).

For surface, line, and point sources, the release rate of a principal radionuclide n into compartment i at time t is calculated by:

$$I_{Si}^{n}(t) = \begin{cases} \dfrac{f_R f Q_s^n(t)}{24 T_R} & t < T_R \\ 0 & t \geq T_R, \end{cases} \tag{D.2}$$

where

f_R = removable fraction of the source material,

f = fraction of removed material that becomes airborne (air release fraction [ARF]),

T_R = time to remove material from the source (lifetime) (d),

$Q_s^n(t)$ = total radionuclide activity in the source (pCi) at time t, and

24 = time conversion factor (number of hours per day) (h/d).

The indoor air concentration, $C_i^n(t)$, at time t of each principal radionuclide n at each compartment i of the building is calculated by using the indoor air quality model discussed in Appendix A.

D.2 INHALATION DOSE

The total committed effective dose equivalent $D_{ih}^n(t)$ from time t to $t + ED$ due to the inhalation of radionuclide n in the indoor air of compartment i, can be calculated with the following equation:

$$D_{ih}^n(t) = F_{in}\ F_i\ IR\ \overline{C_i^n(t)}\ ED\ DCF_h^n, \tag{D.3}$$

where

$D_{ih}^n(t)$ = total effective dose equivalent due to inhalation of radionuclide n in compartment i from time t to $t + ED$ (mrem),

ED = exposure duration (d),

F_{in} = fraction of time spent indoors (dimensionless),

F_i = fraction of indoor time that is spent at compartment i (dimensionless),

IR = inhalation rate (m^3/d),

$\overline{C_i^n(t)}$ = average concentration of radionuclide n (pCi/m^3) over the exposure duration ED starting at time t in the indoor air of compartment i, and

DCF_h^n = inhalation dose conversion factor for radionuclide n (mrem/pCi).

The dose conversion factor DCF_h^n is discussed in Section D.3. The calculation of average concentration, $C_i^n(t)$, is discussed in Appendix H.

The total dose at time t from full occupancy of the building is evaluated as a sum of the dose at each compartment i at time t. That is:

$$D_{th}^n(t) = \sum_{i=1}^{3}\left(D_{in}^n(t)\right) = \left(F_{in}\ \ IR\ DCF_h^n ED\right)\sum_{i=1}^{3}\left(F_i\ \overline{C_i^n(t)}\right) \tag{D.4}$$

D.3 DOSE CONVERSION FACTORS

The default inhalation dose conversion factors used in the RESRAD-BUILD code are the same as those used in the RESRAD code (Yu et al. 2001). Values of dose conversion factors for inhalation were taken from a U.S. Environmental Protection Agency report (Eckerman et al. 1988) and are listed in Table D.1. The values listed in Table D.1 are for dust particles with an activity median aerodynamic diameter (AMAD) of 1 µm. Values for different inhalation classes are also listed in Table D.1. The inhalation class for inhaled radioactive material is defined according to the material's rate of clearance from the lung. The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively. If the inhalation class for a radionuclide is not known, the largest dose conversion factor for that radionuclide should be used. The default value for a radionuclide used in the RESRAD-BUILD code is the largest dose conversion factor for that radionuclide.

TABLE D.1 Committed Effective Dose Equivalent Conversion Factors (DCF_h^n) for Inhalation[a]

Radionuclide[b]	Inhalation Class	DCF_h^n (mrem/pCi)	Radionuclide[b]	Inhalation Class	DCF_h^n (mrem/pCi)
H-3	(H_2O)[c]	6.40×10^{-8}	Tc-99	D	1.02×10^{-6}
C-14	(organic)[c]	2.09×10^{-6}		W	8.33×10^{-6}
	(CO)[c]	2.90×10^{-9}	Ru-106+D	D	5.62×10^{-5}
	(CO_2)[c]	2.35×10^{-8}		W	1.18×10^{-4}
Na-22	D[d]	7.66×10^{-6}		Y	4.77×10^{-4}
Al-26	D	7.96×10^{-5}	Ag-108m+D	D	3.01×10^{-5}
	W	7.22×10^{-5}		W	2.53×10^{-5}
Cl-36	D	2.24×10^{-6}		Y	2.83×10^{-4}
	W	2.19×10^{-5}	Ag-110m+D	D	3.96×10^{-5}
K-40	D	1.24×10^{-5}		W	3.09×10^{-5}
Ca-41	W	1.35×10^{-6}		Y	8.03×10^{-5}
Mn-54	D	5.25×10^{-6}	Cd-109	D	1.14×10^{-4}
	W	6.70×10^{-6}		W	3.96×10^{-5}
Fe-55	D	2.69×10^{-6}		Y	4.51×10^{-5}
	W	1.34×10^{-6}	Sb-125+D	D	3.79×10^{-6}
Co-57	W	2.63×10^{-6}		W	1.39×10^{-5}
	Y	9.07×10^{-6}	I-129	D	1.74×10^{-4}
Co-60	W	3.31×10^{-5}	Cs-134	D	4.63×10^{-5}
	Y	2.19×10^{-4}	Cs-135	D	4.55×10^{-6}
Ni-59	D	1.32×10^{-6}	Cs-137+D	D	3.19×10^{-5}
	W	9.18×10^{-7}	Ce-144+D	W	2.16×10^{-4}
	(vapor)[c]	2.70×10^{-6}		Y	3.74×10^{-4}
Ni-63	D	3.10×10^{-6}	Pm-147	W	2.58×10^{-5}
	W	2.30×10^{-6}		Y	3.92×10^{-5}
	(vapor)[c]	6.29×10^{-6}	Sm-147	W	7.47×10^{-2}
Zn-65	Y	2.04×10^{-5}	Sm-151	W	3.00×10^{-5}
Ge-68+D	D	1.80×10^{-6}	Eu-152	W	2.21×10^{-4}
	W	5.19×10^{-5}	Eu-154	W	2.86×10^{-4}
Sr-90+D	D	2.47×10^{-4}	Eu-155	W	4.14×10^{-5}
	Y	1.31×10^{-3}	Gd-152	D	2.43×10^{-1}
Nb-94	W	3.61×10^{-5}		W	6.48×10^{-2}
	Y	4.14×10^{-4}	Gd-153	D	2.38×10^{-5}

TABLE D.1 (Cont.)

Radionuclide[b]	Inhalation Class	DCF_h^n (mrem/pCi)	Radionuclide[b]	Inhalation Class	DCF_h^n (mrem/pCi)
Au-195	D	4.33×10^{-7}	U-234	D	2.73×10^{-3}
	W	4.18×10^{-6}		W	7.88×10^{-3}
	Y	1.30×10^{-5}		Y	1.32×10^{-1}
Tl-204	D	2.41×10^{-6}	U-235+D	D	2.54×10^{-3}
Bi-207	D	3.23×10^{-6}		W	7.29×10^{-3}
	W	2.00×10^{-5}		Y	1.23×10^{-1}
Pb-210+D	D	2.32×10^{-2}	U-236	D	2.59×10^{-3}
Ra-226+D	W	8.60×10^{-3}		W	7.44×10^{-3}
Ra-228+D	W	5.08×10^{-3}		Y	1.25×10^{-1}
Ac-227+D	D	6.72	U-238+D	D	2.45×10^{-3}
	W	1.74		W	7.03×10^{-3}
	Y	1.31		Y	1.18×10^{-1}
Th-228+D	W	2.53×10^{-1}	Np-237+D	W	5.40×10^{-1}
	Y	3.45×10^{-1}	Pu-238	W	3.92×10^{-1}
Th-229+D	W	2.16		Y	2.88×10^{-1}
	Y	1.75	Pu-239	W	4.29×10^{-1}
Th-230	W	3.26×10^{-1}		Y	3.08×10^{-1}
	Y	2.62×10^{-1}	Pu-240	W	4.29×10^{-1}
Th-232	W	1.64		Y	3.08×10^{-1}
	Y	1.15	Pu-241+D	W	8.25×10^{-3}
Pa-231	W	1.28		Y	4.96×10^{-3}
	Y	8.58×10^{-1}	Pu-242	W	4.11×10^{-1}
U-232	D	1.27×10^{-2}		Y	2.93×10^{-1}
	W	1.49×10^{-2}	Pu-244+D	W	4.03×10^{-1}
	Y	6.59×10^{-1}		Y	3.89×10^{-1}
U-233	D	2.79×10^{-3}	Am-241	W	4.44×10^{-1}
	W	7.99×10^{-3}	Am-243+D	W	4.40×10^{-1}
	Y	1.35×10^{-1}	Cm-243	W	3.07×10^{-1}
			Cm-244	W	2.48×10^{-1}
			Cm-248	W	1.65
			Cf-252	W	1.37×10^{-1}
				Y	1.57×10^{-1}

[a] Inhalation factors are for an AMAD of 1 µm.

[b] Dose conversion factors for entries labeled by "+D" are aggregated dose conversion factors for intake of a principal radionuclide together with radionuclides with a half-life greater than 10 minutes of the associated decay chain in secular equilibrium.

[c] Indicates a gaseous material.

[d] The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively.

D.4 REFERENCES

Eckerman, K.F., et al., 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,* EPA-520/1-88-020, Federal Guidance Report No. 11, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C.

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APPENDIX E:

INGESTION OF RADIOACTIVE MATERIAL

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INGESTION OF RADIOACTIVE MATERIAL

The ingestion pathway considered in the RESRAD-BUILD code includes (1) inadvertent ingestion of removable (loose) material directly from the source and (2) inadvertent ingestion of radioactive dust particulates deposited onto surfaces or food within the compartments of the building.

E.1 DIRECT INGESTION OF REMOVABLE MATERIAL

The component of the total effective dose equivalent, $D_{il}^{n}(t)$ at time *t* over the exposure duration *ED*, due to the ingestion of loose material directly from the source in compartment *i* containing radionuclide *n*, can be calculated by the following equations. For volume sources:

$$D_{il}^{n}(t) = \left(24\ ED\ F_{in} F_{i}\right) ER\ \overline{C_{s}^{n}(t)}\ DCF_{g}^{n}\ , \tag{E.1}$$

where

$D_{il}^{n}(t)$ = component of the total effective dose equivalent due to ingestion of loose material directly from the source containing radionuclide *n* at time *t* over the exposure duration, *ED,* in compartment *i* (mrem);

24 = time conversion factor (h/d);

ED = exposure duration (d);

F_{in} = fraction of time spent indoors (dimensionless);

F_{i} = fraction of indoor time spent at compartment *i* (dimensionless);

ER = ingestion rate of loose material directly from the source (g/h);

$\overline{C_{s}^{n}(t)}$ = average concentration of radionuclide *n* in the source material (pCi/g) over the exposure duration, *ED*, starting at time *t*; and

DCF_{g}^{n} = ingestion dose conversion factor related to radionuclide *n* (mrem/pCi).

For surface, line, and point sources, the component of the total effective dose equivalent at time t over the exposure duration ED due to ingestion of loose material can be calculated as:

$$D_{il}^{n}(t) = \left(24\ ED\ F_{in} F_{i}\right) ER_{l}\ f_{R} \overline{Q_{s}^{n}(t)}\ DCF_{g}^{n}\ , \qquad \text{(E.2)}$$

where

f_R = removable fraction of the source material,

ER_l = ingestion rate of loose material directly from the source as a fraction of the source per unit time (1/h), and

$\overline{Q_s^n(t)}$ = total average radionuclide activity over the exposure duration, ED, in the source (pCi) at time t.

The calculations of average concentration, $\overline{C_s^n(t)}$ and $\overline{Q_s^n(t)}$, are discussed in Appendix H.

E.2 INGESTION OF DEPOSITED RADIOACTIVE DUST

The component of the total effective dose equivalent, $D_{id}^n(t)$, at time t over the exposure duration ED due to the ingestion of radioactive dust particulates deposited onto surfaces of compartment i containing radionuclide n, can be given by the following equation:

$$D_{id}^{n}(t) = \left(24\ ED\ F_{in} F_{i}\right) SER\ \overline{C_{di}^{n}(t)}\ DCF_{g}^{n}\ , \qquad \text{(E.3)}$$

where

$D_{id}^n(t)$ = component of the total effective dose equivalent due to ingestion of deposited dust particulates containing radionuclide n in compartment i at time t over the exposure duration (mrem);

SER = surface ingestion rate or the ingestion rate of dust particulates deposited onto horizontal surfaces (m^2/h);

$\overline{C_{di}^n(t)}$ = average surface concentration of radionuclide n deposited onto horizontal surfaces of compartment i (pCi/m^2) over the exposure duration, ED, starting at time t; and

DCF_g^n = ingestion dose conversion factor for radionuclide n (mrem/pCi).

The total ingestion dose, $D_i^n(t)$, over the exposure duration at time *t* is evaluated as a sum of the dose contribution from both components, D_{ie}^n and D_{id}^n, listed above. Calculation of $\overline{C_{di}^n(t)}$ is discussed in Appendix H.

E.3 DOSE CONVERSION FACTORS

The ingestion dose conversion factors used in the RESRAD-BUILD code are the same as those used in the RESRAD code (Yu et al. 2001). Values of dose conversion factors for ingestion were taken from a U.S. Environmental Protection Agency report (Eckerman et al. 1988) and are tabulated in Table E.1. Dose conversion factors 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 (1979–1982). The dose conversion factors used in RESRAD-BUILD are the values corresponding to the largest values of f_1 in Table E.1

TABLE E.1 Committed Effective Dose Equivalent Conversion Factors (DCF_g^n) for Internal Radiation from Ingestion

Radionuclide[a]	f_1[b]	DCF_g^n (mrem/pCi)	Radionuclide[a]	f_1[b]	DCF_g^n (mrem/pCi)
H-3	1.0	6.40×10^{-8}	Pm-147	3.00×10^{-4}	1.05×10^{-6}
C-14	1.0	2.09×10^{-6}	Sm-147	3.00×10^{-4}	1.85×10^{-4}
Na-22	1.0	1.15×10^{-5}	Sm-151	3.00×10^{-4}	3.89×10^{-7}
Al-26	1.00×10^{-2}	1.46×10^{-5}	Eu-152	1.00×10^{-3}	6.48×10^{-6}
Cl-36	1.0	3.03×10^{-6}	Eu-154	1.00×10^{-3}	9.55×10^{-6}
K-40	1.0	1.86×10^{-5}	Eu-155	1.00×10^{-3}	1.53×10^{-6}
Ca-41	3.00×10^{-1}	1.27×10^{-6}	Gd-152	3.00×10^{-4}	1.61×10^{-4}
Mn-54	1.00×10^{-1}	2.77×10^{-6}	Gd-153	3.00×10^{-4}	1.17×10^{-6}
Fe-55	1.00×10^{-1}	6.07×10^{-7}	Au-195	1.00×10^{-1}	1.06×10^{-6}
Co-57	3.00×10^{-1}	1.18×10^{-6}	Tl-204	1.0	3.36×10^{-6}
	5.00×10^{-2}	7.44×10^{-7}	Bi-207	5.00×10^{-2}	5.48×10^{-6}
Co-60	3.00×10^{-1}	2.69×10^{-5}	Pb-210+D	2.00×10^{-1}	7.27×10^{-3}
	5.00×10^{-2}	1.02×10^{-5}	Po-210	1.00×10^{-1}	1.90×10^{-3}
Ni-59	5.00×10^{-2}	2.10×10^{-7}	Ra-226+D	2.00×10^{-1}	1.33×10^{-3}
Ni-63	5.00×10^{-2}	5.77×10^{-7}	Ra-228+D	2.00×10^{-1}	1.44×10^{-3}
Zn-65	5.00×10^{-1}	1.44×10^{-5}	Ac-227+D	1.00×10^{-3}	1.48×10^{-2}
Ge-68+D	1.0	1.41×10^{-6}	Th-228+D	2.00×10^{-4}	8.08×10^{-4}
Sr-90+D	3.00×10^{-1}	1.53×10^{-4}	Th-229+D	2.00×10^{-4}	4.03×10^{-3}
	1.00×10^{-2}	2.28×10^{-5}	Th-230	2.00×10^{-4}	5.48×10^{-4}
Nb-94	1.00×10^{-2}	7.14×10^{-6}	Th-232	2.00×10^{-4}	2.73×10^{-3}
Tc-99	8.00×10^{-1}	1.46×10^{-6}	Pa-231	1.00×10^{-3}	1.06×10^{-2}
Ru-106+D	5.00×10^{-2}	2.74×10^{-5}	U-232	5.00×10^{-2}	1.31×10^{-3}
Ag-108m+D	5.00×10^{-2}	7.62×10^{-6}		2.00×10^{-3}	6.92×10^{-5}
Ag-110m+D	5.00×10^{-2}	1.08×10^{-5}	U-233	5.00×10^{-2}	2.89×10^{-4}
Cd-109	5.00×10^{-2}	1.31×10^{-5}		2.00×10^{-3}	2.65×10^{-5}
Sb-125+D	1.00×10^{-1}	3.65×10^{-6}	U-234	5.00×10^{-2}	2.83×10^{-4}
	1.00×10^{-2}	3.64×10^{-6}		2.00×10^{-3}	2.61×10^{-5}
I-129	1.0	2.76×10^{-4}	U-235+D	5.00×10^{-2}	2.67×10^{-4}
Cs-134	1.0	7.33×10^{-5}		2.00×10^{-3}	2.81×10^{-5}
Cs-135	1.0	7.07×10^{-6}	U-236	5.00×10^{-2}	2.69×10^{-4}
Cs-137+D	1.0	5.00×10^{-5}		2.00×10^{-3}	2.47×10^{-5}
Ce-144+D	3.00×10^{-4}	2.11×10^{-5}			

TABLE E.1 (Cont.)

Radionuclide[a]	f_1[b]	DCF_g^n (mrem/pCi)	Radionuclide[a]	f_1[b]	DCF_g^n (mrem/pCi)
U-238+D	5.00×10^{-2}	2.69×10^{-4}		1.00×10^{-5}	7.66×10^{-7}
	2.00×10^{-3}	3.74×10^{-5}	Pu-242	1.00×10^{-3}	3.36×10^{-3}
Np-237+D	1.00×10^{-3}	4.44×10^{-3}		1.00×10^{-4}	3.50×10^{-4}
Pu-238	1.00×10^{-3}	3.20×10^{-3}		1.00×10^{-5}	4.92×10^{-5}
	1.00×10^{-4}	3.36×10^{-4}	Pu-244+D	1.00×10^{-3}	3.32×10^{-3}
	1.00×10^{-5}	4.96×10^{-5}		1.00×10^{-4}	3.60×10^{-4}
Pu-239	1.00×10^{-3}	3.54×10^{-3}		1.00×10^{-5}	6.32×10^{-5}
	1.00×10^{-4}	3.69×10^{-4}	Am-241	1.00×10^{-3}	3.64×10^{-3}
	1.00×10^{-5}	5.18×10^{-5}	Am-243+D	1.00×10^{-3}	3.63×10^{-3}
Pu-240	1.00×10^{-3}	3.54×10^{-3}	Cm-243	1.00×10^{-3}	2.51×10^{-3}
	1.00×10^{-4}	3.69×10^{-4}	Cm-244	1.00×10^{-3}	2.02×10^{-3}
	1.00×10^{-5}	5.18×10^{-5}	Cm-248	1.00×10^{-3}	1.36×10^{-2}
Pu-241+D	1.00×10^{-3}	6.85×10^{-5}	Cf-252	1.00×10^{-3}	1.08×10^{-3}
	1.00×10^{-4}	6.92×10^{-6}			

[a] Dose conversion factors for entries labeled "+D" are aggregated dose conversion factors for intake of a principal radionuclide together with radionuclides with a half-life greater than 10 minutes of the associated decay chain in secular equilibrium.

[b] Fraction of a stable element entering the GI tract that reaches body fluids.

E.4 REFERENCES

Eckerman, K.F., et al., 1988, *Limiting Values of Radionuclide Intake and Air Concentration and Dose Conversion Factors for Inhalation, Submersion, and Ingestion,* EPA-520/1-88-020, Federal Guidance Report No. 11, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C.

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APPENDIX F:

EXTERNAL RADIATION EXPOSURE

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EXTERNAL RADIATION EXPOSURE

The external radiation exposure model is used to calculate the effective doses from (1) direct external exposure to the sources, (2) external exposure to deposited material (modeled as an area source), and (3) external exposure to radioactive dust in the indoor air (air submersion). For the air submersion and deposition pathways (2 and 3), the exposure to the receptor is from the radioactive air concentration in the same room only.

Two direct exposure models based on the geometrical type of sources are used. The model for the point and line contamination is a simple dose integral method. The model for area and volume sources is based on a semiinfinite slab source, with corrections for geometrical factors.

The volume source can have up to five layers, with any one layer being contaminated. The exposure model uses the methodology described by Kamboj et al. (1998, 2002) for corrections due to finite size with extension to include differences due to the source material. The area source is treated as a volume source of small thickness (0.01 cm) with unit density. 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.

F.1 EXTERNAL DOSE FROM CONTAMINATED VOLUME SOURCE

The total 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:

$$D_{iV}^{n}(t) = (ED/365)\,F_{in}\,F_i\,\overline{C_{sV}^{n}(\mathrm{t})}\,DCF_{v}^{n}\,F_{G}^{n}, \tag{F.1}$$

where

ED = exposure duration (d);

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 = FGR-12 dose conversion factor for infinite volume source [(mrem/yr)/(pCi/g)];

F_n^G = geometrical factor for finite area, source thickness, shielding, source material, and position of receptor relative to the source for radionuclide n; and

$\overline{C_{sV}^n(t)}$ = average volume source concentration (pCi/g) of radionuclide n over the exposure duration, ED, starting at time t.

The calculation of $\overline{C_{sV}^n(t)}$ is discussed in Appendix H.

The geometrical factor, F_G, is the ratio of the effective dose equivalent for the actual source to the effective dose equivalent for the standard source. The standard source is a contaminated soil of infinite depth and lateral extent with no cover. The geometrical factor is expressed as the product of the depth-and-cover factor, F_{CD}, an area and material factor, F_{AM}, and the off-set factor, $F_{OFF\text{-}SET}$.

Dose conversion factors in Federal Guidance Report-12 (FGR-12) (Eckerman and Ryman 1993) are given for surface and uniformly distributed volume sources at four specific thickness (1, 5, 15 cm, and effectively infinite) with a soil density of 1.6 g/cm^3. FGR-12 assumes that sources are infinite in lateral extent. In actual situations, sources can have any depth, shape, cover, and size. A depth-and-cover factor function, F_{CD}, was developed with regression analysis to express the attenuation for radionuclides. Three independent radionuclide-specific parameters were determined by using the effective dose equivalent values of FGR-12 at different depths. Kamboj et al. (1998) describe how the depth-and-cover factor function was derived using the effective dose equivalent values of FGR-12 at different depths. A depth-and-cover factor function was derived from the depth factor function by considering both dose contribution and attenuation from different depths:

$$F_{CD} = \frac{D(T_c = t_c, T_S = t_s)}{D(T_c = 0, T_S = \infty)} = Ae^{-K_A \rho_c t_c}\left(1 - e^{-K_A \rho_S t_S}\right) + Be^{-K_B \rho_c t_c}\left(1 - e^{-K_B \rho_S t_s}\right), \quad \text{(F.2)}$$

where

A, B = fit parameters (dimensionless);

K_A, K_B = fit parameters (cm^2/g);

t_c = shielding thickness (cm) (it is the sum of all shielding thicknesses between the source and the receptor; the shielding is placed immediately adjacent to the source);

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 source depth, t_s = zero; the DCF should match the contaminated surface DCF.

Fitted values for all the four unknown parameters (A, B, K_A, K_B) were found for 67 radionuclides available in the RESRAD-BUILD computer code and are listed in Table F.1.

For actual geometries (finite area and different materials), 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 contamination but also on source thickness, shielding thickness, gamma energies, and source material through its attenuation and buildup factors. All energies from radionuclide decay are considered separately and weighted by its yield y, energy E, and an energy-dependent coefficient K to convert from air-absorbed dose to effective dose equivalent:

$$F_{AM} = \frac{\sum_{Energies:j} y_j E_j K_j \int_{V'} \frac{B(x')e^{-\propto x'}}{(x')^2} dV'}{\sum_{Energies:j} y_j E_j K_j \int_{V} \frac{B(x)e^{-\propto x}}{(x)^2} dV}, \tag{F.3}$$

where at source thickness t,

$$(x')^2 = r^2 + (t_a + t_c + t)^2, \tag{F.4}$$

$$(x)^2 = r^2 + (100 + t)^2 \tag{F.5}$$

$$\propto = \frac{(t_a \propto_a + t_c \propto_c + t \propto_s)}{(t_a + t_c + t)} \tag{F.6}$$

TABLE F.1 Fitted Parameters A_i, B_i, K_{Ai}, and K_{Bi} Used to Calculate Depth and Cover Factors for 67 Radionuclides

Radionuclide	A_i	B$_i$	K_{Ai}	K_{Bi}
H-3	0.00	0.00	0.00	0.00
C-14	6.421×10^{-1}	3.579×10^{-1}	2.940×10^{-1}	3.369
Na-22	9.263×10^{-1}	7.37×10^{-2}	8.74×10^{-2}	1.331
Al-26	9.276×10^{-1}	7.24×10^{-2}	7.94×10^{-2}	1.284
Cl-36	8.885×10^{-1}	1.115×10^{-1}	1.325×10^{-1}	1.886
K-40	7.26×10^{-2}	9.274×10^{-1}	1.269	7.70×10^{-2}
Ca-41	0.00	0.00	0.00	0.00
Mn-54	8.48×10^{-2}	9.152×10^{-1}	1.215	8.79×10^{-2}
Fe-55	0.00	0.00	0.00	0.00
Co-57	9.288×10^{-1}	7.12×10^{-2}	1.604×10^{-1}	1.671
Co-60	9.235×10^{-1}	7.65×10^{-2}	7.83×10^{-2}	1.263
Ni-59	0.00	0.00	0.00	0.00
Ni-63	0.00	0.00	0.00	0.00
Zn-65	9.271×10^{-1}	7.29×10^{-2}	8.37×10^{-2}	1.327
Ge-68+D[a]	9.270×10^{-1}	7.30×10^{-2}	9.94×10^{-2}	1.412
Sr-90+D	9.074×10^{-1}	9.260×10^{-2}	1.202×10^{-1}	1.699
Nb-94	9.275×10^{-1}	7.250×10^{-2}	9.10×10^{-2}	1.378
Tc-99	7.871×10^{-1}	2.129×10^{-1}	2.106×10^{-1}	2.589
Ru-106+D	9.271×10^{-1}	7.290×10^{-2}	9.57×10^{-2}	1.409
Ag-108m+D	9.282×10^{-1}	7.180×10^{-2}	9.67×10^{-2}	1.442
Ag-110m+D	9.261×10^{-1}	7.390×10^{-2}	8.74×10^{-2}	1.339
Cd-109	6.534×10^{-1}	3.466×10^{-1}	2.047×10^{-1}	4.753
Sb-125+D	9.273×10^{-1}	7.270×10^{-2}	1.005×10^{-1}	1.507
I-129	4.350×10^{-1}	5.650×10^{-1}	7.137×10^{-1}	3.555
Cs-134	9.266×10^{-1}	7.34×10^{-2}	9.26×10^{-2}	1.379
Cs-135	7.254×10^{-1}	2.746×10^{-1}	2.508×10^{-1}	3.030
Cs-137+D	9.281×10^{-1}	7.19×10^{-2}	9.47×10^{-2}	1.411
Ce-144+D	9.116×10^{-1}	8.84×10^{-2}	9.38×10^{-2}	1.411
Pm-147	7.726×10^{-1}	2.274×10^{-1}	2.087×10^{-1}	2.780
Sm-147	0.00	0.00	0.00	0.00
Sm-151	3.540×10^{-2}	9.646×10^{-1}	8.270×10^{-1}	6.15
Eu-152	9.100×10^{-1}	9.000×10^{-2}	8.40×10^{-2}	1.185
Eu-154	8.939×10^{-1}	1.061×10^{-1}	8.25×10^{-1}	1.008
Eu-155	8.569×10^{-1}	1.431×10^{-1}	1.912×10^{-1}	1.486
Gd-152	0.00	0.00	0.00	0.00
Gd-153	8.226×10^{-1}	1.774×10^{-1}	1.986×10^{-1}	1.983
Au-195	8.772×10^{-1}	1.228×10^{-1}	2.380×10^{-1}	1.880
Tl-204	8.679×10^{-1}	1.321×10^{-1}	2.068×10^{-1}	1.923
Bi-207	9.246×10^{-1}	7.540×10^{-2}	8.89×10^{-2}	1.350
Pb-210+D	7.502×10^{-1}	2.498×10^{-1}	1.753×10^{-1}	2.200
Ra-226+D	9.272×10^{-1}	7.280×10^{-2}	8.35×10^{-2}	1.315
Ra-228+D	9.266×10^{-1}	7.340×10^{-2}	8.77×10^{-2}	1.371
Ac-227+D	9.229×10^{-1}	7.710×10^{-2}	1.172×10^{-1}	1.512
Th-228+D	9.277×10^{-1}	7.230×10^{-2}	7.55×10^{-2}	1.262
Th-229+D	9.130×10^{-1}	8.700×10^{-2}	1.130×10^{-1}	1.491
Th-230+D	8.628×10^{-1}	1.372×10^{-1}	1.871×10^{-1}	4.033

TABLE F.1 (Cont.)

Radionuclide	A_i	B_i	K_{Ai}	K_{Bi}
Th-232	8.152×10^{-1}	1.848×10^{-1}	2.082×10^{-1}	5.645
Pa-231	9.295×10^{-1}	7.050×10^{-2}	1.163×10^{-1}	2.014
U-232	8.086×10^{-1}	1.914×10^{-1}	1.754×10^{-1}	6.021
U-233	8.889×10^{-1}	1.112×10^{-1}	1.394×10^{-1}	4.179
U-234	7.229×10^{-1}	2.771×10^{-1}	1.937×10^{-1}	7.238
U-235+D	9.292×10^{-1}	7.080×10^{-2}	1.383×10^{-1}	1.813
U-236	5.932×10^{-1}	4.068×10^{-1}	1.980×10^{-1}	8.379
U-238+D	8.590×10^{-1}	1.410×10^{-1}	9.19×10^{-2}	1.111
Np-237+D	9.255×10^{-1}	7.450×10^{-2}	1.228×10^{-1}	1.671
Pu-238	2.972×10^{-1}	7.028×10^{-1}	1.958×10^{-1}	9.011
Pu-239	8.002×10^{-1}	1.998×10^{-1}	1.348×10^{-1}	6.550
Pu-240	2.977×10^{-1}	7.023×10^{-1}	2.176×10^{-1}	8.997
Pu-241+D	9.132×10^{-1}	8.680×10^{-2}	1.582×10^{-1}	2.027
Pu-242	3.314×10^{-1}	6.686×10^{-1}	2.109×10^{-1}	8.982
Pu-244+D	9.259×10^{-1}	7.410×10^{-2}	9.26×10^{-2}	1.431
Am-241	8.365×10^{-1}	1.635×10^{-1}	3.130×10^{-1}	2.883
Am-243+D	9.098×10^{-1}	9.020×10^{-2}	1.473×10^{-1}	1.642
Cm-243	9.247×10^{-1}	7.530×10^{-2}	1.350×10^{-1}	1.662
Cm-244	7.0×10^{-3}	9.930×10^{-1}	8.461×10^{-2}	2.194
Cm-248	7.333×10^{-1}	2.667×10^{-1}	1.042×10^{1}	1.215
Cf-252	6.505×10^{-1}	3.495×10^{-1}	7.259	1.82×10^{-1}

[a] +D means that associated decay product radionuclides with half-lives less than six month are also included.

$$B(x) = B_a\left(\frac{t_a}{t_a + t_c + t}x\right)B_c\left(\frac{t_c}{t_a + t_c + t}x\right)B_s\left(\frac{t}{t_a + t_c + t}x\right) \tag{F.7}$$

where B and $\propto$ are the buildup factor and the attenuation factor for the appropriate material (a for air, c for shield material, and s for source material or soil reference). The integration volume V' is the desired geometry of specified material with radius r, shielding thickness t_c, and air thickness t_a, whereas V is the reference geometry of soil extending infinitely laterally with no shielding and the receptor midpoint located 1 m from the surface.

The off-set factor, $F_{OFF\text{-}SET}$, is the ratio of the dose estimates from a noncircular shaped contaminated material to a reference shape. The concept of the shape factor is used to calculate the off-set factor. The reference shape is a fully contaminated circular area encompassing the given shape, centered about the receptor. This factor is derived by considering the area, material factors of a series of concentric circles, and the corresponding contamination fraction of the annular regions. The off-set factor is obtained by enclosing the irregularly shaped contaminated area in a circle, multiplying the area factor of each annulus by the fraction of the contaminated annulus area, f_i, summing the products, and dividing by the area factor of a circular contaminated material that is equivalent in area:

$$F_{OFF-SET} = \frac{\sum_{i=1}^{n} f_i \left[F_A(A_i) - F_A(A_{i-1})\right]}{F_A\left[\sum_{i=1}^{n} f_i (A_i - A_{i-1})\right]}, \tag{F.8}$$

where $F_A(A_i)$ is the area factor for circular area A_i of a given source thickness and cover thickness.

F.2 EXTERNAL DOSE FROM CONTAMINATED POINT SOURCE

The model for point sources is simply expressed considering the energy of the radiation and attenuation. The total external dose over the exposure duration, *ED*, from exposure to a point source containing radionuclide *n*, in compartment *i*, $D^n_{ip}(t)$ at time *t*, is:

$$D^n_{iP}(t) = 24\ ED\ F_{in} F_i\ \overline{C^n_{sP}(t)} \sum_j y_{nj}\ E_{nj}\ B(\propto_a t_a)\, d \left[\frac{\propto_{en}(E_{nj})}{\rho}\right]_{air} \frac{e^{-\propto_a t_a - \propto_c t_c}}{4\pi t_a^2}, \tag{F.9}$$

where

24 = time conversion factor (h/d);

ED = exposure duration (d);

$\overline{C^n_{sP}(t)}$ = average total activity of radionuclide *n* in the source over the exposure duration starting at time t (pCi);

y_{nj} = yield for gamma *j* from radionuclide *n*;

E_{nj} = energy for gamma *j* from radionuclide *n* (MeV);

d = unit dose rate per energy absorption; and

$\left[\frac{\propto_{en}(E_{nj})}{\rho}\right]_{air}$ = mass energy absorption coefficient in air (cm^2/g).

The calculation of average total activity $\overline{C^n_{sp}(t)}$ is discussed in Appendix H.

F.3 EXTERNAL DOSE FROM CONTAMINATED LINE SOURCE

The model for line sources differs from that of the point source in the more complicated geometrical factor. The total external dose over the exposure duration from exposure to a line source in compartment *i*, containing radionuclide *n*, $D_{iL}^{n}(t)$ at time *t*, is expressed as:

$$D_{iL}^{n}(t) = 24\ ED\ F_{in} F_{i}\, \overline{C_{sL}^{n}(t)} \sum_{j} y_{nj} E_{nj} B(z')\, d \left[\frac{\propto_{en}(E_{nj})}{\rho} \right]_{air} A_{L}, \qquad \text{(F.10)}$$

$$z' = \propto_{a} t_{a'} \qquad \text{(F.11)}$$

$$A_{L} = e^{-\propto_{c} t_{c}} \int_{line} \frac{e^{-\propto_{a}\sqrt{x^{2}+t_{a}^{2}}}}{4\pi(x^{2}+t_{a}^{2})}\, dx\ , \qquad \text{(F.12)}$$

where

$\overline{C_{sL}^{n}(t)}$ = average line source concentration of radionuclide *n* over the exposure duration *ED* starting at time *t* (pCi/m),

t_{a} = perpendicular distance to receptor, and

$t_{a'}$ = distance from the receptor to the midpoint of the line source.

These geometrical parameters are shown in Figure F.1 and are calculated on the basis of the input geometrical parameters of the source and the location of the receptor. The calculation of $\overline{C_{sL}^{n}(t)}$ is discussed in Appendix H.

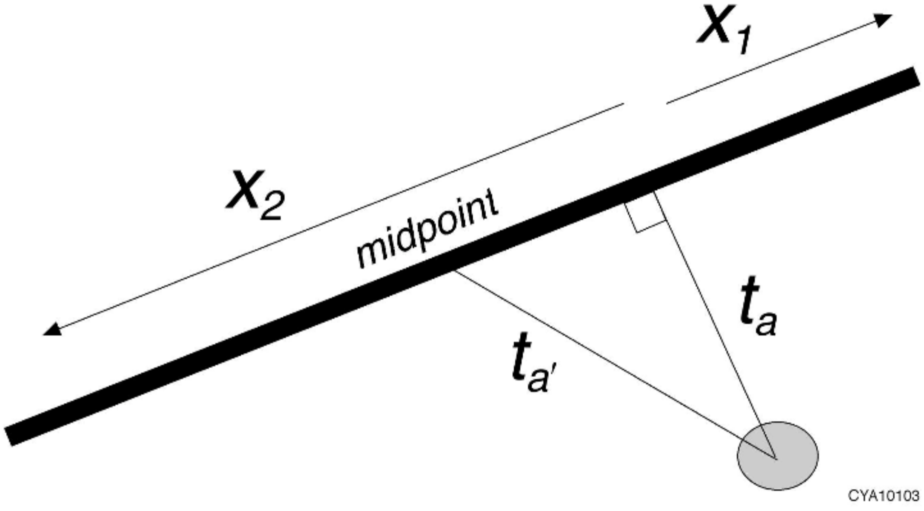

FIGURE F.1 Geometry in the Line Source Model

F.4 EXTERNAL DOSE FROM CONTAMINATED DUST IN INDOOR AIR

The total air submersion external dose over the exposure duration, *ED*, $D^n_{i,sub}(t)$, at time *t* from exposure to indoor contaminated dust in the air is calculated by using the following equation:

$$D^n_{i,sub}(t) = (ED/365) F_{in} F_i \overline{C^n_i(t)}\, DCF^n_{sub} \;, \tag{F.13}$$

where

ED = exposure duration (d);

365 = time conversion factor (d/yr);

$D^n_{i,sub}(t)$ = total air submersion effective dose equivalent over the exposure duration, *ED,* from radionuclide *n* at time *t* in compartment *i* (mrem);

$\overline{C^n_i(t)}$ = 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^n_{sub} = air submersion dose conversion factor for radionuclide *n* (mrem/yr per pCi/m^3).

The DCF^n_{sub} is for a semi-infinite cloud source; no correction (reduction) for the finite indoor air volume was performed in the RESRAD-BUILD code. The calculation of $\overline{C^n_i(t)}$ is discussed in Appendix H.

F.5 DOSE CONVERSION FACTORS

Values of dose conversion factors for external exposure were taken from a U.S. Environmental Protection Agency report (Eckerman and Ryman 1993). Table F.2 lists the dose conversion factors for the surface (infinite plane) source, the infinite depth volume source, and the air submersion exposure.

TABLE F.2 Effective Dose Equivalent Conversion Factors (DCF_{i1}) for External Gamma Radiation from Contaminated Ground

Radionuclide	Surface Factors[a] (mrem/yr)/(pCi/cm^2)	Volume Factors[b] (mrem/yr)/(pCi/g)	Submersion[c] (mrem/yr)/(pCi/m^3)
H-3	0.00	0.00	0.0
C-14	1.88×10^{-5}	1.34×10^{-5}	2.62×10^{-8}
Na-22	2.46	1.34×10^{1}	1.26×10^{-2}
Al-26	2.91	1.74×10^{1}	1.59×10^{-2}
Cl-36	7.87×10^{-4}	2.39×10^{-3}	2.61×10^{-6}
K-40	1.71×10^{-1}	1.04	9.42×10^{-4}
Ca-41	0.00	0.00	0
Mn-54	9.50×10^{-1}	5.16	4.79×10^{-3}
Fe-55	0.00	0.00	0
Co-57	1.35×10^{-1}	5.01×10^{-1}	6.56×10^{-4}
Co-60	2.75	1.62×10^{1}	1.47×10^{-2}
Ni-59	0.00	0.00	0
Ni-63	0.00	0.00	0
Zn-65	6.47×10^{-1}	3.70	3.39×10^{-3}
Ge-68+D[c]	1.10	5.62	5.36×10^{-3}
Sr-90+D	6.56×10^{-3}	2.46×10^{-2}	2.31×10^{-5}
Nb-94	1.79	9.68	9.01×10^{-3}
Tc-99	9.13×10^{-5}	1.26×10^{-4}	1.90×10^{-7}
Ru-106+D	2.48×10^{-1}	1.29	1.22×10^{-3}
Ag-108m+D	1.87	9.65	9.14×10^{-3}
Ag-110m+D	3.10	1.72×10^{1}	1.59×10^{-2}
Cd-109	2.63×10^{-2}	1.47×10^{-2}	3.44×10^{-5}
Sb-125+D	5.07×10^{-1}	2.45	2.38×10^{-3}
I-129	3.02×10^{-2}	1.29×10^{-2}	4.45×10^{-5}
Cs-134	1.78	9.47	8.86×10^{-3}
Cs-135	3.90×10^{-5}	3.83×10^{-5}	6.61×10^{-8}
Cs-137+D	6.49×10^{-1}	3.41	3.19×10^{-3}
Ce-144+D	6.82×10^{-2}	3.24×10^{-1}	3.29×10^{-4}
Pm-147	3.99×10^{-5}	5.01×10^{-5}	8.11×10^{-8}
Sm-147	0.00	0.00	0
Sm-151	5.89×10^{-6}	9.84×10^{-7}	4.22×10^{-9}
Eu-152	1.29	7.01	6.61×10^{-3}
Eu-154	1.39	7.68	7.18×10^{-3}
Eu-155	6.90×10^{-2}	1.82×10^{-1}	2.91×10^{-4}
Gd-152	0.00	0.00	0
Gd-153	1.24×10^{-1}	2.45×10^{-1}	4.34×10^{-4}
Au-195	9.17×10^{-2}	2.07×10^{-1}	3.76×10^{-4}
Tl-204	1.73×10^{-3}	4.05×10^{-3}	6.54×10^{-6}
Bi-207	1.73	9.38	8.82×10^{-3}
Pb-210+D	4.14×10^{-3}	6.12×10^{-3}	1.05×10^{-5}
Ra-226+D	1.94	1.12×10^{1}	1.04×10^{-2}
Ra-228+D	1.09	5.98	5.59×10^{-3}
Ac-227+D	4.53×10^{-1}	2.01	2.16×10^{-3}
Th-228+D	1.64	1.02×10^{1}	9.41×10^{-3}
Th-229+D	3.70×10^{-1}	1.60	1.72×10^{-3}

TABLE F.2 (Cont.)

Radionuclide	Surface Factors[a] (mrem/yr)/(pCi/cm^2)	Volume Factors[b] (mrem/yr)/(pCi/g)	Submersion[c] (mrem/yr)/(pCi/m^3)
Th-230+D	8.78×10^{-4}	1.21×10^{-3}	2.04×10^{-6}
Th-232	6.45×10^{-4}	5.21×10^{-4}	1.02×10^{-6}
Pa-231	4.76×10^{-2}	1.91×10^{-1}	2.01×10^{-4}
U-232	1.18×10^{-3}	9.02×10^{-4}	1.66×10^{-6}
U-233	8.38×10^{-4}	1.40×10^{-3}	1.91×10^{-6}
U-234	8.75×10^{-4}	4.02×10^{-4}	8.93×10^{-7}
U-235+D	1.95×10^{-1}	7.57×10^{-1}	9.03×10^{-4}
U-236	7.61×10^{-4}	2.15×10^{-4}	5.86×10^{-7}
U-238+D	3.53×10^{-2}	1.52×10^{-1}	1.60×10^{-4}
Np-237+D	2.62×10^{-1}	1.10	1.21×10^{-3}
Pu-238	9.80×10^{-4}	1.51×10^{-4}	5.71×10^{-7}
Pu-239	4.29×10^{-4}	2.95×10^{-4}	4.96×10^{-7}
Pu-240	9.40×10^{-4}	1.47×10^{-4}	5.56×10^{-7}
Pu-241+D	6.07×10^{-6}	1.89×10^{-5}	2.56×10^{-8}
Pu-242	7.80×10^{-4}	1.28×10^{-4}	4.69×10^{-7}
Pu-244+D	3.88×10^{-1}	2.02	1.90×10^{-3}
Am-241	3.22×10^{-2}	4.37×10^{-2}	9.57×10^{-5}
Am-243+D	2.53×10^{-1}	8.95×10^{-1}	1.15×10^{-3}
Cm-243	1.46×10^{-1}	5.83×10^{-1}	6.88×10^{-4}
Cm-244	1.03×10^{-3}	1.26×10^{-4}	5.74×10^{-7}
Cm-248	7.02×10^{-4}	8.78×10^{-5}	3.97×10^{-7}
Cf-252	8.45×10^{-4}	1.76×10^{-4}	5.92×10^{-7}

[a] Surface factors represent infinite thinness.

[b] Volume factors represent infinite depth.

[c] Effective dose equivalent conversion factors for entries labeled with "+D" are aggregated factors of a principal radionuclide, together with the associated radionuclides with half-lives less than six month.

F.6 REFERENCES

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APPENDIX G:

EXPOSURES TO TRITIUM IN BUILDINGS

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EXPOSURES TO TRITIUM IN BUILDINGS

G.1 INTRODUCTION

Except for radon, most of the radionuclides considered in the RESRAD-BUILD code are in solid forms that adsorb to building material. Consequently, these radionuclides would only be available for inhalation or ingestion as the result of mechanical forces or the weathering process. These actions would erode or loosen the contaminated building material so that it would be dispersed into the indoor air and be inhaled, or the material would attach to the hands of a human receptor and inadvertently be ingested. Tritium contamination requires special consideration, because in addition to erosion, tritium, which most often is in the chemical form of tritiated water (HTO), can vaporize and diffuse out of the building material and reach the indoor air. The amount of vaporization and the vaporization rate depend on the amount of free HTO molecules (i.e., those trapped in pore spaces and not incorporated into the building material) in the building (source) material. This appendix discusses the methodology used to estimate tritium exposures from various pathways, as well as a transport model developed for evaluating the tritium release rate caused by vaporization from a volume contamination source. While the transport model focuses on tritium in the chemical form of HTO, the methodology used to estimate tritium exposures from different pathways is similar to that used for other radionuclides and, therefore, can be applied to consider exposures to tritium in other chemical forms (such as tritiated organic compounds and metal tritides) that adsorb to building material.

G.2 SURFACE SOURCES

The surface sources defined in this section are the point, line, and area sources. Volume sources are discussed in Section G.3. The external radiation dose for tritium is essentially zero, because tritium emits only low-energy beta radiation. Radiation exposures to tritium from the inhalation and ingestion pathways are evaluated in the same manner as those exposures to other radionuclides. Exposures to other radionuclides are discussed in Appendixes D and E. One pathway that is unique to tritium is exposure through dermal absorption. This pathway is discussed in Section G.2.3.

G.2.1 Inhalation

For surface sources, potential tritium exposures through the inhalation pathway are considered through the “removable fraction (f_R),” “air release fraction (f),” and “source lifetime (T_R)” parameters. These three parameters are used in Equation D.2 in Appendix D to estimate the injection rate of tritium into the indoor air, which is then used in the indoor air quality model to estimate the air concentration of tritium in each building compartment. Whether the released tritium is in vapor or solid form would depend on the chemical form of the contaminant; the form would need to be determined to select the proper input values for these three parameters.

Tritium in the chemical form of HTO is most likely to be released in vapor form (free HTO), unless it is incorporated into the entity of the building material through molecular exchange, which would prohibit the vaporization of HTO.

For solid radionuclides that are assumed to adsorb to the source material, the removable fraction is the same as the source material. However, for tritium in a chemical form that can vaporize easily, the removable fraction should be greater than the removable fraction of the source material. In general, when considering tritium in the form of HTO, a removable fraction of 1 is recommended for yielding conservative results. Realistically, however, not all the HTO will vaporize through molecular exchange; some of the tritium may be incorporated into the entity of the building material. A value of 0.1 was used by both the International Organization for Standardization (ISO 1988) and the U.S. Department of Energy (DOE 1991) when considering the release of tritium in a generic situation (i.e., tritium in different chemical forms and from different contamination sources).

When in the form of HTO, tritium can be released through vaporization without the source material being removed; the “removable fraction” parameter should be assigned a value of 1 for the dose calculation.

The “source lifetime” parameter is used to determine the release rate of tritium to the indoor air. The elapsed time for free HTO molecules that escape from the source through vaporization would be very small. For tritium in a solid form, the elapsed time would depend on the weathering process or the potential mechanical forces that remove the source material.

G.2.2 Ingestion

RESRAD-BUILD considers both direct ingestion and secondary ingestion of contaminants. Direct ingestion refers to ingestion of the contaminant from the source area. Secondary ingestion refers to ingestion of the contaminant that deposits from the air onto the surfaces of walls or equipment and is not restricted to the source area. The ingestion rates of these two mechanisms depend directly and indirectly, respectively, on the amount of removable contaminant. Potential tritium exposures through the ingestion pathway are considered through the “removable fraction of the contaminant (f_R),” “direct ingestion rate (ER),” “source lifetime (T_R),” “deposition velocity (u_d),” “resuspension rate (λ_R),” and “indirect ingestion rate (SER)” parameters. These parameters are used in Equations E.2, E.3, and B.3 of Appendixes E and B, respectively, to estimate the ingestion doses of tritium from direct ingestion, secondary ingestion, and the concentration of tritium on the walls or equipment due to deposition of airborne dust particles. Section G.1.1 discusses parameters f_R and T_R. The other parameters, ER, u_d, λ_R, and SER, are discussed below.

The “direct ingestion rate” (ER) parameter is the same as that used for other radionuclides. The removable contaminant is assumed to become airborne, be ingested directly, or drop to the floor and be swept away. If all the removable contaminant becomes airborne, then there would be no loose contaminant left for ingestion. Consequently, the value for this parameter would be 0. This is generally the case for tritium in the form of HTO. For tritium in a solid form that adsorbs to the source material and does not vaporize, the value for this parameter should be the same as that for other radionuclides.

Deposition of airborne tritium onto the surfaces of walls or equipment is considered for the tritium in a solid form only. The values for u_d, λ_R, and *SER* for tritium released in solid form should be the same as those for other radionuclides. Tritium that is released in a vapor form such as HTO is assumed not to deposit (with a deposition velocity of 0) and will not cause secondary ingestion. When the deposition velocity is set to 0, the values of the resuspension rate and indirect ingestion rate will not affect the dose results.

G.2.3 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 from dermal absorption, the inhalation dose is increased by 50%. The radiation doses listed for the inhalation pathway in the output text report include the contribution from dermal absorption.

G.3 VOLUME SOURCES

The methodology used to assess exposures to tritium from a volume source is based on the methodology used to assess exposures to other radionuclides but modified to consider the release of tritium through vaporization. Currently, for volume sources, RESRAD-BUILD only considers the vaporization of HTO, the most common chemical form of tritium. Tritium in any other chemical form is assumed to be released in solid form (absorbing or adsorbing to source material and not vaporizing); the release would occur through erosion only, which is consistent with the approach for other radionuclides.

Because tritium emits only low-energy beta radiation, potential radiation exposures would occur through inhalation, ingestion, and dermal absorption pathways. The methodologies used to estimate the potential exposures are discussed below.

G.3.1 Inhalation

The potential release of tritium from a volume source would occur through erosion and, if in the form of HTO, vaporization. To simplify the modeling of the vaporization mechanism, 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 transport path of the H_2O molecules. The release rate of tritium through the erosion mechanism is estimated on the basis of Equation D.1 in Appendix D. The release rate of tritium through the vaporization mechanism is estimated on the basis of a transport model discussed in Section G.4.

Equation D.1 is used to estimate the release rate through erosion for other radionuclides. Because the release rate estimated is based on the assumption that all the contaminants adsorb to the source material, Equation D.1 is modified to subtract the amount of tritium that has already been released through the vaporization mechanism. The underlying assumption is that vaporization and diffusion through the source material occur much faster than erosion, so that the eroded source material would contain only the tritium that does not vaporize. An additional term is introduced into Equation D.1 and the equation becomes:

$$I_{Si}^{n}(t)=\frac{10{,}000\, f\ E\ A_s\ \rho_{bs}\ C_s^{n}(t)(1-f_{rel})}{24}\ , \qquad \text{(G.1)}$$

where f_{rel} is the "fraction of tritium available for vaporization," that is, "fraction of tritiated water molecules available for vaporization (the free water molecules)." The factor ($1-f_{rel}$) is used to account for incorporation of the HTO and H_2O molecules into the source entity, which prohibits HTO and H_2O from vaporization. The incorporation to the source entity is assumed to distribute homogeneously. When there is no incorporation to prohibit the vaporization of HTO or H_2O molecules, the value of f_{rel} is 1. For tritium in a chemical form other than HTO, that is assumed to be in a solid form, the value of f_{rel} should be set to 0.

Once the release rates of tritium from vaporization and erosion are estimated, the values are summed to give the total injection rate of tritium to the indoor air. This value is then used in the indoor air quality model discussed in Appendix A to estimate the concentration of tritium in each building compartment.

G.3.2 Ingestion

For the ingestion pathway, the radiation dose is estimated on the basis of Equation E.1 (Appendix E), with additional multiplication by a factor of ($1-f_{rel}$), for direct ingestion and Equation E.3 for secondary ingestion. The factor ($1-f_{rel}$) is included in Equation E.1 because vaporization occurs much faster than erosion, and the tritium that is released through vaporization would not be available for ingestion. The value of f_{rel} would depend on the chemical form of tritium.

Secondary ingestion is considered mainly for tritium released in solid form. Therefore, for tritium released in vapor form (HTO vapor), the deposition velocity is usually set to 0. As for the surface contamination source, the tritium concentration in the secondary surface source formed by the deposition of airborne solid particles is estimated with Equation E.3.

G.3.3 Dermal Absorption

The potential dermal absorption from the volume source is considered by increasing the inhalation dose by 50%, the same as for the surface source.

G.4 TRITIUM TRANSPORT MODEL

The tritium transport model incorporated into the RESRAD-BUILD code is used to estimate the injection 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 the building (walls or floor) or equipment material and be distributed homogeneously within a depth of h (cm) to h_p (cm) (from the surface) within the material (shown in Figure G.1). The region where the water is distributed is called the wet zone; the dry zone is between the wet zone and the interface of the indoor air and the contaminated material. 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 void space of the contaminated material, free (not adsorbing to the source material) H_2O molecules exist in liquid and vapor phases. Assuming the equilibrium condition, the water content 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 void space of the wet zone, the water vapor molecule 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 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

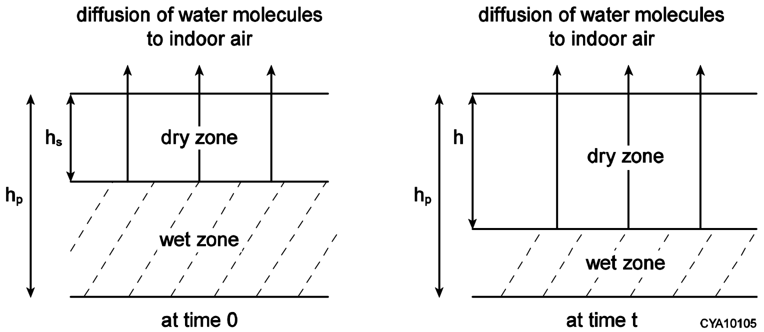

FIGURE G.1 Schematic Representation of the Dry Zone and Wet Zone Considered in the Tritium Transport Model

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 (h) would increase, and the thickness of the wet zone ($h_p – h$) would decrease (see Figure G.1).

According to Fick's law, the diffusion rate of H_2O molecules through the dry zone can be expressed as:

$$q_{water}(t) = \frac{D_e (C_g - C_{g,amb})}{h(t)} A_s \ , \tag{G.2}$$

where

$q_{water}(t)$ = diffusion rate of H_2O molecules across the surface of the source material per unit time at time t (g/s),

D_e = effective diffusion coefficient of H_2O molecules in the source material (cm^2/s),

C_g = concentration of H_2O molecules in the vapor phase of the source material (g/cm^3),

$C_{g,amb}$ = concentration of water vapor in the indoor air, that is, the absolute humidity in the indoor air (g/cm^3),

$h(t)$ = 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,

$$q_{water}(t) = A_s \ C_s \ f_{rel} \frac{dh(t)}{dt} \ , \tag{G.3}$$

where

C_s = mass concentration of water in the wet zone (g/cm^3) and

f_{rel} = fraction of free H_2O molecules available for vaporization.

After combining Equations G.2 and G.3 and rearranging parameters, integration can be performed on both sides of the equation to obtain Equation G.4:

$$\int_{0}^{t} D_e (C_g - C_{g,amb})\, dt = \int_{h_s}^{h} C_s\, f_{rel}\, h\, dh\,, \tag{G.4}$$

where

h_s = dry zone thickness at the beginning of time (t = 0) (cm).

Assuming that the values of C_g and $C_{g,amb}$ are not functions of time, the dry zone thickness at any time t can be calculated by the following equation:

$$h\,(t) = \sqrt{h_s^2 + \frac{2\;D_e (C_g - C_{g,amb})\, t}{C_s\;f_{rel}}}\;\;, \tag{G.5}$$

where

t = elapsed time since the beginning of the vaporization process (s).

The parameter Cg' is used to represent ($C_g - C_{g,amb}$) to simplify the expression of equations:

$$Cg' = (Cg - C_{g,amb})\;\;. \tag{G.6}$$

Replacing parameter h in Equation G.2 with Equation G.5, the water diffusion rate at any time (t in seconds or t' in years) can be calculated as:

$$q_{water}\;(t') = \frac{D_e\;C_g'\;A_s}{\sqrt{h_s^2 + \dfrac{2\,D_e\,C_g'\;t'\;f_{time}}{C_s\;f_{rel}}}}\;, \tag{G.7}$$

where

t' = elapsed time since the beginning of the vaporization process (yr) = $t\,/\,f_{time}$ and

f_{time} = a conversion factor (3.1536×10^7 s/yr).

To estimate the release rate of tritium into the air, the value of q_{water} needs to be multiplied by the activity concentration of tritium in water at time zero (A_{H3}) and by a decay factor. Equation G.8 is used to estimate the release rate of tritium into the indoor air:

$$q_{\mathrm{H3}}\,(t') = 3{,}600\;\;A_{\mathrm{H3}}\,e^{-\lambda\,t'}\;q_{water}\,(t'), \tag{G.8}$$

where

$q_{H3}(t')$ = release rate (diffusion rate) of tritium at time t' (pCi/h),

$A_{H3}(t')$ = activity concentration of tritium in water at time zero (pCi/g),

λ = radiological decay constant of tritium (1/yr), and

3,600 = a conversion factor of time (s/h).

The activity concentration of tritium in water, A_{H3}, is related to the activity concentration of tritium in the contaminated zone, C_{H3}, as shown in the following equation:

$$A_{H3} = C_{H3}\left(1 + \frac{\rho_b}{\rho_{water}\, W}\right) , \tag{G.9}$$

where

C_{H3} = activity concentration of tritium in the contaminated zone (pCi/g),

ρ_{water} = density of water (g/cm^3),

ρ_b = bulk density of the porous material (g/cm^3), and

W = moisture content in the contaminated zone (cm^3/cm^3).

The effective diffusion coefficient (D_e) used in Equation G.7 is dependent on the internal geometry and porosity of the porous 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:

$$D_e = D_i \; n^{4/3} \;, \tag{G.10}$$

where n is the total porosity of the source material, and D_i equals 0.2444 cm^2/s.

The mass concentration of water in the contaminated zone (wet zone), C_s, can be calculated as:

$$C_s = W \rho_{water} \,. \tag{G.11}$$

The concentration of water vapor in the void space of the wet zone, C_g, is related to the saturated vapor pressure of water, P_{sat}, by the following equation:

$$C_g = \frac{P_{sat}\; MW}{R \quad T} \;, \tag{G.12}$$

where

P_{sat} = saturated vapor pressure of water (0.0245 atm),

MW = molecular weight of water (18 g/mol),

R = the gas constant [82 (atm · cm^3)/(mol · K)], and

T = room temperature (298 K).

The amount of time required for the remaining free water in the wet zone to vaporize, $t_d(t)$, is dependent on the thickness of the dry zone [$h(t)$] and the wet zone [$h_p - h(t)$]. By the time all the water molecules vaporize, h would be equivalent to h_p. Therefore, the value of t_d can be derived for any time t with Equation G.5 after setting h to h_p and h_s to h. The resulting equation is:

$$t_d\,(t) = \frac{C_s \left[h_p^2 - h^2(t)\right] f_{rel}}{2\, D_e\, C'_g}, \qquad \text{(G.13)}$$

where t_d is expressed in seconds and can be converted to years by dividing by the time conversion factor f_{time}.

RESRAD-BUILD estimates the average release rate of tritium over the exposure duration, *ED*. The exposure duration is always compared with the time required for the remaining free water to vaporize, t_d. When t_d is less than *ED*, the average release rate for the time period t_d is estimated first, then normalized by the exposure duration, *ED*. If t_d is equivalent to or greater than *ED*, the average release rate over the exposure duration is calculated directly and does not need normalization. The Newton-Cotes open integration method is used to estimate the average release rate of tritium (Carnahan et al. 1977).

Once the average release rate of tritium is obtained, it can be added to the release rate of tritium from erosion. The sum of the release rates can then be used to estimate the tritium concentration in each building compartment.

The model described in this appendix neglects the isotopic effect and does not account for other mechanisms, such as adsorption and desorption, that may also affect the release rate of HTO. Additional complexity in the model to account for these other mechanisms would make an analytical solution impossible and would require introduction of new parameters with high degrees of uncertainty. As a result, the tritium vaporization model in the RESRAD-BUILD code should be used for screening purposes only.

G.5 REFERENCES

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APPENDIX H:

CALCULATION OF INTEGRATED DOSES

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The radiation doses calculated by the RESRAD-BUILD code are the total (integrated) doses incurred by the receptor over the entire exposure duration. The exposure duration is an input parameter located under the Time Parameters section in the main input screen. The calculation of total dose for each individual pathway is accomplished by using the various equations listed in Appendixes D through F. In the equations, average air concentrations — [$\overline{C_i^n(t)}$], average source concentrations — [$\overline{C_s^n(t)}$, $\overline{C_{di}^n(t)}$, $\overline{C_{sV}^n(t)}$, $\overline{C_{sL}^n(t)}$], and average activities — [$\overline{Q_s^n(t)}$ and $\overline{C_{sP}^n(t)}$] are used. For example, in Equation E.1:

$$D_{il}^n(t) \quad = 24\ ED\ F_{in}\ F_i\ ER\ \overline{C_s^n(t)}\, DCF_g^n \ , \qquad \text{(H.1)}$$

where $\overline{C_s^n(t)}$ is the average concentration of radionuclide n in the source material over the exposure duration, (ED), starting at time t. Equation H.1 is identical to Equation E.1. The average source concentration over the exposure duration used in Equation H.1 can be calculated by the following equation:

$$\overline{C_s^n\ (t)} = \frac{\int_t^{t+ED} C_s^n\ (t')\ dt'}{\int_t^{t+ED} dt'} \ , \qquad \text{(H.2)}$$

where $C_s^n(t')$ is the concentration of radionuclide n in the source material at any time t', and t is the start time for dose calculations. Similarly, average air concentrations, average source concentrations, and average activities are calculated.

The integration of concentrations or activities from time t to $t + ED$ is evaluated numerically with Simpson's formula. The user can specify the maximum number of integration points, up to 257, in the window brought up by pressing the Evaluation Times button in the main input screen. The integration point is 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 $t + ED$. Source concentrations or total activities corresponding to t, $t + ED$, and the additional time points in between are calculated and multiplied by certain weighting factors according to Simpson's formula. The sum of the weighted source concentrations or activities over all the time points is then an estimate of the integrated source concentration or activity starting at time t over the exposure duration. This integrated source concentration or activity is then divided by the exposure duration to calculate the average source concentrations or activities as shown in Equation H.2.

The integration is initiated by using 1 and 2 integration points. The integration results are compared with each other to see if they agree within 1%, that is, the differences are less than 1%. If they agree, no further integration calculation is needed, and the results obtained using two integration points are reported. If they do not agree within 1%, additional integration with three integration points is performed and the results are compared with those obtained using two integration points. If the results agree within 1%, then the results obtained using three integration points are reported. Otherwise, further integration calculations are performed. The number of integration points is then increased in the $2^n + 1$ sequence, starting with 2 (i.e., 2, 3, 5, 9, 17, … 257). The calculations and comparison do not stop until either the user-specified maximum integration point is reached or a better than 1% convergence is achieved. The last calculated integration results are reported.

APPENDIX I:

UNCERTAINTY ANALYSIS

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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 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 ranked 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.

I.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 input variables. 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 N_{var} probabilistic/uncertain variables, 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 correlated variable by inputting the correlation coefficients 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, 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 and risk vary with the number of samples chosen. The accuracies of the mean dose and of 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.

I.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 distribution are available in the LHS routine. These distribution types and distribution parameters are summarized in Table I.1, at the end of this appendix.

I.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 grand total dose, total dose from each source, total dose to each receptor, and total dose attributed to each source and receptor combination. These statistics are provided at each user 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 each nuclide. These tables are provided for each user 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. 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 time, and dose to each receptor via each or all pathways from all sources at each user 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.

I.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.

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 $N_{obs} \cdot N_{rep}$ lines in this file: Data for each sample are in a single line. The columns are described in line 4.

I.3.2 Description of Uncbuild.cdl (comma delimited ASCII)

Header lines:

Line 1: $N_{obs} \cdot N_{rep}$, NTime, NRcp, NSrc, and Npath: the number of evaluation times, the number of receptors, the number of sources, and the number of pathways.

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 · ∑NNucs(isrc) lines are repeated for each of the $N_{obs} \cdot N_{rep}$ 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 I.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 code actually cuts off the lower and upper 0.1% tails and samples between $V_{0.001}$ and $V_{0.999}$ in the latter case. The relationship between the two sets of defining parameters follows: $\mu = (V_{0.999} + V_{0.001})/2$ and $\sigma = (V_{0.999} - V_{0.001})/2/3.09$. Conditions on inputs: $\sigma > 0,\ V_{0.001} < V_{0.999}$. Probability density function (pdf): $f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x - \propto}{\sigma}\right)^2\right]$.
Normal-B	Value of the 0.1% ($V_{0.001}$) Value of the 99.9% ($V_{0.999}$)	
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 cutoff is the minimum value or the lower quantile, and the upper cutoff is the maximum value or the upper quantile, which are related by min = V_{Lq} and max = V_{Uq}. Conditions on inputs: min < max, $Lq < Uq$. pdf: $f(x) = \frac{\frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x - \propto}{\sigma}\right)^2\right]}{Uq - Lq}$.
Truncated Normal	Mean (μ) Standard deviation (σ) Lower quantile (Lq) Upper quantile (Uq)	

TABLE I.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 code actually cuts off the lower and upper 0.1% tails and samples between $V_{0.001}$ and $V_{0.999}$ in the second case. The relationship between the three sets of defining parameters follows: $\mu = (\ln V_{0.999} + \ln V_{0.001})/2 = \ln M - \sigma^2/2$ and $\sigma = (\ln V_{0.999} - \ln V_{0.001})/2/3.09 = 1\text{n}EF/1.645$. 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. Conditions on inputs: $M > 0$, $EF > 1$, $\sigma > 0$, $V_{0.001} < V_{0.999}$. pdf: $f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right].$
Lognormal-B	Value of the 0.1% ($V_{0.001}$) Value of the 99.9% ($V_{0.999}$)	
Lognormal-N	Mean (μ) of the underlying normal distribution Standard deviation (σ) of the underlying normal distribution	

TABLE I.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 cutoff is the minimum value or the lower quantile, and the upper cutoff is the maximum value or the upper quantile, which are related by min = V_{Lq} and max = V_{Uq} .
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:
Truncated Lognormal	Mean (M) Error factor (EF) Lower quantile (Lq) Upper quantile (Uq)	$f(x)=\dfrac{\dfrac{1}{x\sigma\sqrt{2\pi}}\exp\left[-\dfrac{1}{2}\left(\dfrac{\ln x-\mu}{\sigma}\right)^2\right]}{Uq-Lq}.$
Truncated Lognormal-N	Mean (μ) of the underlying normal distribution Standard deviation (σ) of the underlying normal distribution Lower quantile (Lq) Upper quantile (Uq)	

TABLE I.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: $f(x) = \frac{1}{\max - \min}$.
Loguniform	Minimum value (min) Maximum value (max)	Conditions on inputs: 0 < min < max. pdf: $f(x) = \frac{1}{x(\ln \max - \ln \min)}$.
Uniform*	Number of subintervals (N_{int}) Limits of subintervals (L_i) $i = 0$ to N_{int} Number of observations in subinterval (O_{int})	This is a collection of adjacent uniform distributions. Conditions on inputs: $N_{int} > 1, L_{i-1} < L_i , O_i > 0$, $N_{obs} = \sum_{i=1}^{N_{int}} O_i$. pdf: $f_i(x) = \frac{1}{L_i - L_{i-1}} \frac{O_i}{N_{obs}}$.

TABLE I.1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Loguniform*	Number of subintervals (N_{int}) Limits of subintervals (L_i) $i = 0$ to N_{int} Number of observations in subinterval (O_{int})	This is a collection of adjacent loguniform distributions. Conditions on inputs: $N_{int} > 1, 0 < L_O, L_{i-1} < L_i, 0_i > 0,\ N_{obs} = \sum_{i=1}^{N_{int}} O_i$. pdf: $f_i(x) = \dfrac{1}{x(\ln L_i - \ln L_{i-1})} \dfrac{O_i}{N_{obs}}$.
Continuous Linear	Number of points (N_{pts}) Values of points (V_i) $i = 1$ to N_{pts} cdf of points (cdf_i) $i = 1$ to N_{pts}	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: $N_{pts} > 2, V_i < V_{i+1}, cdf_1 = 0, cdf_{N_{pts}} = 1$. pdf: $f_i(x) = \dfrac{cdf_i - cdf_{i-1}}{V_i - V_{i-1}}$.

TABLE I.1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Density Function
Continuous Frequency	Number of points (N_{pts}) Values of points (V_i) $i = 1$ to N_{pts} Frequency of points (f_i) $i = 1$ to N_{pts}	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: $cdf_1 = 0.$ $cdf_i = cdf_{i-1} + \frac{f_{i-1} + f_i}{2} \div \sum_{i=2}^{N_{pts}} \frac{f_{i-1} + f_i}{2}.$ Conditions on inputs: $N_{pts} > 2$, $V_i < V_{i+1}$, $f_i > 0$. pdf: $f_i(x) = \frac{cdf_i - cdf_{i-1}}{V_i - V_{i-1}}$
Continuous Logarithmic	Number of points (N_{pts}) Values of points (V_i) $i = 1$ to N_{pts} cdf of points (cdf_i) $i = 1$ to N_{pts}	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: $f_i(x) = \frac{cdf_i - cdf_{i-1}}{x(\ln V_i - \ln V_{i-1})}$

TAB LE I.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 $\leq$ mod $\leq$ max, min < max. pdf: $f(x) = \frac{2}{\max - \min} \frac{x - \min}{\mathrm{mod} - \min} \; \textit{when } x \leq \mathrm{mod}.$ $f(x) = \frac{2}{\max - \min} \frac{\max - x}{\max - \mathrm{mod}} \; \textit{when } x \geq \mathrm{mod}.$
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 $x \geq \beta.$
Exponential		
Exponential	Lambda (λ)	Conditions on inputs: $\lambda < 0.$ pdf: $f(x) = \lambda \exp(-\lambda x).$

TABLE I.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 cutoff is the minimum value or the lower quantile, and the upper cutoff is the maximum value or the upper quantile, which are related by $1 - \exp(-\lambda \text{min}) = V_{Lq}$ and $1\text{-}\exp(-\lambda \text{max}) = V_{uq}$.
Truncated Exponential	Lambda (λ) Lower quantile (*Lq*) Upper quantile (*Uq*)	Conditions on inputs: min < max, $Lq < Uq$. pdf: $f(x) = \dfrac{\lambda\, exp(-\lambda x)}{Uq - Lq}$.
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: $\alpha > 0, \beta > 0$. pdf: $f(x) \dfrac{\alpha}{\beta}\left(\dfrac{x}{\beta}\right)^{\alpha-1} exp\left(-\dfrac{x}{\beta}\right)^{a}$.

TABLE I.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: $\min < \max, 0.001 \leq P \leq 10^7, 0.001 \leq Q \leq 10^7$. 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 I.1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Mass[a] Function
Poisson	Mean (λ)	Conditions on inputs: $\lambda > 0$. Probability mass function (pmf): $p(n) = \dfrac{\lambda^n \exp(-\lambda)}{n!}$, where $n = 0, 1, 2, \ldots \infty$.
Geometric	Probability of success (p)	Conditions on inputs: $0 < p < 1$. pmf: $p(n) = (1-p)^{n-1} p$, where $n = 0, 1, 2, \ldots \infty$.
Binomial	Probability of success (p) Number of trials (N)	Conditions on inputs: $0 < p < 1, N > 1$. pmf: $p(n) = \dfrac{N!\, p^n (1-p)^{N-n}}{n!(N-n)!}$, where $n = 0, 1, 2, \ldots N$.

TABLE I.1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Mass[a] 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 $n = N, N+1, \ldots\ \infty$.
Hypergeometric	Size of population (N_{pop}) Sample size (N_{samp}) Successes in population (N_{succ})	The second input has to be the smaller of N_{samp}, N_{succ}. The third input is the larger of the two. Conditions on inputs: $N_{pop} > N_{samp} > 0, N_{pop} > N_{succ} > 0.$ 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 $n = \max(0, N_{succ} + N_{samp} - N_{op}), \ldots \min(N_{succc}, N_{samp})$

TABLE I.1 (Cont.)

Statistical Distribution	Defining Parameters	Description, Conditions, and Probability Mass[a] Function
Discrete Cumulative	Number of points (N_{pts}) Values of points (V_i) $i = 1$ to N_{pts} cdf of points (cdf_i) $i = 1$ to N_{pts}	Conditions on inputs: $N_{pts} > 2$, $V_i < V_{i+1}$, $cdf_1 > 0$, $cdf_{Npts} = 1$. pmf: $p(n) = cdf_n - cdf_{n-1}$.
Discrete Histogram	Number of points (N_{pts}) Values of points (V_i) $i = 1$ to N_{pts} Frequency of points (f_i) $i = 1$ to N_{pts}	$cdf_i = f_i / \sum_{i=1}^{N_{pts}} f_i$. Conditions on inputs: $N_{pts} > 2$, $V_i < V_{i+1}, f_i > 0$. pmf: $p(n) = cdf_n - cdf_{n-1}$.

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[a] Probability density function is for continuous distributions; mass function probability is for discrete distributions.

I.4 REFERENCES

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APPENDIX J:

PARAMETER DESCRIPTIONS

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J.1 TIME PARAMETERS

J.1.1 Exposure Duration

Definition: The exposure duration is the total length of time considered by the dose assessment, including intervals during which receptors may be absent from the building (see Section J.1.2 on the indoor fraction) or a contaminated indoor location (see Section J.3.4 on the receptor time fraction). The exposure duration is used to calculate the amount of time at each receptor location as time at receptor location = exposure duration × indoor fraction × receptor time fraction.

Parameter Name: TTIME **Units:** Days (d) **Range:** > 0

Deterministic Analysis Default Value: 365

Probabilistic Analysis Default Distribution: None assigned

Window: 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 short-term exposures, such as building renovation, 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).

J.1.2 Indoor Fraction

Definition: The indoor fraction is the fraction of the exposure duration (see Section J.1.1 on exposure duration) spent by one or more receptors inside a building. The indoor fraction is used in the exposure calculations to calculate the amount of time spent at each receptor location. Actual exposure times at each location are estimated by multiplying the exposure duration by the indoor fraction and the fraction of time at the receptor location. This parameter applies to all indoor receptor locations.

Parameter Name: FTIN **Units:** Unitless **Range:** ≥ 0

Deterministic Analysis Default Value: 0.5

Probabilistic Analysis Default Distribution: User-defined continuous with linear interpolation
Defining Values for Distribution:
See Table J.1 for the input values.

Window: 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 through out 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 total time may be used for a renovation scenario (e.g., 90 days, of which 500 hours are spent working). This difference in exposure duration, however, would not affect the indoor fraction. Residential occupancy scenarios might result in higher indoor fractions than would occupational scenarios.

With the exposure duration given in units of days, the indoor fraction is represented by the fraction an individual spends indoors at work in the case of occupational exposure. Beyeler et al. (1998) examined records from the Bureau of Labor Statistics (BLS) concerning the hours at work for persons employed in the agricultural and nonagricultural industries (BLS 1996). The distribution given in Table J.2 was based on the assumption that full-time nonagricultural workers spent 35 hours or more a week at work. However, some workers may spend some time outside.

The U.S. Environmental Protection Agency's (EPA's) Exposure Factors Handbook (EPA 1997) contains a comprehensive review of human activity patterns, including time spent at work. That review extracts data for time spent at work from the most complete and current study on activity patterns (Tsang and Klepeis 1996). Table J.3 summarizes a number of distributions, including distributions for time spent indoors at unspecified work locations in a plant/factory/warehouse. The distribution for full-time workers in the plant/factory/warehouse category is expected to be a good representation for workers in a building occupancy scenario and is the default distribution for the indoor fraction for RESRAD-BUILD. For perspective, the 50th percentile value for this distribution, 0.365, corresponds to an 8.76-hour work day. The cumulative distribution function for the indoor fraction is shown in Figure J.1.

The EPA's comprehensive review of human activity patterns (EPA 1997) also contains statistics on the amount of time spent indoors at a residence. Table J.4 summarizes the relevant subset of distributions provided in the Exposure Factors Handbook (EPA 1997) for this time fraction. These distributions can be used when evaluating the potential use of a building for a residential setting. It can be seen that the indoor fraction is substantially lower for an occupational setting (50th percentile range of 0.194 to 0.365 in Table J.3) than for a residential setting (50th percentile range of 0.625 to 0.729 in Table J.4).

TABLE J.1 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

TABLE J.2 Relative Frequency of Hours Worked by Persons Working 35 Hours or More per Week

		Assuming a 5-Day Work Week	
Hours Worked per Week[a]	Relative Frequency[a]	Hours per Day	Fraction of Day
35–39	9.96×10^{-2}	7–7.8	0.325
39–41	4.81×10^{-1}	7.8–8.2	0.342
41–48	1.59×10^{-1}	8.5–9.6	0.400
49–59	1.53×10^{-1}	9.8–11.8	0.492
60–65	1.08×10^{-1}	12–13	0.542

[a] Source: Beyeler et al. (1998).

TABLE J.3 Statistics for Fraction of Time Spent Indoors at Work[a]

Category	Population Group	N[b]	Min	Max	Percentile 5	25	50	75	90	95	98	99
Fraction per Day Indoors at a Plant/Factory/Warehouse												
All		383	0.001	0.692	0.021	0.243	0.354	0.394	0.465	0.490	0.535	0.594
Gender	Male	271	0.001	0.692	0.021	0.253	0.358	0.399	0.469	0.500	0.542	0.604
Gender	Female	112	0.003	0.569	0.010	0.218	0.354	0.385	0.417	0.469	0.490	0.500
Age (years)	18-64	353	0.003	0.692	0.021	0.267	0.361	0.396	0.465	0.490	0.535	0.594
Employment	Full-Time	333	0.003	0.692	0.035	0.306	0.365	0.403	0.469	0.500	0.542	0.594
Fraction per Day Spent Indoors at Work (unspecified)												
All		137	0.003	0.680	0.010	0.125	0.306	0.385	0.460	0.563	0.653	0.667
Gender	Male	96	0.007	0.680	0.014	0.170	0.328	0.415	0.531	0.583	0.667	0.680
Gender	Female	41	0.003	0.542	0.010	0.063	0.194	0.344	0.382	0.410	0.542	0.542
Age (years)	18-64	121	0.003	0.680	0.010	0.167	0.313	0.389	0.458	0.551	0.590	0.667
Employment	Full-Time	97	0.007	0.680	0.010	0.208	0.333	0.406	0.479	0.566	0.667	0.680

[a] Derived from cumulative minutes per day spent indoors as listed in EPA (1997).

[b] Number of subjects in the survey.

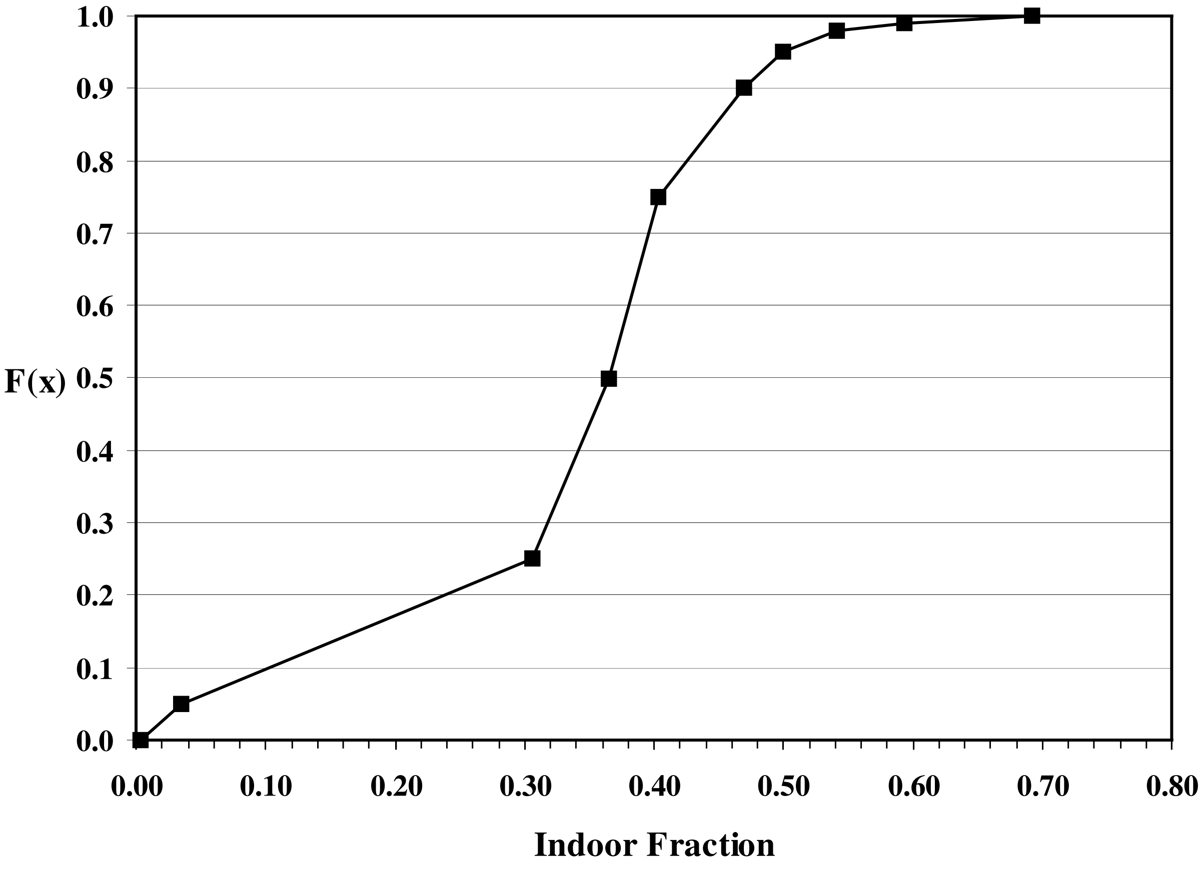

FIGURE J.1 Indoor Fraction Cumulative Distribution Function for an Occupational Setting

TABLE J.4 Statistics for Fraction of Time Spent Indoors in a Residence[a]

					Percentile							
Category	Population Group	N[b]	Min.	Max.	5	25	50	75	90	95	98	99
Fraction per Day Indoors in a Residence (all rooms)												
All		9,343	0.006	1	0.399	0.552	0.684	0.858	0.969	1	1	1
Gender	Male	4,269	0.006	1	0.375	0.521	0.625	0.806	0.938	0.993	1	1
Gender	Female	5,070	0.021	1	0.431	0.583	0.729	0.889	0.986	1	1	1
Age (years)	18-64	6,022	0.006	1	0.375	0.521	0.625	0.809	0.938	0.992	1	1

[a] Derived from cumulative minutes per day spent indoors as listed in EPA (1997).

[b] Number of subjects in the survey.

J.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. This parameter allows the user to assess the dose at different times (years) to evaluate any time-dependent effects, such as source removal or erosion and radioactive decay and ingrowth (see Sections J.1.1 and J.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

Window: 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 or source loss during the assessment period 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.

J.1.4 Time

Definition: This parameter refers to the beginning time(s) of the exposure duration for which dose calculations are performed.

Parameter Name: DOSE_TIME **Units:** Years **Range:** ≥ 0 to 100,000

Default Value: 1

Window: 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 dose calculations. The code will always calculate the dose at time zero. These times can be integer years or fractions of years. The dose is calculated over the specified exposure duration (see Section J.1.1 on exposure duration) in days following each assessment 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 incurred during the first (time zero is always calculated), second, and eleventh year. For short-lived radionuclides, or when significant ingrowth occurs during the assessment period, the user may divide the assessment time into equally spaced time intervals to account for changing dose rates. For example, an actual assessment time of 90 days may be divided into three equal intervals of 30 days each. The exposure duration would then be entered as 30 days, and the user would enter the number of times for calculation (see Section J.1.3 on number of times for calculation) as 3, setting calculation times at $t = 0$, 0.083, and 0.167 years. The code would then calculate the dose over the first, second, and third 30-day periods, respectively. The total dose to each receptor would be the sum of the receptor dose at each calculation time.

The dose assessment times should be based on estimated or actual exposure durations for the selected scenarios. These times should be consistent with actual, proposed, or hypothetical future use scenarios for the building. For example, if the postulated 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.

The user may change the times by editing the parameter fields or by dragging the clock icons across the time horizon chart. The times need not be arranged in chronological order. However, the user may rearrange the times by clicking on the reorder button, and also does so automatically upon exiting the input window. To avoid overlapping dose calculations, the user should check that the exposure duration does not exceed the interval between times for calculations.

J.1.5 Maximum Time Integration Points

Definition: This parameter refers to the maximum number of points used in integrating the dose rate over the exposure duration.

Parameter Name: POINT **Units:** Unitless **Range:** 1, 2, 3, 5, 9, 17, 33, 65, 129, 257

Default Value: 17

Window: Time Parameters → Maximum Time Integration Points

Discussion: The dose reported at any evaluation time is obtained by numerically integrating the dose rate over the exposure duration at each receptor location. The user can specify the maximum number of points to be used for the time integration. The code will use as many time integration points as is necessary to achieve the present convergence criteria, subject to the maximum points (limits) specified.

The user can select 1, 2, 3, 5, 9, 17, 33, 65, 129, or 257 as the number of points to calculate the time-integrated dose. If the user selects 1, then the instantaneous dose at the user-specified time is calculated. The use of integration points is discussed in Appendix H.

J.1.6 References

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J.2 BUILDING PARAMETERS

J.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, 2, or 3

Default Value: 1

Window: Building Parameters

Discussion: Probabilistic input is not available for this parameter. The number of rooms can be set from one (to represent complete instantaneous air mixing of the internal volume being modeled) to three (to represent three separate airflow regions with well-characterized air exchange patterns). The three rooms might be three levels of a house, two levels of a building plus the stairwell, or similar combinations. The more rooms there are in a problem, the more complicated the airflow specification will be (see Sections J2.6, J.2.7, and J.2.8 on the air exchange rate, net flow, and outdoor inflow, respectively). Figure J.2 shows various room configuration examples. The number of airflow input parameters strongly depends on the number of rooms parameter.

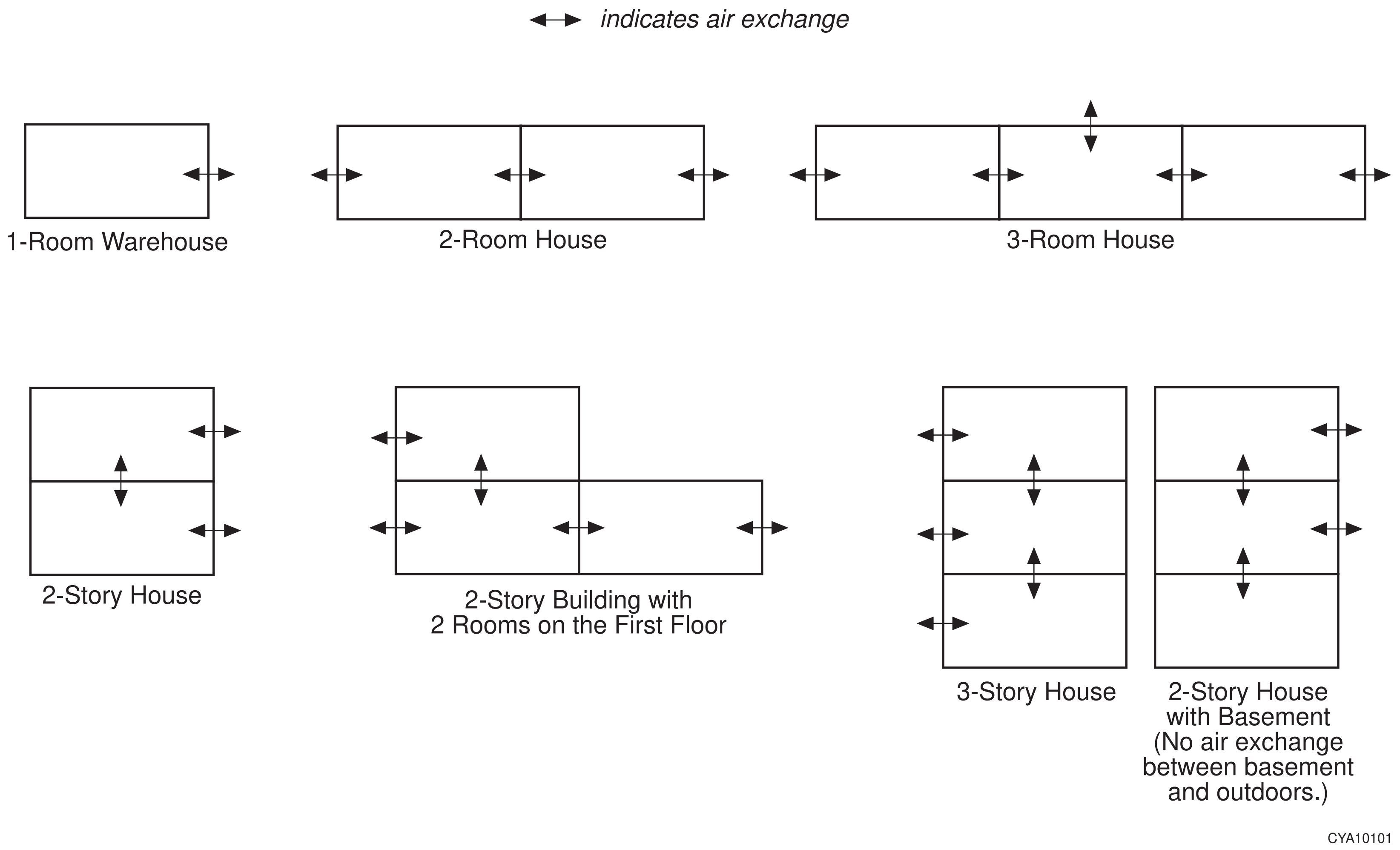

FIGURE J.2 Examples of Potential Discrete Airflow Regimes in a Building

J.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: 0.01

Probabilistic Analysis Default Distribution: Loguniform
Defining Values for Distribution:
Minimum: 2.7×10^{-6} Maximum: 2.7×10^{-3}

Window: Building Parameters

Discussion: The buildup of radionuclides on surfaces as a result of deposition of airborne radioactive materials is an important process in several exposure pathways. Deposited beta- and gamma-emitting radionuclides contribute to exposure from external radiation. Deposited radioactive materials also can become airborne because of mechanical disturbances or airflow (see Section J.2.3 on resuspension rate) and serve as a source of radionuclide inhalation or additional contamination. The same deposition velocity is used for all 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 another for the vapors. The appropriate deposition velocity should be specified for each case.

The deposition velocity characterizes the rate at which particles in the indoor air deposit on a surface. The decay rate, λ_d, of particles in indoor air due to deposition is often expressed as:

$$\lambda_d = \frac{u_d A_d}{V} , \qquad \text{(J.2.2-1)}$$

where

u_d = deposition velocity,

A_d = surface area available for deposition, and

V = volume of air.

For indoor deposition, the deposition velocity depends on particle and room properties. Important particle properties include diameter, density, and shape; room properties include air viscosity and density, turbulence, thermal gradients, and surface geometry.

Nazaroff and Cass (1989) have developed a relationship for the indoor deposition velocity of particulates as a function of particle size. Such theoretical calculations are not likely to produce satisfactory results because of lack of knowledge about near-surface flow conditions (Nazaroff et al. 1993), but they can provide insight into the general trend of deposition velocity as a function of particle size. Figure J.3 presents an idealized representation of deposition velocity on a floor as a function of particle size on the basis of the methodology in Nazaroff and Cass (1989). A similar trend is observed for deposition of particles outdoors (Sehmel 1980).

Because deposition velocities depend on particle size, it is expected that the probability density function distribution of deposition velocities is dependent on the particle size distribution. The particle size distribution in the atmosphere typically exhibits three modes (Seinfeld and Pandis 1998). Fine particles (particles less than 2.5 μm in diameter) can be divided into two modes — nuclei and accumulation. The nuclei mode (particles approximately 0.005 to 0.1 μm in diameter) contains the largest number of particles in the atmosphere but represents only a few percent of the total mass of airborne particles (Seinfeld and Pandis 1998). Nuclei mode particles are formed from condensation of atmospheric gases, such as combustion products. Depletion of nuclei mode particles occurs primarily through coagulation with larger particles. The accumulation mode (particles approximately 0.1 to 2.5 μm in diameter) accounts for a large portion of the aerosol mass. Accumulation mode particles are formed through coagulation of particles in the nuclei mode and through condensation of gases onto smaller particles. Because removal mechanisms are not as efficient for this size range, particles tend to accumulate (hence the term "accumulation mode"). Coarse particles (diameters greater than 2.5 μm) constitute the third mode. Coarse mode particles are formed primarily from mechanical processes. Other sources of coarse particles include windblown dust and plant particles.

Each of the three particle size modes can be well characterized by lognormal distributions (John 1993). In using the means and standard deviations from Whitby and Sverdrup (1980), Figure J.4 demonstrates the trimodal nature of the particle size distributions commonly found. Similar distributions are expected for indoor air concentrations, with the exception of some indoor source contributions, because, as discussed in Yu et al. (2000), the building shell has been shown to be an insignificant barrier to particle sizes under 10 μm.

A broad probability density function distribution is expected for the deposition velocity when comparing the trend in deposition velocity with the distribution of particles by size (Figures J.3 and J.4, respectively) and taking into consideration the variability of each. Experimental estimates provide support for such an assumption, as shown in Tables J.5 through J.7. In addition, Vette et al. (2001) and Mosley et al. (2001) both observed a comparable U-shaped curve, as suggested by Figure J.3, when plotting particle size against indoor deposition rate (decay rate, Equation J.2.2-1), which is directly proportional to the deposition velocity. However, numerical information was not presented in either study for further evaluation here.

Deposition rate data over a broad particle size range were presented by Wallace et al. (1997) and Abt et al. (2000). These data, as converted to deposition velocity in Table J.5, provide further supporting evidence. A similar trend for deposition velocity as a function of particle size, as suggested by Figure J.3, is also observed for deposition of particles outdoors (Sehmel 1980).

In conjunction with particle size and mass, a small difference in the local air handling system (such as changes due to climate or season) can easily cause a shift in deposition velocity because deposition is dependent on local airflow patterns (Nazaroff and Cass 1989). 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 recommended when using probabilistic input, with minimum and maximum values of 2.7×10^{-6} m/s and 2.7×10^{-3} m/s, respectively, as found in Tables J.5 through J.7. This distribution is shown in Figure J.5.

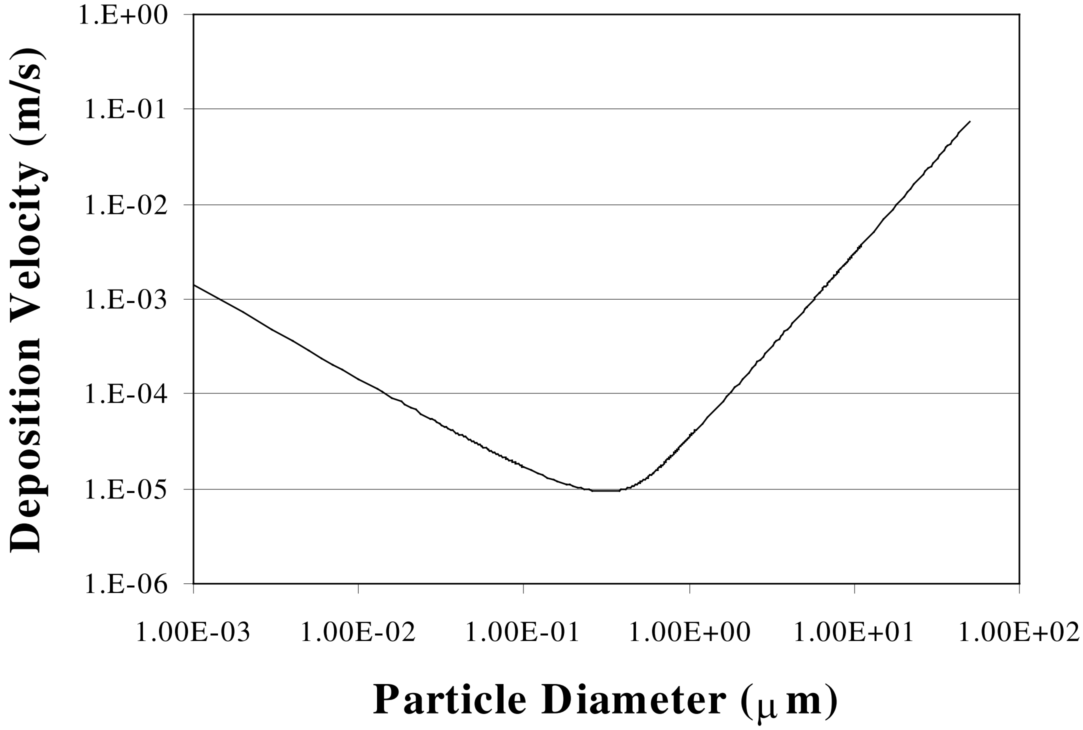

FIGURE J.3 Idealized Representation of Indoor Particle Deposition Velocity

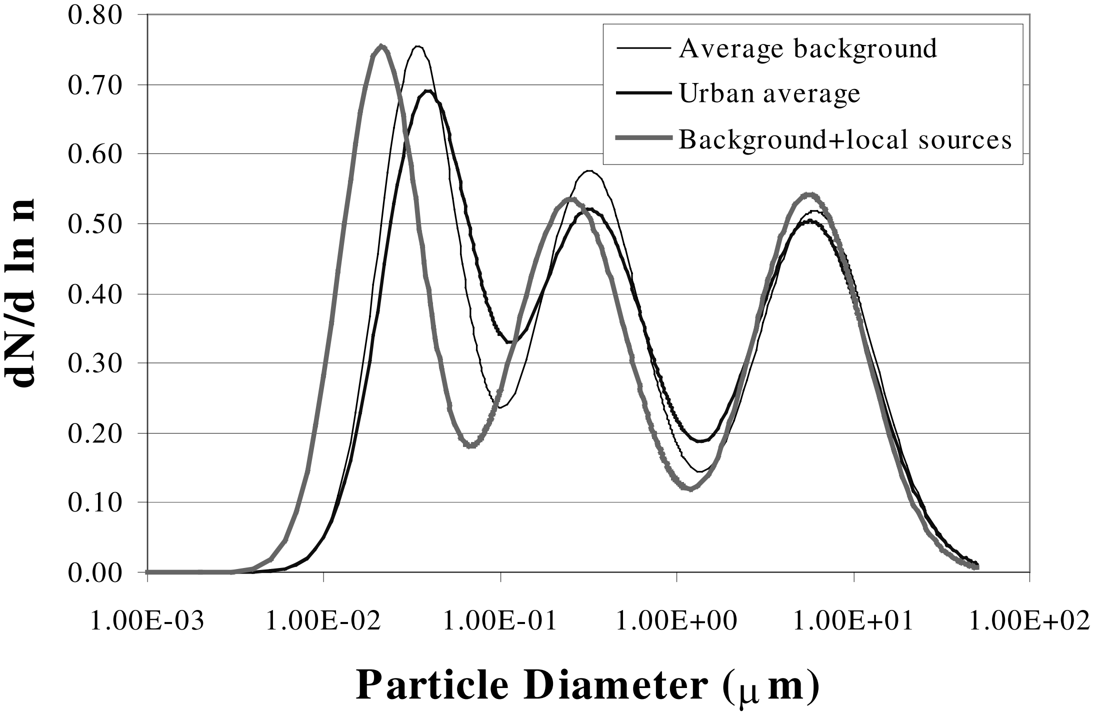

FIGURE J.4 Trimodal Nature of Aerosol Particle Size Distribution

TABLE J.5 Estimated Indoor Deposition Velocities by Particle Size

Particle Size (μm)	Deposition Velocity (m/s)	Comments	Reference
0.71	1.7×10^{-5}	^{7}Be with natural air exchange	Lang (1995)
1.4	1.3×10^{-5}		
2.8	6.7×10^{-5}		
0.71	1.33×10^{-4}	^{7}Be with forced air exchange	
1.4	2.66×10^{-4}		
2.8	3.88×10^{-4}		
1–2	1.7×10^{-4}	Data set 1 (different sample dates using sulfur hexafluoride [SF_6] tracer)	Thatcher and Layton (1995)
2–3	3.7×10^{-4}		
3–4	5.1×10^{-4}		
4–6	1.1×10^{-3}		
1–2	1.9×10^{-4}	Data set 2	
2–3	5.0×10^{-4}		
3–4	5.6×10^{-4}		
4–6	1.2×10^{-3}		
1–5	3.1×10^{-4}	Data set 3	
5–10	9.1×10^{-4}		
10–25	1.6×10^{-3}		
>25	2.7×10^{-3}		
0.07	1.72×10^{-5}	Estimates based on data in Offermann et al. (1985) from cigarette combustion	Nazaroff and Cass (1989)
0.10	2.7×10^{-6}		
0.12	3.8×10^{-6}		
0.17	3.8×10^{-6}		
0.22	4.7×10^{-6}		
0.26	8.9×10^{-6}		
0.35	8.2×10^{-6}		
0.44	8.7×10^{-6}		
0.56	9.8×10^{-6}		
0.72	1.51×10^{-5}		
0.91	1.3×10^{-4}		
<2.5	3×10^{-5} and 3×10^{-5}	Sulfate ion particulates at two locations	Sinclair et al. (1985)
2.5–15	1×10^{-2} and 2×10^{-3}	Calcium ion particulates at two locations	
0.3	1.4×10^{-4}	Estimated from decay rates by using Eq. J.2.2-1 and assuming a residence with an 8-ft (2.438-m) ceiling height and all deposition to the floor. Area/volume = 1/2.438 1/m.	Wallace et al. (1997)

TABLE J.5 (Cont.)

Particle Size (µm)	Deposition Velocity (m/s)	Comments	Reference
0.5	2.5×10^{-4}		
1	4.0×10^{-4}		
2.5	5.2×10^{-4}		
5	1.0×10^{-3}		
>10	1.9×10^{-3}		
0.02–0.1	7.3×10^{-4}	Particles generated during cooking activities. Estimated from decay rates by using Eq. J.2.2-1 and assuming a residence with an 8-ft (2.438-m) ceiling height and all deposition to the floor. Area/volume = 1/2.438 1/m.	Abt et al. (2000)
0.1–0.2	7.5×10^{-4}		
0.2–0.3	5.4×10^{-4}		
0.3–0.4	5.1×10^{-4}		
0.4–0.5	4.74×10^{-4}		
0.7–1	7.3×10^{-4}		
1–2	6.6×10^{-4}		
2–3	8.0×10^{-4}		
3–4	1.0×10^{-3}		
4–5	1.2×10^{-3}		
5–6	1.3×10^{-3}		
6–10	2.1×10^{-3}		

TABLE J.6 Estimated Deposition Velocities by Particle Size in Residences with and without Furniture

Particle Size (μm)	Average Deposition Velocity (m/s) Without Furniture	With Furniture
0.5	6.1×10^{-5}	8.2×10^{-5}
2.5	1.33×10^{-4}	1.73×10^{-4}
3.0	1.37×10^{-4}	2.25×10^{-4}
4.5	2.88×10^{-4}	2.88×10^{-4}
5.5	3.04×10^{-4}	3.24×10^{-4}

Source: Fogh et al. (1997).

TABLE J.7 Estimated Indoor Deposition Velocities for Various Radionuclides

Isotope	Mean Deposition Velocity (m/s)
Cs-137	6.4×10^{-5}
Cs-134	6.2×10^{-5}
I-131 (particulate)	1.1×10^{-4}
Be-7	7.1×10^{-5}
Ru-103	2.0×10^{-4}
Ru-106	1.7×10^{-4}
Ce-141	3.1×10^{-4}
Ce-144	3.9×10^{-4}
Zr-95	5.8×10^{-4}
Nb-95	1.9×10^{-4}

Source: Roed and Cannell (1987).

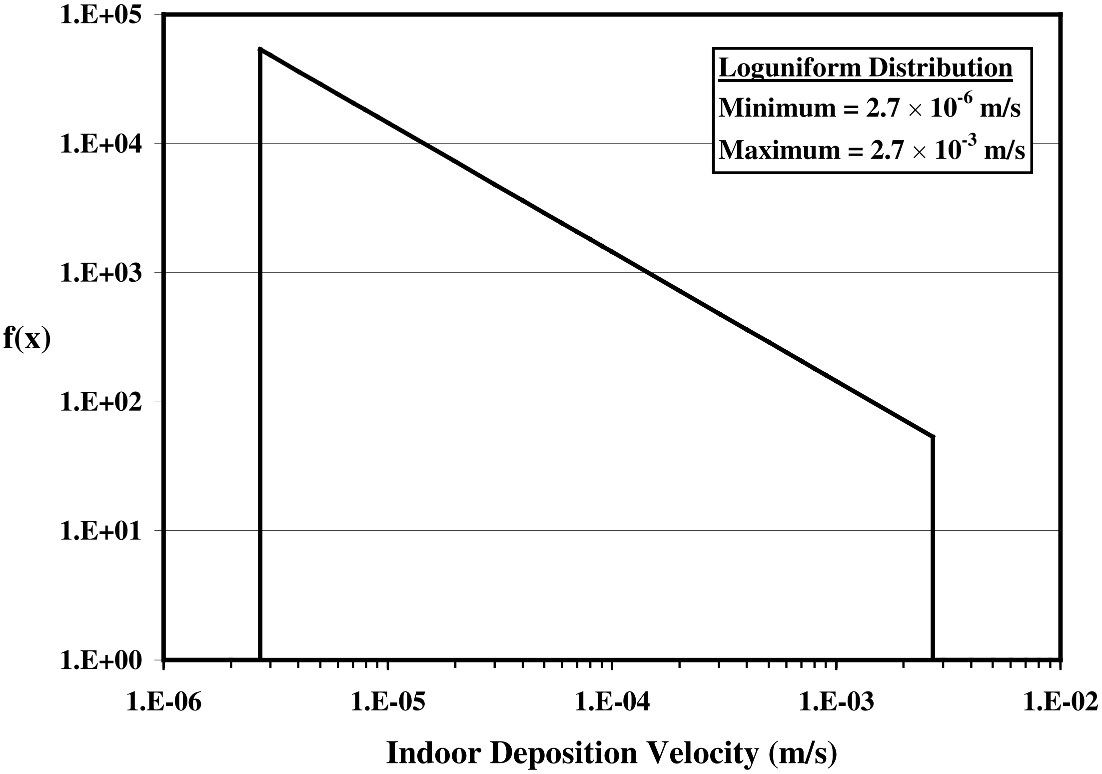

FIGURE J.5 Indoor Deposition Velocity Probability Distribution

J.2.3 Resuspension Rate

Definition: The resuspension rate (indoor) represents the rate at which material deposited on interior surfaces is 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: $5 \cdot 10^{-7}$

Probabilistic Analysis Default Distribution: Loguniform
Defining Values for Distribution:
Minimum: 2.5×10^{-11} Maximum: 1.3×10^{-5}

Window: Building Parameters

Discussion: Indoor resuspension of contamination 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.

Relatively little work has been conducted in measuring or estimating indoor resuspension rates. The most recent work by Thatcher and Layton (1995) monitored an sulfur hexafluoride (SF_6) tracer in a residential setting under varying conditions. Table J.8 gives the results based on particle size. These results demonstrate that the larger particle sizes are more susceptible to resuspension. Other studies investigating the characteristics and dynamics of indoor dust behavior have shown that the primary source of larger particle sizes in indoor air is resuspension (Wallace et al. 1997; Vette et al. 2001). Thus, it is important to note, as has been done previously (Jones and Pond 1967), that a large fraction of resuspended material is nonrespirable.

Nonrespirable material is material that cannot be inhaled directly into the lungs. Larger particulates, greater than approximately 2.5 ∝m in diameter, cannot reach the deep respiratory tract where gas exchange occurs. This material becomes trapped in the nasal passages or upper respiratory tract, where it can dissolve and be absorbed into the blood or cleared by mechanical action (swallowing) into the gastrointestinal tract or exhaled. Current radiological inhalation dose conversion factors (e.g., those presented in Eckerman et al. 1999) are based on a particle size of approximately 1 ∝m in diameter. Risks from smaller or larger particles could be lower or higher, depending on the radionuclide and its speciation. Currently, not enough information is available to provide this type of radiological risk information on the basis of particle size. Neither is there enough information to provide estimates of resuspension rate according to particle size. Thus, the current resuspension rate model is particle size independent; however, the assigned distribution is influenced by the available data on varying particle sizes. The latest available resuspension rate information is discussed below.

Earlier studies of indoor resuspension of radioactive contamination reported the extent of resuspension in terms of a resuspension factor (R_f), that is, the ratio of airborne contamination to the amount deposited on surfaces. The following derivation provides an approximate conversion between the resuspension factor and the resuspension rate. When conservation of mass is assumed, the total change in the amount of airborne particulate material in a room (the left side of Equation J.2.3-1) is equal to an increase due to the amount resuspended, a decrease due to depositing material, and a decrease due to ventilation (terms 1 through 3, respectively, on the right side of Equation J.2.3-1).

$$V\frac{dC_A}{dt} = \mathrm{C}_S \cdot \mathrm{A} \cdot \lambda_r - C_A \cdot A \cdot u_d - C_A \cdot V \cdot n \,, \qquad \text{(J.2.3-1)}$$

where

C_A = contaminant air concentration,

C_S = contaminant surface concentration,

λ_r = resuspension rate,

V = $A \cdot H$ (the room volume),

A = contaminated surface area (assumed to be the floor where deposition occurs),

H = room height,

u_d = deposition velocity, and

n = number of air changes per unit time.

When both sides of the equation are divided by the room volume and when equilibrium conditions ($dC_A/dt = 0$) are assumed, the following is obtained:

$$C_S\frac{\lambda_r}{H} \quad C_A\frac{u_d}{H} \quad C_A \cdot n = 0 \,. \qquad \text{(J.2.3-2)}$$

Separation of the surface and air terms gives:

$$C_s \frac{\lambda_r}{H} = C_A\left(\frac{u_d}{H} + n\right) \quad . \tag{J.2.3-3}$$

The resuspension factor is the ratio of the air to surface concentration, as shown in Equation J.2.3-4. From this, the relationship between the resuspension rate and the resuspension factor is derived (see Equation J.2.3-5).

$$R_f = \frac{C_A}{C_S} = \frac{\lambda_r}{u_d + n \cdot H} \quad . \tag{J.2.3-4}$$

$$\lambda_r = R_f\left(u_d + n \cdot H\right). \tag{J.2.3-5}$$

Table J.8 gives some indoor resuspension rates and the corresponding resuspension factors as determined by using Equation J.2.3-5. Only those references with the additional requisite data (room height and air exchange rate) were used to estimate the resuspension rate from the resuspension factor. Because the deposition velocity was not measured in each case, the minimum and maximum values from the deposition velocity distribution (Section J.2.2) were used to provide a resuspension rate range for each resuspension factor. Data for the resuspension rates were provided in the case of Thatcher and Layton (1995), from which corresponding resuspension factors were derived by using deposition velocities supplied in that reference. Healy (1971) previously studied the correlation of the resuspension factor with the resuspension rate. Sansone (1987) and Beyeler et al. (1999) reviewed the earlier work in the context of resuspension factors rather than rates. Table J.9 summarizes previous work in the area of resuspension factors not addressed in Table J.8.

A number of factors (ventilation, physical activity/location, contaminated particle/floor characteristics, contamination source, and housekeeping practices) must be considered in selecting an appropriate distribution for the resuspension rate from the data discussed above. Many of the studies from which resuspension factors were derived or presented do not include enough information on room volume, contaminated surface area, and/or the ventilation rate in order to make a rough estimate of the resuspension rate by using the relationship in Equation J.2.3-1. The magnitude of the resuspension factor, however, can be roughly correlated with the conditions under which it was obtained and can be compared with resuspension factors that have corresponding resuspension rates, as shown in Table J.8.

Ventilation rates in commercial buildings that might fall under the light industrial classification for the building scenario are expected to be near 1 air change per hour (see Section J.2.6). Those studies conducted with no ventilation are expected to overestimate the resuspension factor because some removal of the air contamination would occur under normal operating conditions. In contrast, those studies with excessive ventilation might underestimate the reported resuspension factor because more air contamination would be removed under these conditions than under normal operating conditions.

Physical activity is an important factor in the resuspension of particulate matter. A dramatic example was presented by Wallace et al. (1997), who monitored air particle concentrations during a study of an occupied townhouse. Coarse particle (5–10 µm) air concentrations were shown to be orders of magnitude higher during the periods of time that the occupants were not sleeping or away. Even working in front of a computer had a large impact on coarse particle (> 2.5 µm) resuspension (Wallace et al. 1997). Other studies have also indicated that a major source of larger particles (> 1.0 µm) in indoor air is resuspension (Vette et al. 2001). Thus, those resuspension factor studies with high levels of physical activity are not representative of what an average individual might experience in the course of a working day. At the other extreme, studies conducted with no physical activity are also nonrepresentative and might underestimate the value of the resuspension factor.

The location of the surface-contaminated area(s) will affect the estimated resuspension factor and resuspension rate. Deposited material on the floor in a high-traffic area is much more likely to be resuspended than deposited material on equipment, walls, or seldom-traversed areas. The same is also true for "fixed" residual contamination in remediated areas. The larger the constantly disturbed area, the larger the resuspension factor. Thus, this consideration is closely allied with physical activity, as previously discussed.

The likelihood of particle resuspension is related to its adherence to the surface. Contamination remaining after remediation is expected to be relatively "fixed," that is, hard to remove because it is tightly bound (e.g., chemically bonded) or deep within microscopic depressions of the surface. In the latter case, it is actually the result of the inability of mechanical action to contact the contamination when a rough surface is encountered. In contrast, deposited material is generally loosely bound and relatively easily resuspended. Thus, the primary source of the contamination ("fixed" or deposited) must also be taken into consideration when determining the resuspension factor or resuspension rate for use in risk assessment.

Normal housekeeping operations, such as dusting. sweeping, mopping, and vacuuming, in a light industrial environment will minimize potential risks to building occupants from resuspension of contaminated materials during normal working hours. Risks to the cleaning staff will be elevated, but only for short periods of time. These operations reduce the buildup of contaminated material from deposition and further reduce any residual "fixed" contamination. Thus, those buildings with more frequent cleaning schedules are expected to have lower resuspension factors/rates than those sporadically cleaned, because the more loosely bound material from deposition is maintained at lower levels.

The RESRAD-BUILD input parameters, such as the source lifetime, removable fraction, and air release fraction, are used to control the amount of contaminated material that becomes available within the building from residual contamination. In turn, the resuspension rate in RESRAD-BUILD must account for resuspension of the resultant deposited contamination. In

DandD, however, the resuspension factor is the only input that accounts for airborne contamination and, therefore, must be more concerned with the source (residual contamination), which is not as easily removed as is deposited material. Thus, the input distribution in RESRAD-BUILD for the resuspension rate covers a wider range of equivalent values than the input distribution for the resuspension factor in the DandD code (McFadden et al. 2001). In the latter, values should be limited to “fixed” contamination in order to avoid violating the contamination mass balance and overestimating the inhalation exposure.

A loguniform distribution is suggested to represent the resuspension rate in RESRAD-BUILD because of the limited data available and the wide range of estimated values. The wide range in the estimated values can be attributed primarily to differences in particle size and indoor human activity levels. To represent an occupational setting, the lowest value involving any type of activity in Table J.8 was chosen, 2.5×10^{-11} s^{-1}. Similarly, the largest value in Table J.8, 1.3×10^{-5} s^{-1}, was chosen as the maximum value for the distribution. Figure J.6 shows the probability density function selected for the indoor resuspension rate.

TABLE J.8 Indoor Resuspension Rates

Resuspension Rate (1/s)[a]					
Minimum	Maximum	Resuspension Factor (m^{-1})	Conditions	Reference	Comments
7.7×10^{-7}	1.1×10^{-6}	1.2×10^{-4}	4–6 people walking	Brunskill (1967)	Change room, 1 – 3% removed by smears, 50% by water wash.
5.1×10^{-10}	5.1×10^{-7}	1.9×10^{-4}	Vigorous work, including sweeping (ZnS)	Fish et al. (1967)	Measurements of ZnS and CuO tracers.
1.1×10^{-10}	1.1×10^{-7}	3.9×10^{-5}	Vigorous walking (ZnS)		
2.5×10^{-11}	2.5×10^{-8}	9.4×10^{-6}	Collecting contaminated samples (ZnS)		
1.9×10^{-9}	1.9×10^{-6}	7.1×10^{-4}	Light sweeping with fans on for circulation (CuO)		
3.3×10^{-8}	2.2×10^{-7}	4×10^{-6} to 2×10^{-5}	Pu	Ikezawa et al. (1980)	Cleanup following accidental failure of a Pu glove box.
1.9×10^{-10}	2.5×10^{-10}	2×10^{-8}	Plutonium oxide, no movement	Jones and Pond (1967)	Contamination applied in solution and allowed to dry.
9.5×10^{-8}	1.2×10^{-7}	1×10^{-5}	14 steps/min		
4.8×10^{-7}	6.1×10^{-7}	5×10^{-5}	36 steps/min		
1.9×10^{-10}	2.5×10^{-10}	2×10^{-8}	Plutonium nitrate, no movement		
9.5×10^{-9}	1.2×10^{-8}	1×10^{-6}	14 steps/min		
4.8×10^{-8}	6.1×10^{-8}	5×10^{-6}	36 steps/min		
4.2×10^{-8}	4.8×10^{-8}	2.5×10^{-6}	Alpha, no work performed	Khvostov and Kostiakov (1969)	Investigation of a “hot” laboratory.
3.3×10^{-8}	3.9×10^{-8}	2.0×10^{-6}	Beta, no work performed		
3.7×10^{-6}	4.3×10^{-6}	2.2×10^{-4}	Alpha, floors scrubbed with cotton		
1.1×10^{-5}	1.3×10^{-5}	6.8×10^{-4}	Beta, floors scrubbed with cotton		
2.4×10^{-9}	2.4×10^{-6}	9.0×10^{-4}	$Ba^{35}SO_4$	Shapiro (1970)	Membrane with $Ba^{35}SO_4$ ignited and combustion products deposited on floor; maximum value of subsequent measurements made while banging on floor.
1.4×10^{-6}	2.0×10^{-6}	2.2×10^{-4}	Personal air samplers	Tagg (1966)	100 steps/min, contaminated floor;
3.8×10^{-7}	5.4×10^{-7}	5.9×10^{-5}	Area air samplers		100 steps/min, contaminated clothing.
3.2×10^{-6}	4.5×10^{-6}	4.9×10^{-4}	Personal air samplers		
2.1×10^{-6}	2.9×10^{-4}	3.2×10^{-5}	Area air samplers		

TABLE J.8 (Cont.)

Resuspension Rate (1/s)[a]					
Minimum	Maximum	Resuspension Factor (m^{-1})	Conditions	Reference	Comments
2.8×10^{-10}	NA[b]	1.4×10^{-6}	0.3–0.5 µm particles	Thatcher and Layton (1995)	Estimated for residence with four residents performing “normal” activities. Assumed air exchange rate of 0.3 h^{-1}.
1.2×10^{-10}	NA[b]	6.0×10^{-7}	0.5–1 µm particles		
5.0×10^{-9}	NA[b]	9.4×10^{-6}	1–5 µm particles		
2.3×10^{-8}	NA[b]	2.0×10^{-5}	5–10 µm particles		
1.1×10^{-7}	NA[b]	6.1×10^{-5}	10–25 µm particles		
9.4×10^{-9}	NA[b]	3.2×10^{-6}	> 25 µm particles		

[a] Estimated from the resuspension factor using Equation J.2.3-5 and minimum and maximum values for the deposition velocity from Section J.2.2.

[b] Not applicable. Resuspension factors were estimated from resuspension rates for Thatcher and Layton (1995).

TABLE J.9 Resuspension Factors from Previous Studies

Resuspension Factor (m^{-1})[a]	Conditions	Reference	Comments
	I-131		
1.8×10^{-6}	Active work in open space	Chamberlain and Stanbury (1951)	I-131 labeled brick and plaster dust (bulk of dust <1 µm), as reported in Sansone (1987).
4.3×10^{-5}	Active work in confined, unventilated space		
$2.5 – 19 \times 10^{-5}$	UF_4 powder	Bailey and Rohr (1953)	Normal operations at a uranium processing plant.
1×10^{-9} – 4.2×10^{-6}	Uranium, total surface activity using ratemeter, larger if removable activity values used.	Eisenbud et al. (1954)	Estimated from surface and airborne activity at 5 uranium processing plants.
7×10^{-8} – 4×10^{-5}	Ra, total surface activity using ratemeter, larger if removable activity values used.		Estimated from surface and airborne activity at 10 radium plants
4×10^{-5}	"Dusty operations"	Barnes (1959)	As reported in McKenzie et al. (1998).
	U compounds		
5×10^{-4}	0.5-h samples	Becher (1959)	As reported in Sansone (1987). Wipes used to measure surface activity
3×10^{-5}	8-h samples		
	U		
$0.2 – 5.9 \times 10^{-5}$	Ore sampling plant	Utnage (1959)	As reported in Sansone (1987).
$0.5 – 14 \times 10^{-4}$	Uranium reduction plant		
	Be and compounds		
1.5×10^{-2}	Loading/unloading Be blocks	Hyatt et al. (1959)	Resuspension factor as estimated by Sansone (1987). Surface contamination measured by wipe; maximum values for wipe and air concentration used.
$5 – 12 \times 10^{-3}$	Cleaning Be blocks		
7.9×10^{-3}	Be cyclotron target preparation		
9.3×10^{-3}	Be compound synthesis		
2 × 10-2	Warehouse inventory		
	U compounds		
$0.4 – 26 \times 10^{-5}$	8-h air samples	Schulz and Becher (1963)	As estimated by Sansone (1987), measurements from operating UF_6 manufacturing plant, surface contamination measured by wipes.
$0.8 – 14 \times 10^{-4}$	10-min air samples		
	U		
1.0×10^{-4}	Undisturbed	Glauberman et al. (1967)	As reported in Sansone(1987), operating uranium processing plant, abandoned precious metals.
1.3×10^{-4}	Fans on		
1.45×10^{-4}	Fans on with movement		
1.0×10^{-4}	Pu		Recovery plant (Pu contamination), surface contamination measured with smears.
1.35×10^{-3}	Undisturbed		
9.7×10^{-3}	Fans on		
	Fans on with movement		

TABLE J.9 (Cont.)

Resuspension Factor (m^{-1})[a]	Conditions	Reference	Comments
	Be		
4.2×10^{-4}	Two men sweeping vigorously	Mitchell and Eutsler (1967)	As reported in Sansone(1987). Unventilated storeroom with wood floor, smears used for surface contamination.
1.0×10^{-2}	Sweeping after vacuuming		
	UO_2		
<=1.7×10^{-7}	In ethanol, undisturbed	Cortissone et al. (1968)	As reported in Sansone (1987).
$4.7 – 7.5 \times 10^{-6}$	In ethanol, 60 steps/min		
<=0.7×10^{-7}	Powder, undisturbed		
$1.0 – 1.7 \times 10^{-5}$	Powder, 60 steps/min		
	Chrysotile		
$1.2 – 5.3 \times 10^{-3}$	Contaminated lab coat	Carter (1970)	As reported in Sansone (1987), surface contamination measured by vacuuming.
$2.0 – 4.2 \times 10^{-3}$	handling contaminated materials		
1.2×10^{-4}	Sr applied in solution	Gorodinsky et al. (1972)	As reported in Sansone (1987), after 1 h in wind tunnel; steel, painted steel, stainless steel, vinyl plastic, and organic glass surfaces had essentially the same results.
3.3×10^{-4}	Co applied in solution		
	Be (aqueous suspension applied)		
	Fan on	Kovygin (1974)	As reported in Sansone (1987).
$0.2 – 13 \times 10^{-6}$	Fan off		From polyvinyl chloride surface, 1.8 m/s airflow with fan on.
$0.01 – 1.5 \times 10^{-6}$	Ammonium fluoroberyllate (aqueous solution applied)		
	Fan on		
$0.3 – 10 \times 10^{-6}$	Fan off		
$0.08 – 1.5 \times 10^{-6}$			
4×10^{-5}	Pu under unspecified conditions	Wrixon et al. (1979)	As estimated in Sansone (1987), using data from the reference.
5.7×10^{-4}	Workplace for I-125 immunoassay studies	Dunn and Dunscombe (1981)	Surface contamination measured using wipes with 70% isopropyl alcohol.
5.5×10^{-8} to 1.1×10^{-7}	Radioactive particulates	Ruhter and Zurliene (1988)	Activity in Three Mile Island auxiliary building during cleanup after accident.
4.25×10^{-7}	U; surface contamination measured using wipes, three 1-year averages	Spangler (1998)	U storage area at operating uranium fuel fabrication plant.
7.79×10^{-6}			
8.97×10^{-7}			
	Primarily Co-60 and Cs-137		
1.7×10^{-7}	during decommissioning	Nardi (1999)	No forced air ventilation, measurements at a “pump repair” facility.
4.2×10^{-8}	shutdown mode		

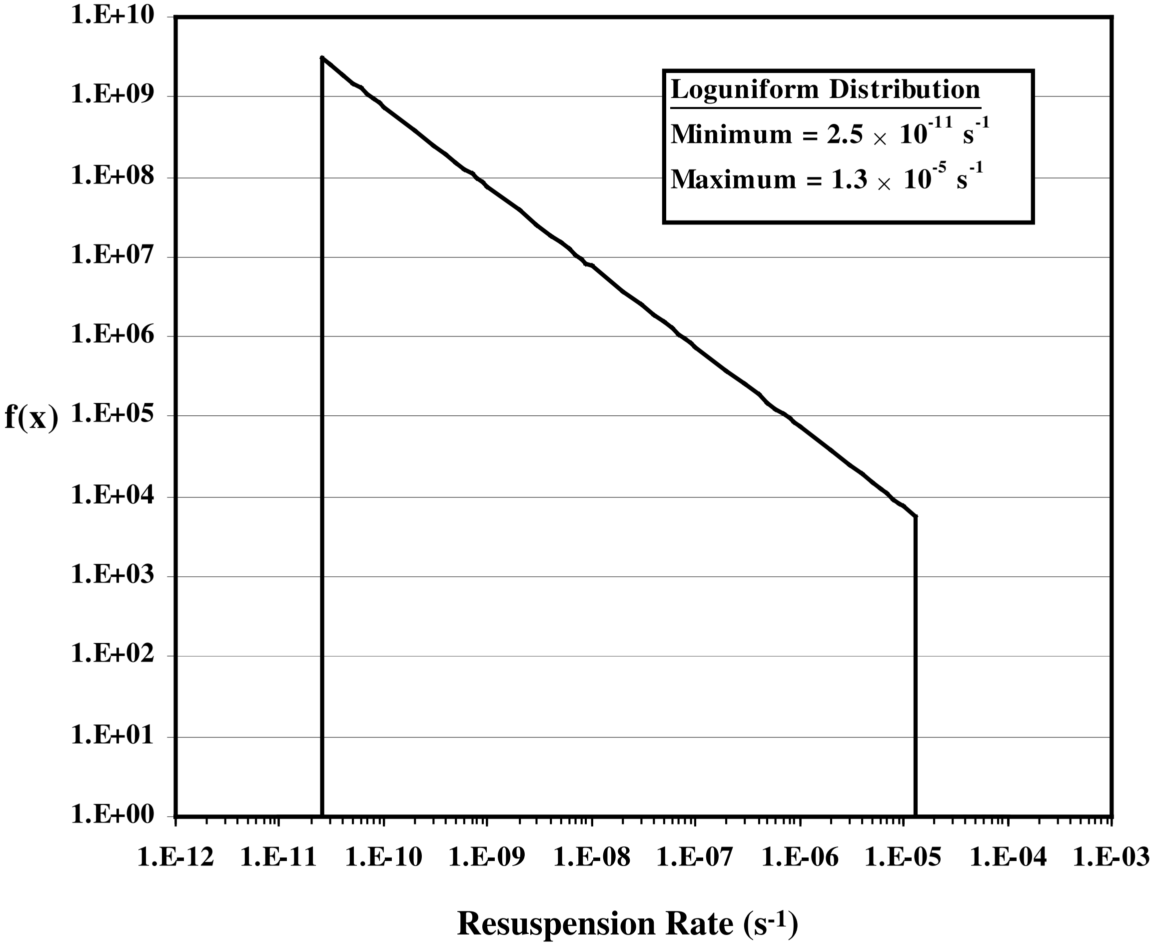

FIGURE J.6 Indoor Resuspension Rate Probability Density Function

J.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

Probabilistic Analysis Default Distribution: Triangular
Defining Values for Distribution:
Minimum: 2.4 Maximum: 9.1 Most likely: 3.7

Window: Building Parameters → Airflow (room details)

Discussion: The room height is used in determining the mixing volume of each distinct airflow volume (room) and the equilibrium of resuspension and deposition. It is used in conjunction with the area of the room and the airflow rates to compute the building air exchange rate and the room air exchange rate. By its nature, the airflow volume could also represent 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 height is set for each defined room in the analysis and should be consistent with the definition of that room.

Over half the new single-family homes constructed annually have room heights of 2.4 m (8 ft), as shown in Table J.10. The 2.4-m (8-ft) height is considered to be typical of residential housing (EPA 1997). Minimum room heights of 2.1 m (7 ft) below beams and girders are required by the Council of American Building Officials, with a ceiling height of not less than 2.3 m (7.5 ft) for half of the required area (National Association of Home Builders [NAHB] 1998). The U.S. Department of Housing and Urban Development requires a minimum ceiling height of not less than 2.1 m (7 ft) for at least half of the floor area and 1.9 m (6 ft 4 in.) under ducts and beams.

No comprehensive study of room height in commercial buildings exists. Room height can vary within the same occupational setting as well as between industries. Room height may also vary according to climate (because of energy efficiency considerations). A typical room height in commercial buildings is 3.7 m (12 ft) (EPA 1997). A minimum of 2.4 m (8 ft) is found in smaller rooms, such as those used for individual offices or conference rooms. Larger room heights are found in warehousing (shipping/receiving) operations, which may have room heights of up to approximately 9.1 m (30 ft). Thus, for an occupational scenario, such as light industry, a default triangular distribution for the room height is suggested, with a most likely value of 3.7 m and minimum and maximum values of 2.4 and 9.1 m, respectively. This distribution is a rough generalization, and site-specific data should be used when available. The probability density function is shown in Figure J.7.

TABLE J.10 Room Height in New Conventional and Manufactured Homes, 1996

Room Height (m) [ft]	Conventional Homes (first floor), (percent of total)	Manufactured Homes (percent of total)
≤ 2.1 [≤ 7]	0.1	48.2
2.3 [7.5]	1.6	37.4
2.4 [8.0]	57.8	5.1
2.6 [8.5]	0.8	1.5
2.7 [9.0]	24.2	7.7
> 2.7 [> 9]	15.5	–

Source: NAHB (1998).

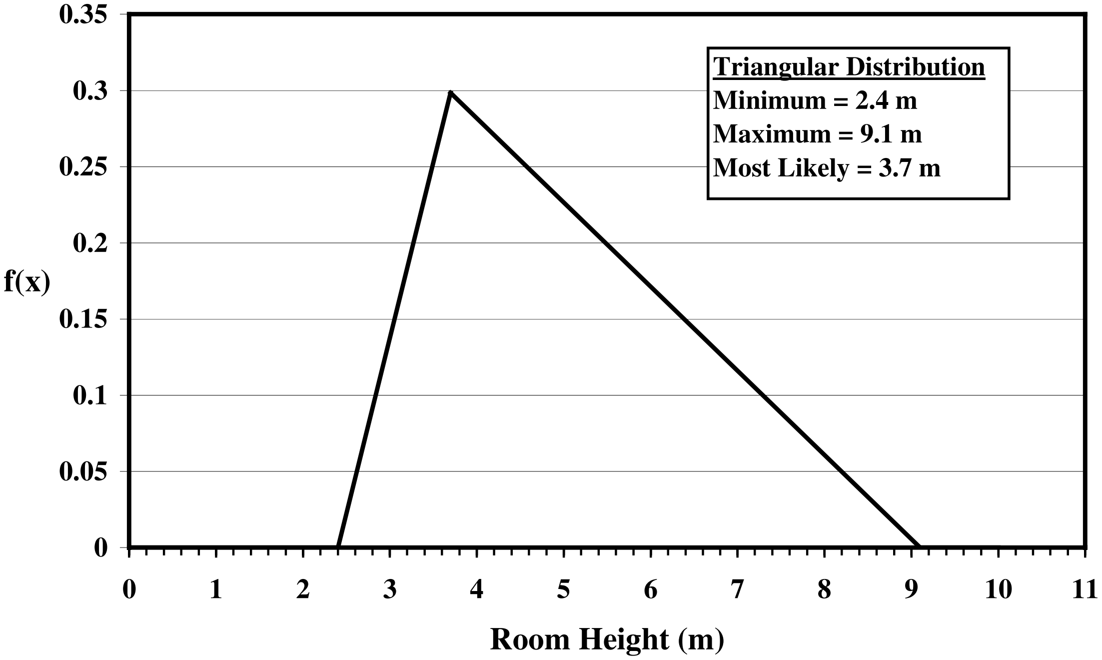

FIGURE J.7 Room Height Probability Density Function

J.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

Window: Building Parameters → Airflow (room details)

Discussion: The room area is used in determining the mixing volume of each distinct airflow volume (room) and the equilibrium of resuspension and deposition. It is used in conjunction with the height of the room and the airflow rates to compute the building air exchange rate and the room air exchange rate. By its nature, the airflow volume could represent the space within a small storage area (e.g., about 1 m^2) or a warehouse (e.g., thousands of m^2). The area is set for each defined room in the analysis and should be consistent with the definition of that room.

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 $1.5 \cdot 2$ 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, $3 \text{ m} \cdot 4$ m) and is in the range of what might be expected for a multioccupant office room. Figure J.8 presents the probability density function suggested for the room area.

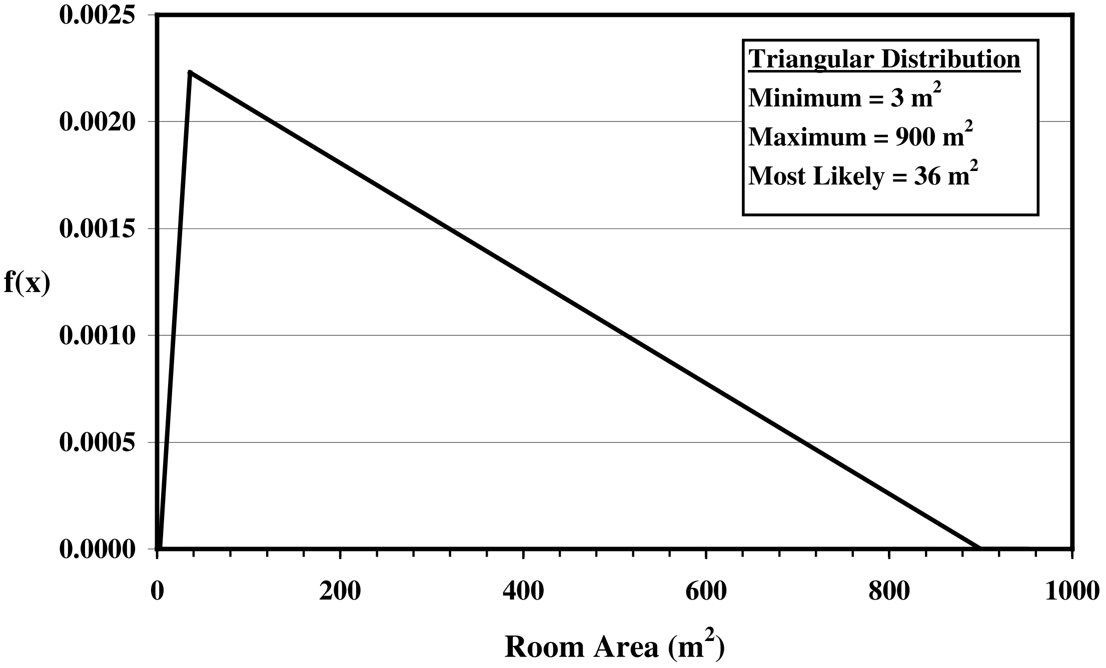

FIGURE J.8 Probability Density Function for Room Area

J.2.6 Air Exchange Rate

Definition: The air exchange (or ventilation) rate for a building or a room is the total volume of air in the building or room replaced by outside air per unit of time. For example, a building (or room) with a ventilation rate of 1 per hour (1/h) has its air replaced once each 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: lognormal-n (probabilistic input is only available for LAMBDAT, the building air exchange rate)
Defining Values for Distribution:

Underlying mean value:	0.4187	Lower quantile value:	0.001
Standard deviation:	0.88	Upper quantile value:	0.999

Window: Building Parameters → Airflow (room details)

Discussion: The building air exchange rate is input by the user for a one-room building. It is computed by using the heights and the areas of the rooms and by using the airflow rates into and out of the rooms for two-or three-room buildings. In RESRAD-BUILD, 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 air exchange rate parameter is used in the air quality model. For the one-room model, the air exchange rate for the building and that for the room are the same value; this value is an input required by the code. For the two-room and three-room models, inflow from outside and the flow between the rooms are required. The room air exchange rate for two- or three-room buildings is computed by using the height and the area of the room and the airflow rates into and out of the room. 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.

The average infiltration rate for a building can be expressed as the number of air changes per hour or air exchange rate (h^{-1}). 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. A number of studies have attempted to characterize building air exchange rates under different environmental conditions for buildings with different leakage characteristics.

Measurement of the ventilation rate in a building (or room) can be accomplished directly by first injecting a tracer gas, SF_6, into the house and then, after a mixing time, using an infrared analyzer to measure the gas concentration as a function of time. The ventilation rate is equal to the rate of decay of the tracer concentration (Nero 1988).

A passive measurement technique that is available releases a gaseous tracer from a small source at a constant rate inside the building. A collector monitor, consisting of a diffusive tube and an absorber, measures the average concentration during the time the system is in operation. The measured concentration is proportional to the inverse of the ventilation rate. Further references for these ventilation rate measurement techniques, as well as some predictive quantitative models, can be found in Nazaroff et al. (1988), Nero (1988), and Sherman (1990).

The air exchange rate can be found by dividing the room air-volume exchange rate by the room volume. These parameters can be estimated if the building specifications are known (e.g., the air-volume exchange rate in a forced-air heating/cooling system can be estimated by multiplying the vent area and the velocity of forced air). The air exchange rate of the entire building is the total volume of air going out of the building per unit of time divided by the total volume of the building.

A comprehensive study of residential ventilation rates was published by Pandian et al. (1993). To evaluate the distribution of ventilation rates of a large population of homes in the United States, the researchers analyzed a Brookhaven National Laboratory (BNL) database consisting of more than 4,000 residential perfluorocarbon tracer (PFT) measurements from approximately 100 individual studies. Table J.11 presents summary statistics from that study on air exchange rates in the United States and regionally. Pandian et al. (1993) also analyzed the data by season and by the number of levels with the homes. They concluded that exchange rates are higher in the Southwest than in the Northeast and Northwest; summer ventilation rates are much higher than winter and fall rates; and multilevel residences have higher air exchange rates than single-level residences. The authors present both arithmetic and geometric means and standard deviations, as well as percentile distributions.

Murray and Burmaster (1995) also used the data compiled by BNL using the PFT technique to estimate univariate parametric probability distributions for air exchange rates for residential structures in the United States. The analysis was characterized by four key points: the use of data for 2,844 households; a four-region breakdown based on heating degree days; estimation of lognormal distributions as well as provision of empirical (frequency) distributions; and provision of these distributions for all of the data. The authors summarized distributions for subsets of the data defined by climate region and season. The coldest region (region 1) was defined as having 7,000 or more heating degree days, the colder region (region 2) as having 5,500 to 6,999 degree days, the warmer region (region 3) as having 2,500 to 5,499 degree days, and the warmest region (region 4) as having fewer than 2,500 degree days. The months of December, January, and February were defined as season 1; March, April, and May as season 2; June, July, and August as season 3; and September, October, and November as season 4. The authors concluded that the air exchange rate was well fit by lognormal distributions for small samples sizes except in a few cases. The mean and standard deviations are listed in Table J.11. The authors recommended that the empirical or lognormal distribution may be used in indoor air models or as input variables for probabilistic health risk assessments.

In a study sponsored by the EPA (Koontz and Rector [1995]), a similar data set as analyzed by Murray and Burmaster (1995) was used. However, an effort was made to compensate for the nonrandom nature of the data by weighting results to account for each state's share of occupied housing units. As shown in Table J.11, the results of Murray and Burmaster (1995) are similar to those of Koontz and Rector (1995).

Air exchange rates from other representative residential studies are also summarized in Table J.11. The type of distribution can vary, depending on the type of study. For example, a survey of various housing types by Grimsrud et al. (1983) demonstrated that houses generally have air exchange rates that fall in a lognormal distribution between 0.1 and approximately 3 h^{-1}, with most clustered in the 0.25 to 0.75 range; however, some older ("leaky") houses, including low-income housing, had infiltration rates exceeding 3 h^{-1}. In contrast, Lipschutz et al. (1981) obtained measurements of air infiltration into 12 energy-efficient houses in Oregon by using a tracer gas decay analysis. A narrow range of values was found (0.08 to 0.27 h^{-1}), reflecting the extremely "tight" building construction and ventilation systems installed in the houses.

Doyle et al. (1984) measured air exchange rates in 58 weatherized houses during a 4- to 5-month period during both winter and summer sampling periods. The houses were located in Fargo, North Dakota; Colorado Springs, Colorado; Portland, Maine; and Charleston, North Carolina. The investigators determined the geometric means and geometric standard deviations for air exchange rates for each city and for the entire sample. Because of the relatively small number of measurements in each city, conclusions about the geographic distribution of air exchange rates are limited. However, combining the data for the cities provides an overall lognormal distribution of 0.8 ±1.8 h^{-1} (ranging from 0.2 to 2.3 h^{-1}), which appears to encompass most air exchange rates determined in other studies.

Studies on the air exchange rates of large commercial buildings have been much more limited. Table J.12 lists results from some studies on commercial buildings. It can be seen that these values are relatively close to those for residential construction. Although the primary outside air source for large buildings is the mechanical ventilation system, infiltration is the primary outside air source for residential homes (American Society of Heating, Refrigeration, and Air-Conditioning Engineers [ASHRAE] 1997). In either case, a continuous supply of outside air is required to dilute and eventually remove indoor contaminants. Thus, the air exchange requirements are expected to be similar for both residential and commercial construction.

However, differences in local airflow and temperature, as well as air exchange, may be required to maintain workers' comfort according to their activity level.

Turk et al. (1987) examined the outdoor exchange rates of 38 buildings in the Pacific Northwest. The buildings included schools, libraries, and office buildings in mild and harsh climates measured during different seasons of the year. Results are shown in Table J.12. The arithmetic mean and standard deviation are 1.52 h^{-1} and 0.873, respectively. Although this set of data is limited, the mean falls between the arithmetic means determined Pandian et al. (1993) and Murray and Burmaster (1995), 1.99 and 0.76 h^{-1}, respectively, for residential air exchange rates. The air exchange data from Persily and Grot (1985) and Silberstein and Grot (1985), as shown in Table J.12, fall within the range observed by Turk et al. (1987). The studies by Weschler et al. (1994), Dietz and Goodrich (1995), and Fisk et al. (2000) also fall within the same range. The study of a laboratory/office complex by Weschler et al. (1989) has two values outside this range, 4.0 and 8.2 h^{-1}. However, maximum values of 11.77 and 45.6 h^{-1} were used by Murray and Burmaster (1995) and Pandian et al. (1993), respectively.

While the data on commercial building air exchange rates are limited, the distribution of rates is expected, in part because of human comfort considerations, to be similar to 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 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. As discussed above, 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 data set and variations across different industries, climates, and seasons, this distribution is only an approximation to potential building air exchange rates for light industry. Figure J.9 displays the probability density function for the building air exchange rate. The same lognormal distribution is assigned to room exchange rates because the building air exchange rate is an average of the rooms within.

TABLE J.11 Residential Air Exchange Rate (h^{-1}) Distribution Characteristics

Distribution Type	Min.	Max.	Mean	SD	Comments	References
Lognormal	0.3	2.2	0.9	1.8	Charleston, S.C. (*n* = 20 houses)	Doyle et al. 1984
	0.2	2.3	0.6	1.8	Colorado Springs, Colo. (*n* = 16 houses)	
	0.3	2.2	0.5	2.1	Fargo, N.D. (*n* = 11 houses)	
	0.7	1.4	1.0	1.3	Portland, Maine (*n* = 11 houses)	
	0.2	2.3	0.8	1.8	All cities (*n* = 58 houses)	
					Calculated infiltration rates based on post-weatherization measurements of “effective leakage area.”	
Normal					Pre-retrofit in one house:	Berk et al. 1981
	0.36	0.71	0.62	0.25	*n* = 17 measurements with fan on	
	0.18	0.56	0.33	0.14	*n* = 11 measurements with fan off	
					Post-retrofit in one house:	
	0.22	0.69	0.49	0.11	*n* = 16 measurements with fan on	
	0.10	0.33	0.20	0.08	*n* = 11 measurements with fan off	
Normal	0.08	0.27	0.17	0.06	*n* = 12 energy-efficient houses	Lipschutz et al. 1981
Lognormal	0.1	3.1	0.5 median		*n* = 312 houses in North America	Grimsrud et al. 1983, as cited in Godish 1989
	0.1	3.6	0.9 median		Subsample of low-income housing	
Lognormal	0.17	1.33	0.33 median		*n* = 8 mobile home measurements	Godish and Rouch 1988
	0.18	1.45	0.36 median		*n* = 10 UFF-insulated home measurements	
Normal					*n* = 9 houses in upstate New York	Offermann et al. 1985
	0.22	0.50	0.35	0.08	With mechanical ventilation off	
	0.47	0.78	0.63	0.10	With mechanical ventilation on	
Normal					*n* = 10 houses in Washington state	Lamb et al. 1985
	0.40	0.98	0.27		Pre-weatherization retrofit	
	0.23	1.00	0.30		Post-weatherization retrofit	

TABLE J.11 (Cont.)

Distribution Type	Min	Max	Mean	SD	Comments	References
Lognormal						
			0.89	3.44	All regions (*n* = 1,836) geometric mean, SD	Pandian et al. 1993
			0.34	1.88	Northwest (*n* = 423)	
			0.40	2.07	Northeast (*n* = 423)	
			1.86	3.02	Southwest (*n* = 990)	
			1.99	3.28	All regions (*n* = 1,836) arithmetic mean, SD	
			0.42	0.33	Northwest (*n* = 423)	
			0.60	2.23	Northeast (*n* = 423)	
			3.25	3.79	Southwest (*n* = 990)	
			0.76	0.88	All regions All seasons (*n* = 2844)	Murray and Burmaster 1995
			0.55	0.47	All regions Season 1 (*n* = 1139)	
			0.65	0.57	All regions Season 2 (*n* = 1051) arithmetic mean, SD	
			1.50	1.53	All regions Season 3 (*n* = 529)	
			0.41	0.58	All regions Season 4 (*n* = 125)	
			0.40	0.30	Region 1 All seasons (*n* = 467)	
			0.55	0.48	Region 2 All seasons (*n* = 496)	
			0.55	0.42	Region 3 All seasons (*n* = 332)	
			0.98	1.09	Region 4 All seasons (*n* = 1,549)	
			0.66	0.87	West Region (arithmetic mean and SD)	Koontz and Rector 1995
			0.57	0.63	North Central Region	
			0.71	0.60	Northeast Region	
			0.61	0.51	South Region	
			0.63	0.65	All	
			0.47	2.11	West Region (geometric mean and SD)	
			0.39	2.36	North Central Region	
			0.54	2.14	Northeast Region	
			0.46	2.28	South Region	
			0.46	2.25	All	

TABLE J.12 Outside Air Exchange Rates for Commercial Buildings

Building Air Exchange Rate (h^{-1})	Building Description	Reference
0.33 – 1.04	Large office buildings	Persily and Grot (1985)
0.9	The National Archive Building	Silberstein and Grot (1985)
	38 commercial buildings studied in the Pacific Northwest during all seasons of the year. Two buildings were sampled twice at different times of the year.	Turk et al. (1987)
	Number of buildings:	
0.0 – 0.5	3	
0.5 – 1.0	10	
1.0 – 1.5	9	
1.5 – 2.0	8	
2.0 – 2.5	6	
2.5 – 3.0	2	
3.0 – 3.5	0	
3.5 – 4.0	1	
4.0 – 4.5	1	
0.6, 4.0, and 8.2	Three buildings in an office/laboratory complex	Weschler et al. (1989)
0.3 – 1.9	1st floor of Burbank, California, office building over a 14-month period	Weschler et al. (1994)
2.5	Classroom building on a college campus	Dietz and Goodrich (1995)
0.45 – 0.53 and 0.68 – 0.74	Two different floors, each with its own air handling unit, in the same office building. Range of air exchanges observed over a 7-week period.	Fisk et al. (2000)

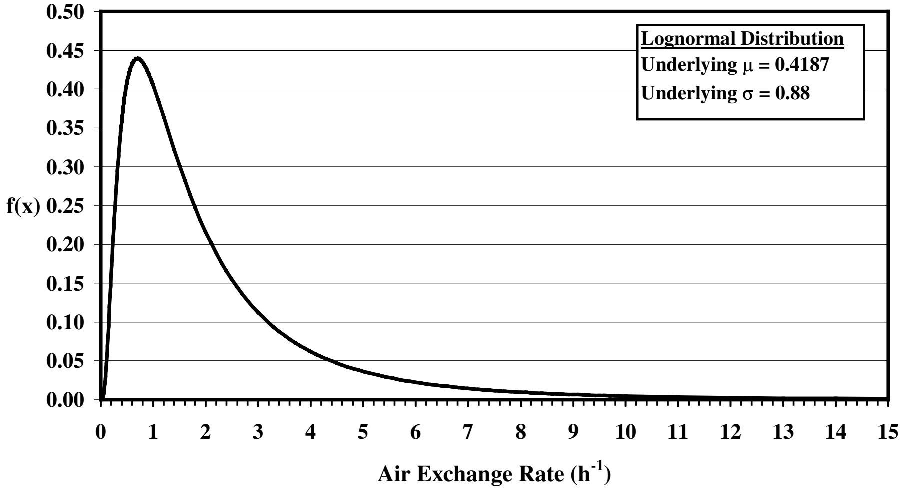

FIGURE J.9 Building Air Exchange Rate Probability Density Function

J.2.7 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 the one-room model.

Parameter Name: Q12 and Q21 (two-room and three-room model); Q23 and Q32 (three-room model only)

Units: m^3/h **Range:** Unlimited

Default Value: Not applicable (default one-room model); Q12 and Q21 = 30 m^3/h (two-room model); Q12 = 0, Q21 = 0, Q23 = 30, and Q32 = 30 m^3/h (three-room model)

Window: Building Parameters → Airflow (room details)

Discussion: This parameter is not eligible for probabilistic input. The flow rate between rooms depends strongly on other air quality model parameters, such as the number of rooms and the air exchange rate. For the one-room model, this parameter is not required. In the code, no air exchange is assumed between rooms 1 and 3; therefore, there is no airflow from room 1 to room 3. For the two-room model, two flow rate parameters (in cubic meters per hour, or m^3/h) are required; for the three-room model, four flow rate parameters are required. The net flow corresponds to the net volume of air exchanged between the two rooms per unit of time.

The net flow rate between two rooms may be positive, zero, or negative. The net inflow rate from room 1 to room 2 can be negative, which means that the net airflow is from room 2 to room 1. In the two-room model, the net flow between the two rooms must be balanced with the outside airflow into or out of each room. In the three-room model, the net flow between the first and second rooms must equal the sum of the net flow between the second and third rooms plus the outside airflow into or out of each room. The same logic is true when the net flow between the second and third room is being calculated. The measurement of the net flow between two rooms may be estimated from building specifications for the ventilation system.

J.2.8 Outdoor Inflow and Outflow

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 multiroom buildings; they will only be equal if there is no net air flow between the adjoining rooms.

Parameter Name: Q10 and Q01 (one-, two-, and three-room model); Q20 and Q02 (two-room and three-room model); Q30 and Q03 (three-room model only)

Units: m^3/h **Range:** unlimited

Default Value: (default one-room model); Q10 = Q01 = 72 m^3/h (one-room model); Q10 = Q01 = 84 m^3/h and Q20 = Q02 = 60 m^3/h (two-room model); Q10 = Q01 = 96 m^3/h and Q20 = Q02 = Q30 = Q03 = 60 m^3/h (three-room model)

Window: Building Parameters → Airflow (room details)

Discussion: This parameter is not eligible for probabilistic input. The outdoor inflow and outflow parameters strongly depend on other air quality model parameters, such as the number of rooms and air exchange rate. For the one-room model, this parameter is not required. For the two-room model, four flow parameters (in m^3/h) are required; for the three-room model, six flow parameters are required. The net outdoor flow rate (inflow-outflow) like the net flow rate between rooms may be positive, zero, or negative. Increasing or decreasing this parameter will affect other dependent airflow parameter values. The measurement of net flow between two rooms may be estimated from building specifications for the ventilation system.

J.2.9 References

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J.3 RECEPTOR PARAMETERS

J.3.1 Number of Receptors

Definition: This parameter represents the number of individuals who are the subjects of the dose assessment.

Parameter Name: ND **Units:** Unitless **Range:** Integer values from 1 to 10, inclusive

Default Value: 1

Window: Receptor Parameters

Discussion: This parameter is not eligible for probabilistic input. The number of receptor parameters may or may not represent the actual number of exposed receptors. The number of receptors may be used to represent (1) a number of different locations occupied by the same individual at different times or (2) a number of different individuals with similar characteristics who occupy the same location (see Section J.3.4 on the receptor time fraction). Therefore, each receptor does not necessarily represent a unique individual; rather, it helps define the characteristics of the one or more individuals who are the targets of the dose assessment.

One to 10 receptors may be defined, each with associated parameters such as location within a building or room, time fraction at each location, and inhalation/ingestion rates. The number of receptors may be estimated on the basis of anticipated occupancy patterns or the purpose of the dose assessment. If a dose assessment is to be performed for a single individual who will be in only one room at a fixed location during the assessment period, the number of receptors is one. This case will also be true if the individual is expected to be at various locations within the room, and there are no significant sources of direct gamma radiation. However, if there are gamma radiation sources, the dose rate to the individual may depend on the location, and a number of receptors greater than one may be defined to represent various points within the room with different direct gamma dose rates. The time fraction spent by the individual at each location (see Sections J.3.3 and J.3.4 on receptor location and receptor time fraction, respectively) may then be estimated on the basis of actual experience or anticipated occupancy patterns such as those found in time-motion studies.

If a dose assessment is to involve multiple individuals (collective dose assessment), the number of receptors could still be one if all the individuals will be in only one room (possibly at various locations), and there are no significant sources of direct gamma radiation. Also, a single receptor may be used to represent multiple individuals of whom two or more may be in the same location at different times (e.g., shift work). Multiple receptor locations will have to be defined when multiple individuals occupy different rooms, or when the direct gamma dose rate is a function of location and a significant component to the total dose.

J.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, or 3

Default Value: 1

Window: 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 allowed by the code. The identification of the room in which a receptor is located affects the air pathways but not the direct gamma radiation pathway. If only one room has been defined, the receptor room will be one. If two rooms have been defined, a receptor may be placed in room 1 or 2. If three rooms have been defined, a receptor may be placed in room 1, 2, or 3.

Placement of a receptor in one of up to three rooms will depend on site-specific and scenario-specific assumptions. The number of rooms must first be defined (see Section J.2.1 on the number of rooms) before a receptor may be located in one of them. The code then requires that, for each receptor, the receptor room be set at an integer value of 1, 2, or 3. The maximum value of the receptor room is determined by the number of rooms.

If a scenario that was originally set up for a two- or three-room model is modified by removing a room, any receptors previously located in rooms 2 or 3 are automatically relocated to room 1; however, their spatial coordinates are not changed. The user is advised to reevaluate the number of receptors, receptor rooms, and receptor locations before running the modified problem.

J.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

Window: Receptor Parameters

Discussion: This parameter is not eligible for probabilistic input. The receptor location is important only to assess direct external gamma exposure from a source; all other pathways make use of the room in which the receptor is located (see Section J.3.2 on the receptor room) to assess the dose. The spatial coordinates (x, y, and z) of the receptor location may be in one of three rooms inside the building. In addition, the spatial coordinates must be within the designated room. Typically, a dose assessment is made at 1 meter above the floor over which the receptor is located. However, different geometrical considerations may reduce or increase this number (e.g., if the receptor is working at heights or sleeping). Also, since a receptor is represented in the code by using a single point defined by Cartesian coordinates, points that are physically inappropriate for human receptors should be avoided (e.g., in contact with or within a source or building structure).

The receptor location is important only for assessing direct external gamma exposure from a source. The average location within a room may be used to establish the receptor location. However, if the receptor might be at different points inside a room where the direct gamma radiation contribution might vary significantly, it might be useful to assess more than one receptor location within the room and adjust the receptor time fraction accordingly. The receptor location parameter may also be used to assess the collective dose impact on a number of receptors occupying the room at the same time, or it may be used to assess the total dose to a single receptor that spends time in more than one room.

The code requires that, for each receptor, a location must be entered with spatial coordinates (in meters) for the receptor midpoint relative to the selected origin. The user must ensure that these coordinates are appropriate for the room's dimensions. For all source types, a source may not be located at the same coordinates as 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 the source.

J.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:** Unitless **Range:** > 0

Default Value: 1

Window: Receptor Parameters

Distribution: This parameter is not eligible for probabilistic input. If only a single receptor is modeled, the time fraction spent at any location inside the building may be any number greater than zero but less than or equal to 1. If a single receptor spends time at more than one location, the sum of the time fractions at each location should not exceed 1. If multiple receptors are modeled and more than one receptor is assumed to spend time at the same location, this parameter may exceed 1 (see Section J.3.3 on the receptor location). The total receptor time spent by one or more receptors inside the building is given by the product of the sum of receptor time fractions at each location, the indoor fraction, and the total time for dose evaluation.

The receptor time fraction may be estimated on the basis of anticipated occupancy patterns. For example, if a single receptor is always inside the same room while inside the building, the receptor time fraction is 1. However, if the room is used by more than one occupant (e.g., shift work), the receptor time fraction may be greater than 1, and the resulting dose at the receptor location should be interpreted as a collective dose. The user must ensure that the sum of receptor time fractions for all receptor locations does not exceed the number of building occupants. The determination of receptor time fractions may be made according to predicted occupancy patterns for the type of occupancy anticipated inside the building.

J.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

Window: Receptor Parameters

Discussion: If more than one receptor location is chosen, the breathing rate at each location must be specified. If inhalation pathways are not analyzed in a scenario, the inhalation rate can be set to zero. The range of estimates of inhalation rate (Table J.13) reflects the differences in patterns of time and activity levels, as well as age, sex, and weight of the individual. Until recently, inhalation rates for the "reference man and woman," as described by the International Commission on Radiological Protection (ICRP 1975), were often used as default values. The ICRP best estimates, which are based on 16 hours of light activity and 8 hours of rest, are as follows: 23 m^3/d (range of 23–31 m^3/d) for adult males; 21 m^3/d (range of 18–21 m^3/d) for adult females; and 15 m^3/d for a 10-year-old child. By using different patterns for the time and activity levels, the EPA has proposed a wider range of adult inhalation rates but recommends essentially the same point estimates as the ICRP for "average" adults (EPA 1985, 1989, 1991, 1997).

The distribution varies widely because of differences in time-use activity patterns that are developed for outdoor/indoor and occupational/residential exposures. Because activity levels of various individuals and groups can vary to a significant extent, it is preferable to derive a range of inhalation rates by using activity data specific for the population under study. The daily average inhalation rate in RESRAD-BUILD is meant to represent workers in an occupational setting. For assessments involving other specific activities, inhalation rates can be selected that are thought to be representative of these particular activities. Similarly, if receptors of a certain age group are being evaluated, breathing rate values should be selected specifically for that age group.

Layton (1993) proposed three alternative approaches for deriving inhalation rates that are based on oxygen uptake associated with energy expenditures: (1) average daily intakes of food energy from dietary surveys, (2) average daily energy expenditure calculated from ratios of total daily expenditure to basal metabolism, and (3) daily energy expenditures determined from a time-activity survey. These approaches consistently yield inhalation rate estimates that are lower than the EPA's best "reasonable worst case" estimates and ICRP (1975) reference values. Layton's inhalation rate estimates fall in the recommended range and may be more accurate values for point estimates. However, the approach needs to be further reviewed and validated in the open literature before these lower, less conservative inhalation rate estimates are used.

The available studies on inhalation rates have been summarized by the EPA (1997). Inhalation rates are reported for adults and children (including infants) performing various activities and for outdoor workers and athletes. The activity levels have been categorized as resting, sedentary, light, moderate, and heavy. Table J.14 summarizes inhalation rate values recommended by the EPA both for long-term and short-term exposure. The daily average inhalation rates for long-term exposure for adults are 11.3 m^3/d for women and 15.2 m^3/d for men.

A default triangular distribution is used for input to RESRAD-BUILD for a building occupancy scenario. 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). 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 and falls within the range of moderate to heavy activities for both adults and outdoor workers (Table J.14). Figure J.10 presents the probability density function for the default inhalation rate distribution.

As discussed above, the breathing rates of individuals are a well-measured parameter that require no additional site-specific measurements unless the receptors involved are significantly different from the average individual. On the basis of the assumed exposure scenario and anticipated activity profile, the average breathing rate for a receptor location may be estimated by using time-weighted inhalation rates for the different receptor types and activity levels presented in Table J.14. The code requires that the average breathing rate (in m^3/d) be defined for each receptor location. The default deterministic value is 18 m^3/d. Setting this parameter to zero effectively suppresses the dust inhalation pathway.

TABLE J.13 Inhalation Rate Distributions

Basis	Distribution Type	Inhalation Rate (m^3/d) Min.	Max.	Mean	Most Likely	References
Based on time-weighted average food-energy intakes adjusted for reporting bias	Triangular					Layton 1993
Males (lifetime average)		13	17		14	
Females (lifetime average)		9.6	13		10	
Based on average age-adjusted daily energy expenditure rates	Triangular					Layton 1993
Males (18–60+ yr)		13	17		15	
Females (18–60+ yr)		9.9	11		11	
Based on age-adjusted activity patterns and metabolic rates for an “average day”	Triangular					Layton 1993
Males (20–74 yr)		13	17		16	
Females (20–74 yr)		11	15		13	
“Reference man” - Based on light activity (16 hours) and resting (8 hours)	Triangular					ICRP 1975
Adult male		23	31		23	
Adult female		18	21		21	
Child		-	-		15	
Based on “typical” outdoor activity levels[a]	Triangular					EPA 1985, 1989, 1991
Adult female		17	70	25	20	
Adult male		13	79	40	20	
Average adult		-	-	34	20	
Based on “typical” indoor activity levels[b]	Triangular					EPA 1985, 1989, 1991
Adult female		7	34	11	15	
Adult male		4	38	21	15	
Average adult		-	-	15	15	
Study of age-dependent breathing rates at realistic activity levels	-					Roy and Courtay 1991
0–0.5 yr					1.62	
0.5–2 yr					5.14	
2–7 yr					8.71	
7–12 yr					15.3	
12–17 yr					17.7	

[a] Resting: 28%, light activity: 28%, moderate activity: 37%, heavy activity: 7%.

[b] Resting: 48%, light activity: 48%, moderate activity: 3%, heavy activity: 1%.

TABLE J.14 Summary of EPA's Recommended Values for Inhalation

Population	Mean (m^3/d)	Population	Mean (m^3/h)
Long-Term Exposures		***Short-Term Exposures***	
Infants (<1 year)	4.5	Adults	
		Rest	0.4
Children		Sedentary activities	0.5
1–2 years	6.8	Light activities	1.0
3–5 years	8.3	Moderate activities	1.6
6–8 years	10	Heavy activities	3.2
9–11 years			
Males	14	Children	
Females	13	Rest	0.3
12–14 years		Sedentary activities	0.4
Males	15	Light activities	1.0
Females	12	Moderate activities	1.2
15–18 years		Heavy activities	1.9
Males	17		
Females	12	Outdoor Workers	
		Hourly average[a]	1.3
Adults (19–65+yrs)		Slow activities	1.1
Females	11.3	Moderate activities	1.5
Males	15.2	Heavy activities	2.5

[a] Upper percentile = 3.3 m^3/h.

Source: EPA (1997).

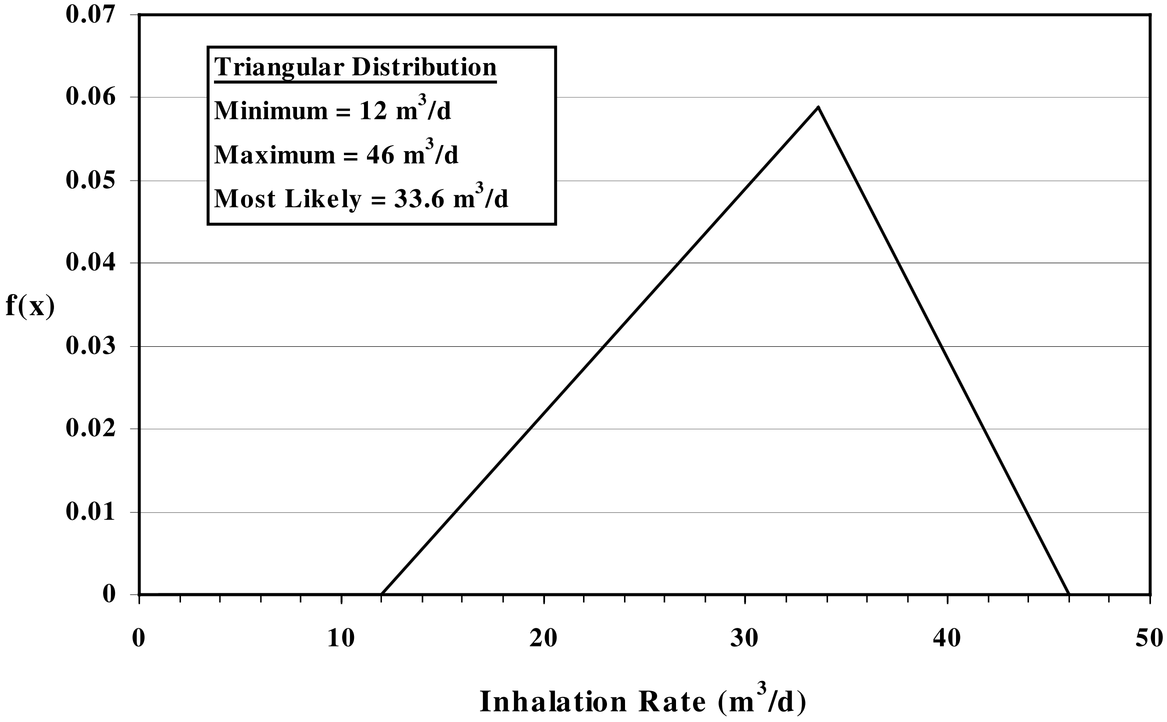

FIGURE J.10 Inhalation Rate Probability Density Function

J.3.6 Indirect Ingestion Rate

Parameter Name: INGE2

Definition: This parameter represents the ingestion rate of deposited material for a receptor at a specified location inside the building. 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 by 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: $2.8 \cdot 10^{-5}$ Maximum: $2.9 \cdot 10^{-4}$

Window: Receptor Parameters

Discussion: Only limited information is available on the values for this parameter. As reported in Beyeler et al. (1998), only eight data references are available (Dunster 1962; Gibson and Wrixon 1979; Healy 1971; Kennedy et al. 1981; Sayre et al. 1974; Lepow et al. 1975; Walter et al. 1980; Gallacher et al. 1984). However, half of these studies concerned intake by children, not adults in an occupational setting. A larger, secondary set of data from soil ingestion studies is available (see Section J.4.8). Again, however, the primary emphasis has been soil ingestion rates of children because 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 (1997) and Simon (1998).

Because the indirect ingestion rate is specified as the surface area contacted per unit time, estimates of the daily ingested amount were converted to the proper units by using estimates for deposited contamination (soil) concentrations on surfaces and soil loadings on the hand (Beyeler et al. 1998). Thus, a large uncertainty for the indirect ingestion rate is expected; in fact, the uncertainty is larger than the anticipated variability across sites (Beyeler et al. 1998). For this reason, Beyeler et al. (1998) have proposed two alternative distributions. However, Beyeler's suggested procedure produces an effective ingestion rate. It incorporates the number of hand-to-mouth events per day and transfer efficiencies between surface-to-hand and hand-to-mouth, because these factors were not explicitly accounted for in the calculation.

The two alternative distributions were proposed on the basis of mean ingestion rates of 0.5 and 50 mg/d. These rates fall within the 0 to 70 mg/d range 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 were taken to be 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 an upper 95% 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 loguniform distributions (Table J.15) for the indirect ingestion rate parameter ranged from $4.4 \cdot 10^{-4}$ to $4.6 \cdot 10^{-3}$ m^2/d, with a mean of $1.8 \cdot 10^{-3}$ m^2/d; and from $5.1 \cdot 10^{-2}$ to $4.3 \cdot 10^{-1}$ m^2/d, with a mean of $1.8 \cdot 10^{-1}$ m^2/d. For use in RESRAD-BUILD, a 16-hour day was assumed, resulting in distributions with means of $1.1 \cdot 10^{-4}$ and $1.1 \cdot 10^{-2}$ m^2/h for the low and high average ingestion rate distributions presented in Table J.15. As discussed in Beyeler et al. (1998), an ingestion rate corresponding to $1 \cdot 10^{-2}$ 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 adult ingestion rates can often approach zero (the lower bound), the lower ingestion rate distribution has been selected as a default for use in RESRAD-BUILD. Figure J.11 presents the probability density function.

The code requires that the average indirect ingestion rate in m^2/h be defined for each receptor location. The default deterministic value of 0.0001 m^2/h is consistent with the mean value of the default probabilistic input distribution. Setting this parameter to zero effectively suppresses the indirect ingestion pathway.

TABLE J.15 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] Assumes a 16-hour day using the results from Beyeler et al. (1998).

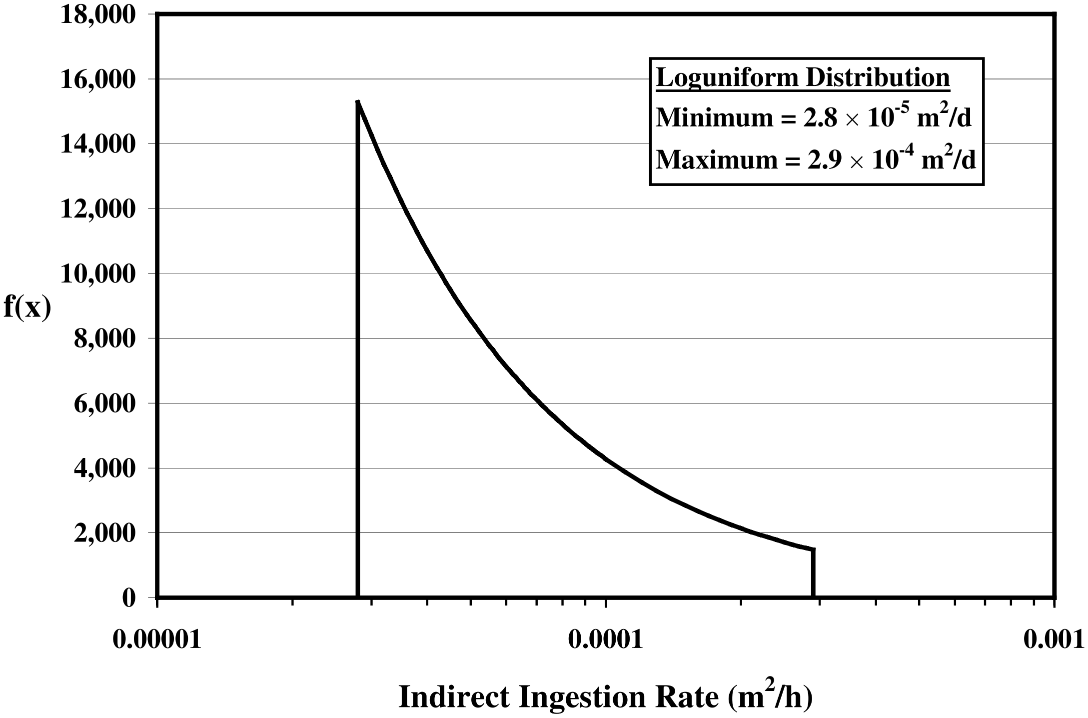

FIGURE J.11 Indirect Ingestion Rate Probability Density Function

J.3.7 References

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J.4 SOURCE PARAMETERS

J.4.1 Number of Sources

Definition: The number of sources specifies the number of radioactive source locations to be considered in the dose assessment.

Parameter Name: NS **Units:** Unitless **Range:** Integer between 1 to 10, inclusive

Default Value: 1

Window: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. One to 10 sources may be defined, each with associated parameters, such as location within a building or room, source type and direction, and source details.

The number of sources may be estimated on the basis of the actual number of independent radioactive sources present in the building. Single sources may also 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. An area or volume source whose length is twice as large as its width may be modeled as two sources of equal lateral dimensions, since the code models such sources as disks or cylinders, respectively. Another reason to divide a source into two or more components is if it is a heterogeneous distribution of radionuclides. For example, a source may be volumetrically contaminated with certain radionuclides but may also have a surface contaminated with different or higher concentrations of the same radionuclides. The code requires at least one source (and its associated geometrical, physical, and radiological characteristics).

J.4.2 Source Room (also Primary Room)

Definition: The source room or primary room is the room number containing a particular source.

Parameter Name: SLVL **Units:** Unitless **Range:** Integer value of 1, 2, or 3

Default Value: 1

Window: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. If only one room has been defined, the source room will be room 1. If two rooms have been defined, a source may be placed in room 1 or 2. If three rooms have been defined, a source may be placed in room 1, 2, or 3. The identification of the room in which a source is located affects the air pathways and the direct ingestion pathway but not the direct gamma radiation pathway.

Placement of a source in one of up to three rooms will depend 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 user must select a primary room into which any source material may be initially released. For example, a wall between two rooms may be volumetrically contaminated, but most of the source is located on one side of the wall. The source room would be the one into which most of the contaminants would be released. For uniform contamination, the user may divide the source into two (see "Number of Sources") 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 J.4.13 and J.4.14 on number of regions in volume source and contaminated region, respectively).

The number of rooms must first be defined (see Section J.2.1 on the number of rooms) before a source may be located in one of them. The code then requires that, for each source, the source room be set at an integer value of 1, 2, or 3. The maximum value of the source room is determined by the number of rooms. If a scenario originally set up for a two- or three-room model is modified by removing a room, any sources previously located in rooms 2 or 3 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 the modified problem.

J.4.3 Source Type

Definition: The source type specifies the geometrical representation of the physical distribution of radioactive material within a source. One of four source types — volume, area, line, or point — is selected to represent the best approximation for modeling a source that has a uniform distribution of radionuclides within it.

Parameter Name: STYPE **Units:** Unitless **Range:** Volume, area, line, or point

Default Value: Volume

Window: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. Depending on geometric appearance, a source may be represented by one of four types: volume, area, line, or point.

- *Volume source:* This source has a circular exposed area with some finite depth perpendicular to this area. This means that many details of the building component and contamination must be specified. The user may specify up to five different regions along the thickness of the source.

- *Area source:* This source has a circular exposed area with no thickness.

- *Line source:* This source has no thickness or depth.

- *Point source:* This source has no dimensional or directional characteristics.

The external dose from a source of equal strength could depend strongly on the source geometry. The volume type and other types also are distinguished in the air quality model. The injection and radon release models are different.

The source type is not a measurable quantity. However, the source type will determine the measurement methodology for the source activity or concentration. 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 width or depth may be treated as a line source.

The code requires the designation of a source type (volume, area, line, or point) for each source represented. At least one source with an assigned type must be represented, and up to a total of 10 sources, each with an assigned type, may be represented. The source type selected will automatically adjust the proper input units for source activity or concentration. The selected source type will also determine if additional descriptive parameters will be required. At a minimum, the source location will be required (all source types). Other required parameters may include source length (line source), source area (volume and area sources), source direction (volume, area, and line sources), and source thickness (volume source). The code models area sources as disks and volume sources as cylinders.

J.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

Window: 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 J.12 provides examples of source direction for line and area sources.

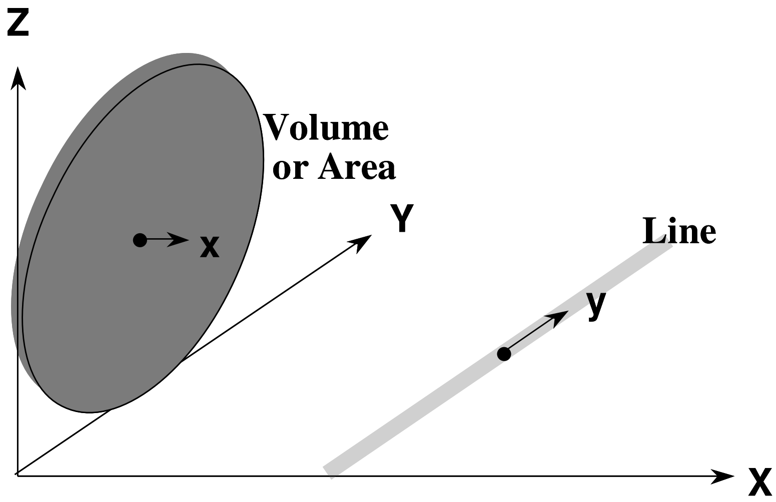

FIGURE J.12 Source Direction for Line, Area, and Volume Sources

J.4.5 Source Location

Definition: The source location specifies the spatial position of the source center point in three-dimensional space relative to the origin. 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

Window: Source Parameters

Discussion: This parameter is not eligible for probabilistic input. The spatial coordinates (x, y, and z) of the source location 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.

The source location is determined by the number of rooms modeled. For volume sources, radon may diffuse into two rooms through a common wall, but the user must determine the primary room into which particulates are released. In addition, the location of the source center point must be provided relative to the coordinate system's origin. For point sources, the coordinates of the source are all that is required. The measurements for additional parameters are needed to define the extent of other source types (see Sections J.4.6 and J.4.15 on source length/area and source thickness, respectively). The user is free to place the origin anywhere in the building; however, the same origin must be used when specifying the locations of the receptor(s) and source(s). If volume sources are present, the origin must be placed so that the surface of the source from which the particulate and tritium releases occur is closer to the origin than the other surfaces of the source.

Although the source may be located at any physically allowable point in space, users must ensure that the placement of the source matches the scenario desired. The geometric coordinates used to define the center point of the source must be entered in meters. At least one point representing the center of each source must be defined by x, y, and z coordinates measured with respect to an absolute reference point. 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.

J.4.6 Source Length/Area

Definition: This parameter specifies the extent of the contamination. It is the exposed area for an area or volume source, or it is the length for a line source. It 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

Window: Source Parameters → Source Details

Discussion: For calculating direct external gamma doses, the source may have a large extent. However, for all other pathways, the source should be limited to the dimensions of the room into which radionuclides are being released.

For a line source, the length of the source must be measured. It is assumed that the contamination is distributed uniformly along the length. For area and volume sources, the area of contamination must be determined. For the area and volume sources, it is assumed that the contamination is distributed uniformly over the area. Sources whose geometries depart significantly from the idealized geometries used in the code may be broken down into smaller sources (see Section J.4.1 on the number of sources). In addition, the depth of contamination must be measured for a volume source (see Section J.4.15 on source thickness).

A line source requires the source length (in meters, or m). Area and volume sources require the surface area (in square meters, or m^2). If room dimensions are changed, the user must ensure that the source dimensions remain consistent with the new room dimensions. The code models area sources as disks and volume sources as cylinders.

J.4.7 Air Release Fraction

Definition: The air release fraction is the amount 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

Window: Source Parameters → Source Details

Discussion: The fraction released to the air is the amount of the contaminated material removed from the source that is suspended in air; the balance of the material (1 − AIRFR) is assumed to be instantaneously removed from the room. The value of this parameter can range from 0 (all eroded material is removed instantaneously from the room) to 1 (all eroded material is suspended instantaneously in the respirable room air). 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 0 means that none of the removable material will be released to the air that is respirable. The dose contributions from deposition, immersion, dust inhalation, and indirect ingestion are effectively suppressed. Entering 1 is very conservative because it will maximize the dose contributions from these pathways. If either the removable fraction (Section J.4.9) or erosion rate (Section J.4.17) are 0, the contributions from these pathways will be suppressed no matter what value is given to the air release fraction.

The DOE handbook on airborne release fractions (ARFs) and respirable fractions (RFs)[1] (DOE 1994a) provides a compendium and analysis of experimental data from which ARFs and

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[1] 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.

RFs may be derived. The data are given by the physical form of the material affected (e.g., gas, liquid, solid, surface contamination) and different suspension stresses (e.g., spill, thermal stress, shock wave, blast stress). The American Nuclear Society (ANS) has published an American national standard for airborne release fractions at nonreactor nuclear facilities (ANS 1998).

For materials in gaseous form, such as H-3, the recommended ARF is 1.0. All materials in the gaseous state can be transported and inhaled; therefore, the RF is also 1.0 (DOE 1994a).

The DOE handbook provides release fractions for three categories of solid materials: metals, nonmetallic or composite solids, and powders. The bounding ARF for plutonium metal formed by oxidation at elevated temperatures was found to be 3×10^{-5}, with an RF value of 0.04. ARF and RF values of 1×10^{-3} and 1.0 were assessed to be bounding during complete oxidation of metal mass (DOE 1994a). The bounding values for contaminated, noncombustible solids were found to be 0.1 and 0.7 for ARF and RF, respectively (these release values are for loose surface contamination on the solid, not the solid as a whole).

Little information is available for building occupancy; therefore, a triangular distribution based on the above data is used. The maximum value is assumed to be 1 (for gaseous forms), the minimum value chosen is that for plutonium metal ($3 \times 10^{-5} \times 0.04 = 1.2 \times 10^{-6}$), and the mode (most likely value) is the bounding value for contaminated noncombustible solids ($0.1 \times 0.7 = 0.07$). The probability density function is displayed in Figure J.13.

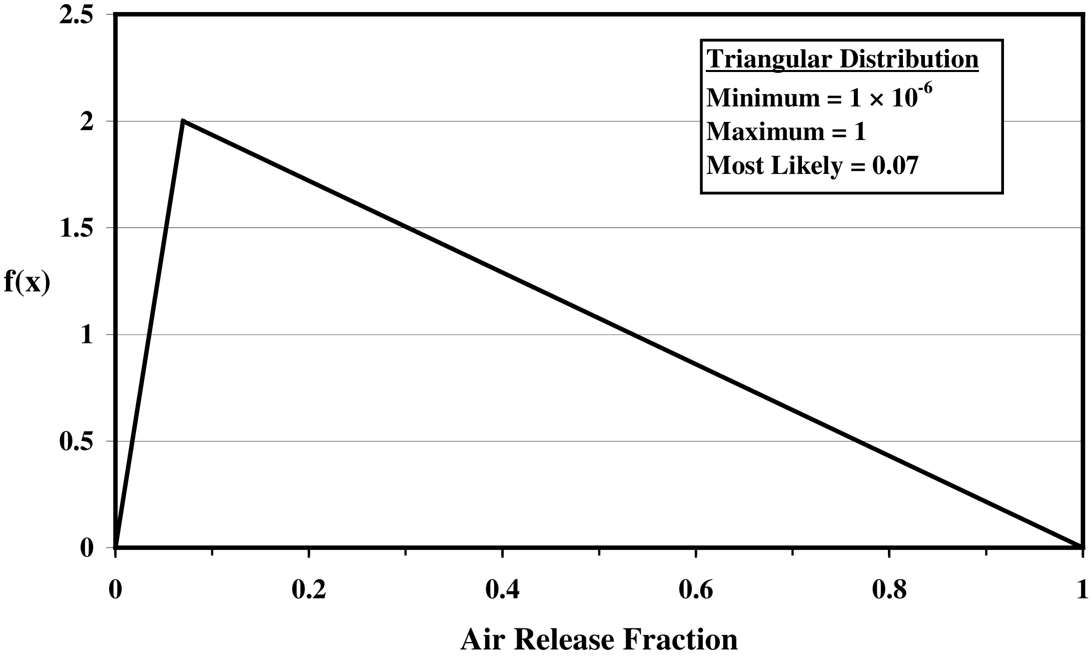

FIGURE J.13 Air Release Fraction Probability Density Function

J.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

Window: Source Parameters → Source Details

Discussion: This is the direct ingestion rate of the source by any receptor in the room. Each receptor will ingest the source at a rate determined by the product of the ingestion rate and the amount of contamination in the source at that time. Direct ingestion is possible only if the receptor and the source are in the same room. The direct ingestion rate is included in the RESRAD-BUILD code for unlikely events when a receptor could directly ingest source material. Such a receptor could be conducting a maintenance or renovation activity that involved physical contact with the source. The direct ingestion rate is normally set to 0 for most calculations.

The magnitude of the direct ingestion rate is highly correlated with other input parameters. For volume sources, the total amount of material ingested may range from 0 to a maximum specified by the mass of the source (area [Section J.4.6] × thickness [Section J.4.15] × density [Section J.4.16]). In addition, the direct ingestion rate cannot exceed the amount removed per unit time as determined by the source erosion rate (Section J.4.17). Indirect ingestion (Section J.3.6) must also be taken into account, as must time spent in the room with the source. Also, the direct ingestion rate should not cause the total physical mass of the source to be depleted over the time of exposure and must take into account the mass balance because of erosion of the source resulting from other mechanisms (Section J.4.17).

For the other source types (point, line, and area), the direct ingestion rate is expressed as a fraction of the source ingested per hour. This rate may range from 0 to a value less than or equal to the removal rate that is determined by the removable fraction (Section J.4.9) and the source lifetime (Section J.4.10) input parameters. If the direct ingestion rate is large enough to match the removal rate, then the air release fraction (Section J.4.7) input must be set to 0 to maintain mass balance.

J.4.9 Removable Fraction

Parameter Name: RMVFR

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

Window: Source Parameters → Source Details

Discussion: The removable fraction can account for various events that reduce the amount of source activity over time. In RESRAD-BUILD calculations, this fraction of the source will be linearly removed between time 0 and the source lifetime (Section J.4.10). Source activity may be reduced over a period of time as a result of such events as surface washing (chemical and mechanical action) or foot or equipment traffic if the source is on the floor (mechanical action). Because source activity could remain on a wall indefinitely or be removed entirely because of heavy traffic across floor contamination, the default distribution for the removable fraction ranges from 0 to 1 for use in a triangular distribution. Figure J.14 displays the distribution's probability density function.

The DOE *Radiological Control Manual* (DOE 1994b) allows a maximum removable concentration that is 20% of the maximum allowable total surface contamination for most radionuclides except for some transuranics and tritium (Table 2-2 in DOE 1994b). The maximum allowed removable transuranic or tritium contamination is 4% or 100%, respectively, of the maximum allowable surface contamination. However, under these restrictions, conditions may exist for unrestricted use in cases where the removable surface contamination constitutes 20% of the surface contamination for all radionuclides. For the NRC, maximum acceptable removable concentrations are 10% of the average surface concentrations for all radionuclides (NRC 2000). Like the DOE regulations, however, the removable fraction can be higher than 0.1 if overall surface concentrations are lower. Thus, a triangular distribution, as shown in Figure J.14, is suggested for the removable fraction, with a most likely value of 0.1 and minimum and maximum values of 0 and 1, respectively, as discussed above.

For specific situations, a number of factors must be considered, including location of the contamination (e.g., wall or floor and proximity to human activity), the nature of the contaminated surface (e.g., type of material [chemical and physical properties]), the original form of the contaminant (chemical and physical properties [e.g., powder versus liquid and chemical reactivity]), and the removal mechanism (such as washing or foot traffic).

Smear tests are often used to determine the amount of “fixed” versus “non-fixed” (or removable) contamination (Frame and Abelquist 1999). Although the definition of removable contamination varies, it applies to radioactive “contamination which is removable or transferable under normal working conditions” (International Organization for Standardization [ISO] 1988) or “radioactivity that can be transferred from a surface to a smear test paper by rubbing with moderate pressure” (NRC 1979a,b) or “radioactive material that can be removed from surfaces by non-destructive means such as casual contact, wiping, brushing, or washing” (DOE 1994b). However, smear tests can vary because of the material of the smear wipes used and the potential use of a wetting agent (Frame and Abelquist 1999). Also, smear tests will vary according to the contaminant, the surface, and the pressure and technique used by each technician performing the test (Sansone 1987; Jung et al. 2001). Table J.16 lists results from early experiments that demonstrate that the nature of the contamination and of the surface can influence how easily removable the radioactive contamination can be. Thus, a specific distribution for the removable fraction must be made on a case-by-case basis. Other measurement tests in the past have included tape and modified air sensor tests. Table J.17 presents some results comparing these methods with smear tests on different surfaces.

In assigning a removable fraction, a number of factors must be taken into account. In a decommissioned and decontaminated building, any residual contamination might be expected to be predominantly fixed because decontamination efforts should have used reasonable steps in cleaning the building. Weber (1966) demonstrated that up to 99.9% of deposited (dried solution) radioactive surface contamination could be removed in some cases by using the proper cleaning solution. This removal efficiency is much higher than that shown by smears or other sampling methods (e.g., see Table J.17). Thus, the removable fraction is highly dependent on the decommissioning activities used to bring the building surfaces into compliance and future on housekeeping activities.

No information appears to be available regarding smear tests on freshly cleaned surfaces. Smears may be more indicative of what contamination is available for removal by such processes as resuspension. Multiple smears on the same area may also be used in determining the removal fraction (Frame and Abelquist 1999). Jung et al. (2001) studied the effect of multiple smears on stainless steel (with different surface finishes), aluminum, and titanium metal samples after submersion in a spent fuel storage pool. In each case, the 10th consecutive smear contained approximately 5 to 10% of the total removed contamination for all 10 smears. Extrapolating their smear results for the stainless-steel samples, Jung et al. (2001) estimated the total removable contamination to be approximately 8 to 11%; the first smear picked up only 2 to 4% of the removable contamination.

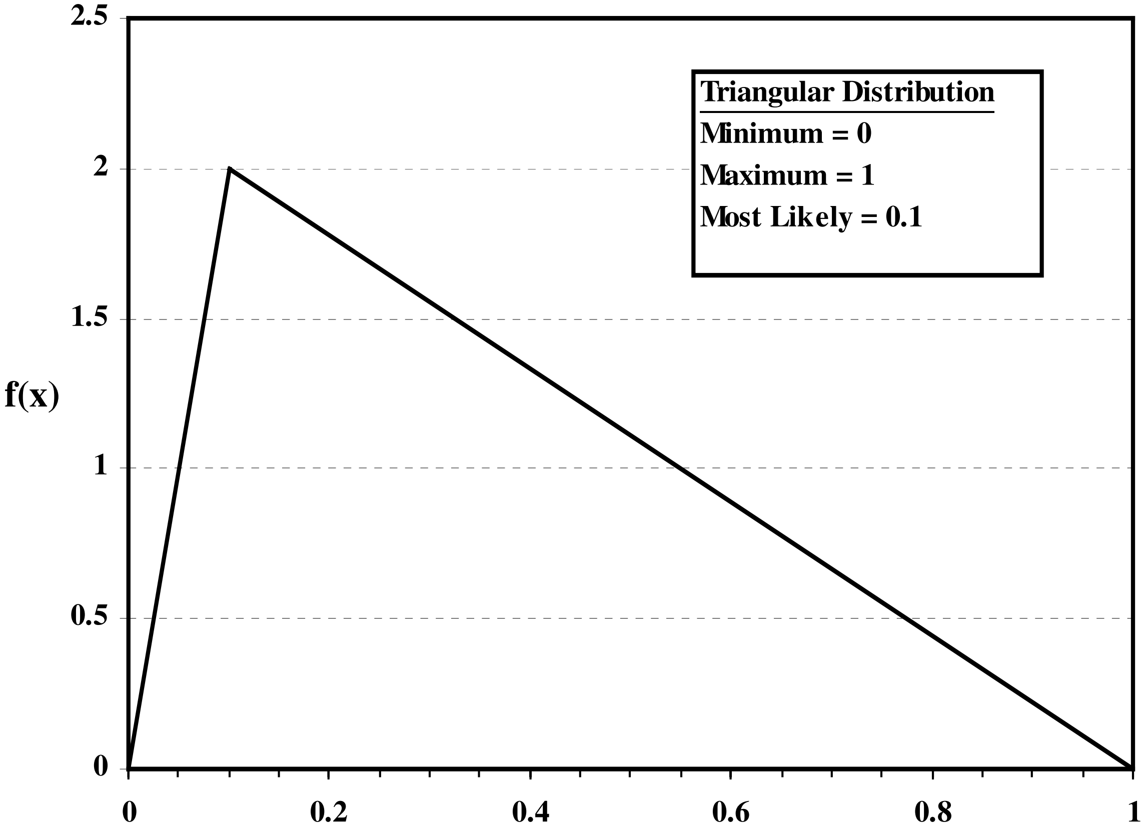

FIGURE J.14 Removable Fraction Probability Distribution

TABLE J.16 Influence of Surface and Contaminant Types on Smear Tests

Contamination	Percentage Contamination Removed	Surface	Comments	Reference
Low level from normal use	1 to 3	Granolithic concrete floor		Brunskill (1967)
	50		Water wash of floor	
Plutonium nitrate	0.1 to 0.2 6 20 to 30	Paper Waxed and polished linoleum Polyvinyl chloride	Plutonium nitrate or oxide in solution was applied to the floor and allowed to dry for 16 hours	Jones and Pond (1967)
PuO_2	10 to 20 20 to 30 50 to 60	Polyvinyl chloride Unwaxed linoleum Waxed and polished linoleum		

TABLE J.17 Percent Removal of Contamination for Different Sampling Methods[a]

	Removal (%)		
Surface	Adhesive Paper	Smear	Modified Air
Polyethylene	70.3	56.6	10.9
Glass	75.0	64.6	27.2
Plexiglass	78.0	71.3	15.8
Fiberboard (waxed)	53.8	44.3	10.2
Fiberboard (scrubbed)	56.9	23.5	9.0
Fiberboard (untreated)	73.4	23.5	6.6
Formica	73.4	70.6	26.5
Aluminum (painted)	70.0	50.3	24.8
Asphalt floor tile (untreated)	58.6	48.5	14.6
Asphalt floor tile (waxed)	74.5	74.5	30.3
Concrete (unsealed)	55.5	39.5	22.0
Concrete (sealed [seal and wax 1])	62.2	59.5	24.0
Concrete (sealed [seal and wax 2])	54.8	47.7	27.2
Concrete (greased)	43.5	37.5	1.32
Stainless steel	67.7	50.5	10.5

[a] Modified air sampler (referred to as a “smair” sampler by the authors) causes air intake to blow across the sample surface when the sample head is pressed against a surface.

Source: Royster and Fish (1967); contamination was simulated by thorium dioxide dust particles approximately 1 µm in diameter at a concentration of about 1 × 10^6 particles per square centimeter.

J.4.10 Source Lifetime (also Time for Source Removal)

Definition: This parameter represents the time over which the removable part of the source is (linearly) eroded. The parameter is used in conjunction with the removable fraction of source material parameter (Section J.4.9) and the air release fraction (Section J.4.7) to obtain the emission rate of radionuclides into the indoor air.

Parameter Name: RF0 **Units:** Days (d) **Range:** > 0

Deterministic Analysis Default Value: 365

Probabilistic Analysis Default Distribution: Triangular
Defining Values for Distribution:
Minimum: 1,000 Maximum: 100,000 Most likely: 10,000 (27.4 yr)

Window: Source Parameters → Source Details

Discussion: The RESRAD-BUILD model considers the potential entrainment of loose contamination from a contaminated surface to the indoor atmosphere. The entrainment rate of the loose contamination is calculated by using the “removable fraction” parameter (Section J.4.9), the “time for source removal or source lifetime” parameter (Section J.4.10), and the total contaminant inventory on the surface. Information on the time for source removal or source lifetime 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.

Different mechanisms can result in the entrainment of loose surface particles to the atmosphere. Mechanical abrasion during renovation activities would result in the highest entrainment rate in the shortest period of time. However, for normal building occupancy conditions, renovation activities were excluded from consideration.

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 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. The probability density function is shown in Figure J.15.

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 air concentration in a one-room air quality model under equilibrium conditions for a surface source with long-lived radionuclide contamination (or for chemicals where no decay is involved) can be given as (derived from Equation A.28):

$$C^n = \frac{f_R f Q_s^n}{24 T_R Q_0} \tag{J.4.10-1}$$

where

$$Q_0 = \lambda_b^a V, \tag{J.4.10-2}$$

$$Q_s^n = C_{surf} As, \tag{J.4.10-3}$$

$$V = AH, \tag{J.4.10-4}$$

$\lambda^a{}_b$ = air exchange rate (1/h),

A_s = source area (m^2),

A = area of the compartment (m^2),

H = height of the compartment (m),

C_{surf} = surface concentration (pCi/m^2),

f_R = removable fraction of the source material,

f = fraction of removed material that becomes indoor dust, and

T_R = time to remove material from the source (source lifetime) (d).

When the whole floor is contaminated, the air concentration reduces to

$$C^n = \frac{f_R f \; C_{surf}}{24 T_R \; \lambda_b^a \, H} \quad . \tag{J.4.10-5}$$

The resuspension factor, R_F, under these assumptions can be given as

$$R_F = \frac{f_R f}{24 T_R \lambda_b^a H} \quad . \tag{J.4.10-6}$$

The air release fraction, f, in RESRAD-BUILD is the fraction of contaminated material removed from the source released into the air that is in the respirable particulate range. Assuming a surface source on the floor with a removable fraction of 0.1 (Section J.4.9) and an air release fraction of 0.07 (Section J.4.7), the resuspension factor can be estimated from the source lifetime. A floor area of 36 m^2 (Section J.2.5), a room height of 3.7 m (Section J.2.4), and a room air exchange rate of 1.52 h^{-1} (Section J.2.6) were used. In this case, the source lifetime of 10,000 days is equivalent to a resuspension factor of $5 \cdot 10^{-9}$/m.

Table J.18 gives the source lifetime (days) for different air exchange rates and heights for a fixed resuspension factor of 1×10^{-6} m^{-1}. For these calculations, it is assumed that the removable fraction is 1 and that the fraction that become airborne is also 1. When an airborne fraction of 1, an air exchange rate of 0.5 h^{-1}, and a room height of 2.3 m are assumed, the source lifetime (in years) can be related to resuspension factor, as shown in Table J.19.

The source lifetime depends on how easily the source material can be removed and the external conditions to which the source is exposed (e.g., corrosion, mechanical contact, heat). If the source is fixed, the removable fraction should be set to 0, so the source lifetime is immaterial. The code assumes a linear removal over time. For example, for a source with a lifetime of 1 year, 50% of the removable fraction is assumed to be removed after 6 months. The code requires a source lifetime for each area, line, and point source whenever a nonzero removable fraction is entered. If the removable fraction for a source is 0, the code ignores any lifetime value entered by the user for that source.

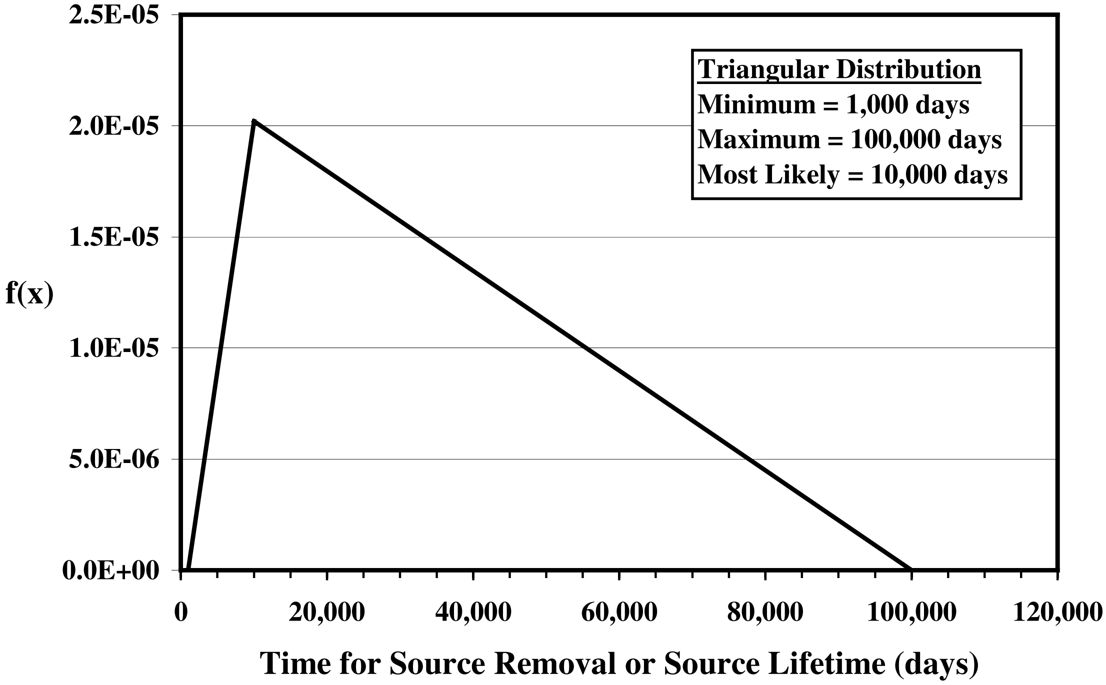

FIGURE J.15 Time for Source Removal or Source Lifetime Probability Density Function

TABLE J.18 Source Lifetime (d) Variation with Air Exchange Rate and Room Height for a Fixed Resuspension Factor of 1 × 10^{-6} m^{-1}

	Air Exchange Rate (h^{-1})				
Height (m)	0.2	0.5	0.8	1.0	1.5
2.5	8.3E+04	3.3E+04	2.1E+04	1.7E+04	1.1E+04
3.0	6.9E+04	2.8E+04	1.7E+04	1.4E+04	9.3E+03
6.0	3.5E+04	1.4E+04	8.7E+03	6.9E+03	4.6E+03
10.0	2.1E+04	8.3E+03	5.2E+03	4.2E+03	2.8E+03

TABLE J.19 Source Lifetime (yr) and Resuspension Factor for Different Removable Fractions for a House with an Air Exchange Rate of 0.5 h^{-1} and a 2.3-m Room Height

Resuspension Factor (m^{-1})	Removable Fraction (%)	Source Lifetime (yr)
1E-08	100	10,000
	10	1,000
1E-06	100	100
	10	10
1E-04	100	1
	10	0.1

J.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: 0.1

Probabilistic Analysis Default Distribution: None assigned

Window: Source Parameters → Source Details

Discussion: 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 concentrations 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 J.4.19 and J.4.20 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. 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.

If an area, line, or point source is selected and if that source contains a radionuclide that is a radon precursor, the user must enter a radon release fraction between 0 and 1. The precursor radionuclides are listed in Section J.4.18 on source porosity. Setting a value of 0 for the radon release fraction effectively suppresses the radon pathway for area, line, or point sources.

J.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

Window: Source Parameters → Source Details

Discussion: Any of the following four units of radiological activity can be selected: (1) Ci or curie, defined as $3.7 \cdot 10^{10}$ 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 have one contaminated layer and up to four additional uncontaminated layers.

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 distribution of radionuclides. These subregions, along with their respective radionuclide concentrations, should then be entered as separate sources in the code (see Section J.4.1 on the number of sources).

Up to 10 radionuclides per source may be considered from a list of 67 radionuclides in the RESRAD-BUILD database. 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.

J.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

Window: Source Parameters → Source Details

Discussion: The volume source can be split into as many as five regions along its thickness. Such splitting is useful if only part of the thickness of the building component (wall, floor, etc.) is contaminated. This parameter is not eligible for probabilistic input. Up to five distinct regions may be assigned to each volume source. When more than one region is specified, the contaminated region has to be identified. Only one of the regions can be specified to be contaminated. The uncontaminated regions will act as a shield for external gamma radiation on the basis of thickness (Section J.4.15) and density (Section J.4.16) and will act as a barrier for the inhalation pathways. 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. An exception to this rule should be made for a volume source that forms a common boundary between rooms. In this case, the source should be divided into two overlapping subsources, each consisting of two layers (see Section J.4.2 on the source room). The code requires that at least one layer, but no more than five layers, be entered for each volume source.

If the source has more than one region, region 1 is the one that is closest to the origin used to define the coordinates of the sources and the receptors. All releases from the source, other than those of radon, are assumed to occur from region 1. This assumption imposes a restriction on the choice of the origin.

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.

J.4.14 Contaminated Region (Volume Source)

Parameter Name: FCONT0

Definition: This parameter specifies the 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

Window: Source Parameters → Source Details → Wall 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 J.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.

J.4.15 Source Region Thickness (Volume Source)

Parameter Name: THICK0

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

Window: Source Parameters → Source Details → Wall 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 a source 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 J.16 presents the probability density function for the source thickness.

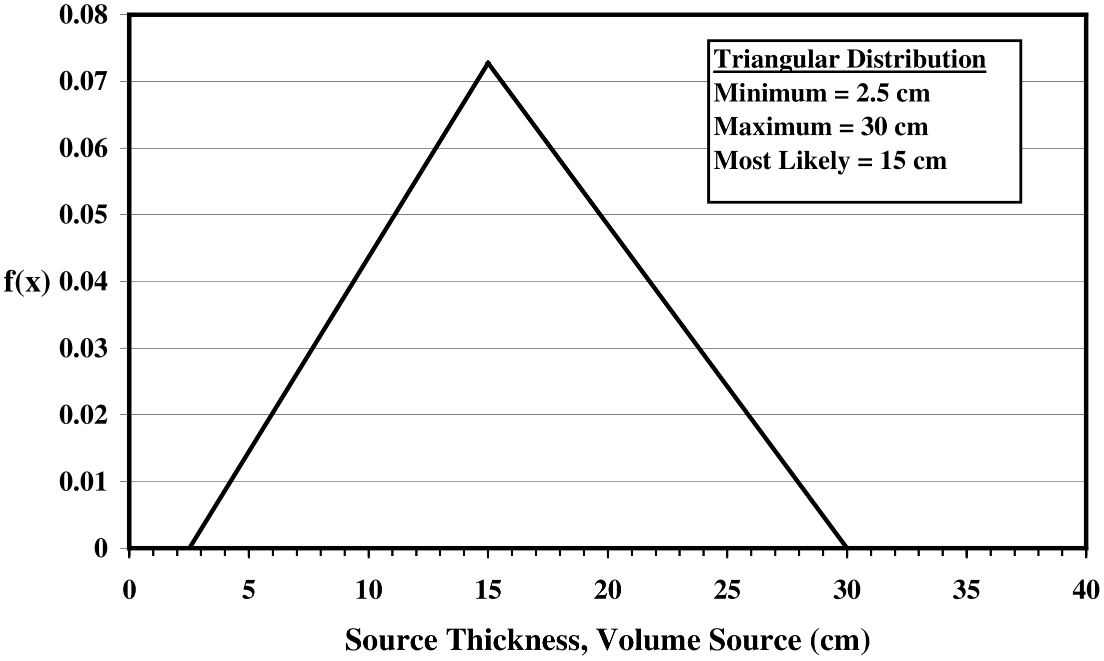

FIGURE J.16 Source Thickness Probability Density Function

J.4.16 Source Density (Volume Source)

Definition: The source density parameter represents the bulk density of each cylindrical 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

Window: Source Parameters → Source Details → Wall Region Parameters

Discussion: The source density parameter is used to calculate the total amount of radionuclides in the source volume, and it affects the external pathway doses. In the RESRAD-BUILD code, the 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. RESRAD-BUILD allows the following eight materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Each source layer is defined by its physical properties, such as thickness, density, porosity, radon effective diffusion coefficient, radon emanation fraction, and erosion rate.

As is the case for shield density, the source density will never exceed 22.5 grams per cubic centimeter (g/cm^3). Table J.20 lists the density range (if appropriate) or a single value of density for the RESRAD-BUILD materials that have a narrow range of density (except concrete). The table lists a range for cast iron and a single value of density for each of the other materials. The values are taken from *The Health Physics and Radiological Health Handbook* (Shleien 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide 1998) (for cast iron, uranium, and tungsten). Table J.21 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 value used in the code is for ordinary concrete. If the type of concrete is known, a uniform distribution between the given range for a known concrete type can be used. The probability density function for the concrete source density is shown in Figure J.17.

TABLE J.20 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 J.21 Source (Concrete) Density from Various Sources

	Concrete Density (g/cm^3)		
Aggregate	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) 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.

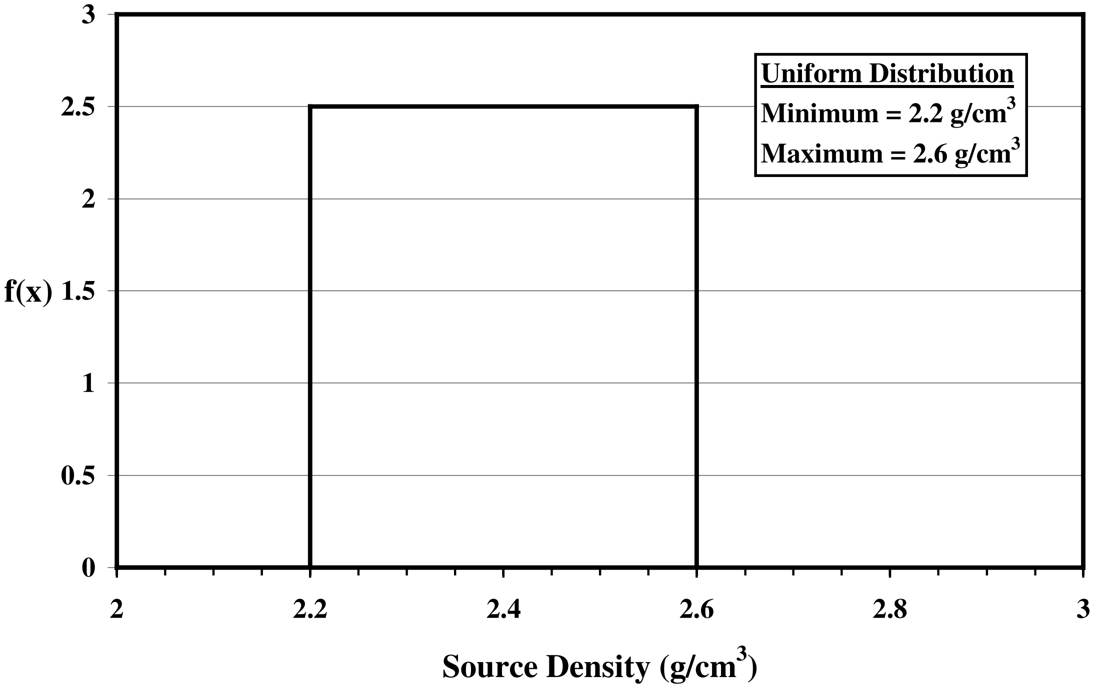

FIGURE J.17 Concrete Source Density Probability Distribution Function

J.4.17 Source Erosion Rate (Volume Source)

Parameter Name: EROS0

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

Window: Source Parameters → Source Details → Wall 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 released into the air, the amount of the source remaining to contribute to external exposure, and the amount of material through which the radon must diffuse. Also, at each evaluation time, the erosion rates of all the layers are used to identify the exposed layer.

The source erosion rate is highly dependent on the location of the contamination. In a building occupancy scenario, contamination on walls could remain indefinitely if located in little-used areas not subject to periodic washing or cleaning. Furthermore, such residual wall contamination could have been covered with paint or another type of sealant during prior remediation or general maintenance activities. In addition, little or no wear can be expected for some floor areas for the same reasons. At the other extreme are contaminated floor areas subject to heavy foot traffic or vehicle traffic, such as in warehousing operations. However, such areas are usually covered (carpet or tile), sealed, or waxed on a periodic basis, thus 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 because contamination on both walls and floors in little-used areas can be expected to remain in place indefinitely. Even high-use areas may not experience erosion if they remain protected by paint or sealant. Under normal occupancy conditions (not remedial activities), a maximum value is expected as a result of traffic over floor areas. Contaminated wood, concrete, and (possibly) ceramic tile are expected to be the primary flooring materials affected. Contaminated carpet would be expected to have been removed by remedial activities. However, aside from studies on abrasion, little information is available in the general literature on normal wear of concrete or wood surfaces over extended periods of time.

A rough approximation for the maximum value can be obtained by considering that any eroded materials would become airborne for at least short periods of time. A conservative assumption was made that all airborne indoor particulate matter is a result of erosion of the floor surface. Typically, outdoor air is a significant source of indoor air particulate concentrations (Wallace 1996), but this contribution was not considered. The erosion rate of a concrete floor was estimated to maintain an average particulate air concentration of 100 $\mu g/m^3$ with a room air exchange rate of 1.52/h (Section J.2.6). A floor area of 36 m^2 (Section J.2.5), a room height of 3.7 m (Section J.2.4, used to estimate the room volume), and a concrete density of 2.4 g/cm^3 (Section J.4.16) were used. The estimated erosion rate was 5.6×10^{-7} cm/d. Figure J.18 shows the probability density function used for the source erosion rate.

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.

In the case of contaminated metal sources, the database generated by the National Bureau of Standards (NBS; currently the National Institute for Standards and Technology) can provide some information on carbon and stainless steels (Sullivan 1993). In a study conducted over a period of 17 years in 47 different soils, carbon steel's uniform erosion rates ranged from 2×10^{-6} to 5×10^{-5} cm/d, with a mean value of 1×10^{-5} cm/d (Romanoff 1957). Another other study was conducted over a period of 14 years in 15 soils for 304 and 316 stainless steels. The erosion rates for 304 stainless steel ranged from 4.7×10^{-8} to 3.0×10^{-10} cm/d, with a mean value of 1.4×10^{-8} cm/d; for 316 stainless steel, the range was from 1.6×10^{-8} to 7.7×10^{-11} cm/d, with a mean value of 3.6×10^{-9} cm/d (Gerhold et al. 1981). It was also observed that the corrosion rates typically decreased over time. Because these corrosion rates were obtained while the steel was in contact with soil, lower rates might be expected in less corrosive environments. Thus, these rates (used as erosion rates) are near the most likely value of 0 for the source erosion rate shown in Figure J.18.

In summary, the erosion rate depends on how easily the source material can be removed and the external conditions to which it is exposed. If the layer is not removable, the erosion rate should be set to zero. The code requires a source erosion rate in centimeters per day (cm/d) for every layer of each volume source.

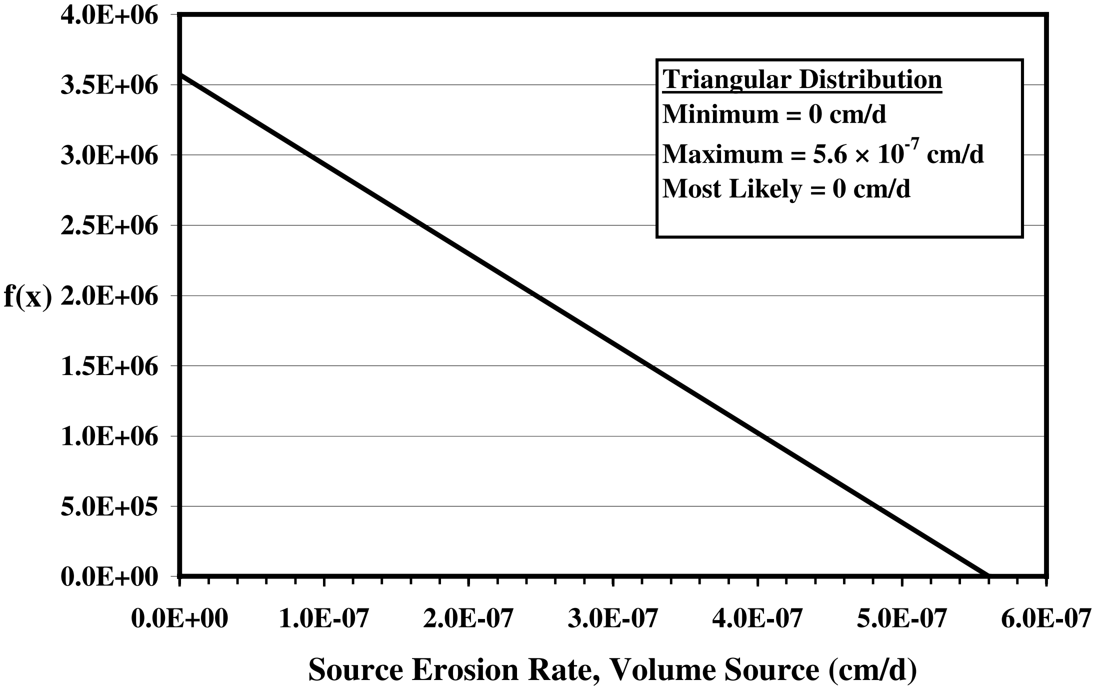

FIGURE J.18 Source Erosion Rate Probability Density Function

J.4.18 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

Window: Source Parameters → Source Details → Wall 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 is applicable to the tritium inhalation and the radon inhalation pathways. This parameter is only required as input if a tritium volume source is selected or if radon (radon-220 or radon-222) precursors are entered as part of the volume source. It is not required for area, line, or point sources. Precursor radionuclides 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 each of up to five layers in each volume source containing one or more radon precursors must be entered.

Porosity may be reported as a decimal fraction or as a percentage. Input to the RESRAD-BUILD code is as a decimal fraction. A value of 0 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.

Widespread variations in concrete porosity occur because of the differences in the aggregates used, water/cement ratios in the cement paste, and curing conditions. Cement paste in concrete occupies from 23 to 36% of the total volume (Culot et al. 1976), sand 25 to 30%, and aggregates the remainder. Overall porosity of concrete depends on the porosity of the cement paste as well as of the aggregates. The porosity of concrete was found to range from 0.05 to 0.25 (Culot et al. 1976).

The porosity estimated for a concrete structure made of Portland cement was found to vary from 0.04 to 0.20 (Frankowski et al. 1997). Table J.22 gives the bulk density and porosity of the rocks commonly used as building materials (Bever 1986). Other materials, such as wood, particle board, and drywall, will have porosities of around 0.5. Materials used for thermal insulation tend to have a very high air content, with porosities approaching 1. Material porosity is inversely correlated with material density; low-porosity materials have higher densities than porous materials.

On the basis of the definition of porosity, the porosity of a material could be evaluated by directly measuring the pore volume and the total volume. The American Society for Testing and Materials (ASTM) has established a standard procedure (B-276) for cemented carbide to rate three types of porosities, depending on the pore diameters (Type A, pore diameters <10 µm; Type B, pore diameters between 10 and 25 µm; and Type C, covering porosity developed by the presence of free carbon). Similarly, the ASTM has developed standard test methods for porosity of metal structure parts, and porosity tests for electrodeposits and related metallic coatings (http://www.astm.org/sitemap.html).

For generic applications, a uniform distribution from 0.04 to 0.25 is suggested for the source porosity for concrete. The minimum and maximum values were those reported by Frankowski et al. (1997) and Culot et al. (1976), respectively. The probability density function is shown in Figure J.19.

A material's porosity could be evaluated by directly measuring its pore volume (V_p) and total volume (V_t). The total volume is easily obtained by measuring the total volume of the sample. In principle, the pore volume could be evaluated directly by measuring the volume of water needed to completely saturate the sample. In practice, this measurement is very difficult to make. Porosity is usually evaluated indirectly by using the expression $p = 1 - (V_s/V_t) = 1 - (\rho_b/\rho_s)$, where p is the porosity as a decimal fraction, V_s is volume of the solid components, V_t is the total volume, ρ_b is the dry bulk density of the sample, and ρ_s is the density of the solid component (U.S. Department of the Army 1970, Appendix II; Danielson and Sutherland 1986). If the density of the solid component is unknown, it may be estimated by crushing or grinding the sample to eliminate most of the void spaces.

TABLE J.22 Bulk Density and Porosity of Rocks Commonly Used as Building Materials

Rock	Bulk Density (g/cm^3)	Porosity (%)
Granite	2.6-2.7	0.5-1.5
Basalt	2.8-2.9	0.1-1.0
Sandstone	2.0-2.6	0.5-25.0
Limestone	2.2-2.6	0.5-20.0
Gneiss	2.9-3.0	0.5-1.5
Marble	2.6-2.7	0.5-2.0

Source: Bever (1986).

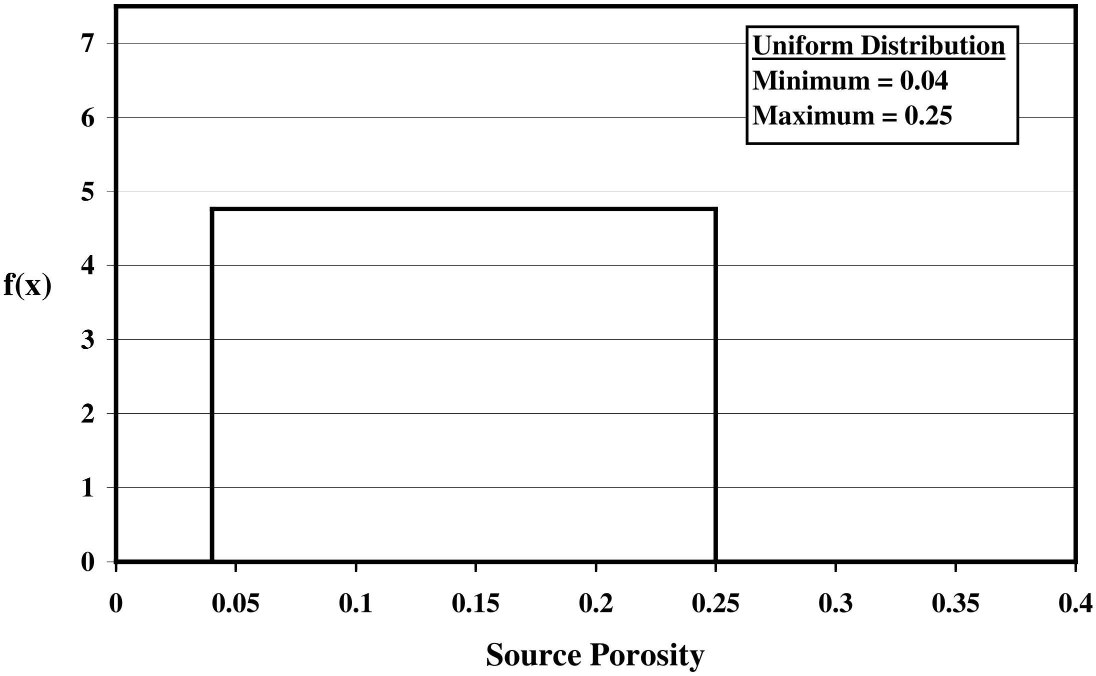

FIGURE J.19 Concrete Source Porosity Probability Density Function

J.4.19 Radon Effective Diffusion Coefficient

Definition: This parameter represents the diffusivity of radon in air or materials.

Parameter Name: EFDIF0 **Units:** m^2/s **Range:** > 0 to $1.1 \cdot 10^{-5}$ m^2/s

Deterministic Analysis Default Value: 2×10^{-6}

Probabilistic Analysis Default Distribution: Loguniform
Defining Values for Distribution:
Minimum: 6×10^{-10} Maximum: 7.2×10^{-6}

Window: Source Parameters → Source Details → Wall Region Parameters

Discussion: In air, the diffusion of radon gas atoms results from a net migration of radon gas toward the direction of its decreasing concentration. The diffusion of radon in open air can be described by Fick's law, which states that the flux density of the diffusing substance is linearly proportional to its concentration gradient. The diffusion coefficient of radon in air can be expressed as the ratio of the flux and the concentration gradient. In porous materials, the radon effective diffusion coefficient is defined as the ratio of the diffusive flux density of radon across the pore area to the gradient of the radon concentration in the pore or interstitial space. This parameter is used by RESRAD-BUILD to calculate the diffusion of radon from a volume source and is only applicable to the radon inhalation pathway. Therefore, it is only required as input when radionuclides that decay to radon are entered as part of a volume source. It is not required for area, line, or point sources. Additional information on the radon effective diffusion coefficient (D_e) can be found in the RESRAD Data Collection Handbook (Yu et al. 1993).

The effective radon diffusion coefficient varies over a wide range, depending on the diffusion medium. The upper limit of D_e is given by the diffusion coefficient in open air, which is about $1.1 \cdot 10^{-5}$ 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.

Radon diffusion decreases with decreasing porosity. Diffusion in brick and concrete is typically 1 to 2 orders of magnitude lower than that found in soils because of the decrease in porosity (Nero and Nazaroff 1984). The observed range of variation of D_e in concrete is from $8 \cdot 10^{-9}$ to $4 \cdot 10^{-7}$ m^2/s (Nazaroff et al. 1988). The effective diffusion coefficient in other building materials ranges from $8 \cdot 10^{-8}$ to $3 \cdot 10^{-7}$ m^2/s for brick and from $1 \cdot 10^{-6}$ to $4 \cdot 10^{-6}$ m^2/s for gypsum (drywall). Radon diffusion also decreases with an increase in volumetric water content, varying by as much as three orders of magnitude when the dry weight percent moisture is taken from <1% to about 18% (Rogers et al. 1984). The diffusion coefficient is also affected to a lesser degree by particle shape and size; packing; and changes in the composition, temperature, and pressure of the gas-filled pore space and those for the liquid occupying the remaining pore volume. Further information can be found in Stranden and Berteg (1980) and Rogers and Nielson (1991). In general, the effective diffusion coefficient approaches its upper limit for fibrous insulation material and its lower limit for relatively impermeable materials or membranes, such as metals or sealants.

The diffusion coefficient (or diffusivity) of radon in materials can be measured by both field and laboratory experiments. In either case, the experimental evaluation of diffusivity consists in determining the numerical value of the coefficient appearing in Fick's equation. Because of the difficulty in implementing field methods, laboratory methods are generally used to determine the radon diffusivity in porous media. The methods may be separated into two distinct groups: the steady-state diffusion method and the transient diffusion method (Nielson et al. 1982). The methods discussed apply specifically to soils but may be extended to other porous materials.

A steady-state diffusion method for determining D_e in uncontaminated (no radon source) materials was implemented by Silker and Kalkwarf (Silker 1981; Silker and Kalkwarf 1983) on the basis of theoretical developments by Cohen (1979). The apparatus used in this method consists of a column of test material of known depth, which is sealed at one end to an air chamber of known volume containing a radon source with a known and constant strength. The other end of the test column is kept open. As a boundary condition for this system, it is assumed that in a steady-state situation, the effective flux density of radon activity at the bottom of the column is constant and uniquely dependent on the strength of the radon source and the geometry of the system. Also, the radon activity concentration at the open end of the column is assumed to be negligible. Therefore, by selecting the size (i.e., thickness) of the test sample, determining the effective flux density on the basis of the strength of the radon source and the column diameter, and making several measurements of the radon concentration, Fick's equation in one dimension may be solved.

The samples used in the determination of D_e typically have a cylindrical shape, with a height of 10 cm and an inner diameter of 14 cm. After equilibration, the steady-state radon concentration in the bottom chamber is determined by several measurements taken over a 7- to 14-day period. Each measurement consists of withdrawing about 5 cm^3 of gas from a typical 800-cm^3 bottom chamber and determining the radon concentration by using either a scintillation flask technique (such as a Lucas cell) or charcoal absorption and gamma-ray spectrometry (Silker 1981).

In RESRAD-BUILD, each time a volume source is selected, if the source contains a radionuclide that is a radon precursor, the user must enter a radon effective diffusion coefficient in units of square meters per second (m^2/s). These precursor radionuclides are listed in Section J.4.18 on source porosity. Effective diffusion coefficients are material dependent and must be entered for each layer of each volume source considered. Setting a value of 0 for the radon diffusion coefficient in 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. Figure J.20 presents the probability density function for the radon effective diffusion coefficient.

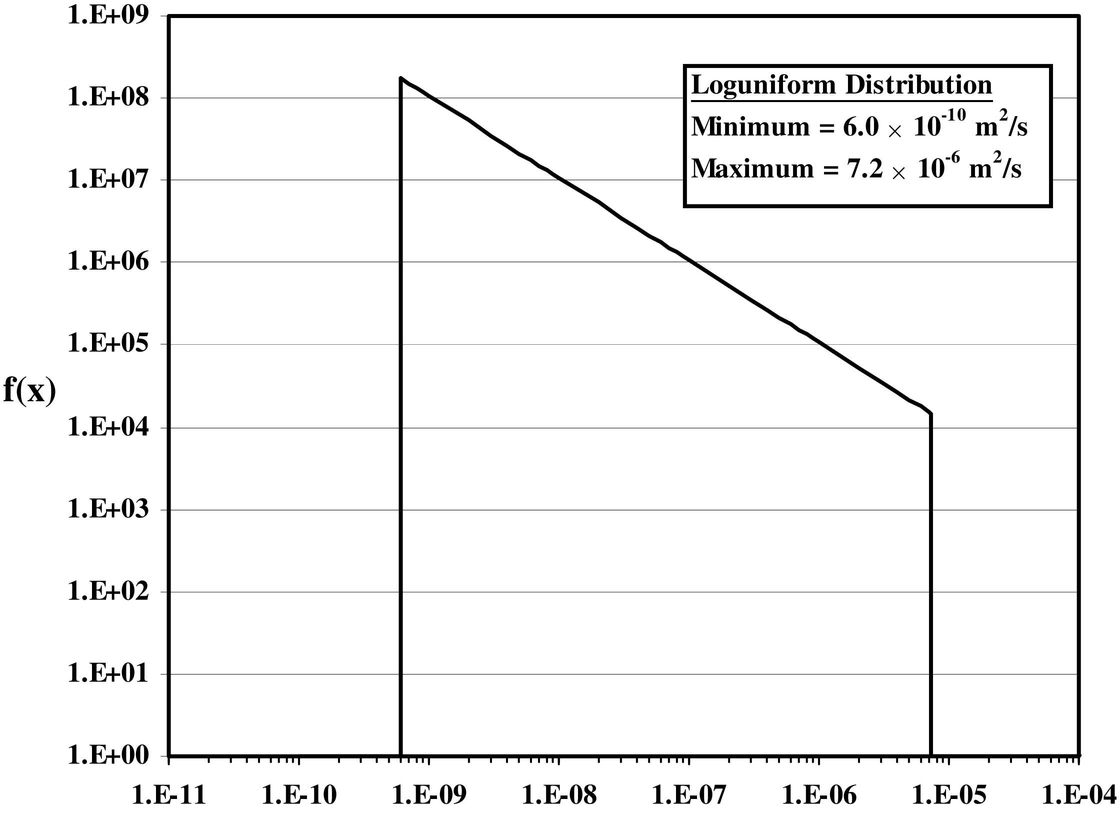

FIGURE J.20 Radon Effective Diffusion Coefficient (m^2/s)

J.4.20 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: 0.2

Probabilistic Analysis Default Distribution: loguniform
Defining Values for Distribution:

Minimum: 0.002 Maximum: 0.83

Window: Source Parameters → Source Details → Wall 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 radium-228 to calculate the release of radon-222 and radon-220, respectively, into the pore space of a volume source and is only applicable to the radon inhalation pathway. It is only required as input when radionuclides that decay to radon are entered as part of a volume source. It is not required for area, line, or point sources (see Section J.4.11, Radon Release Fraction). Additional information on the radon emanation fraction can be found in the RESRAD Data Collection Handbook (Yu et al. 1993).

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 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 spaces inside the contaminated material. The values of the radon emanation fraction have been measured mostly for soils. Experimental measurements conducted by various investigators have been reported in Nazaroff et al. (1988); they show variations in the radon emanation fraction ranging from 0.02 to 0.72, with average values ranging from 0.12 to 0.30.

The radon emanation fraction varies with total porosity and the volumetric water content. More pore space (larger pore size) in a sample increases the likelihood of the radon recoil terminating outside of a soil grain. An increased water content also increases the probability of a radon recoil terminating in a pore space because of the damping effect of the water on the radon progression (Nero and Nazaroff 1984). The damping effect generally accounts for less than an order of magnitude change in the emanation fraction with an increase in water content (Strong and Levins 1982). In contrast, larger grain size (longer path to an opening) decreases the probability of the radon's escaping to the pore areas. The distribution of the parent radium in the grains is therefore an influencing factor if the distribution is uneven. The majority of information available is for the more common isotope Rn-222. The emanation fraction for Rn-220 has been studied only to a limited extent. Megumi and Mamuro (1974) studied the differences (from the different recoil energies) between Rn-220 and Rn-222 in soil.

Additional information on the radon emanation fraction can be found in documents by Tanner (1964, 1980); Barretto et al. (1972); Pensko et al. (1972); Wilkening (1974); Periera (1980); Ingersoll (1983); Schery et al. (1984); Damkjaer and Korsbech (1985); Van der Lugt and Scholten (1985); Schery and Whittlestone (1989); Rogers and Nielson (1991); Markkanen and Arvela (1992); and Rood et al. (1998).

The methodology for measuring the radon emanation fraction of a porous material contaminated with radium consists basically of measuring the radon concentration of the air inside a sealed accumulation chamber in which the sample of contaminated material has been left for a period of time (about 4 days) until the radon concentration has reached equilibrium. A detailed description of a variation of this method is presented in Strong and Levins (1982). Their experimental apparatus consisted of an ingrowth (accumulation) chamber, a sampling cylinder, a diaphragm pump, a scintillation cell, and supporting electronics for the radiation measurement.

If a volume source is selected and the source contains a radionuclide that is a radon precursor, the user must enter a radon emanation fraction. The precursor radionuclides are listed in Section J.4.18 on source porosity. Different emanation fractions may be entered for radon-222 and radon-220 within the same source. Emanation fraction must be entered for each volume source considered, but only for the contaminated layer of a multilayer 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 J.21 presents the probability density function for the radon emanation fraction.

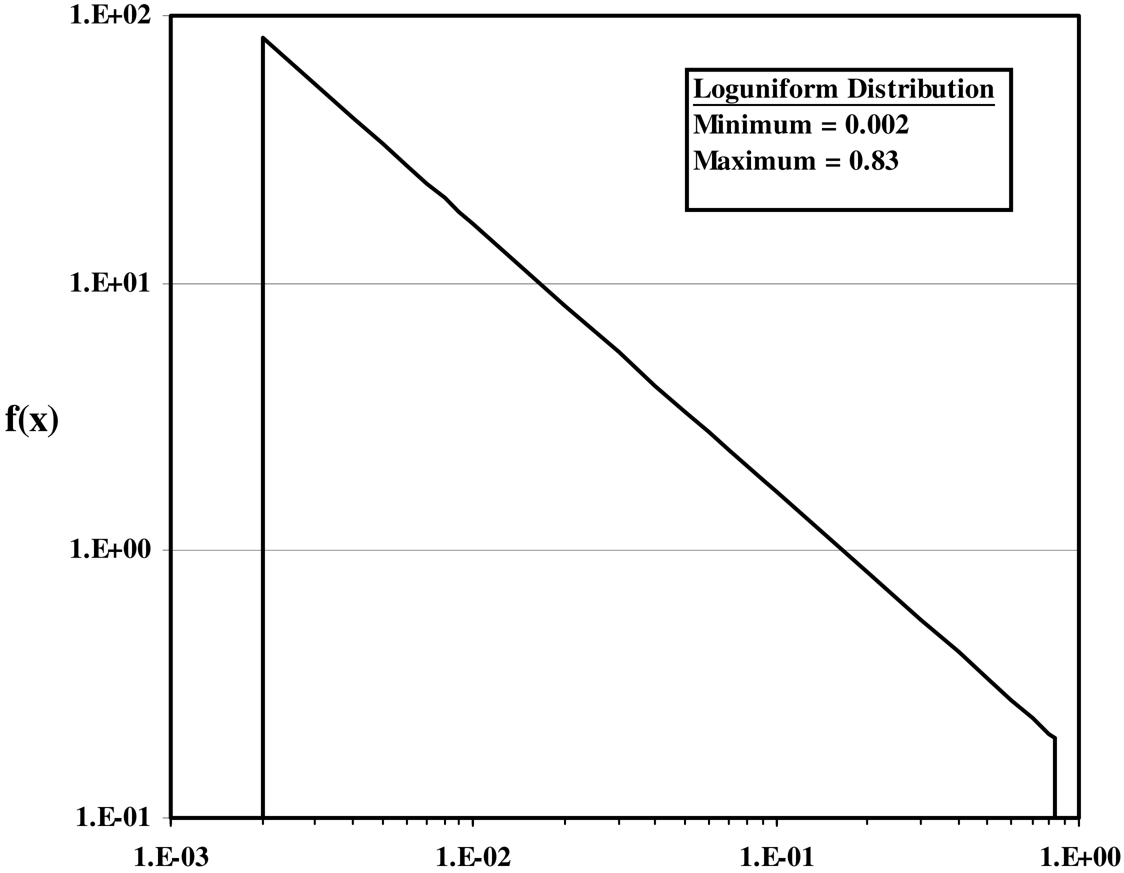

FIGURE J.21 Radon Emanation Fraction

J.4.21 Source Material

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

Window: Source Parameters → Source Details

Discussion: The source material determines the attenuation cross section used in calculating the external dose. This parameter is only required for a volume source. This parameter is not eligible for probabilistic input and is important only for the external pathway.

The user can select among eight source materials: (1) concrete, (2) water, (3) aluminum, (4) iron, (5) copper, (6) tungsten, (7) lead, and (8) uranium. This parameter can be determined from direct inspection, standard building codes, and/or building design specifications.

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J.5 SHIELDING PARAMETERS

J.5.1 Shielding Thickness

Definition: This parameter represents the effective thickness of shielding between a source and receptor pair.

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

Window: Shielding Parameters

Discussion: The shielding thickness parameter is used in determining the attenuation of direct external radiation from each source to each receptor. Shielding thickness only affects the external exposure pathway. For situations in which only air is present between the source and receptor, the shielding thickness is 0. The RESRAD-BUILD code requires the shielding thickness for every source and receptor pair (e.g., if there were 4 sources and 6 receptors, the code would require 24 [6 × 4] shielding thickness input values). The same shielding object might be assigned different thicknesses for different source-receptor pairs because of geometry considerations. It is highly recommended that the shielding thickness value be obtained from a direct measurement based on the site-specific condition. For example, to calculate dose for a receptor in a room other than the room in which the source is located, a shielding thickness equivalent to the wall thickness should be assumed.

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 approximates an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. A shielding thickness of 30 cm would reduce the dose significantly from the external exposure pathway for all radionuclides, including high-energy gamma emitters.

Little information is available for the shielding thicknesses in actual D&D situations; therefore, a triangular distribution is assumed. The maximum value is assumed to be 30 cm, the minimum value is chosen as 0 cm, and the most likely value also is chosen to be 0 cm (this assumption would yield the most conservative dose results for the external exposure pathway). The probability density function is shown in Figure J.22.

Since the attenuation of gamma radiation within a volume source is calculated separately, this parameter should account only for the thickness of shielding material external to the volume source. The user should ensure that the thickness entered does not exceed the distance between the source surface and the receptor.

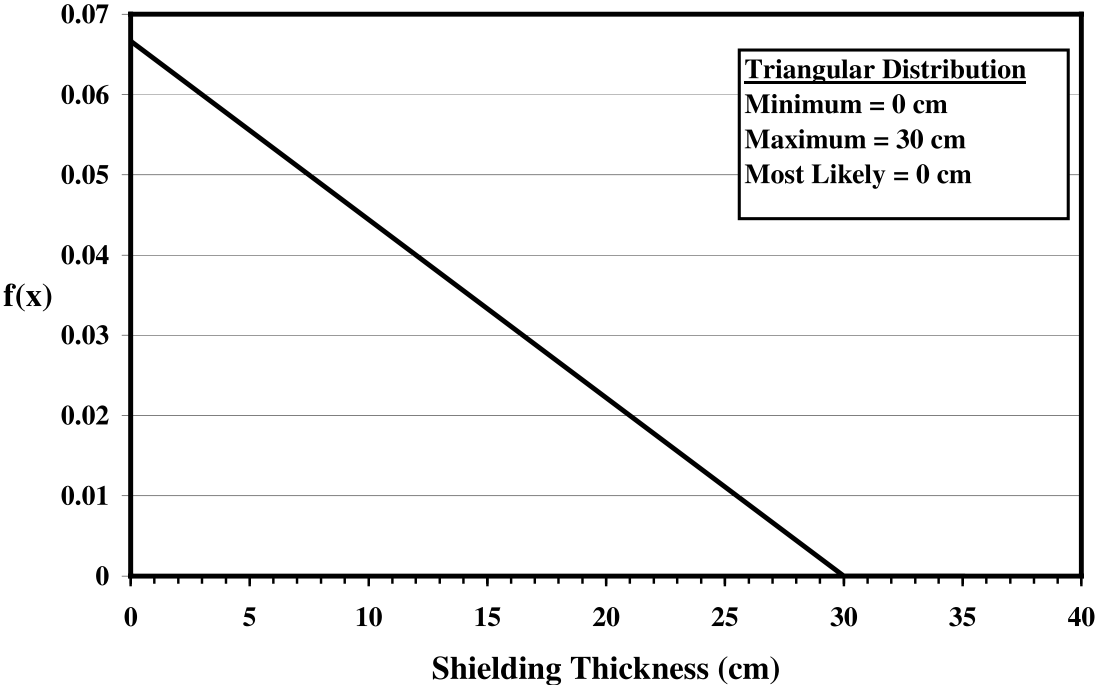

FIGURE J.22 Shielding Thickness Probability Density Function

J.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

Window: Shielding Parameters

Discussion: The type of shielding material, along with the shielding thickness and density, determines the gamma attenuation properties of the shield. This parameter is important for the 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). RESRAD-BUILD accommodates eight types of shielding materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Table J.23 gives the density range (if appropriate) and a single value of density for the RESRAD-BUILD shielding materials that have a narrow range (except concrete). The table lists ranges for cast iron and gives a single-value density for other materials. The values are taken from *The Health Physics and Radiological Health Handbook* (Shleien 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide 1998). Table J.24 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 value used in the code is for ordinary concrete. If the type of concrete is known, a uniform distribution between the given range for a known concrete type can be used. The probability density function for concrete shielding density is displayed in Figure J.23.

TABLE J.23 Density of Shielding 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 data were not available.

Sources: Shleien (1992); Lide (1998).

TABLE J.24 Shielding (Concrete) Density from Various Sources

	Concrete Density (g/cm^3)		
Aggregate	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) 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	-	0.36–1.5.	-
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 data were not available.

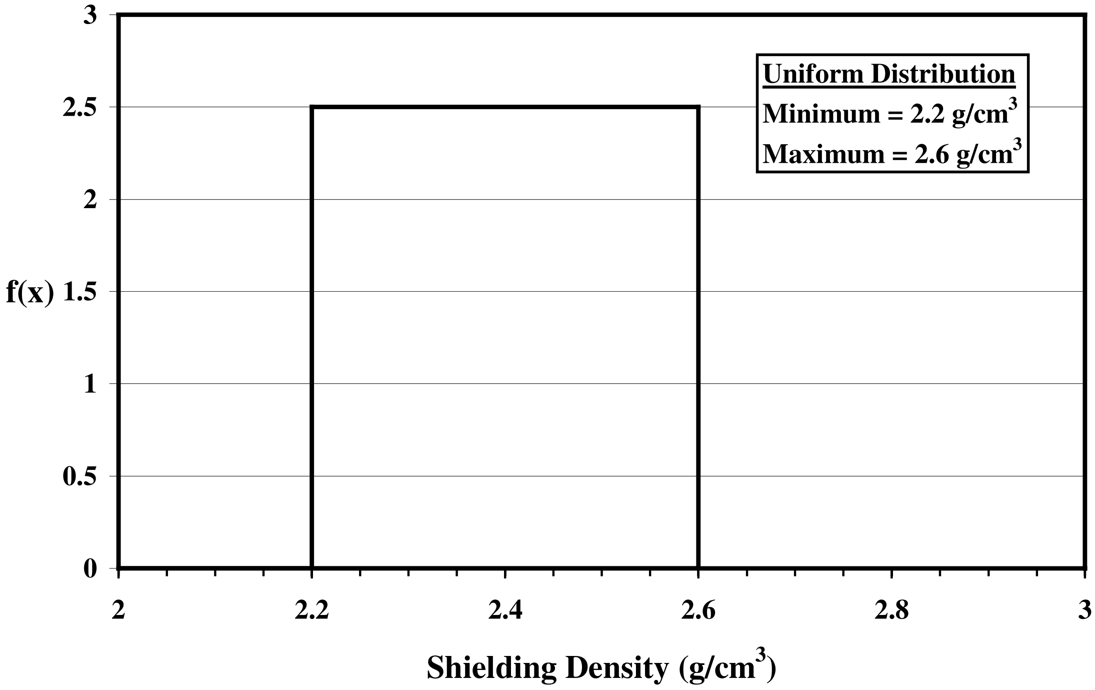

FIGURE J.23 Concrete Shielding Density Probability Density Function

J.5.3 Shielding Material

Definition: This parameter specifies the type of material used in the shield between the receptor and source.

Parameter Name: MTLC **Units:** Unitless

Range: Concrete, water, aluminum, iron, copper, tungsten, lead, or uranium

Default Value: Concrete

Window: Shielding Parameters

Discussion: This parameter is not eligible for probabilistic input. If air is the only medium between the source and receptor, there is no shielding material present. The type of shielding material, along with the shielding thickness and density, determines the gamma attenuation properties of the shield. This parameter is important only for the external pathway.

The user can select among eight shielding materials: concrete, water, aluminum, iron, copper, tungsten, lead, and uranium. This parameter can be determined from direct inspection, standard building codes, and/or building design specifications. When there are many materials in the shielding, the input material that most closely approaches the weighted average atomic number of the shield should be chosen.

The code requires the shielding material parameter to be set for every source and receptor pair. For example, if there are two sources and four receptors, the code requires eight independent shielding materials to be entered. It is up to the user to specify the correct densities for the shielding materials (see Section J.5.2, Shielding Density).

J.5.4 References

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J.6 TRITIUM MODEL PARAMETERS

J.6.1 Dry Zone Thickness

Description: Dry zone thickness is the depth of the uncontaminated layer overlying the tritium contaminated (wet) layer.

Parameter Name: DRYTHICK **Units:** cm **Range:** 0–wet + dry zone thickness

Default Value: 0

Window: Source Parameters → Details

Discussion: The tritium vaporization model in RESRAD-BUILD considers only a volume source that is situated inside the concrete wall or floor of a contaminated building. The user can specify the depth of the dry zone, which is an uncontaminated region, and the depth of the wet + dry zone. The difference between these two depths gives the thickness of the contaminated zone.

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 model assumes that the vaporization rate is controlled by the diffusion rate of water molecules through the pore space of the solid material. The difference between the vapor concentration of water in the air and the vapor concentration of water in the pore space of the contaminated zone is the driving force of 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 do not adsorb to the solid matrix) in the contaminated zone are peeled off layer by layer. This process creates a dry zone with increasing thickness between the surface of the contaminated material and the remaining contaminated zone inside the material. As water molecules vaporize, tritium is released to the indoor air and results in potential radiation exposure. To estimate the release rate of tritium, the values of several additional parameters (see Sections J.6.2 through J.6.5) are required. The 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.

J.6.2 Wet + Dry Zone Thickness

Description: This parameter represents the depth from the surface of the contaminated material to the deepest point of the contaminated 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

Window: Source Parameters → Details

Discussion: The wet + dry zone thickness parameter is used in RESRAD-BUILD in modeling the emission rate of tritiated water (HTO) vapor from the contamination source to the indoor atmosphere. In a tritium-handling facility, tritium contamination of the construction material and the 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 diffuse through many of them, resulting in contamination of the bulk as well as of the surface. The tritium that is absorbed/adsorbed to the surrounding materials can then be desorbed and 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 diffusion of the 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 discussion for the “water fraction available for evaporation” parameter, Section J.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 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, 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 J.24.

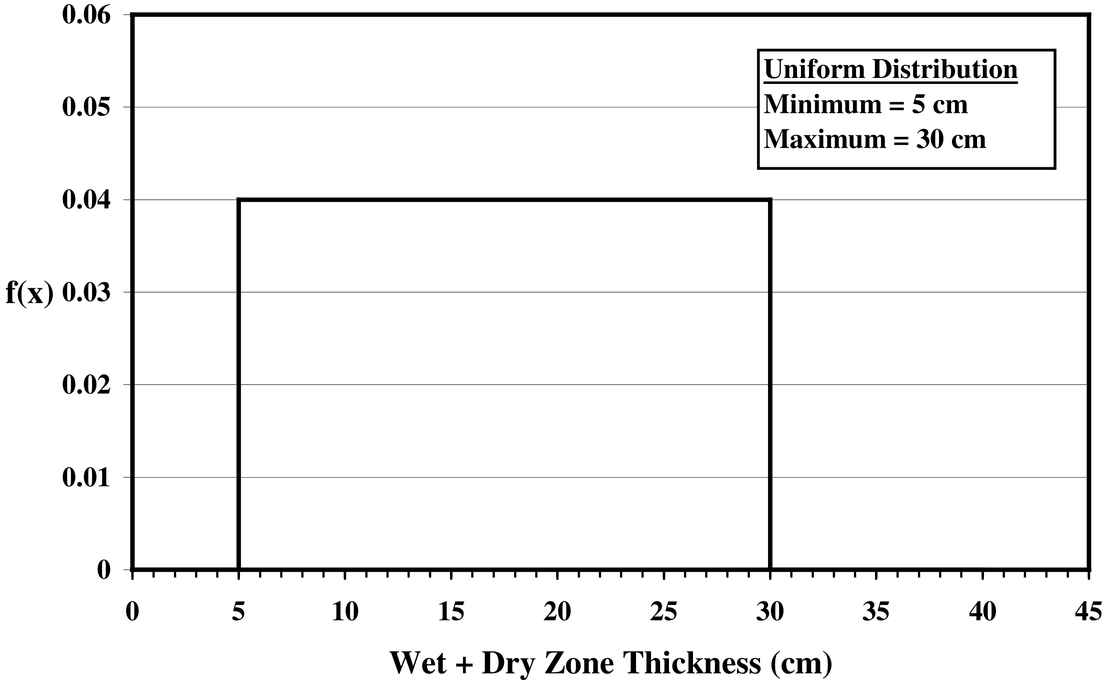

FIGURE J.24 Wet + Dry Zone Thickness Probability Density Function

J.6.3 Volumetric Water Content

Description: The volumetric water content is the volume of water per unit volume of the porous material.

Parameter Name: H3VOLFRACT **Units:** Unitless **Range:** >0 to 1

Deterministic Analysis Default Value: 0.03

Probabilistic Analysis Default Distribution: Uniform
(allowed only for concrete for volume contamination with tritium)
Defining Values for Distribution:
Minimum: 0.04 Maximum: 0.25

Window: Source Parameters → Details

Discussion: The volumetric water content is used in RESRAD-BUILD when evaluating the radiological risks from a volume source contaminated with tritium. The assumption is made that any tritium is present as tritiated water. Because the contamination 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. Thus, the distribution for the volumetric water content is expected to be the same as the source porosity (Section J.4.18). In any case, the maximum value assigned to the volumetric water content should not be greater than the maximum of the source porosity.

J.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 be released to the indoor air through the diffusion mechanism under room temperature.

Parameter Name: H3RMVF **Units:** Unitless **Range:** 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

Window: Source Parameters → Details

Discussion: In a tritium-handling facility, tritium contamination of the construction material and the equipment is recognized as an important radiation 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 and can diffuse through many of them, resulting in both bulk (volumetric) and surface contamination. The tritium that is absorbed or adsorbed to the surrounding materials can then be desorbed from the materials and 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 tritiated water (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). On the other hand, 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 the metal samples was in the form of HTO, although the samples were exposed to 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 diffusion of the HTO molecules from inside of the concrete matrix to the concrete-atmosphere interface.

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.

According to the experimental observations of Numata and Amano (1988), water exists in concrete in two states: free water and bound water. Free water is the liquid water that fills the pore space and capillaries in the concrete. Bound water is the water that combines with constituent compounds in concrete or the concrete itself. The fraction of free water was determined by Numata and Amano (1988) in their thermal desorption experiments as the fraction that was desorbed from concrete samples when the heating temperature was less than 200ºC. The existence of free water versus bound water was verified in an investigation by Ono et al. (1992), who studied sorption and desorption of tritiated water on paints. That study found that recovery of tritium sorbed to various paint materials was not complete by gas sweeping under 30ºC. Residual tritium sorbed was recovered by heating up the samples up to 800ºC. Although the samples used by Ono et al. (1992) were different from the concrete samples used by Numata and Amano (1988), it is quite conclusive that some tritiated water can strongly bond with the source materials. In the RESRAD-BUILD tritium model, it is assumed that under ordinary building occupancy conditions, only the water that fills the pore space and capillaries of the concrete materials will vaporize and diffuse to the indoor atmosphere.

Numata and Amano (1988) reported that the fraction of free tritiated water in concrete samples depended on the duration of the previous exposure of the samples to tritiated water vapor. A shorter exposure duration resulted in a larger fraction of free tritiated water. However, as the exposure duration was increased to more than 60 days, equilibrium values were observed. The fraction of free tritiated water at equilibrium was 0.72 for hardened cement paste and 0.74 for mortar. The fraction of free ordinary water was lower than that for tritiated water because the ordinary water originally exists in the samples and was the residual water left during crystallization of the cement samples. The free fraction was about 0.58 for both hardened cement paste and mortar samples. The free fractions of ordinary water reported by Numata and Amano (1988) are consistent with the suggestion in DOE (1994) regarding the air release fraction of tritiated water from concrete materials under accidental conditions that can cause the temperature to reach as high as 200ºC. Tritiated water was assumed in the DOE report to be used in concrete formation, which is the same role as ordinary water in Numata and Amano's experiments.

On the basis of the above discussion, the following conclusions can be made: (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 J.25.

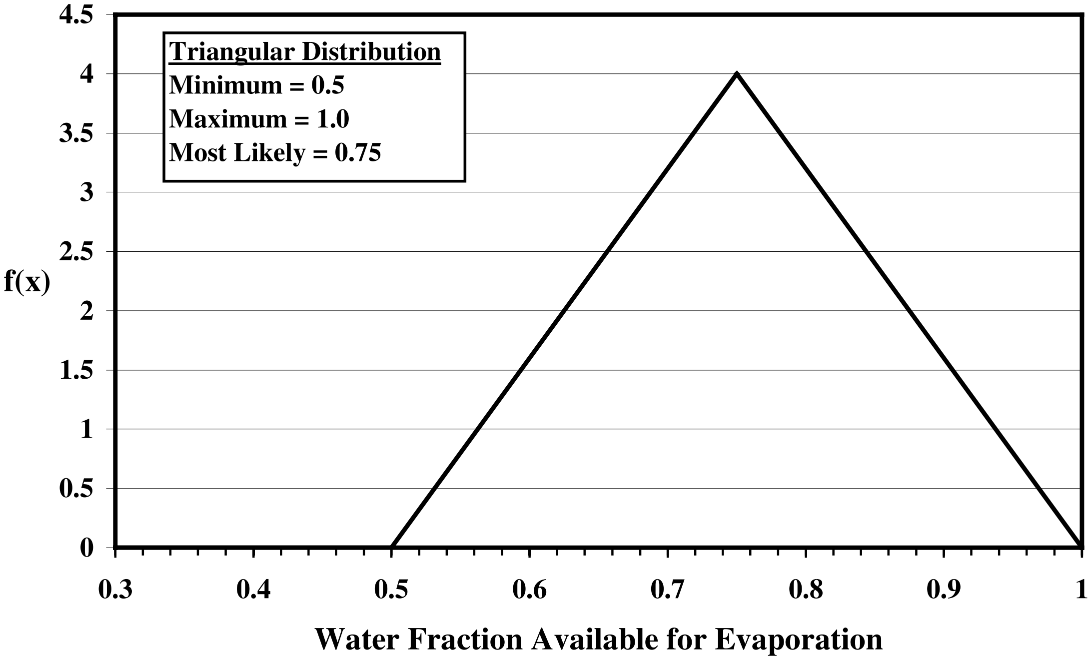

FIGURE J.25 Water Fraction Available for Evaporation Probability Density Function

J.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 volume source model.

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

Window: Source Parameters → Details

Discussion: RESRAD-BUILD requires input for the absolute humidity, the actual concentration of water vapor in air. 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 J.26. 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 (National Climatic Data Center [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 J.27. 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.

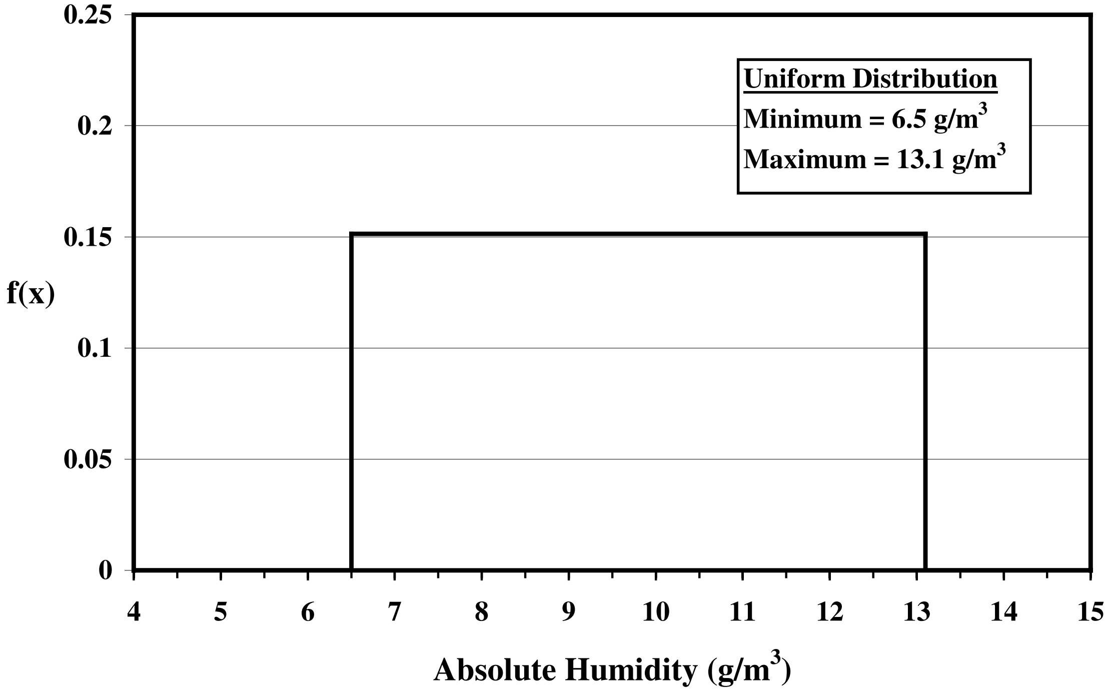

FIGURE J.26 Default Indoor Absolute Humidity Probability Density Function

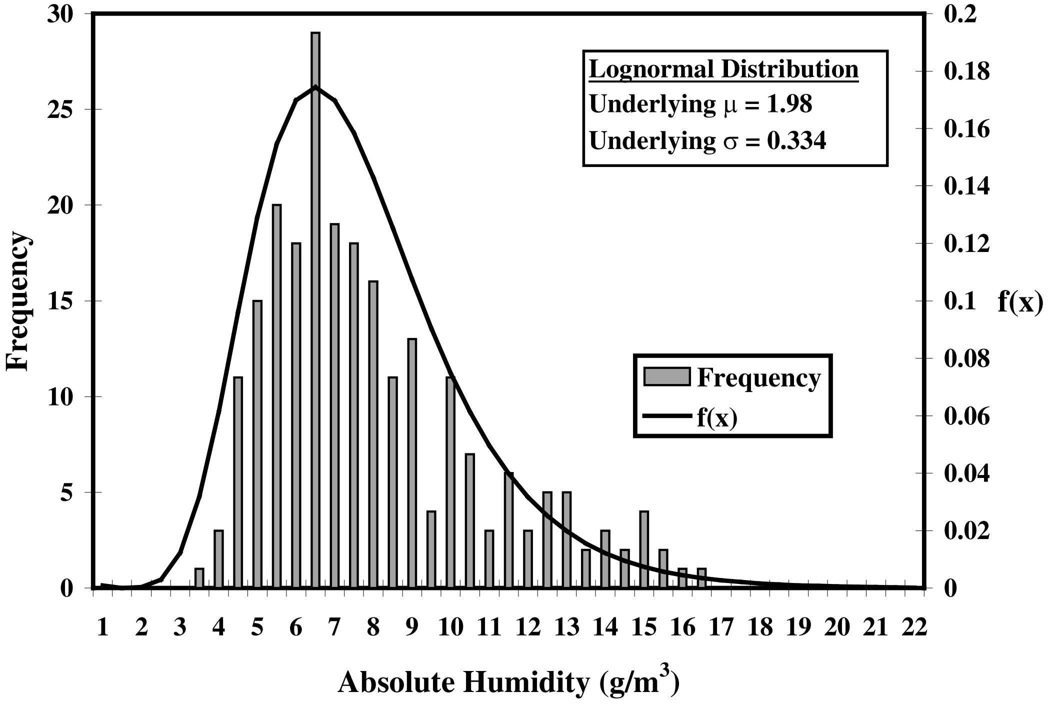

FIGURE J.27 Representative Probability Density Function for Outdoor Ambient Humidity

J.6.6 References

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Ono, F., et al., 1992, "Sorption and Desorption of Tritiated Water on Paints," *Fusion Technology* 21:827–832.

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J.7 RADIOLOGICAL UNITS

J.7.1 Activity Units

Definition: Any of the following four units of radiological activity can be selected: (1) Ci or curie, defined as $3.7 \cdot 10^{10}$ 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	$1 \cdot 10^{18}$
P	peta	$1 \cdot 10^{15}$
T	tera	$1 \cdot 10^{12}$
G	giga	$1 \cdot 10^{9}$
M	mega	$1 \cdot 10^{6}$
k	kilo	$1 \cdot 10^{3}$
h	hecto	$1 \cdot 10^{2}$
	none	1
d	deci	$1 \cdot 10^{-1}$
c	centi	$1 \cdot 10^{-2}$
m	milli	$1 \cdot 10^{-3}$
m	micro	$1 \cdot 10^{-6}$
n	nano	$1 \cdot 10^{-9}$
p	pico	$1 \cdot 10^{-12}$
f	femto	$1 \cdot 10^{-15}$
a	atto	$1 \cdot 10^{-18}$

Default: pCi (picocurie)

Window: 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 activity unit change.

J.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	$1 \cdot 10^{18}$
P	peta	$1 \cdot 10^{15}$
T	tera	$1 \cdot 10^{12}$
G	giga	$1 \cdot 10^{9}$
M	mega	$1 \cdot 10^{6}$
k	kilo	$1 \cdot 10^{3}$
h	hecto	$1 \cdot 10^{2}$
	none	1
d	deci	$1 \cdot 10^{-1}$
c	centi	$1 \cdot 10^{-2}$
m	milli	$1 \cdot 10^{-3}$
m	micro	$1 \cdot 10^{-6}$
n	nano	$1 \cdot 10^{-9}$
p	pico	$1 \cdot 10^{-12}$
f	femto	$1 \cdot 10^{-15}$
a	atto	$1 \cdot 10^{-18}$

Default: mrem (millirem)

Window: 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.