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Technical Basis for Calculating Radiation Doses for the Building Occupancy Scenario Using the Probabilistic RESRAD-BUILD 3.0 Code

Argonne National Laboratory

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TECHNICAL BASIS FOR CALCULATING RADIATION DOSES FOR THE BUILDING OCCUPANCY SCENARIO USING THE PROBABILISTIC RESRAD-BUILD 3.0 CODE

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Submitted to

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ABSTRACT

The purpose of this report is to illustrate the use of the probabilistic RESRAD-BUILD 3.0 code to simulate the light industrial use of a decontaminated building as one of the building occupancy scenarios described in NUREG/CR-5512 and NUREG-1727. The report illustrates how a data template file of updated input parameters and their distributions may be constructed to transition from the screening approach for dose analysis in NUREG/CR-5512 to a site-specific approach of the RESRAD-BUILD code. The intent of this illustration is not to recommend a set of “default“ parameters, but to assist users in formulating a method for selecting and constructing a set of parameters to be used with the code for demonstrating compliance with the dose criteria in the license termination rule. The report describes an example of a dose analysis performed by using the probabilistic RESRAD-BUILD 3.0 code and the data template file developed for this report to provide insight into the dose values that may be obtained by simulating light industrial use as the building occupancy scenario.

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EXECUTIVE SUMMARY

The U.S. Nuclear Regulatory Commission (NRC) has developed a Standard Review Plan (SRP [NUREG-1727]) to assist in demonstrating compliance with the radiological criteria that decontaminated and decommissioned licensed nuclear facilities must meet. A graded approach is given for dose modeling that ranges from a conservative screening to a site-specific analysis. The conservative approach is embodied in NUREG-5512, where a screening approach is used to assess potential radiation doses to individuals for the building occupancy scenario. While the transition from a screening approach to a site-specific approach was discussed conceptually in the SRP, a direct application was not given. This report discusses the use of the RESRAD-BUILD 3.0 computer code for performing such a site-specific analysis. The technical basis for the light industrial building occupancy scenario, the screening approach, and the site-specific approach are examined, and a process is developed for selecting the appropriate site-specific input parameters for use in RESRAD-BUILD.

The probabilistic RESRAD-BUILD 3.0 code was used to simulate the light industrial use of a decontaminated building for the building occupancy scenario as described in NUREG/CR-5512 and NUREG-1727. Because RESRAD-BUILD is designed to model more detailed, sophisticated scenarios than those implemented in the screening approach, more detailed input data are needed to satisfy the requirements for the RESRAD-BUILD analysis. Both RESRAD-BUILD and the NRC screening method model external exposure from surface sources, inhalation of resuspended contamination, and inadvertent ingestion of surface contamination. The screening method relies on a generic release model using the resuspension factor as the primary controlling release parameter. On the other hand, RESRAD-BUILD uses a different approach and considers many important factors, including the removable fraction, source lifetime, air release fraction, mixing and transport in air, and surface deposition and resuspension.

Parameter distributions for RESRAD-BUILD were updated, and appropriate input data were selected and placed in a template file. Only six distributions were selected for use in the template file on the basis of applicability and site-specificity. Those parameters for which a distribution was used were the deposition velocity, resuspension rate, building air exchange rate, receptor indirect ingestion rate, air release fraction, and the time for source removal. Deterministic values for the other parameters were selected according to their treatment in NUREG/CR-5512. The template file was developed not for the purpose of recommending a set of “default” parameters for a site-specific analysis, but to provide users with a reasonable method, consistent with the technical basis for the light industrial building occupancy scenario as explained in this report, for selecting appropriate input data for a site-specific analysis. Sample probabilistic runs of RESRAD-BUILD were conducted using the template file with six radionuclides (Co-60, Sr-90, Cs-137, Ra-226, U-238, and Pu-239) to provide the analyst with an idea of the type of results that could be expected when performing a site-specific analysis.

FOREWORD

This contractor technical report, NUREG/CR-6755, was prepared by Argonne National Laboratory[1] staff under their U.S. Department of Energy (DOE) Interagency Work Order (JCN Y6112) with the Radiation Protection, Environmental Risk and Waste Management Branch, Division of Systems Analysis and Regulatory Effectiveness, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission.

The purpose of this report is to illustrate the use of the probabilistic RESRAD-BUILD 3.0 code to simulate the light industrial use of a decontaminated building as one of the building occupancy scenarios described in NUREG/CR-5512, “Residual Radioactive Contamination From Decommissioning.” The report explains how to transition from the screening approach for dose analysis in NUREG/CR-5512 to a site-specific approach by using the RESRAD-BUILD code. It illustrates how a set of updated parameter values and their distributions may be constructed to be used with the code for site-specific dose analysis. The purpose of this illustration is not to recommend a set of “default” parameters, but to assist code users in formulating a method for selecting and constructing a set of parameters for site-specific and probabilistic dose analysis to demonstrate compliance with the license termination rule, 10 CFR Part 20, Subpart E, in a risk informed manner.

This NUREG/CR report is not a substitute for NRC regulations, and compliance is not required. The approaches and/or methods describe in this report are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein. Use of product or trade names is for identification purposes only and does not constitute endorsement by the NRC or Argonne National Laboratory.

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ABBREVIATIONS

ANS	American Nuclear Society
ARF	airborne release fraction
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BLA	Bureau of Labor Statistics
BNL	Brookhaven National Laboratory
EC	degree(s) Centigrade
CFR	Code of Federal Regulations
cm	centimeter(s)
cm^2	square centimeter(s)
cm^3	cubic centimeter(s)
d	day(s)
DCF	dose conversion factor
DOE	U.S. Department of Energy
D&D	decontamination and decommissioning
dpm	disintegration(s) per minute
EPA	U.S. Environmental Protection Agency
FGR	Federal Guidance Report
EF	degree(s) Fahrenheit
ft	foot (feet)
ft^2	square foot (feet)
g	gram(s)
h	hour(s)
HT	tritium gas
HTO	tritiated water
HVAC	heating, ventilation, and air-conditioning
ICRP	International Commission on Radiological Protection
in.	inch(es)
ISO	International Organization for Standardization
LHS	Latin Hypercube Sampling
m	meter(s)
m^2	square meter(s)
m^3	cubic meter(s)
µg	microgram(s)
µm	micrometer(s)
mg	milligram(s)
mm	millimeter(s)
mrem	millirem
NAHB	National Association of Home Builders
NBS	National Bureau of Standards
NCDC	National Climatic Data Center
NRC	U.S. Nuclear Regulatory Commission
pCi	picocurie(s)
PFT	perfluorocarbon tracer
RF	respirable fraction
RH	relative humidity
s	second(s)
SD	standard deviation
yr	year(s)

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has taken steps to ensure that residual radioactive contamination remaining after licensed nuclear facilities are decontaminated and decommissioned meets established requirements and radiological criteria (Subpart E to Title 10, *Code of Federal Regulations*, Part 20 [10 CFR Part 20]). To support the implementation of the requirements, the NRC developed the Decommissioning Standard Review Plan (NRC, 2000) in which the technical basis is provided regarding dose modeling for demonstrating compliance with the radiological criteria. In that approach, the NRC prescribed a graded approach to dose modeling that ranges from a conservative screening to a site-specific analysis, taking into account site conditions and the relevant information available.

The conservative approach is exemplified in NUREG/CR-5512 (Kennedy and Strenge, 1992; McFadden et al., 2001), where a screening approach is used to assess potential radiation doses to individuals. On the other hand, the site-specific analysis is embodied in the RESRAD-BUILD 3.0 computer code designed to accommodate a more in-depth site-specific analysis for buildings with residual contamination (NUREG/CR-6697 [Yu et al., 2001]).

The RESRAD-BUILD computer code (Yu et al., 1994) is designed to provide a site-specific approach. This code has been developed by Argonne National Laboratory and approved by the U.S. Department of Energy (DOE) for use in evaluating radioactively contaminated buildings and is used in the United States and abroad. The RESRAD-BUILD code complements NRC's licensing efforts in developing methods for demonstrating compliance with decontamination and decommissioning (D&D) rules. Representative parameter distributions were developed for input to the RESRAD-BUILD computer code for use in a building occupancy scenario (NUREG/CR-6697 [Yu et al., 2000]). These distributions were initially derived to test the probabilistic analysis capabilities that were being added to the RESRAD-BUILD code. A further benefit of these distributions and the additional related information presented with them (Yu et al., 2000) was to give the user a starting point for developing site-specific distributions for a customized analysis. RESRAD-BUILD is designed to provide a site-specific analysis, and the representative distribution provided for a given input parameter, such as the room area, is often inappropriate for the specific site being analyzed. The representative distribution was developed to encompass a range of potential sites and may not be appropriate for a specific site. It is intended that the representative distribution be replaced with values specific to the site being analyzed.

Although the transition from a screening approach to a site-specific approach has been discussed conceptually in the NRC's Standard Review Plan (NRC, 2000), it is desirable to understand the technical basis leading to such a transition. To accomplish this purpose, this report evaluates the technical bases of the screening approach and the site-specific approach, from which representative parameters of importance are identified. In particular, it focuses on the scenario representing the light industrial use of a building following decontamination. In this process, the analysis also evaluates reasonable sets of input parameters to be used for a site-specific analysis. The intended purpose is not to recommend a set of "default" parameters, rather it is to assist users in formulating a method of selecting a reasonable set of parameters for meeting the dose criteria.

Section 2 of this report evaluates the technical basis for the building occupancy scenario. The scenario itself and the approaches taken in both the RESRAD-BUILD code and the DandD code (designed to implement the screening approach [McFadden et al., 2001]) to address the exposure pathways considered are discussed. This discussion provides insight to help determine whether a site may qualify for release using the more site-specific analysis provided by RESRAD-BUILD when the DandD screening model criteria are not met. The relative importance of the various input parameters to a potential exposure pathway for each model is also discussed.

The representative RESRAD-BUILD parameter distributions from NUREG/CR-6697 are reexamined in Section 3 of this report. Included in that section is an updated list of data and representative distributions for those RESRAD-BUILD input parameters for which more information was available. Where appropriate, related DandD parameters are discussed to highlight differences in the RESRAD-BUILD and DandD models. For completeness, those distributions not updated from NUREG/CR-6697 are provided in Appendix A. Appendix B describes the parametric distribution types supported in RESRAD-BUILD.

Section 4 details the methodology used to select a reasonable set of input parameters for RESRAD-BUILD to evaluate a building occupancy scenario. These parameters were placed in a template input file for analysis. The results of the analysis are discussed in Section 5. A report summary is given in Section 6.

2 EVALUATION OF THE TECHNICAL BASIS OF THE BUILDING OCCUPANCY SCENARIO USING THE RESRAD-BUILD and DandD CODES

The building occupancy scenario as described in NUREG/CR-5512 (Kennedy and Strenge, 1992) calculates potential exposure of a screening group to both fixed and removable thin-layer surface-contamination sources. The screening group, as defined in NUREG-1549 (NRC, 1998), consists of adult males who work in light industry. They occupy and work in a commercial facility in a normal manner without deliberately disturbing sources of residual contamination. The occupancy is assumed to begin immediately after decommissioning and release of the building, before significant radioactive decay of residual radionuclides occurs. The length of exposure is a full work year. Behavioral parameters represent the characteristics of the screening group, and the parameter values chosen for this analysis represent the average behavior within that group. The screening group is used as a surrogate group for assessing potential exposures to contaminated buildings at all sites. The exposure pathways selected are (1) external exposure to penetrating radiation from surface sources, (2) inhalation of resuspended surface contamination, and (3) inadvertent ingestion of surface contamination. Both RESRAD-BUILD (Yu et al., 1994) and DandD (McFadden et al., 2001) can estimate the dose to a receptor in the building for the building occupancy scenario. Both use the dose conversion factors from Federal Guidance Report (FGR) 11 (Eckerman et al., 1988) for inhalation and ingestion intake and dose coefficients from FGR 12 (Eckerman and Ryman, 1993) for external exposure. Both codes use the radionuclide data from International Commission on Radiological Protection (ICRP) Publication 38 (ICRP, 1983).

The RESRAD-BUILD code is a pathway analysis model designed to evaluate the potential radiological dose to an individual who works or lives in a building contaminated with radioactive material. It considers the releases of radionuclides into the indoor air by diffusion, mechanical removal, or erosion. The transport of radioactive material inside the building from one room or compartment to another is calculated with an indoor air quality model. The air quality model evaluates the transport of radioactive dust particulates, tritium, and radon progeny due to (1) air exchange between rooms and with outdoor air, (2) the deposition and resuspension of particulates, and (3) radioactive decay and ingrowth. A single run of the RESRAD-BUILD code can model a building with up to 3 rooms or compartments, 10 distinct source locations, 4 source geometries, 10 receptor locations, and 8 shielding materials. A shielding material can be specified between each source-receptor pair for external gamma dose calculations.

Seven exposure pathways are considered in RESRAD-BUILD: (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; (6) inadvertent ingestion of radioactive material directly from the sources; and (7) inadvertent ingestion of materials deposited on the surfaces of the building rooms or compartments. Figure 2.1 illustrates the different exposure pathways in the RESRAD-BUILD code and shows the relationship of the release mechanism to pathways. The user can define the source as a point, line, area, or volume. The volume source can consist of five layers of different materials, with each layer being porous, homogeneous, and isotropic. Currently, 67 radionuclides are included in the RESRAD-BUILD database. All 67 radionuclides have half-lives of 6 months or greater and are referred to as principal radionuclides. It is assumed that the short-lived progeny with half-lives of 6 months or less, referred to as the associated radionuclides, are in secular equilibrium with their parent principal radionuclide.

The DandD code is intended to be a screening tool for assessing potential doses from decommissioned sites on the basis of a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary. These levels of calculations are intended to produce generic dose estimates that are unlikely to be exceeded at real sites.

Various scenarios can be analyzed with the DandD code, including the building occupancy

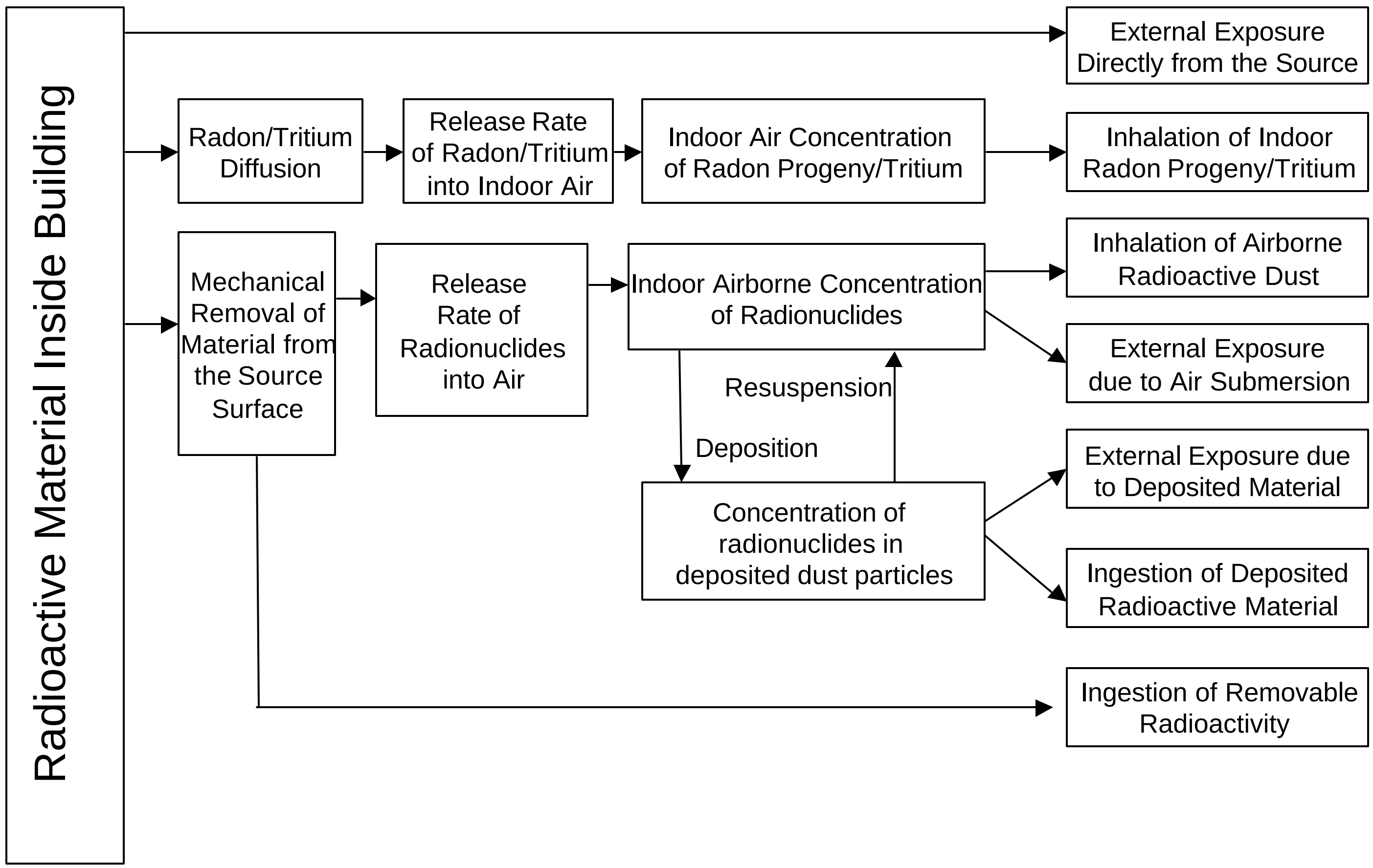


Figure 2.1 Exposure Pathways in the RESRAD-BUILD Code

scenario. The exposure pathways selected in the building occupancy scenario include external exposure to penetrating radiation from surface sources, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination. The DandD code database contains 249 primary radionuclides. All dose values generated by the DandD scenario analysis are calculated by multiplying the parent nuclide activity by a dose factor. This dose factor accounts for the contributions to the dose values from exposure to radiation from the parent and the progeny in the following manner. The radiations included in the dose factors for a parent are those associated with decay of the parent, plus radiation from progeny that are always in secular equilibrium (half-lives less than 9 hours and less than one-tenth the listed parent half-life). Radiation from decay chain members that meet these criteria are included with the radiation from their parent radionuclides as implicit progeny; the progeny that are not implicit are defined as explicit.

The capabilities of the RESRAD-BUILD and DandD codes for evaluating the building occupancy scenario are presented in Table 2.1. Table 2.2 lists the parameters used in the RESRAD-BUILD and DandD codes for different pathways. Very few parameters are required in DandD; RESRAD-BUILD, however, requires many more site-specific parameters. Some of the parameters in the two codes are common or related. Figure 2.2 shows the mechanism involved in inhalation pathway dose calculations in the DandD and RESRAD-BUILD codes.

Physical parameters that can be changed in the DandD analysis are the resuspension factor, area of contamination, and the removable fraction. For an area of contamination of 10 m^2 or greater, the calculated pathway doses are independent of the area of contamination. For an area of contamination of less than 10 m^2, the calculated pathway doses change linearly with the area of contamination. The resuspension factor and the removable fraction affect the inhalation pathway dose. The external pathway doses in DandD do not depend on these two physical parameters. For calculating the external pathway dose using an area of contamination of 10 m^2 or greater, the area source is assumed to be infinite in lateral extent, and no correction is applied for finite source size or receptor distance relative to the source.

The total receptor dose in the RESRAD-BUILD code from all pathways except direct external exposure depends on the radionuclide air concentration in the room. The radionuclide air concentration in turn depends on the source injection rate. Air deposition of particulates also depends on the air concentration in the room.

The physical parameters required in RESRAD-BUILD to calculate the source injection rate for a point, line, or area source are (1) removable fraction, (2) source lifetime, and (3) air release fraction. For a volume source, the parameters include (1) source erosion rate, (2) source area, (3) density of source material, and (4) air release fraction.

Equation 2.1 below gives the source injection rate for a point, line, or area source in RESRAD-BUILD (Equation D.2 from Yu et al., 1994). The source injection rate is zero for times greater than the time required to remove the entire source ($t > T_R$). To calculate the air concentration of a principal radionuclide in a one-room air quality model, some additional physical parameters are required, including deposition velocity, resuspension rate, room dimensions, and air exchange rate. Equation 2.2 (derived from Equation A.28 in Yu et al., 1994) gives the air concentration of principal radionuclide n under equilibrium conditions. Since the room dimensions are fixed in a site-specific analysis, the physical parameters required to calculate air concentration for an area source are (1) removable fraction, (2) source lifetime, (3) air release fraction, (4) deposition velocity, (5) resuspension rate, and (6) air exchange rate.

$$I_s^n = \frac{f_R \, f \, Q_s}{24 T_R}, \quad (t < T_R) \tag{2.1}$$

where

I_s^n = injection rate of radionuclide n into the indoor air of the room (pCi/h),

f_R = removable fraction of the source material,

f = fraction of removed material that becomes indoor dust,

Table 2.1. Evaluation of the Technical Basis for the Building Occupancy Scenario Using the RESRAD-BUILD and DandD Codes

Component	RESRAD-BUILD[a,b]	DandD	Remarks
Source description	• Up to 10 sources • Volume, area, line, or point source of any dimension	• Floor is contaminated • Infinite area source for the direct exposure pathway	
Handling of radionuclides[c]	• 67 principal radionuclides • Half-lives 6 months or longer • In secular equilibrium with progeny of half-lives less than six months	• 249 primary radionuclides • Half-lives 10 minutes or longer • In secular equilibrium with progeny if half-lives are (1) less than 9 hours and (2) less than one-tenth the listed parent half-life	DandD has many more short-lived radionuclides in its database.
Building description	• Up to a three-room structure • Air exchange.	• One large structure • Air exchange is not explicitly modeled	
Receptor location with respect to source	• Up to 10 receptor locations at any distance from the source	• Only one receptor at a fixed location (specified by FGR 12 geometry) with respect to the source	RESRAD-BUILD has an external exposure model to handle any source-receptor configuration.
Pathways	• Direct external exposure from surface source • Inhalation of airborne radioactive particulates • Inadvertent ingestion of source material directly G Inadvertent ingestion of deposited materials G Exposure to deposited materials G Exposure due to air submersion G Inhalation of aerosol indoor radon progeny	• External exposure due to surface source • Inhalation of resuspended surface contamination • Inadvertent ingestion of surface contamination	RESRAD-BUILD is a more sophisticated code and can model site-specific situations.
Time dependence	• 10 time steps in a single run • Calculates average time-integrated dose over the exposure duration • Radionuclide concentration changes with radioactive ingrowth, decay, and mechanical erosion	• A single time step • Calculates average time-integrated dose over one-year duration • Radionuclide concentration changes with radioactive ingrowth and decay	
Air concentration	• Dynamic air quality model • Different source release mechanisms: diffusion and particulate injection	• Simple and static linear relationship between air concentration and contamination	DandD assumes infinite source, and air concentration is derived from the resuspension factor,

			whereas in RESRAD-BUILD there is uniform depletion of source over the source lifetime.
Ingestion pathway	• Direct ingestion of removable material G Ingestion of deposited material	• Direct ingestion of removable material	RESRAD-BUILD also considers ingestion from deposited materials.

Table 2.1. Evaluation of the Technical Basis for the Building Occupancy Scenario Using the RESRAD-BUILD and DandD Codes (Continued)			
Component	**RESRAD-BUILD[a,b]**	**DandD**	**Remarks**
External exposure pathways	• Directly from the source G Materials deposited on the floor G Air submersion	• Directly from the source	RESRAD-BUILD considers two more external exposure pathways.
Shielding correction	G Eight shielding materials	• No shielding correction	
Transport of contamination from one room to another	G With an indoor air quality model G Air exchange between the rooms and with outside air G The deposition and resuspension of particulates G Radioactive decay and ingrowth	• No transport considered	
H-3 (tritium)	G Special H-3 model for volume source	• No special H-3 model	
Radon	G Radon diffusion and radon flux model	• Not included	Not required for NRC compliance.

[a] RESRAD-BUILD includes four more pathways than DandD (as indicated by open squares).

[b] An open square (**G**) represents pathways, models, and mechanisms not included in the DandD code.

[c] DandD includes many more short-lived radionuclides than RESRAD-BUILD.

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

Q_s^n = total radionuclide activity in the source (pCi), and

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

$$C^n = \frac{I_s^n}{(l_m + l_d - \frac{l_R\, l_d}{l_m + l_R})V + Q_0}, \qquad (2.2)$$

where

C^n = air concentration of radionuclide *n* in the room(pCi/m^3),

$?_{r\,n}$ = radioactive decay constant of radionuclide *n* (1/h),

$?_d$ = deposition rate in the room (1/h), = $\frac{V_d \times A}{V}$,

V_d = deposition velocity (m/h),

$?_R$ = resuspension rate (1/h),

V = volume of the room (m^3), and

Q_0 = flow of air from the room to the outside (m^3/h).

A parameter's relative importance would also depend on the contaminants of concern. For example, for a long-lived radionuclide or in a situation where the radioactive decay constant is much smaller than the resuspension rate, the air concentration in a one-room air quality model under steady-state condition (RESRAD-BUILD code assumption) does not depend on resuspension rate and deposition rate. For other radionuclides, when all other parameters are kept fixed in RESRAD-BUILD and the resuspension rate value is reduced, the resultant air concentration also decreases, in turn reducing the inhalation and immersion pathway doses. However, the surface contamination from deposition may increase, in turn increasing the dose from indirect ingestion and external exposure from deposited material. In this case, the total dose may increase in RESRAD-BUILD even though the inhalation

Table 2.2. Technical Basis Used in RESRAD-BUILD and DandD Codes for the Building Occupancy Scenario

Pathway	Common Parameters	RESRAD-BUILD	DandD
Direct external exposure[a]	• Exposure duration (d) • Average surface source activity (pCi/m^2) • DCF for surface source [(mrem/yr)/(pCi/m^2)]	• Source area (m^2) • Shielding parameters (material thickness in cm and density in g/cm^3) • Source location (m,m,m) • Receptor location (m,m,m)	• Source area (unlimited or size in m^2)
Inhalation	• Occupancy factor • DCF (mrem/pCi) • Removable fraction • Receptor inhalation rate (m^3/d) • Average surface source activity (pCi/m^2)	• Source area (m^2) • Room dimension (area in m^2 and height in m) • Air exchange rate (1/h) • Air release fraction • Source lifetime (d) • Resuspension rate (1/s) • Deposition velocity (m/s)	• Resuspension factor (1/m) • Source area (unlimited or size in m^2)
Direct ingestion[b]	• Exposure duration (d) • Average surface activity (pCi/m^2) • DCF (mrem/pCi)	• Source area (m^2) • Direct ingestion rate (1/h)	• Effective transfer rate for ingestion (m^2/h) • Source area (unlimited or size in m^2)
Ingestion of deposited materials	NA[c]	• All inhalation pathway parameters except for inhalation rate and DCF • Indirect ingestion rate (m^2/h)	NA

		• DCF (mrem/pCi)	
External exposure to deposited materials	NA	• All inhalation pathway parameters except for inhalation rate and DCF • Shielding parameters • Receptor location • DCF [(mrem/yr)/(pCi/g)]	NA
External exposure due to air submersion	NA	• All inhalation pathway parameters except for inhalation rate and DCF • Air submersion DCF [(mrem/yr)/(pCi/m^3)]	NA
Inhalation of indoor radon progeny	NA	• All inhalation pathway parameters • Radon release fraction	NA

[a] RESRAD-BUILD uses FGR 12 volumetric dose conversion factors (DCFs) and surface source DCFs (Kamboj et al., 1998).

[b] To calculate the direct ingestion pathway dose, the effective transfer rate for ingestion is required for the DandD code and the source area and direct ingestion rate are required for the RESRAD-BUILD code. The effective transfer rate for ingestion in the DandD code is related to the source area and the direct ingestion rate in the RESRAD BUILD code. This relationship is:

effective transfer rate for ingestion = source area × direct ingestion rate.

[c] NA = not applicable.

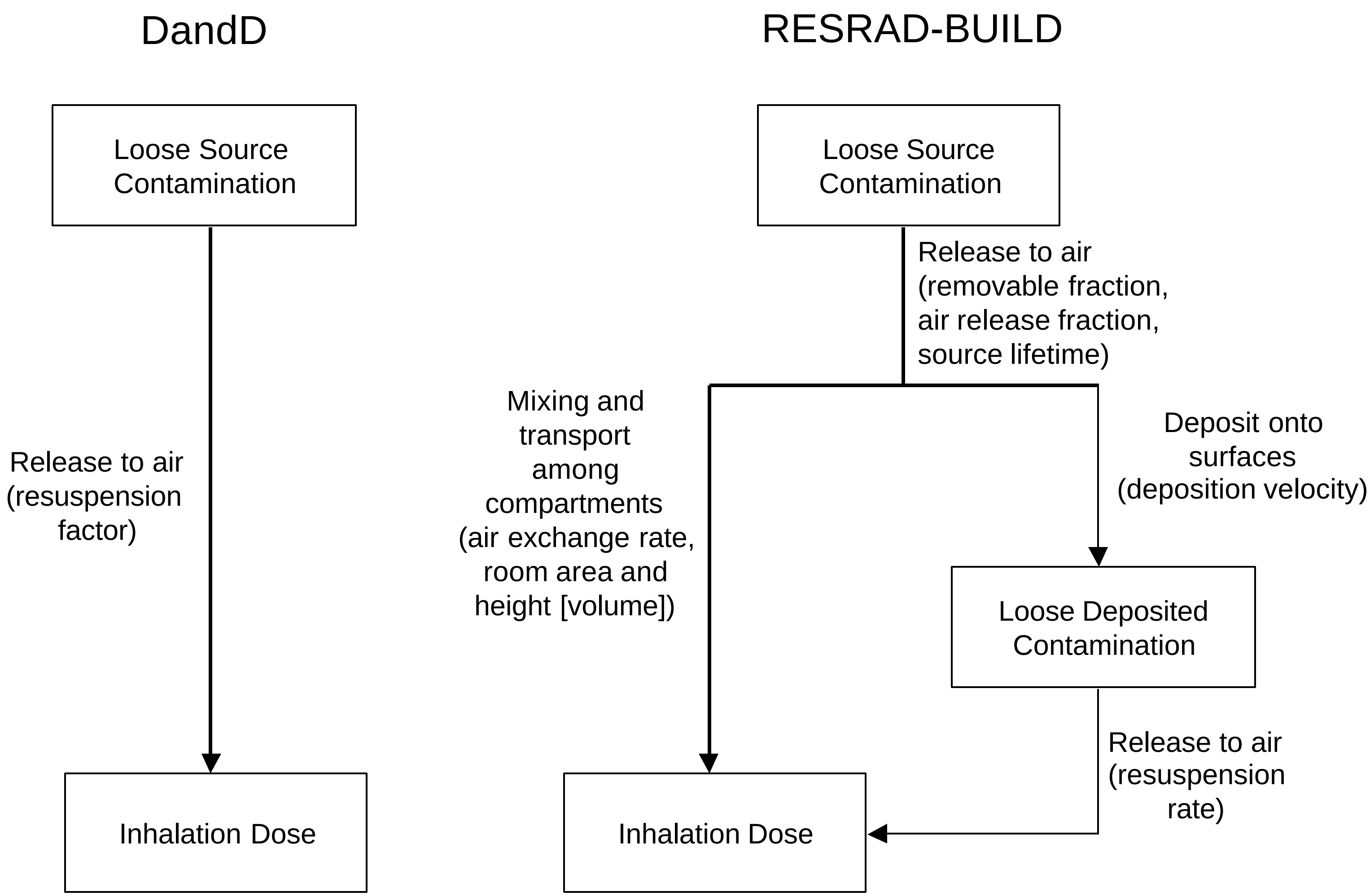


Figure 2.2 Inhalation Pathway in DandD and RESRAD-BUILD Codes

pathway dose is reduced with the decrease in the resuspension rate, because of a higher indirect ingestion dose resulting from increased deposition. The surface contamination from deposition (C_d^n), assuming a steady-state condition, can be given by Equation 2.3 (Equation B.3 in Yu et al., 1994).

$$C_d^n = \left(\frac{V_d}{I_{rn} + I_R}\right) C^n \ . \qquad (2.3)$$

The physical parameters required for the direct external exposure pathway in RESRAD-BUILD depend on the source type, source receptor locations, and the shielding characteristics between the source-receptor pair. For the area source, the other important parameter is the source area; for the volume source, the other important parameters are source material, area, thickness, and source erosion rate. If the source receptor locations are fixed and there is no shielding between the source-receptor pair in a particular scenario, the important parameters in the external exposure pathway are the source area, thickness, and material.

3 UPDATED RESRAD-BUILD INPUT PARAMETER INFORMATION

A strategy was previously developed to rank the input parameters as to their importance (high, medium, and low priority) and to identify parameters for detailed distribution analysis (Yu et al., 2000 [NUREG/CR-6697]). Table 3.1 lists those parameters (i.e., high and medium priority; referred to as 1st and 2nd priority) selected for the assignment of probability density functions. These parameters were reexamined in light of the discussion in Section 2, their site specificity, and the additional data collected since NUREG/CR-6697 was prepared. However, data for a number of the parameters are site-specific, relatively easy to obtain, and will not be further evaluated. These parameters include the indoor fraction, room area, room height, and humidity.

New information is provided in this report for the six parameters for which additional information is available. Supporting data have been added to the resuspension rate, air exchange rate, deposition velocity, source erosion rate, removable fraction, and source lifetime parameter descriptions. The assigned input parameter distribution for RESRAD-BUILD has changed slightly for the resuspension rate and removable fraction. In addition, the sections on the resuspension rate and source lifetime have been expanded with a more indepth discussion concerning their relationship with the resuspension factor as used in DandD.

The following sections address those parameters for which additional data have been obtained. For completeness, Appendix A contains the information on the remaining parameters as provided in NUREG/CR-6697 (Yu et al., 2000).

3.1 Resuspension Rate (Indoor)

Description: The resuspension rate (indoor) represents the rate at which material deposited on interior surfaces is resuspended into the indoor air. Resuspension is the result of airflow or a mechanical disturbance, such as walking across a surface or sweeping.

Unit: 1/s

Probabilistic Input:

Distribution: Loguniform

Defining Values for Distribution:

Minimum: 2.5×10^{-11} Maximum: 1.3×10^{-5}

Discussion: Indoor resuspension of contamination can lead to internal exposure via inhalation and external exposure via submersion. The resuspension rate is the fraction of deposited particles resuspended per unit time. Factors that can affect resuspension include the type of disturbance (air flow 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 SF_6 tracer in a residential setting under varying conditions. Table 3.2 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 source of larger particle sizes in indoor air is primarily from 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 that material that cannot be inhaled directly into the lungs. Larger particulates, greater than approximately 2.5 µm, 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

Table 3.1. RESRAD-BUILD Parameters Selected (Priority 1 and 2) for Assignment of Probability Density Functions

Parameter	Priority[a]	Type[b]	Assigned Distribution Type	Report Section[c]
Removable fraction	1	P,B	Uniform	3.5
Resuspension rate (1/s)	1	P,B	Loguniform	3.1
Shielding density (g/cm^3)	1	P	Uniform	A.1.1
Source density, volume source (g/cm^3)	1	P	Uniform	A.2.1
Air exchange rate for building and room (1/h)	2	B	Lognormal	3.2
Air release fraction[c]	2	B	Triangular	A.2.4
Deposition velocity (m/s)	2	P	Loguniform	3.3
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	2	B	None recommended	A.3.2
Humidity (g/m^3)	2	P,B	Uniform	A.1.6
Indoor fraction	2	B	Empirical	A.1.2
Indirect ingestion rate (m^2/h)	2	B	Loguniform	A.3.3
Receptor inhalation rate (m^3/d)	2	M,B	Triangular	A.3.1
Room area (m^2)	2	P	Triangular	A.1.3
Room height (m)	2	P	Triangular	A.1.4
Shielding thickness (cm)	2	P,B	Triangular	A.1.5
Source erosion rate, volume source (cm/d)	2	P,B	Triangular	3.4
Source porosity	2	P	Uniform	A.2.2
Source thickness, volume source (cm)	2	P	Triangular	A.2.6
Time for source removal or source lifetime (d)	2	P,B	Triangular	3.6
Volumetric water content	2	P	Uniform	A.2.3
Water fraction available for evaporation	2	P	Triangular	A.2.7
Wet + dry zone thickness (cm)	2	P	Uniform	A.2.5

[a] Priority as determined in NUREG/CR-6697 (Yu et al., 2000). For RESRAD-BUILD, excluded parameters include radionuclide concentration and source length or area.

[b] P = physical, B = behavioral, M = metabolic; when more than one type is listed, the first is primary and the next is secondary.

[c] Section of this report providing the distribution assigned to the parameter.

gastrointestinal tract or exhaled. Current radiological inhalation dose conversion factors (e.g., those presented in Eckerman et al., 1988) are based on the assumption that the particle diameter size follows a lognormal distribution with an activity median aerodynamic diameter of 1 :m. However, as discussed above, such a distribution may not be the case for resuspended material where the median may be skewed to larger particle sizes. On the other hand, not enough information is available to provide definitive resuspension rate estimates according to particle size. Thus, the current resuspension rate model and assigned distribution are particle size independent; the assigned distribution incorporates data from all studies with and without particle size determination. 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. Assuming a conservation of mass, the total change in the amount of airborne particulate material in a room (the left-side of Equation 3.1) is equal to an increase due to the amount resuspended, a decrease due to depositing material, and a

Table 3.2. Indoor Resuspension Rates

Resuspension Rate (1/s)[a]							
Minimum	**Maximum**	**Resuspension Factor (m^{-1})**	**Air Exchange Rate (1/h)**	**Room Height (m)**	**Conditions**	**Reference**	**Comments**
7.7×10^{-7}	1.1×10^{-6}	1.2×10^{-4}	9.0	2.59	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}	0.0	2.44	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}	10	3.00	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}	10.9	3.15	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}	20	3.00	Alpha, no work performed	Kvostov and Kostyakov (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		

Table 3.2. Indoor Resuspension Rates (Continued)

Resuspension Rate (1/s)[a]							
Minimum	**Maximum**	**Resuspension Factor (m^{-1})**	**Air Exchange Rate (1/h)**	**Room Height (m)**	**Conditions**	**Reference**	**Comments**
2.4×10^{-9}	2.4×10^{-6}	9.0×10^{-4}	0	1.22	$Ba^{35}SO_4$	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}	9.0	2.59	Personal air samplers	Tagg (1966)	100 steps/min, contaminated floor; 100 steps/min, contaminated clothing.
3.8×10^{-7}	5.4×10^{-7}	5.9×10^{-5}			Area air samplers		
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		
2.8×10^{-10}	NA[b]	1.4×10^{-6}	0.3	2.4	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 3.5 and minimum and maximum values for the deposition velocity from Section 3.3.

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

decrease due to ventilation (terms 1 through 3, respectively, on the right-side of Equation 3.1).

$$V\frac{dC_A}{dt} = C_s \cdot A \cdot \lambda_r - C_A \cdot A \cdot v_{dep} - C_A \cdot V \cdot \lambda_a \quad (3.1)$$

where

C_A = the contaminant air concentration,

C_S = the contaminant surface concentration,

λ_r = the resuspension rate,

V = A ⋅ H, the room volume,

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

H = room height,

v_{dep} = the deposition velocity, and

$?_a$ = air exchange rate, the number of air changes per unit time.

Dividing both sides of the equation by the room volume and assuming equilibrium conditions (dC_A/dt = 0), we obtain:

$$C_S\frac{\lambda_r}{H} - C_A\frac{v_{dep}}{H} - C_A \cdot \lambda_a = 0. \quad (3.2)$$

Separation of the surface and air terms gives

$$C_S\frac{\lambda_r}{H} = C_A\left(\frac{v_{dep}}{H} + \lambda_a\right). \quad (3.3)$$

The resuspension factor is the ratio of the air to surface concentration, as shown in Equation 3.4, from which the relation between the resuspension rate and the resuspension factor is derived (see Equation 3.5).

$$R_f = \frac{C_A}{C_S} = \frac{\lambda_r}{v_{dep} + \lambda_a \cdot H} \quad (3.4)$$

$$\lambda_r = R_f\left(v_{dep} + \lambda_a \cdot H\right) \quad (3.5)$$

Table 3.2 gives some indoor resuspension rates and the corresponding resuspension factors as determined using Equation 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 3.3) were used to provide a resuspension rate range for each resuspension factor. Data for the resuspension rates was provided in the case of Thatcher and Layton (1995), from which corresponding resuspension factors were derived using deposition velocities supplied in that reference. Healy (1971) has previously studied the correlation of the resuspension factor with the resuspension rate. Sansone (1987) and Beyeler et al. (1999) have reviewed the earlier work in the context of resuspension factors rather than rates. Table 3.3 summarizes previous work in the area of resuspension factors not addressed in Table 3.2.

A number of factors (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 using the relationship in Equation 3.1. The magnitude of the resuspension factor, however, can be roughly correlated with the conditions under which they were obtained and can be compared with resuspension factors that have corresponding resuspension rates, as shown in Table 3.2.

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). Thus, because of the lower air concentrations

Table 3.3. Resuspension Factors from Previous Studies

Resuspension Factor (m^{-1})	Conditions	Reference	Comments
 1.8×10^{-6} 4.3×10^{-5}	I-131 Active work in open space Active work in confined, unventilated space	Chamberlain and Stanbury (1951)	I-131 labeled brick and plaster dust (bulk of dust < 1 μm), as reported in Sansone (1987).
$2.5 – 19 \times 10^{-5}$	UF_4 powder	Bailey and Rohr (1953)	Normal operations at a uranium processing plant.
1×10^{-9} – 4.2×10^{-6} 7×10^{-8} – 4×10^{-5}	Uranium, total surface activity using ratemeter, larger if removable activity values used. Ra, 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. Estimated from surface and airborne activity at 10 radium plants
4×10^{-5}	"Dusty operations"	Barnes (1959)	As reported in NUREG-1640.
 5×10^{-4} 3×10^{-5}	U compounds 0.5-h samples 8-h samples	Becher (1959)	As reported in Sansone (1987). Wipes used to measure surface activity
 $0.2 – 5.9 \times 10^{-5}$ $0.5 – 14 \times 10^{-4}$	U Ore sampling plant Uranium reduction plant	Utnage (1959)	As reported in Sansone (1987).
 1.5×10^{-2} $5 – 12 \times 10^{-3}$ 7.9×10^{-3} 9.3×10^{-3} 2×10^{-2}	Be and compounds Loading/unloading Be blocks Cleaning Be blocks Be cyclotron target preparation Be compound synthesis Warehouse inventory	Hyatt et al. (1959)	Resuspension factor as estimated by Sansone (1987). Surface contamination measured by wipe; maximum values for wipe and air concentration used.
 $0.4 – 26 \times 10^{-5}$ $0.8 – 14 \times 10^{-4}$	U compounds 8-h air samples 10-min air samples	Schulz and Becher (1963)	As estimated by Sansone (1987), measurements from operating UF_6 manufacturing plant, surface contamination measured by wipes.
 1.0×10^{-4} 1.3×10^{-4} 1.45×10^{-4} 1.0×10^{-4} 1.35×10^{-3} 9.7×10^{-3}	U Undisturbed Fans on Fans on with movement Pu Undisturbed Fans on Fans on with movement	Glauberman et al. (1967)	As reported in Sansone(1987), operating uranium processing plant, abandoned precious metals. Recovery plant (Pu contamination), surface contamination measured with smears.

 4.2×10^{-4} 1.0×10^{-2}	Be Two men sweeping vigorously Sweeping after vacuuming	 Mitchell and Eutsler (1967)	 As reported in Sansone(1987). Unventilated storeroom with wood floor, smears used for surface contamination.
 #1.7×10^{-7} $4.7 – 7.5 \times 10^{-6}$ #0.7×10^{-7} $1.0 – 1.7 \times 10^{-5}$	UO_2 In ethanol, undisturbed In ethanol, 60 steps/min Powder, undisturbed Powder, 60 steps/min	 Cortissone et al. (1968)	 As reported in Sansone (1987).

Table 3.3. Resuspension Factors from Previous Studies (Continued)			
Resuspension Factor (m^{-1})	**Conditions**	**Reference**	**Comments**
$1.2 – 5.3 \times 10^{-3}$ $2.0 – 4.2 \times 10^{-3}$	Chrysotile Contaminated lab coat handling contaminated materials	Carter (1970)	As reported in Sansone (1987), surface contamination measured by vacuuming.
1.2×10^{-4} 3.3×10^{-4}	Sr applied in solution Co 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.
  $0.2 – 13 \times 10^{-6}$ $0.01 – 1.5 \times 10^{-6}$ $0.3 – 10 \times 10^{-6}$ $0.08 – 1.5 \times 10^{-6}$	Be (aqueous suspension applied) Fan on Fan off Ammonium fluoroberyllate (aqueous solution applied) Fan on Fan off	Kovygin (1974)	As reported in Sansone (1987). From polyvinyl chloride surface, 1.8 m/s air flow with fan on.
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} 7.79×10^{-6} 8.97×10^{-7}	U; surface contamination measured using wipes, three 1-year averages	Spangler (1998)	U storage area at operating uranium fuel fabrication plant.
1.7×10^{-7} 4.2×10^{-8}	Primarily Co-60 and Cs-137 during decommissioning shutdown mode	Nardi (1999)	No forced air ventilation, measurements at a “pump repair” facility.

measured, studies conducted with no physical activity may be nonrepresentative and might underestimate the value of the resuspension factor in a light industrial environment. Other studies have also indicated that a major source of larger particles (> 1.0 µm) in indoor air is from resuspension (Vette et al., 2001).

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 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.

As discussed in Section 2, 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 deposited material. Thus, the input distribution in RESRAD-BUILD for the resuspension rate covers a wider range of equivalent values than that for input for the resuspension factor in DandD. In the latter, values should be limited to “fixed” contamination in order to avoid violating the contamination mass balance and overestimating 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 3.2 was chosen, 2.5×10^{-11} s^{-1}. Similarly, the largest value in Table 3.2, 1.3×10^{-5} s^{-1}, was chosen as the maximum value for the distribution. Figure 3.1 shows the probability density function selected for the indoor resuspension rate.

3.2 Air Exchange Rate for Building and Room

Description: 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.

Unit: 1/h

Probabilistic Input:

Distribution: Truncated lognormal-n

Defining Values for Distribution:

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

Discussion: Air exchange involves three processes: (1) infiltration — air leakage through random cracks, interstices, and other unintentional openings in the building; (2) natural ventilation — airflow through open windows, doors, and other designed openings in the building; and (3) forced, or mechanical, ventilation — 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 range of air exchange rates, depending on environmental conditions at a particular time (e.g., seasonal/diurnal ambient wind speed and temperature); other factors include building type, construction, 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.

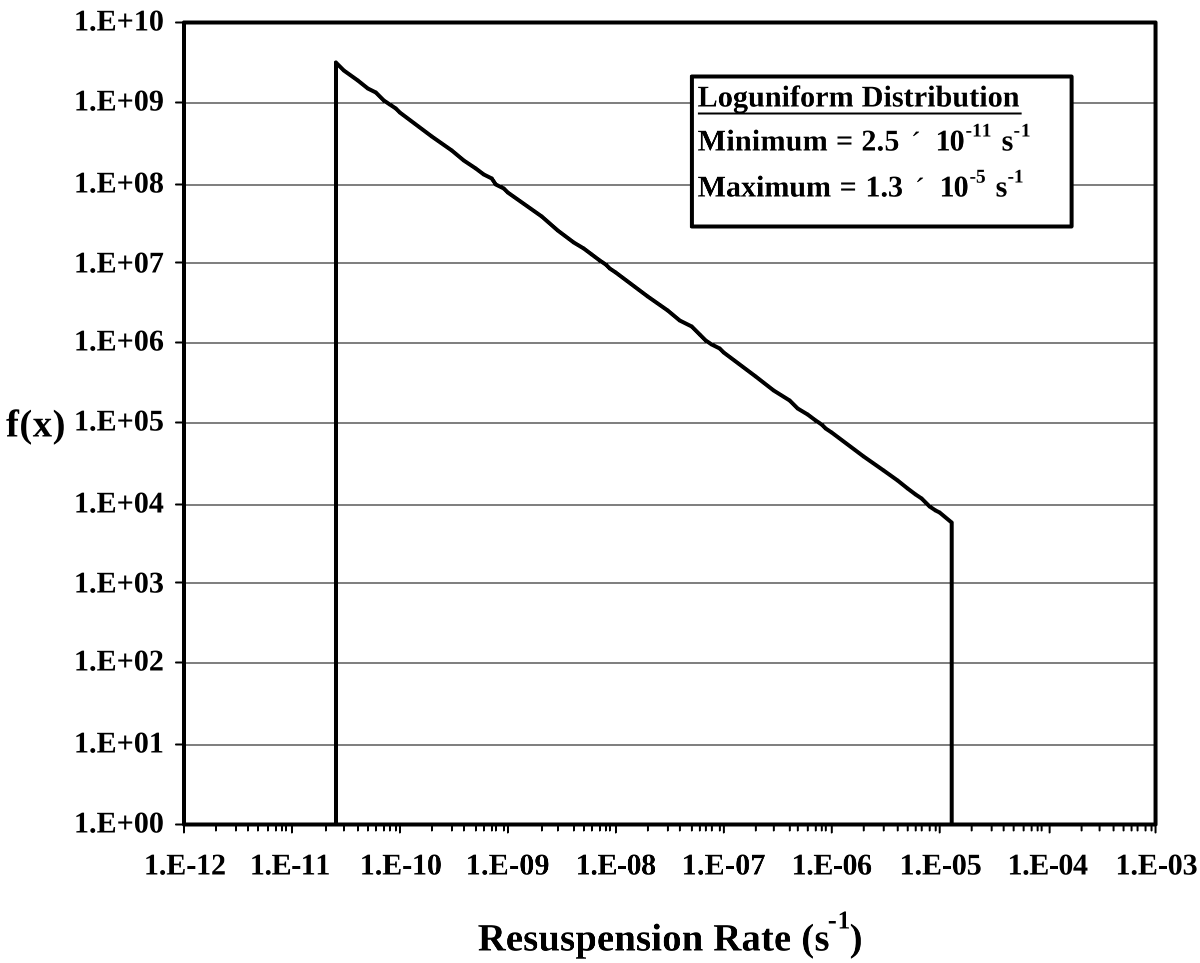


Figure 3.1. Indoor Resuspension Rate Probability Density Function

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 3.4 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 of the homes. They concluded that (1) exchange rates are higher in the Southwest than in the Northeast and Northwest; (2) summer ventilation rates are much higher than winter and fall rates; and (3) 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 and 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: (1) the use of data for 2,844 households; (2) a four-region breakdown based on heating degree days; (3) estimation of lognormal distributions as well as provision of empirical (frequency) distributions; and (4) 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 5,500–6,999 heating degree days, the warmer region (Region 3) as having 2,500–5,499 heating degree days, and the warmest region (Region 4) as having fewer than 2,500 heating degree days. The months of December, January, and February were defined

Table 3.4. Residential Air Exchange Rates (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	0.36	0.71	0.62	0.25	Pre-retrofit in one house:	Berk et al. (1981)
	0.18	0.56	0.33	0.14	*n* = 17 measurements with fan on	
					n = 11 measurements with fan off	
	0.22	0.69	0.49	0.11	Post-retrofit in one house:	
	0.10	0.33	0.20	0.08	*n* = 16 measurements with fan on *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	0.22	0.50	0.35	0.08	n = 9 houses in upstate New York	Offermann et al. (1985)
	0.47	0.78	0.63	0.10	With mechanical ventilation off	
					With mechanical ventilation on	
Normal	0.40	0.98	0.27		n = 10 houses in Washington State	Lamb et al. (1985)
	0.23	1.00	0.30		Pre-weatherization retrofit	
					Post-weatherization retrofit	

Table 3.4. Residential Air Exchange Rates (h^{-1}) Distribution Characteristics (Continued)						
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	

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 sample sizes except in a few cases. The mean and standard deviations are listed in Table 3.4. 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 U.S. Environmental Protection Agency (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 3.4, the results of Murray and Burmaster (1995) are similar to those for Koontz and Rector (1995).

Air exchange rates from other representative residential studies are also summarized in Table 3.4. 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 0.25–0.75 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 (0.08–0.27 h^{-1}), which reflects 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 with a geometric mean of 0.8h^{-1} and a geometric standard deviation of 1.8 (with rates 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 3.5 lists results from some studies on commercial buildings. 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. The results are shown in Table 3.5. 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 by Pandian et al. (1993) and Murray and Burmaster (1995), that is, 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 3.5, 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.

Table 3.5 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. Number of buildings:	Turk et al. (1987)
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)

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 an 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

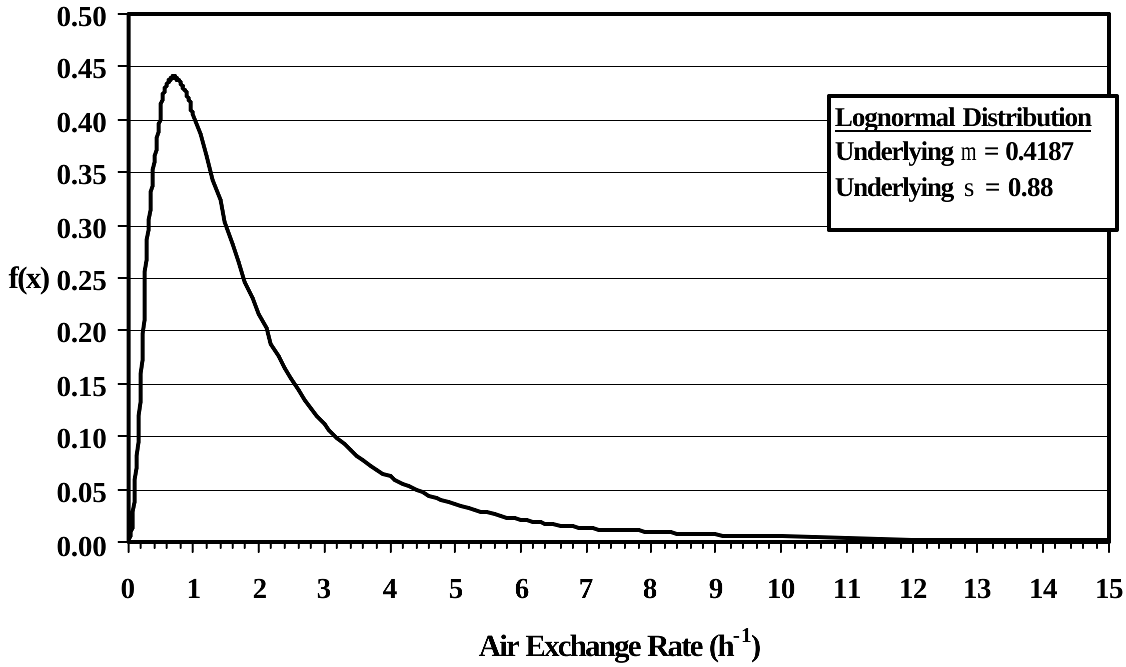


Figure 3.2. Building and Room Air Exchange Rate Probability Density Function

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 3.2 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.

3.3 Deposition Velocity (Indoor)

Description: This parameter represents the indoor deposition velocity of contaminant particles in the building and

Unit: Meters per second (m/s)

Probabilistic Input:

Distribution: Loguniform

Defining Values for Distribution:

Minimum: 2.7×10^{-6} Maximum: 2.7×10^{-3}

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

$$\lambda_d = \frac{v_d A}{V}, \qquad (3.6)$$

where

v_d = the deposition velocity,

A_d = the surface area available for deposition, and

V = the 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 3.3 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).

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 the 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 (thus 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). Using the means and standard deviations from Whitby and Sverdrup (1980), Figure 3.4 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 the building shell has been shown to be an insignificant barrier to particle sizes under 10 μm (Yu et al., 2000).

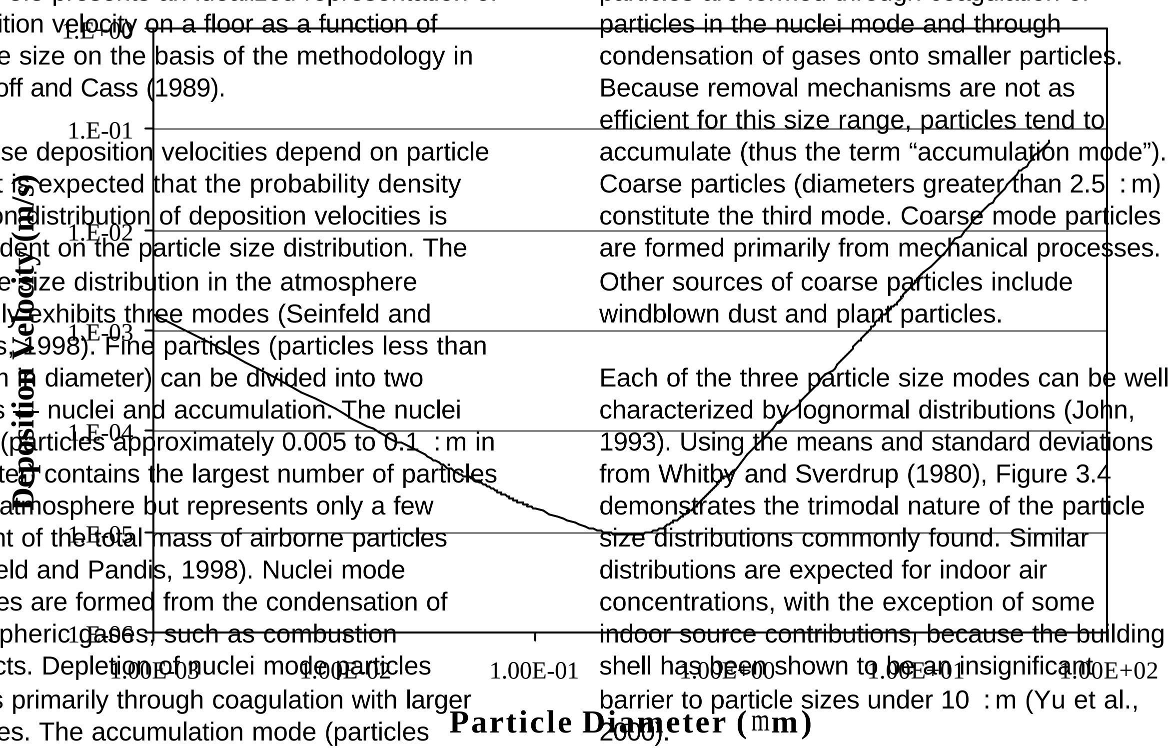


Figure 3.3. Idealized Representation of Indoor Particle Deposition Velocity

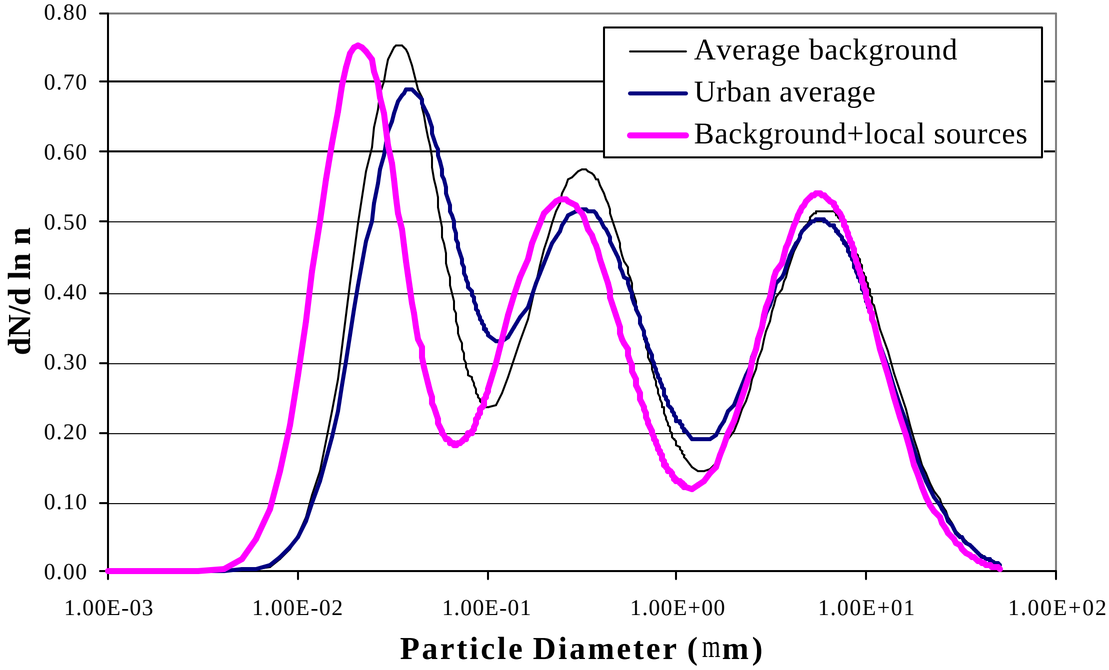


Figure 3.4 Trimodal Nature of Aerosol Particle Size Distribution

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 3.3 and 3.4, respectively) and taking into consideration the variability of each. Experimental estimates provide support for such an assumption, as shown in Tables 3.6 through 3.8. In addition, Vette et al. (2001) and Mosley et al. (2001) both observed a comparable U-shaped curve, as suggested by Figure 3.3, when plotting particle size against indoor deposition rate (decay rate, Eq. 3.6), 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), as converted to deposition velocity in Table 3.6, provide further supporting evidence. A similar trend for deposition velocity as a function of particle size, as suggested by Figure 3.3, 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 assigned, with minimum and maximum values of 2.7×10^{-6} m/s and 2.7×10^{-3} m/s, respectively, as found in Tables 3.6 through 3.8. This distribution is shown in Figure 3.5.

3.4 Source Erosion Rate, Volume Source

Description: 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.

Table 3.6. Estimated Indoor Deposition Velocities by Particle Size

Particle Size (: m)	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 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 using Eq. 3.6, assuming a residence with an 8-ft (2.438-m) ceiling height and all deposition to the floor. Area/volume then equals 1/2.438 1/m.	Wallace et al. (1997)
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 using Eq. 3.6, assuming a residence with an 8-ft (2.438-m) ceiling height and all deposition to the floor. Area/volume then equals 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 3.7. Estimated Deposition Velocities by Particle Size in Residences with and without Furniture

	Average Deposition Velocity (m/s)	
Particle Size (: m)	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 3.8. 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).

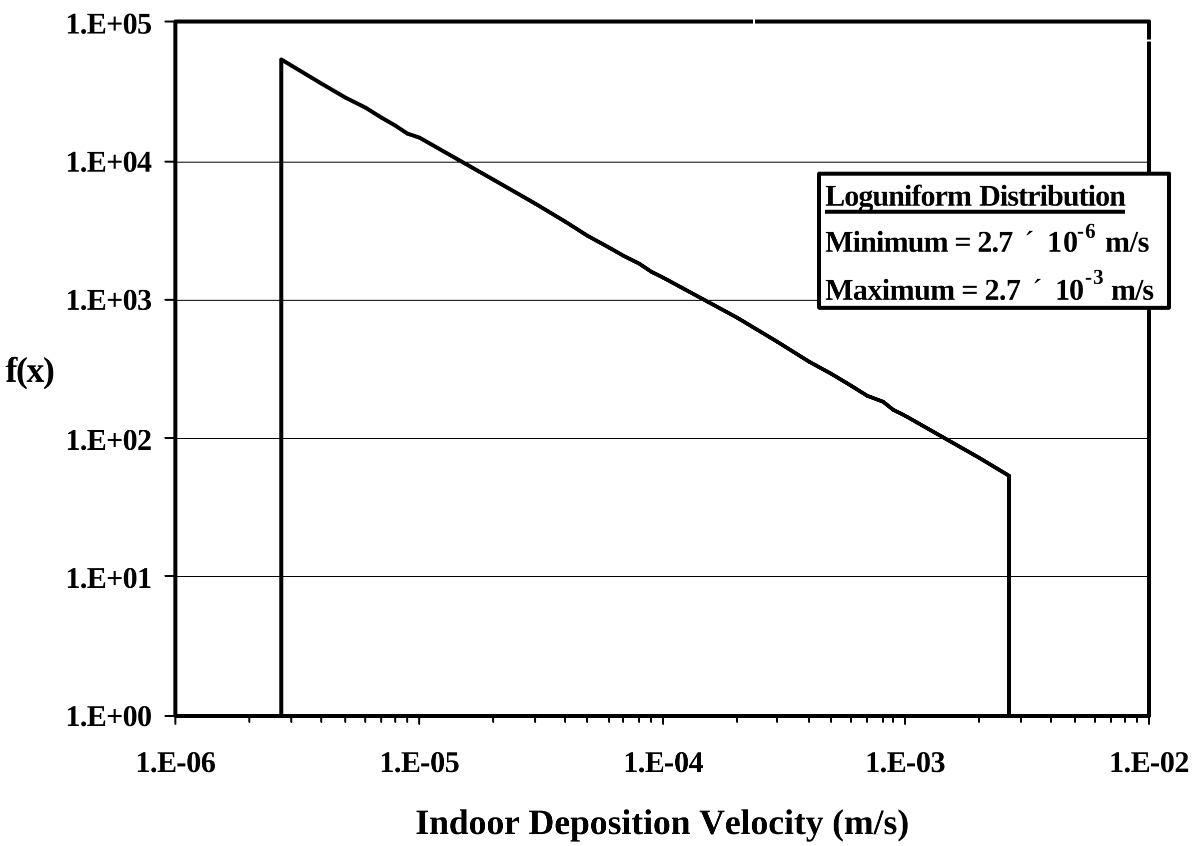


Figure 3.5 Indoor Deposition Velocity Probability Distribution

Unit: Centimeters per day (cm/d)

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum:	0.0
Maximum:	5.6×10^{-7}
Most likely:	0.0

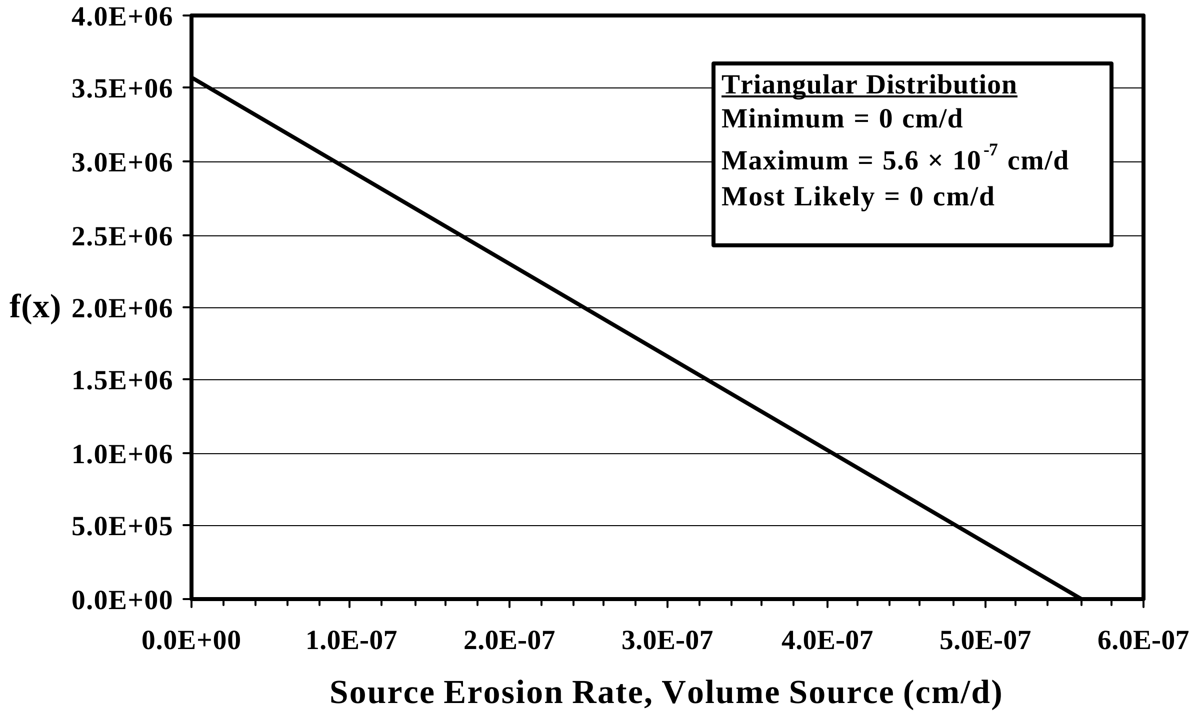
Discussion: The source erosion rate is highly dependent on the location of the contamination. In the building occupancy scenario, contamination on walls could remain indefinitely if located in little-used areas not subject to periodic washing or cleaning. Furthermore, such residual wall contamination could have been covered with paint or another type of sealant during prior remediation or general maintenance activities. In addition, little or no wear also can be expected for some floor areas for the same reasons. At the other extreme are contaminated floor areas subject to heavy foot 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 (see Yu et al., 2000); however, this contribution was not considered. The erosion rate of a concrete floor was estimated to maintain an average particulate air concentration of 100 :g/m^3 (Section 3.4) with a room air exchange rate of 1.52/h (Section 3.2). A floor area of 36 m^2 (Section A.1.3), a room height of 3.7 m (Section A.1.4, used to estimate the room volume), and a concrete density of 2.4 g/cm^3 (Section A.2.1) were used. The estimated erosion rate was 5.6×10^{-7} cm/d. Figure 3.6 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 the 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 that the NBS 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). The 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 other 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 3.6.

3.5 Removable Fraction

Description: The removable fraction is the fraction of a line or area source that can be removed.

Unit: Unitless

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum value:	0.0
Maximum value:	1.0
Most likely:	0.1

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 "time of source removal." 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 3.7 shows the distribution's probability density function.

For most radionuclides, the DOE *Radiological Control Manual* (DOE, 1994) allows a maximum removable concentration that is 20% of the maximum allowable total surface contamination for most radionuclides except for some

Figure 3.6 Source Erosion Rate Probability Density Function

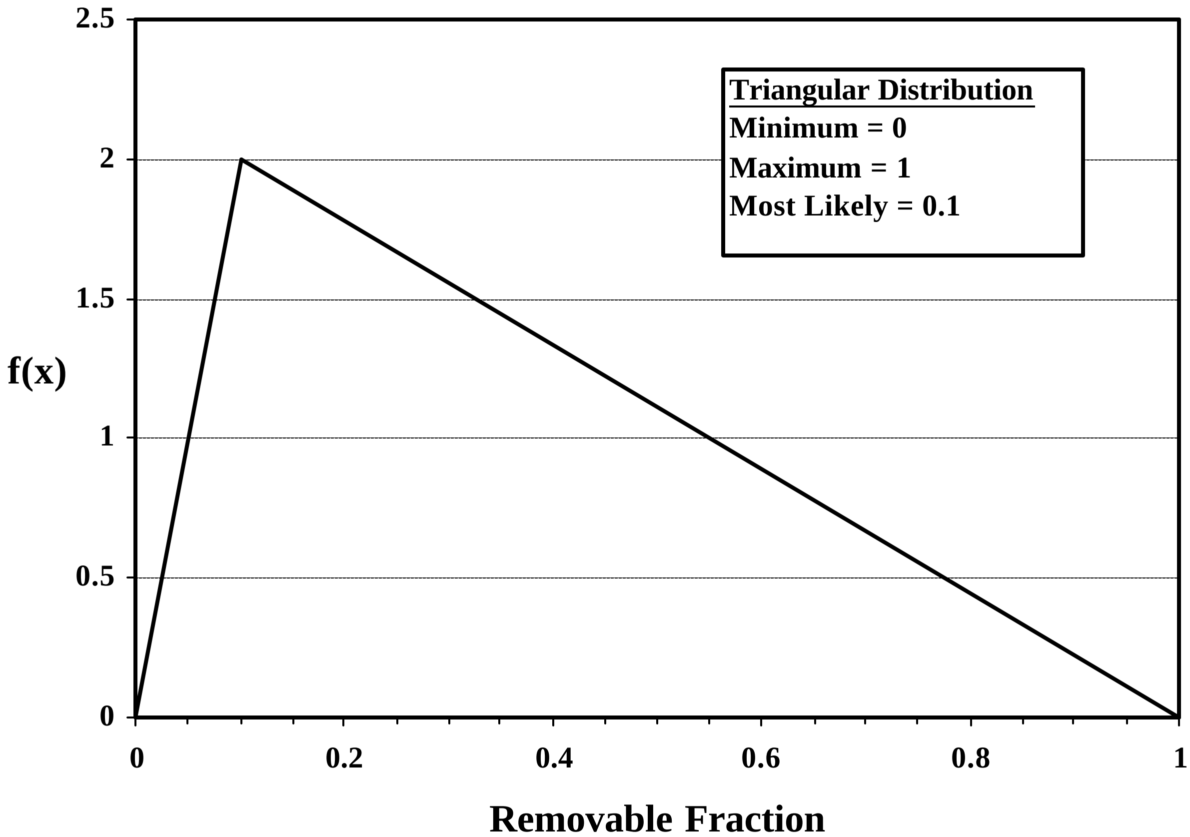


Figure 3.7 Removable Fraction Probability Distribution

transuranics and tritium (Table 2-2 in DOE, 1994). The maximum allowed removable transuranic or tritium contamination is 4% or 100%, respectively, of the maximum allowable surface contamination. However, conditions may exist under these restrictions for unrestricted use where for all radionuclides, the removable surface contamination constitutes 20% of the surface contamination. For the NRC, removable concentrations of 10% were used to estimate radionuclide screening values (NRC, 2000), and like the DOE regulations, the removable fraction can be higher if overall surface concentrations are lower. Also,

NRC (2000) sets the default removable fraction value to 0.1 for the DandD building occupancy scenario. Thus, a triangular distribution, as shown in Figure 3.7, 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 vs. liquid and chemical reactivity]), and the removal mechanism (such as washing or foot traffic).

Smear (wipe) 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 transferrable 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 nondestructive means such as casual contact, wiping, brushing, or washing” (DOE, 1994). 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 3.9 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

Table 3.9 Influence of Surface and Contaminant Types on Smear Tests

Contamination Removed (%)	Contamination	Surface	Comments	Reference
1 – 3	Low level from normal use	Granolithic concrete floor		Brunskill (1967)
50			Water wash of floor	

0.1 – 0.2	Plutonium nitrate	Paper	Plutonium nitrate or oxide in solution was applied to the floor and allowed to dry for 16 hours	Jones and Pond (1967)
6		Waxed and polished linoleum		
20 – 30		Polyvinyl chloride		
10 – 20	PuO_2	Polyvinyl chloride		
20 – 30		Unwaxed linoleum		
50 – 60		Waxed and polished linoleum		

measurement tests in the past have included tape and modified air sensor tests. Table 3.10 presents some results comparing these methods with smear tests on different surfaces.

In assigning a removable fraction, a number of considerations 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 3.10). Thus, the removable fraction is highly dependent on the decommissioning activities used to bring the building surfaces into compliance and future 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 tenth 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.

3.6 Time for Source Removal or Source Lifetime

Description: This parameter represents the time over which surface contamination is removed. The parameter is used in conjunction with the "removable fraction of source material" parameter (Section 3.5) and the "air release fraction" (Section A.2.4) to obtain the emission rate of radionuclides into the indoor air.

Unit: days (d)

Probabilistic Input (allowed only for surface contamination):

Table 3.10 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 :m in diameter at a concentration of about 1 × 10^6 particles per square centimeter.

Distribution: Triangular

Defining Values for Distribution:

Minimum: 1,000
Maximum: 100,000
Most likely: 10,000 (27.4 yr)

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, the time for source removal or source lifetime parameter, 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 the release of solid powders piled up on a heterogeneous surface (e.g., concrete, stainless steel, or glass) under the condition of normal building ventilation flow (ANS, 1998). That rate is equivalent to a lifetime of approximately 1,000 days (or 2.74 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.

The ANS also suggests 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 3.8.

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 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 Eq. 2.2)

(3.7)

where

$$C^n = \frac{f_R f Q_s^n}{24\, T_R\, Q_0}, \quad (3.8)$$

$$Q_s^n = C_{surf} A_s, \quad (3.9)$$

$$Q_0 = \lambda_b^a V,$$

$$V = AH, \quad (3.10)$$

λ_b^a = the 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,

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

When the whole floor is contaminated, the air concentration reduces to

$$C^n = \frac{f_R f C_{surf}}{24 T_R\, \lambda_b^a H}. \quad (3.11)$$

The resuspension factor, R_F, under these assumption can be given as

$$R_F = \frac{f_R f}{24 T_R\, \lambda_b^a H}. \quad (3.12)$$

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 3.5) and an air release fraction of 0.07 (Section A.2.4), the resuspension factor can be estimated from the source lifetime. A floor area of 36 m^2 (Section A.1.3), a room height of 3.7 m (Section A.1.4), and a room air exchange rate of 1.52 h^{-1} (Section 3.2) were used. In this case, the source lifetime of 10,000 days is equivalent to a resuspension factor of 5 x 10^{-9}/m.

Table 3.11 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. Assuming an airborne fraction of 1, an air exchange rate of 0.5 h^{-1}, and a room height of 2.3 m, the source lifetime (in years) can be related to resuspension factor, as shown in Table 3.12.

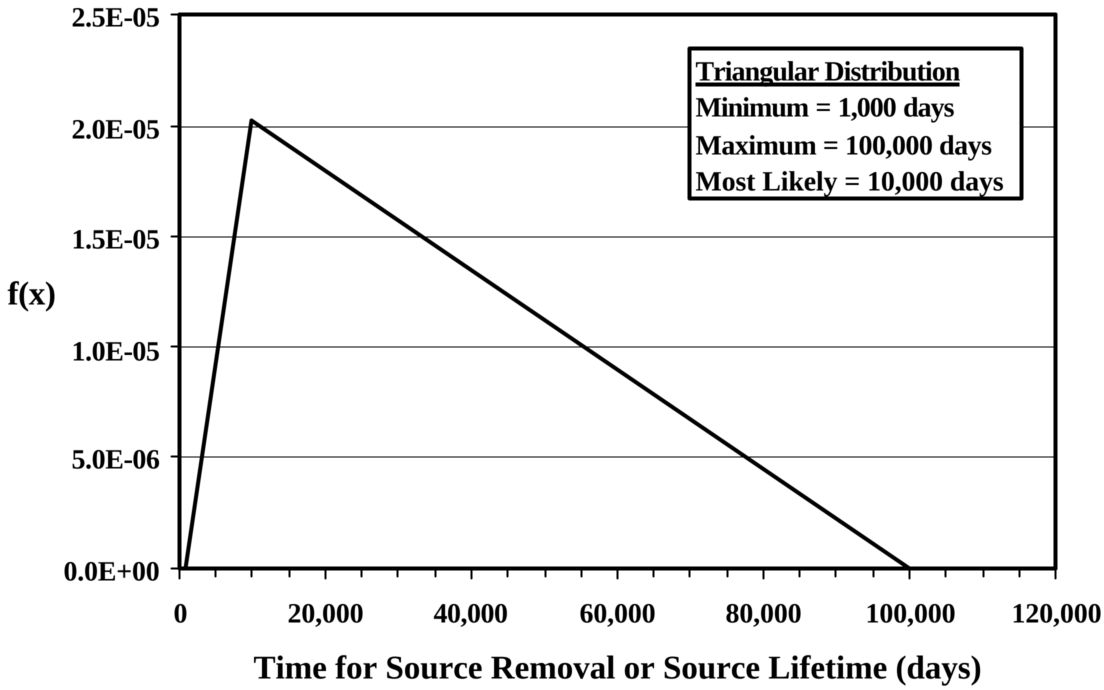


Figure 3.8. Time for Source Removal or Source Lifetime Probability Density Function

TABLE 3.11. 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	2.0	2.5
2.5	8.3E+04	3.3E+04	2.1E+04	1.7E+04	1.1E+04	8.3E+03	6.7E+03
3.0	6.9E+04	2.8E+04	1.7E+04	1.4E+04	9.3E+03	6.9E+03	5.6E+03
6.0	3.5E+04	1.4E+04	8.7E+03	6.9E+03	4.6E+03	3.5E+03	2.8E+03
10.0	2.1E+04	8.3E+03	5.2E+03	4.2E+03	2.8E+03	2.1E+03	1.7E+03

TABLE 3.12. Source Lifetime (yr) and Resuspension Factor for Different Removable Fractions 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

4 DEVELOPMENT OF A RESRAD-BUILD BUILDING OCCUPANCY SCENARIO DATA TEMPLATE FILE

The building occupancy scenario, as described in NUREG/CR-5512 (Kennedy and Strenge,1992) and NUREG-1727 (NRC, 2000), accounts for exposure to both fixed and removable residual radioactivity on the walls, floor, and ceiling of a decommissioned facility. It assumes that after decommissioning, the building will be used for commercial or light industrial activities (e.g., as an office building or warehouse) and that the people working in the facility may be exposed to residual contamination. The exposure pathways included in the building occupancy scenario are external exposure to penetrating radiation, inhalation of resuspended surface contamination, and inadvertent ingestion of surface contamination.

Both RESRAD-BUILD (Yu et al., 1994) and DandD (McFadden et al., 2001) can be used to estimate the dose to a worker (receptor) in the building for the building occupancy scenario. The application of the two models to the building occupancy scenario was discussed in Section 2. A methodology was developed to help ease the transition from conducting a screening analysis with the DandD code to performing a site-specific analysis with the RESRAD-BUILD code for simulated light industrial use of the decontaminated building, as described in NUREG/CR-5512 and NUREG-1727. The methodology involves utilizing a data template file developed for use with the RESRAD-BUILD code in evaluating potential exposure for the building occupancy scenario in deterministic and probabilistic analyses.

Deterministic analysis involves use of single values for input parameters to calculate a single dose value. In probabilistic analysis, a probability distribution is used to describe the uncertainty in each input parameter, resulting in a dose distribution that reflects the uncertainty in the input parameters.

The methodology used to select the deterministic parameter values for the data template file for use in the RESRAD-BUILD building occupancy scenario is discussed below. The basic concept involved is to select a single representative value for a specific parameter that, when used in a deterministic analysis, will result in a single dose estimate that is close to the value of the mean dose estimate that would result from a probabilistic analysis. Section 4.1 discusses the methodology. Section 4.2 discusses the development of the data template file for the RESRAD-BUILD building occupancy scenario.

4.1 Methodology for Developing a RESRAD-BUILD Building Occupancy Scenario Data Template File

The main purpose of developing the representative data template file to be used in deterministic and probabilistic RESRAD-BUILD analyses is to compile the input parameter values needed to simulate light industrial use of the decontaminated building as described in NUREG/CR-5512 (Vol. 1) and NUREG-1727. Therefore, if the value of a parameter was directly available from the scenario description or the derived value of the parameter from NUREG/CR-5512 (Vols. 1–3) was available, that value was used for the data template file. For a probabilistic run, if the value of a parameter was not available from the scenario description or NUREG/CR-5512 (Vols. 1–3), but the probability distribution for that parameter was available, that distribution was used. For the deterministic run, if the value of the parameter was not directly available from the scenario description or NUREG/CR-5512 (Vols. 1–3) but the probability distribution was available for the parameter, then the parameter value for the data template file was derived from the parameter distribution. For the remaining parameters (i.e., those for which neither value nor distribution was available from the scenario description), the current RESRAD-BUILD default values were used. The building occupancy scenario assumes the presence of fixed and removable residual radioactivity on the surfaces of walls, floor, and ceiling of a decommissioned facility. Therefore, the data template file assumes surface sources of uniform contamination on all six surfaces. On the basis of NUREG/CR-5512, Volume 1, the room size is fixed at 64 m^2 in area and 3 m in height. The hypothetical receptor is assumed to be at the center of the floor at a height of 1 m.

The principal assumptions and criteria applied in developing the RESRAD-BUILD data template file for a building occupancy scenario representative of light industrial use are itemized below.

Principal Assumptions:

1. Fixed room area (8 m x 8 m) of 64 m^2 and 3 m height. [These values are consistent with the NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992).]

2. Uniform surface contamination on all six surfaces (floor, ceiling, and four walls). The critical group receptor occupies a room with contaminated floor, ceiling, and walls for light industrial use activity.

3. The receptor is at the center of the floor at a height of 1 m.

Criteria Used in Selecting Parameters Values:

1. If the parameter is directly available from the NUREG/CR-5512 building occupancy scenario description, that value is used (e.g., exposure duration), or if the derived value of the parameter from NUREG/CR-5512 (Vols. 1–3) is available, that value is used (e.g., time spent inside the building, receptor inhalation rate, direct ingestion rate, removable fraction, etc.).

2. If a probability distribution has been developed for the parameter (e.g., the air exchange rate, the air release fraction, time for the source removal or the source lifetime), use the parameter distribution if performing a probabilistic analysis or, for a deterministic analysis, use either the mean, median, or most likely value (in case of triangular distribution only) from the parameter distribution that gives the most conservative dose.

3. If the value is not available from NUREG/CR-5512 and a distribution has not been developed for the parameter, use the current RESRAD-BUILD default value (e.g., number of evaluation times, time, and number of receptors).

4.2 Parameter Values Selected for the Data Template File

For a single source-receptor geometry, 51 parameters are used in the RESRAD-BUILD code to describe the exposure pathways and the associated exposure conditions. Distributions have been developed for 22 of these parameters that have been identified as the most sensitive parameters for the building occupancy scenario (NUREG/CR-6697 [Yu et al., 2000]). Eight of these 22 parameters are applicable to volume sources only and, thus, are not required for the data template file, which deals only with surface sources. These eight parameters are source density, humidity, source erosion rate, source porosity, source thickness, volumetric water content, water fraction available for evaporation, and wet + dry zone thickness. Values for seven parameters can be derived from the scenario description or are available from NUREG/CR-5512 (Vols. 1–3) and thus are considered “fixed.”

These seven fixed parameters are removable fraction, direct ingestion rate, indoor fraction, receptor inhalation rate, room area, room height, and shielding thickness. The shielding density distribution is not required because shielding thickness is considered to be zero in the calculations. The mean, median, and most probable values for the remaining six parameters for which distributions were developed are listed in Table 4.1. These six parameters are deposition velocity, resuspension rate, building air exchange rate, receptor indirect ingestion rate, air release fraction, and the time for source removal (or source life-time).

Distributions were not developed for the remaining 29 RESRAD-BUILD parameters. Dose conversion factors for four parameters (external, inhalation, ingestion, and air submersion) are nuclide dependent. The values for dose conversion factors for these parameters are from federal guidance documents (FGR-11 and FGR-12 [Eckerman et al., 1998; Eckerman and Ryman, 1993]). The building occupancy scenario does not consider the radon inhalation pathway. Therefore, the radon release fraction is set at zero to suppress that pathway. The net flow and outdoor inflow

Table 4.1 Mean, Median, and Most Probable Values of Probabilistic Parameters in the RESRAD-BUILD Building Occupancy Scenario				
		Parameter Values[a]		
Parameter	**Distribution Type and Parameters**	**Mean**	**Median**	**Most Probable[b]**
Deposition velocity, m/s	Loguniform min: 2.7E-6 max: 2.7E-3	**3.9E-4**	8.55E-5	NA[c]
Resuspension rate, 1/s	Loguniform min: 2.5E-11 max: 1.3E-5	1.3E-6	**6.3E-8**	NA
Building air exchange rate, 1/h	Truncated Lognormal-n mean: 0.4187 SD: 0.88 lower: 0.001 upper: 0.999	2.239	**1.52**	0.7
Receptor indirect ingestion rate, m^2/h	Loguniform min: 2.8E-5 max: 2.9E-4	**1.12E-4**	9E-5	NA
Air release fraction	Triangular min: 1E-6 mode: 0.07 max: 1	**0.357**	0.318	0.07
Time for source removal or source life time, d	Triangular min: 1,000 mode: 10,000 max:100,000	37,000	33,255	**10,000**

[a] Parameter values selected for the data template file are in bold type.

[b] This is the value with the highest probability on the distribution curve. For triangular distribution, most probable value is the most likely (mode) value. The sampling in loguniform distribution has high probability for low values.

[c] NA = not applicable.

parameters are not required because only one room is assumed in the scenario. Ten of the other parameters are derived from the scenario description or are available from NUREG/CR-5512 (Vols. 1–3). These parameters are exposure duration, receptor time fraction, receptor room, receptor location, number of sources, source type, source room, source direction, source location, and source area. Eight parameters are applicable to volume sources only and, thus, are not required for the data template file. These eight parameters are number of regions in volume source, contaminated region volume source, source erosion rate, source porosity, radon effective diffusion coefficient, radon emanation coefficient, dry zone thickness, and humidity. Three more of the parameters — (1) the number of evaluation times, (2) time, and (3) number of receptors — are kept at their RESRAD-BUILD default values. Finally the radionuclide concentration is kept fixed at 1 dpm/100 cm^2.

The assumptions and criteria described in Section 4.1 were applied to create a data template file containing the parameter values for the deterministic and probabilistic analysis runs for the building occupancy scenario. For the six parameters for which developed distributions were utilized, this process involved selecting the appropriate value for the deterministic run. The air release fraction, receptor indirect ingestion rate, and deposition velocity were kept fixed at their mean values. The building air exchange rate and resuspension rate were fixed at their median value. For the time for source removal, the most likely value yields the most conservative dose and, thus, was used for the template file for deterministic analysis. Table 4.2 lists all deterministic and probabilistic parameter values. The remarks column in Table 4.2 provides information regarding how the values were obtained. Note that the table includes parameters for six sources and could be modified to accommodate as many sources as were present for a particular case.

Table 4.2. RESRAD-BUILD Building Occupancy Scenario Data Template File for Deterministic and Probabilistic Runs

Parameter	Units	Parameter Values/Distributions		Remarks
		Deterministic[a]	Probabilistic[b]	
External dose conversion factor	(mrem/yr)/(pCi/g)	Nuclide specific	Nuclide specific	Values are from FGR-12.
inhalation dose conversion factor	mrem/pCi	Nuclide specific	Nuclide specific	Values are from FGR-11.
Ingestion dose conversion factor	mrem/pCi	Nuclide specific	Nuclide specific	Values are from FGR-11.
Air submersion dose conversion factor	(mrem/yr)/(pCi/m^3)	Nuclide specific	Nuclide specific	Values are from FGR-12.
Exposure duration	d	365.25	365.25	To match the occupancy period of 365.25 days in NUREG/CR-5512 building occupancy scenario.
Indoor fraction	-[c]	0.267	0.267	To match the 97.4 d/y time in building in NUREG/CR-5512 building occupancy scenario. This is the time the average member of the screening group spends in the building (Table 5.15 in Beyeler et al., 1999)
Number of evaluation times	-	2	2	RESRAD-BUILD current default.
Time	yr	1	1	
Number of rooms	-	1	1	NUREG/CR-5512 building occupancy scenario assumes only one contaminated room.
Deposition velocity	m/s	3.9E-4	Loguniform min: 2.7E-6 max: 2.7E-3	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the mean value from the distribution. To suppress two pathways (1) ingestion of deposited material and (2) exposure from deposited material, which are not in NUREG/CR-5512 building occupancy scenario, the value for deposition velocity can be set at zero.
Resuspension rate	1/s	6.26E-8	Loguniform min: 2.5E-11 max: 1.3E-5	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the median value from the distribution.
Room height	m	3	3	NUREG/CR-5512, Volume 1.
Room area	m^2	64	64	NUREG/CR-5512, Volume 1.

Table 4.2. RESRAD-BUILD Building Occupancy Scenario Data Template File for Deterministic and Probabilistic Runs (Continued)

Parameter	Units	Parameter Values/Distributions		Remarks
		Deterministic[a]	Probabilistic[b]	
Air exchange rate for building and room	1/h	1.52	Truncated Lognormal-n mean: 0.4187 SD: 0.88 lower: 0.001 upper: 0.999	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the median value from the distribution.
Net flow	m^3/h	NR[d]	NR	Only one-room model is used.
Outdoor inflow	m^3/h	NR	NR	Outdoor inflow is calculated from room volume and air exchange rate.
Number of receptors	-	1	1	Dose is calculated for one receptor.
Receptor room	-	1	1	Only one-room model is used.
Receptor location	m	4,4,1	4,4,1	At 1-m height from the center of the contaminated floor surface.
Receptor time fraction	-	1	1	
Receptor inhalation rate	m^3/d	33.6	33.6	To match 1.4 m^3/h breathing rate in NUREG/CR-5512 building occupancy scenario. This is the breathing rate for the average member of the screening group (Table 5.15 in Beyeler et al., 1999).
Receptor indirect ingestion rate	m^2/h	1.12E-4	Loguniform min: 2.8E-5 max: 2.9E-4	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the mean value from the distribution.
Number of sources	-	6	6	Floor, ceiling, and 4 walls of the room are contaminated.
Source1 type	-	Area	Area	Only surface sources are considered in building occupancy scenario.
Source 1 room or primary room	-	1	1	Only one room is considered.
Source 1 direction	-	z	z	The direction perpendicular to the exposed area (floor).
Source 1 location	-	4,4,0	4,4,0	Source center location.
Source 1 length or area	m or m^2	64	64	Floor is contaminated.
Source 2 type	-	Area	Area	Only surface source is considered in building occupancy scenario.
Source 2 room or primary room	-	1	1	It is the primary room of the contaminated source.

Table 4.2. RESRAD-BUILD Building Occupancy Scenario Data Template File for Deterministic and Probabilistic Runs (Continued)				
Parameter	Units	Parameter Values/Distributions		Remarks
		Deterministic[a]	Probabilistic[b]	
Source 2 direction	-	z	z	The direction perpendicular to the exposed area (ceiling).
Source 2 location	-	4,4,3	4,4,3	Source center location.
Source 2 length or area	m or m^2	64	64	Ceiling is contaminated.
Source 3 type	-	Area	Area	Only surface source is considered in building occupancy scenario.
Source 3 room or primary room	-	1	1	It is the primary room of the contaminated source.
Source 3 direction	-	x	x	The direction perpendicular to the exposed area (wall).
Source 3 location	-	0,4,1.5	0,4,1.5	Source center location.
Source 3 length or area	m or m^2	24	24	Wall is contaminated.
Source 4 type	-	Area	Area	Only surface source is considered in building occupancy scenario.
Source 4 room or primary room	-	1	1	It is the primary room of the contaminated source.
Source 4 direction	-	x	x	The direction perpendicular to the exposed area (wall).
Source 4 location	-	8,4,1.5	8,4,1.5	Source center location.
Source 4 length or area	m or m^2	24	24	Wall is contaminated.
Source 5 type	-	Area	Area	Only surface source is considered in building occupancy scenario.
Source 5 room or primary room	-	1	1	It is the primary room of the contaminated source.
Source 5 direction	-	y	y	The direction perpendicular to the exposed area (wall).
Source 5 location	-	4,0,1.5	4,0,1.5	Source center location.
Source 5 length or area	m or m^2	24	24	Wall is contaminated.
Source 6 type	-	Area	Area	Only surface source is considered in building occupancy scenario.
Source 6 room or primary room	-	1	1	It is the primary room of the contaminated source.
Source 6 direction	-	y	y	The direction perpendicular to the exposed area (wall).
Source 6 location	-	4,8,1.5	4,8,1.5	Source center location.
Source 6 length or area	m or m^2	24	24	Wall is contaminated.
Air release fraction for all sources	-	0.357	Triangular min: 1E-6 mode: 0.07 max: 1	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the mean value from the distribution.

Table 4.2. RESRAD-BUILD Building Occupancy Scenario Data Template File for Deterministic and Probabilistic Runs (Continued)

Parameter	Units	Parameter Values/Distributions		Remarks
		Deterministic[a]	Probabilistic[b]	
Direct ingestion rate for all sources	g/h (volume) and 1/h(other)	4.91E-7	4.91E-7	Calculated from the default ingestion rate of 1.1E-4 m^2/h in NUREG/CR-5512 building occupancy scenario. (See relationship in Table 2.2.) The ingestion rate of 1.1 × 10-4 m^2/h represents the average member of the screening group (Beyeler et al., 1999).
Removable fraction	-	0.1	0.1	10% of the contamination is removable (NUREG/CR-5512 building occupancy scenario default). The default parameter value for the loose fraction for the building occupancy scenario is 0.1 (Table C7.1, NUREG-1727).
Time for source removal or source lifetime	d	10,000	Triangular min: 1,000 mode: 10,000 max: 100,000	Value for the deterministic run is determined from the methodology described in Section 4.1 and is the most likely value from the distribution.
Radon release fraction	-	0	0	Radon inhalation pathway is suppressed.
Radionuclide concentration	dpm/ m^2	100	100	For all six sources surface concentration equivalent to 1 dpm/100 cm^2
Number of regions in volume source	-	NR	NR	Only surface source is considered.
Contaminated region-volume source	-	NR	NR	Only surface source is considered.
Source thickness, volume source	cm	NR	NR	Only surface source is considered.
Source density, volume source	g/cm^3	NR	NR	Only surface source is considered.
Source erosion rate, volume source	cm/d	NR	NR	Only surface source is considered.
Source porosity	-	NR	NR	Only surface source is considered.
Radon effective diffusion coefficient	m^2/s	NR	NR	Pathway is suppressed in the analysis.
Radon emanation coefficient	-	0	0	Pathway is suppressed in the analysis.
Shielding thickness	cm	0	0	No shielding is assumed between the source and receptor.
Shielding density	g/cm^3	NR	NR	No shielding is assumed between the source and receptor.
Shielding material	-	NR	NR	No shielding is assumed between the source and receptor.
Dry zone thickness	cm	NR	NR	The parameter is only required for the tritium volume

				source.

Table 4.2. RESRAD-BUILD Building Occupancy Scenario Data Template File for Deterministic and Probabilistic Runs (Continued)

Parameter	Units	Parameter Values/Distributions		Remarks
		Deterministic[a]	Probabilistic[b]	
Wet + dry zone thickness	cm	NR	NR	The parameter is only required for the tritium volume source.
Volumetric water content	-	NR	NR	The parameter is only required for the tritium volume source.
Water fraction available for evaporation	-	NR	NR	The parameter is only required for the tritium volume source.
Humidity	g/m^3	NR	NR	The parameter is only required for the tritium volume source.

[a] Parameter values used in the deterministic run.

[b] Parameter values or distributions used in the probabilistic run. Distributions were developed for many more parameters (such as indoor fraction, room height, room area, receptor inhalation rate, and shielding thickness), but scenario-specific constant values are used in the probabilistic analysis.

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

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

5 RESULTS AND DISCUSSION

To provide insight into the performance of the RESRAD-BUILD code when the template file is used, probabilistic dose distributions were calculated for six radionuclides. The radionuclides used in these examples were Co-60, Sr-90, Cs-137, Ra-226, U-238, and Pu-239. These radionuclides were selected because of their different dominant pathways in dose calculations. The doses are calculated for the first year after the release of the building. For this calculation, the mean of the peak dose and the peak of the mean dose will be the same. For most radionuclides, in the building occupancy scenario in RESRAD-BUILD, the maximum dose would occur from exposure in the first year. However, ingrowth of progency may, in some cases, cause the dose to increase with time (e.g., for Ra-226 and Ra-228). Table 5.1 lists the values obtained from the probabilistic dose analysis (with 200 sample values and 3 repetitions) at 5% cumulative distribution intervals for these selected radionuclides. For this analysis, the values and distributions from Table 4.2 were used.

The results listed in Table 5.1 show that for Co-60 and Cs-137, there was very little variability in dose values. For U-238 and Pu-239, on the other hand, a large variability in doses was observed. Table 5.1 also presents the mean value of the dose distribution and the minimum and maximum dose. The doses are presented at 5-percentile increments.

Table 5.2 presents the dose distribution results for the selected radionuclides for the three dominant pathways — (1) external exposure, (2) inhalation, and (3) ingestion. The results from two other active pathways (air submersion and external exposure from deposited material) are not provided because the doses from those pathways were at least an order of magnitude smaller than those for the pathways shown. This analysis provides information about the dominant pathway for each radionuclide and the dose variation in the individual pathways. Practically no difference was observed in the external exposure pathway at different dose percentiles; therefore, only the mean value from the distribution is given in the table. For the inhalation and ingestion pathways, results at 50%, 90%, 95%, and the mean are provided. For Co-60 and Cs-137, external exposure was the dominant pathway. Since the external exposure pathway did not depend significantly on any parameter for which a distribution was used, practically no variability in dose values was observed. For Sr-90, Ra-226, and Pu-239, ingestion was the dominant pathway; for U-238, inhalation was the dominant pathway. Because the inhalation pathway had the largest variability in this analysis, doses from exposure to U-238 showed the greatest variability (see Table 5.1) in the probabilistic dose analysis results.

Table 5.3 lists the deterministic results for the selected radionuclides on the basis of the data template file parameter values. This table also compares those results (proposed methodology) with the results obtained by using the mean and median value from the distributions. The mean dose obtained from the probabilistic analysis (Table 5.1) was also listed for comparison. As expected, it made no difference which value was used for Co-60 and Cs-137; however, for all other radionuclides, the proposed methodology provided the values closest to the mean value obtained from the probabilistic analysis.

Table 5.1. Results (mrem/yr per dpm/100 cm^2) of Probabilistic Dose Analysis for Selected Radionuclides Using the RESRAD-BUILD Data Template File						
Dose Percentile	**Co-60**	**Sr-90**	**Cs-137**	**Ra-226**	**U-238**	**Pu-239**
5	1.90×10^{-3}	1.89×10^{-4}	5.26×10^{-4}	3.09×10^{-3}	4.88×10^{-4}	4.64×10^{-3}
10	1.90×10^{-3}	1.89×10^{-4}	5.26×10^{-4}	3.10×10^{-3}	5.60×10^{-4}	4.90×10^{-3}
15	1.90×10^{-3}	1.90×10^{-4}	5.27×10^{-4}	3.10×10^{-3}	6.20×10^{-4}	5.12×10^{-3}
20	1.90×10^{-3}	1.91×10^{-4}	5.27×10^{-4}	3.11×10^{-3}	6.75×10^{-4}	5.33×10^{-3}
25	1.90×10^{-3}	1.92×10^{-4}	5.27×10^{-4}	3.11×10^{-3}	7.39×10^{-4}	5.62×10^{-3}
30	1.90×10^{-3}	1.93×10^{-4}	5.27×10^{-4}	3.12×10^{-3}	8.05×10^{-4}	5.85×10^{-3}
35	1.90×10^{-3}	1.93×10^{-4}	5.27×10^{-4}	3.12×10^{-3}	8.69×10^{-4}	6.08×10^{-3}
40	1.90×10^{-3}	1.94×10^{-4}	5.27×10^{-4}	3.13×10^{-3}	9.41×10^{-4}	6.35×10^{-3}
45	1.90×10^{-3}	1.95×10^{-4}	5.27×10^{-4}	3.14×10^{-3}	1.06×10^{-3}	6.83×10^{-3}
50	1.90×10^{-3}	1.97×10^{-4}	5.27×10^{-4}	3.15×10^{-3}	1.13×10^{-3}	7.12×10^{-3}
55	1.90×10^{-3}	1.98×10^{-4}	5.27×10^{-4}	3.16×10^{-3}	1.26×10^{-3}	7.58×10^{-3}
60	1.90×10^{-3}	2.00×10^{-4}	5.27×10^{-4}	3.18×10^{-3}	1.35×10^{-3}	7.97×10^{-3}
65	1.90×10^{-3}	2.01×10^{-4}	5.27×10^{-4}	3.19×10^{-3}	1.50×10^{-3}	8.44×10^{-3}
70	1.90×10^{-3}	2.04×10^{-4}	5.27×10^{-4}	3.21×10^{-3}	1.69×10^{-3}	9.10×10^{-3}
75	1.90×10^{-3}	2.07×10^{-4}	5.28×10^{-4}	3.25×10^{-3}	1.90×10^{-3}	9.98×10^{-3}
80	1.90×10^{-3}	2.10×10^{-4}	5.28×10^{-4}	3.30×10^{-3}	2.16×10^{-3}	1.10×10^{-2}
85	1.90×10^{-3}	2.16×10^{-4}	5.29×10^{-4}	3.34×10^{-3}	2.63×10^{-3}	1.30×10^{-2}
90	1.90×10^{-3}	2.29×10^{-4}	5.31×10^{-4}	3.45×10^{-3}	3.31×10^{-3}	1.51×10^{-2}
95	1.91×10^{-3}	2.58×10^{-4}	5.35×10^{-4}	3.69×10^{-3}	4.30×10^{-3}	1.94×10^{-2}
mean	1.9×10^{-3}	2.06×10^{-4}	5.29×10^{-4}	3.28×10^{-3}	1.65×10^{-3}	9.05×10^{-3}
min.	1.89×10^{-3}	1.87×10^{-4}	5.24×10^{-4}	3.08×10^{-3}	3.83×10^{-4}	4.26×10^{-3}
max.	1.94×10^{-3}	3.94×10^{-4}	6.10×10^{-4}	9.62×10^{-3}	2.47×10^{-2}	9.47×10^{-2}

Table 5.2. Pathway Doses (mrem/yr per dpm/100 cm^2) for Selected Radionuclides Using the RESRAD-BUILD Data Template File

	External[a]	Inhalation				Ingestion			
Radionuclides	**mean**	**50%**	**90%**	**95%**	**mean**	**50%**	**90%**	**95%**	**mean**
Co-60	1.87×10^{-3}	1.32×10^{-6}	4.74×10^{-6}	6.23×10^{-6}	2.04×10^{-6}	2.91×10^{-5}	2.96×10^{-5}	3.03×10^{-5}	2.92×10^{-5}
Sr-90	1.26×10^{-5}	8.27×10^{-6}	2.85×10^{-5}	5.02×10^{-5}	1.44×10^{-5}	1.74×10^{-4}	1.83×10^{-4}	1.96×10^{-4}	1.79×10^{-4}
Cs-137	4.70×10^{-4}	2.12×10^{-7}	7.23×10^{-7}	1.06×10^{-6}	3.39×10^{-7}	5.70×10^{-5}	5.97×10^{-5}	6.22×10^{-5}	5.83×10^{-5}
Ra-226	1.42×10^{-3}	5.98×10^{-5}	2.19×10^{-4}	2.94×10^{-4}	9.76×10^{-5}	1.66×10^{-3}	1.82×10^{-3}	2.06×10^{-3}	1.76×10^{-3}
U-238	2.60×10^{-5}	7.89×10^{-4}	2.88×10^{-3}	3.88×10^{-3}	1.29×10^{-3}	3.10×10^{-4}	3.41×10^{-4}	3.92×10^{-4}	3.31×10^{-4}
Pu-239	7.55×10^{-7}	2.87×10^{-3}	1.05×10^{-2}	1.41×10^{-2}	4.69×10^{-3}	4.08×10^{-3}	4.48×10^{-3}	5.15×10^{-3}	4.36×10^{-3}

[a] For the external exposure pathway, practically no variability in dose values was observed; therefore, only the results at mean value are provided.

Table 5.3. Comparison of Deterministic Dose (mrem/yr per dpm/100 cm^2) Calculated Using Data Template File, Mean, and Median Parameter Values with Mean Dose from Distribution

Radionuclide	Dose Results Based on Choosing Parameter Values for Deterministic Analysis[a]			Mean from Dose Distribution[b]
	Data Template File Value	Mean Value	Median Value	
Co-60	1.90×10^{-3}	1.90×10^{-3}	1.90×10^{-3}	1.90×10^{-3}
Sr-90	2.08×10^{-4}	1.91×10^{-4}	1.93×10^{-4}	2.05×10^{-4}
Cs-137	5.27×10^{-4}	5.27×10^{-4}	5.27×10^{-4}	5.29×10^{-4}
Ra-226	3.22×10^{-3}	3.11×10^{-3}	3.12×10^{-3}	3.28×10^{-3}
U-238	2.32×10^{-3}	7.07×10^{-4}	8.70×10^{-4}	1.65×10^{-3}
Pu-239	1.13×10^{-2}	5.43×10^{-3}	6.02×10^{-3}	9.05×10^{-3}

[a] Parameters and their mean and median values are shown in Table 4.1.

[b] Mean dose values are taken from Table 5.1.

6 SUMMARY

This report examines the use of the probabilistic RESRAD-BUILD 3.0 code to simulate the light industrial use of a decontaminated building as described in NUREG/CR-5512 and NUREG-1727. Because RESRAD-BUILD is designed to model more detailed, sophisticated scenarios than those that the DandD code was designed to model, more detailed input data are needed to satisfy the requirements for the RESRAD-BUILD analysis. Parameter distributions for RESRAD-BUILD were updated, and appropriate input data were selected and placed in a template file. An analysis was performed using the template file to provide insight into the potential results when using RESRAD-BUILD to simulate the building occupancy scenario. Exposure pathways not considered in this scenario were suppressed. Six different radionuclides were selected for use in the analysis to account for different dominant exposure pathways in the calculations.

RESRAD-BUILD and DandD both model external exposure from surface sources, inhalation of resuspended contamination, and inadvertent ingestion of surface contamination. However, more detailed models in the RESRAD-BUILD code allow it to consider more complex situations than the DandD code. As discussed in Section 2, DandD relies on a simple release model using the resuspension factor as the primary controlling release parameter. On the other hand, RESRAD-BUILD uses a different approach and considers many important factors, including the removable fraction, source lifetime, air release fraction, mixing and transport in air, and surface deposition and resuspension.

Previously available parameter distributions for input to RESRAD-BUILD were reviewed and updated with the most recent data in Section 3. Currently, 22 parameters, out of 51 input parameters for a single source-receptor geometry, have been assigned distributions because they have been identified as the most sensitive parameters for the building occupancy scenario. As discussed in Section 4, only six of these distributions were selected for use in the template file on the basis of applicability and site-specificity. Those parameters for which a distribution was used in the template file were the deposition velocity, resuspension rate, building air exchange rate, receptor indirect ingestion rate, air release fraction, and the time for source removal. Deterministic values for the other parameters were selected according to their treatment in NUREG/CR-5512. Several deterministic values used in the template file are site-specific, strongly affect the estimated dose, and should be modified to reflect actual site conditions when applied outside of this report. These parameters include time spent inside the building and room area and height.

Unit contaminant concentrations of six radionuclides (Co-60, Sr-90, Cs-137, Ra-226, U-238, and Pu-239) were used in separate RESRAD-BUILD probabilistic analyses using the data template file. Dose distributions for the two radionuclides that primarily pose an external radiation hazard (Co-60 and Cs-137) were relatively narrow, with the minimum and maximum values of the distribution for the total dose within a few percent of the mean value. For all radionuclides, the distribution of doses calculated for external exposure was similarly narrow. The largest variability was observed in the inhalation pathway, the dominant pathway for U-238. The ingestion pathway was the dominant exposure pathway for Sr-90, Ra-226, and Pu-239.

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APPENDIX A:

UNMODIFIED RESRAD-BUILD INPUT PARAMETER DISTRIBUTIONS

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UNMODIFIED RESRAD-BUILD INPUT PARAMETER DISTRIBUTIONS

A.1 BUILDING CHARACTERISTICS PARAMETER DISTRIBUTIONS

A.1.1 Shielding Density

Description: This parameter represents the effective density of shielding between a receptor and a radiation source.

Unit: Grams per cubic centimeter (g/cm^3)

Probabilistic Input (allowed only for concrete):

Distribution: Uniform

Defining Values for Distribution:

Minimum: 2.2 Maximum: 2.6

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 where 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 [6 × 4] shielding characteristics). RESRAD-BUILD accommodates eight types of shielding materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Table A.1 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 A.2 provides the concrete density from three different sources: *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. Figure A.1 shows the probability density function for the concrete shielding density.

Table A.1. 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] – = data not available.

Sources: Shleien (1992); Lide (1998).

A.1.2 Indoor Fraction

Description: The indoor fraction is the fraction of time an individual spends inside the contaminated building (RESRAD-BUILD).

Unit: Unitless

Probabilistic Input:

Distribution: User-defined, continuous with linear interpolation

Table A.2. Concrete Density from Various Sources

Aggregate	Concrete Density (g/cm^3) Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (siliceous) 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

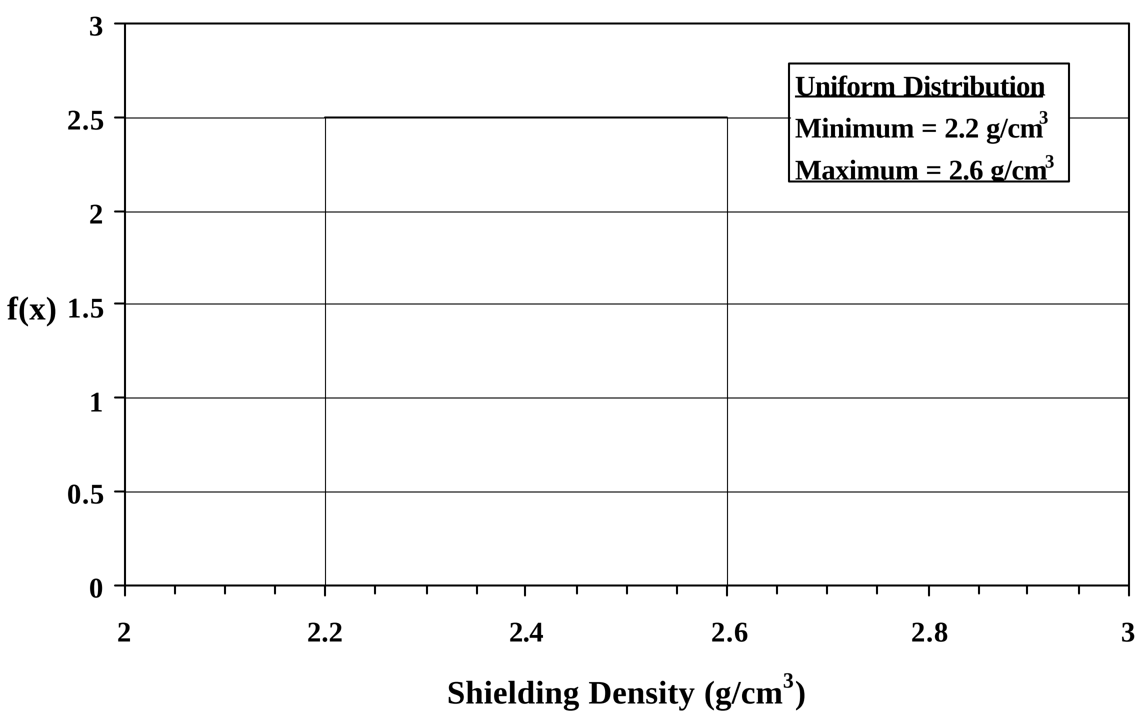

Figure A.1. Concrete Shielding Density Probability Density Function

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 light weight aggregate	–	0.64-higher	–
Nailing	–	0.65-1.6	–
Foam	–	–	0.3-1.75

[a] – = data not available.

Defining Values for Distribution: See Table A.3 for the input values.

Discussion: In RESRAD-BUILD, 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.

With the exposure duration given in units of days in RESRAD-BUILD, the indoor fraction is represented by the fraction of the day an individual spends indoors at work in the case of occupational exposure. Beyeler et al. (1999) 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 A.4 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 A.5 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 the best representation for workers in the building occupancy scenario and is the default for RESRAD-BUILD. For perspective, the 50^{th} percentile value for this distribution, 0.365, corresponds to an 8.76-hour workday. The cumulative distribution function for the indoor fraction is shown in Figure A.2.

A.1.3 Room Area

Description: This parameter represents the floor area of a specific room in the building.

Unit: Square meters (m^2)

Table A.3. Cumulative Distribution Functions for the Indoor Fraction

Cumulative Probability	RESRAD-BUILD
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 A.4. Relative Frequency of Hours Worked by Persons Working 35 Hours or More per Week

Hours Worked per Week[a]	Relative Frequency[a]	Assuming a 5-Day Work Week	
		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. (1999).

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 3 Maximum: 900
Most likely: 36

Discussion: The room area is used to determine the mixing volume of each distinct air flow volume (room) and the equilibrium of resuspension and deposition. 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.

Table A.5. Statistics for Fraction of Time Spent Indoors at Work

					Percentiles							
Category	**Population Group**	**N[a]**	**Min**	**Max**	**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] Number of subjects in the survey.

Source: Derived from cumulative minutes per day spent indoors listed in EPA (1997).

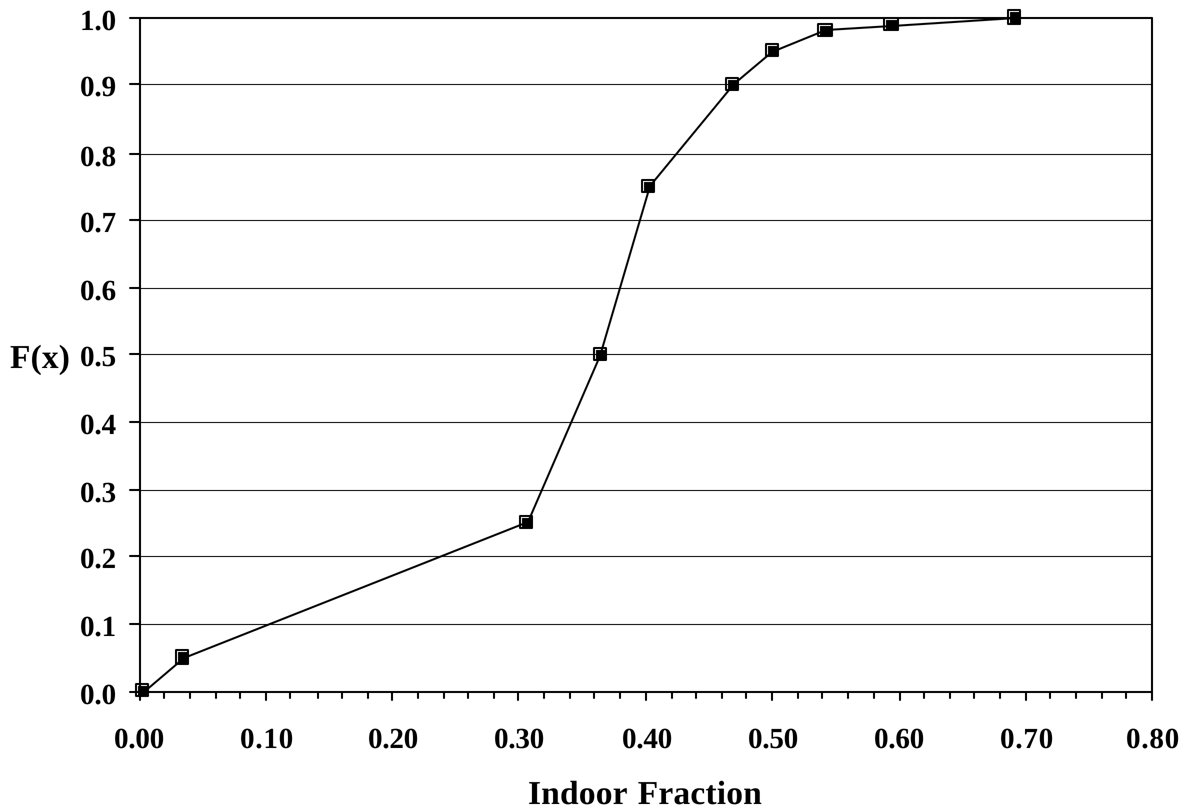

Figure A.2. Indoor Fraction Cumulative Distribution Function for RESRAD-BUILD

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 x 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, suggesting that a uniform distribution between the minimum and maximum areas is not appropriate. The choice of a most likely value for a triangular distribution was arbitrary and attempted to account for this observation. A most likely value of 36 m^2 (390 ft^2) was chosen. This value lies above what might be expected for the area for a single-occupant office room (approximately 12 m^2, 3 m x 4 m) and is in the range of what might be expected for a multioccupant office room. Figure A.3 shows the probability density function suggested for the room area.

A.1.4 Room Height

Description: The room height is the distance between the floor and the ceiling of a specific room in the building.

Unit: Meters (m)

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 2.4 Maximum: 9.1
Most likely: 3.7

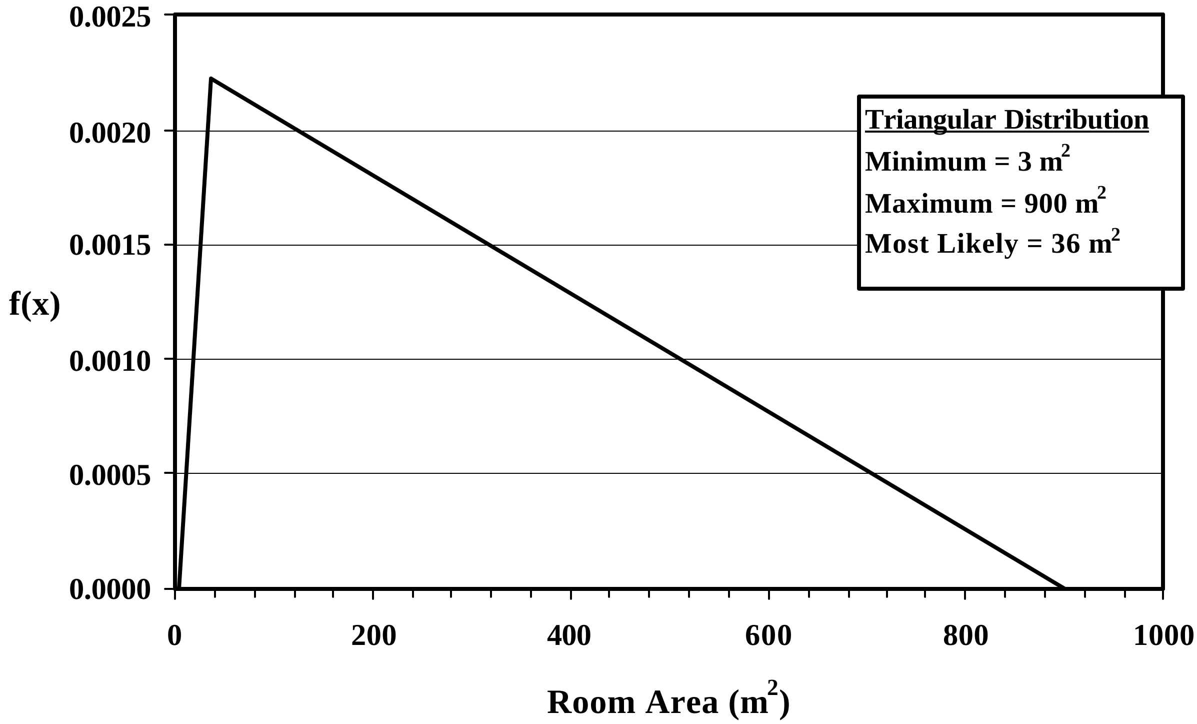

Figure A.3. Probability Density Function for Room Area

Discussion: The room height is used in determining the mixing volume of each distinct air-flow volume (room) and the equilibrium of resuspension and deposition. Over half the new single-family homes constructed annually have room heights of 2.4 m (8 ft), as shown in Table A.6. 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

Table A.6. 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).

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 the occupational scenario, a triangular distribution is used for the room height, with a most likely value of 3.7 m (12 ft) and minimum and maximum values of 2.4 (8 ft) and 9.1 m (30 ft), respectively. This distribution is a rough generalization, and site-specific data should be used when available. The probability density function is shown in Figure A.4.

A.1.5 Shielding Thickness

Description: This parameter represents the effective thickness of shielding between a source and receptor pair.

Unit: Centimeters (cm)

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 0 Maximum: 30
Most likely: 0

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

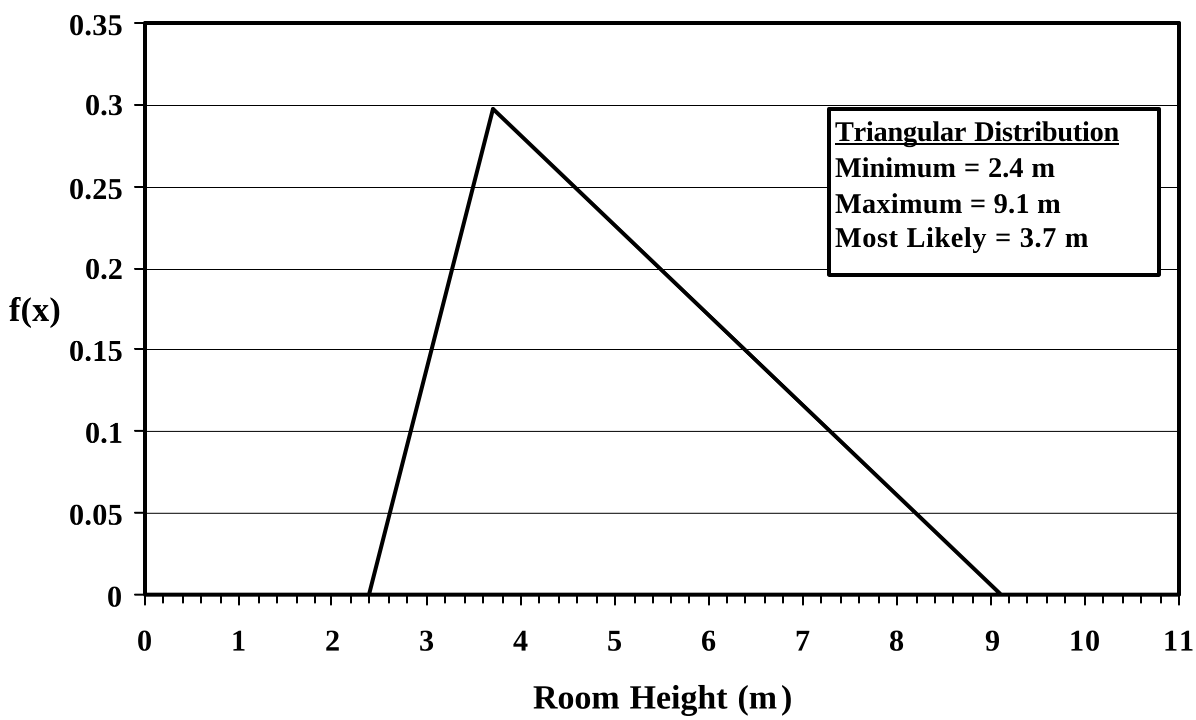

Figure A.4. Room Height Probability Density Function

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 the 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 U.S. Department of Energy (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 12 in. (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 decontamination and decommissioning (D&D) situations; therefore, a triangular distribution is assumed. The maximum value is assumed to be 12 in. (30 cm), the minimum value is chosen as 0 in. (0 cm), and the most likely value also is chosen to be 0 in. (0 cm) (this assumption would yield the most conservative dose results for the external exposure pathway). The probability density function is shown in Figure A.5.

A.1.6 Humidity

Description: In RESRAD-BUILD, this parameter represents the average absolute humidity in the building. The absolute humidity is an input used only for the tritium volume source model.

Unit: Grams per cubic meter (g/m^3)

Probabilistic Input:

Distribution: Uniform

Defining Values for Distribution:

Minimum: 6.5 Maximum: 13.1

Discussion: RESRAD-BUILD requires input for the absolute humidity, that is, 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 section, relative humidity 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 heating, ventilation, and air-conditioning (HVAC) systems of the building. At normal room temperatures, the RH in occupied buildings should be maintained 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 low and high 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 in RESRAD-BUILD. The range of 30 to 60% RH corresponds to an absolute humidity range of 6.5 to 13.1 g of water per cubic meter at 1 atmosphere pressure and 24EC (75EF). The probability density function is shown in Figure A.6. 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 more temperate climates where natural ventilation may be employed, the humidity inside the building will be more representative of the outside levels. Data from 231 weather stations across the coterminous 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 relative humidity 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 A.7. This alternative distribution is only indicative of what

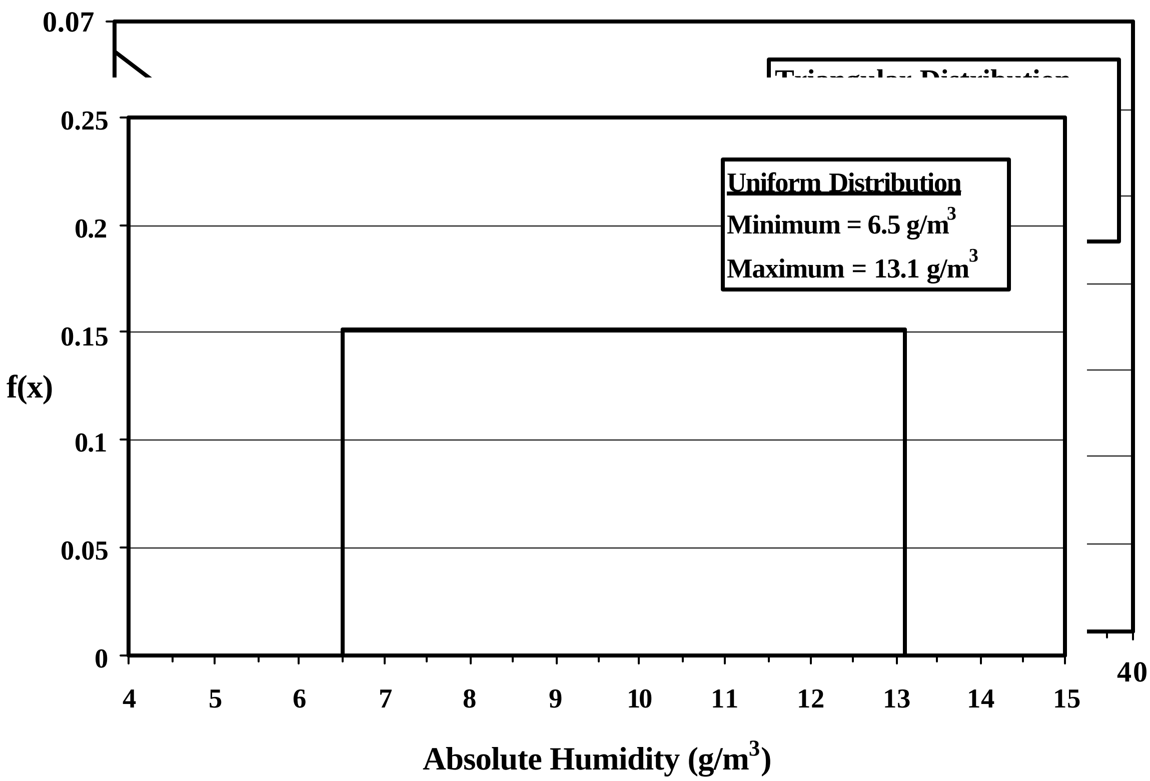

Figure A.5. Shielding Thickness Probability Density Function

Figure A.6. Absolute Humidity Probability Density Function for RESRAD-BUILD

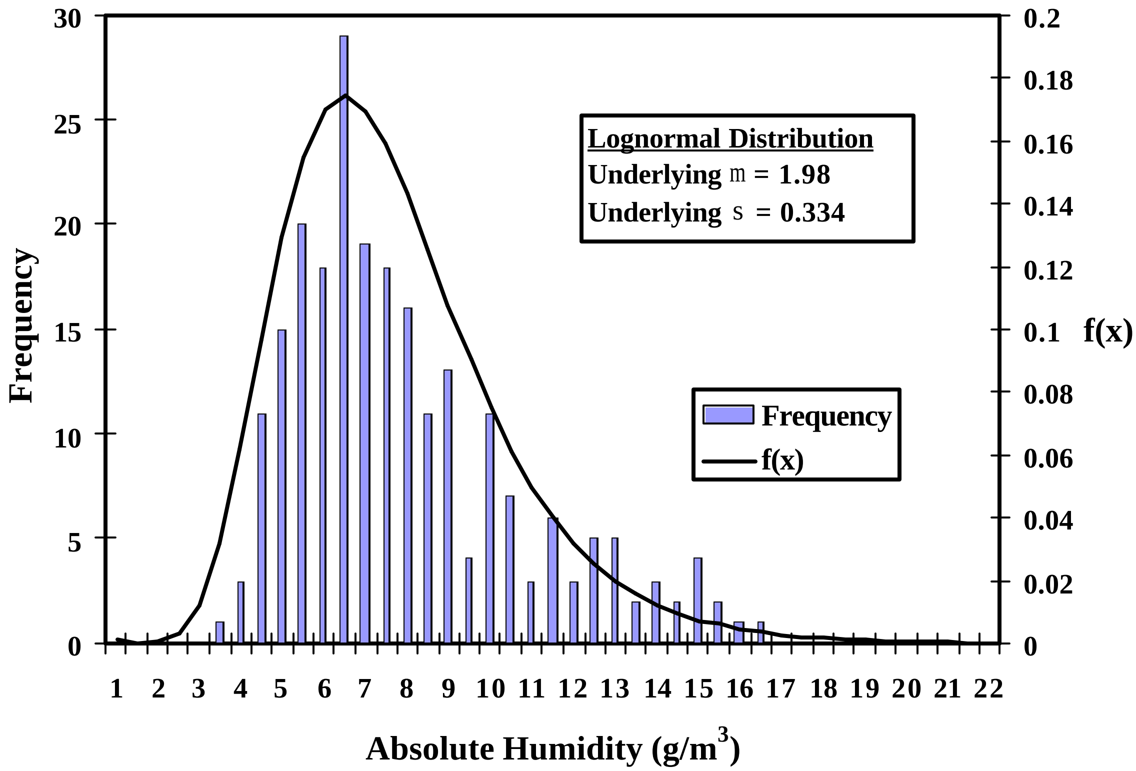

Figure A.7. Alternative Absolute Humidity Probability Density Function Based on Outdoor Humidity Levels

might be expected, because the sampling is not representative of a uniform grid across the United States; it is indicative, however, of the larger population centers. Site-specific data should be used when available.

A.2 SOURCE CHARACTERISTICS PARAMETER DISTRIBUTIONS

A.2.1 Source Density, Volume Source

Description: The source density parameter represents the effective density of each cylindrical layer (region) in an idealized volume source.

Unit: Grams per cubic centimeter (g/cm^3)

Probabilistic Input (allowed only for concrete):

Distribution: Uniform

Defining Values for Distribution:

Minimum: 2.2 Maximum: 2.6

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. Table A.7 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 gives a single-value 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 A.8 provides the concrete density from three different sources: *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. Figure A.8 shows the probability density function for the concrete source density.

Table A.7. 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] – = data not available.

Sources: Shleien (1992); Lide (1998).

A.2.2 Source Porosity

Description: The source porosity is the ratio of the pore volume to the total volume of a representative sample of the source material.

Unit: Unitless

Table A.8. Concrete Density from Various Sources

	Concrete Density (g/cm^3)		
Aggregate	**Shleien (1992)**	**Neville (1996)**	**Merritt et al. (1995)**
Ordinary (siliceous) 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	–	–

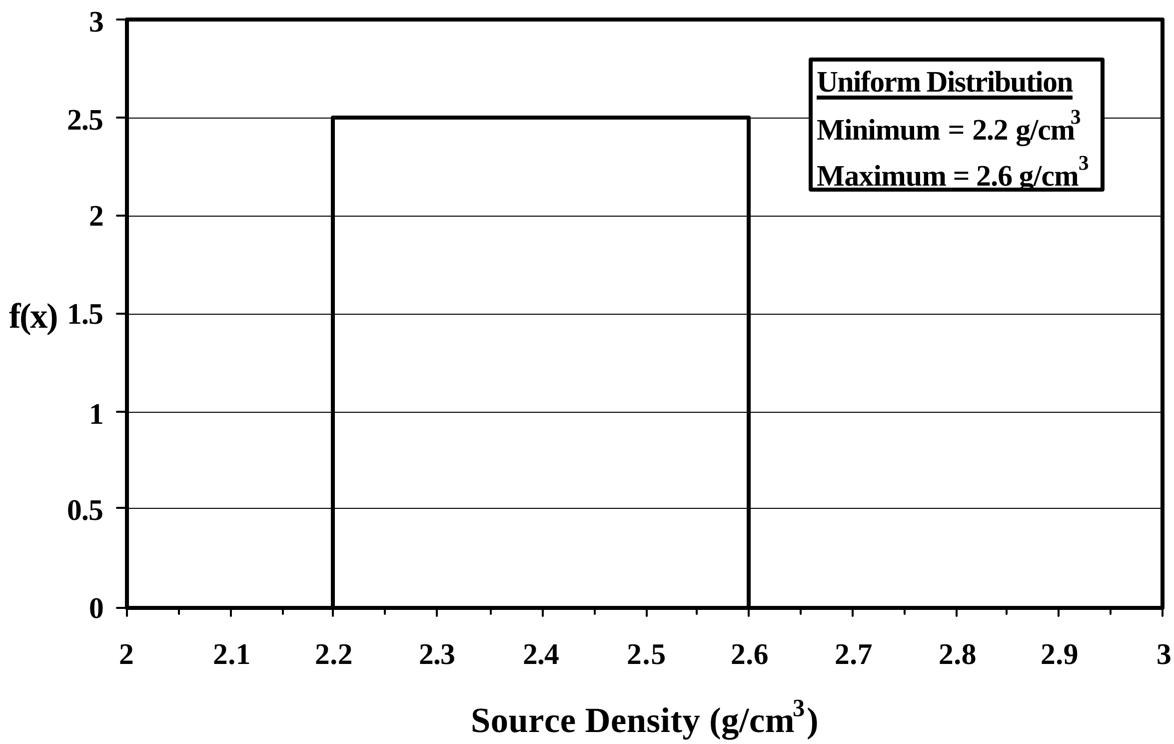

Figure A.8. Concrete Source Density Probability Distribution Function

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 light weight aggregate	–	0.64-higher	–
Nailing	–	0.65-1.6	–
Foam	–	–	0.3-1.75

[a] – = data not available.

Probabilistic Input (allowed only for concrete):

Distribution: Uniform

Defining Values for Distribution:

Minimum: 0.04 Maximum: 0.25

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 and radon-222) precursors are entered as part of the volume source.

Porosity may range from 0 to 1 and 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 ranging from 0 to 0.3.

Widespread variations in concrete porosity have been observed 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 A.9 gives the bulk density and porosity of the rocks commonly used as building materials (Bever, 1986). Materials used for thermal insulation tend to have a very high air content, with porosities approaching 1. Material porosity tends to be inversely correlated with material density; low porosity materials tend to have higher densities than any 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).

Table A.9. 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).

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 Frankowskiet al. (1997) and Culot et al. (1976), respectively. The probability density function is shown in Figure A.9.

A.2.3 Volumetric Water Content

Description: The volumetric water content is the volume of water per unit volume of the porous material.

Unit: Unitless

Probabilistic Input (allowed only for concrete):

Distribution: Uniform

Defining Values for Distribution:

Minimum value: 0.0 Maximum value: 0.25

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 is assumed to result from a recent spill, 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

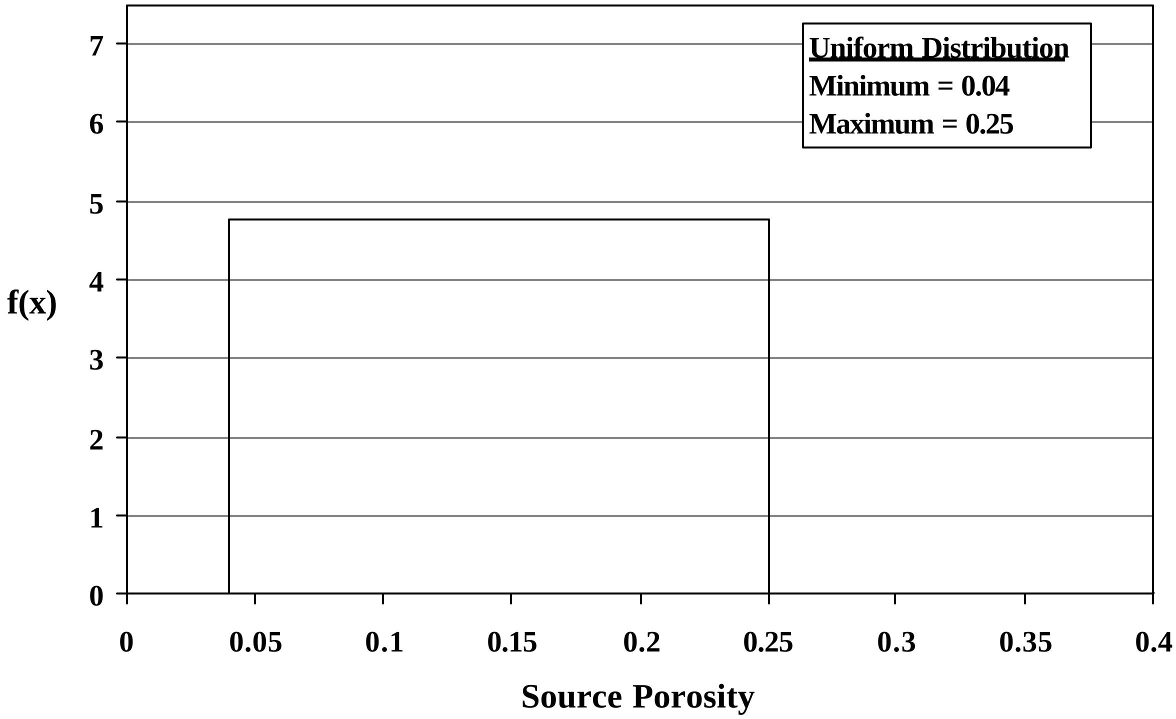

Figure A.9. Concrete Source Porosity Probability Density Function

(Section A.2.2). In any case, the maximum value assigned to the volumetric water content should not be greater than the maximum of the source porosity.

A.2.4 Air Release Fraction

Description: The air release fraction is the amount of the contaminated material removed from the source that is released into the air and in the respirable particulate range.

Unit: Unitless

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 1×10^{-6} Maximum: 1
Most likely: 0.07

Discussion: The fraction released to the air is the amount of the contaminated material removed from the source that is actually suspended in air; the balance of the material is assumed to be instantaneously removed from the room. It is a dimensionless parameter that 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. Dusting would result in low erosion rates, but a relatively high fraction of removed material may become suspended in air. Vacuuming may result in higher erosion rates than dusting, but a smaller fraction would become airborne; a significant fraction would be trapped in the vacuum. 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.

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 or the erosion rate is 0, the contributions from these pathways will be suppressed, no matter what value is given to the air release fraction.

The U.S. Department of Energy (DOE) handbook on airborne release and respirable fractions (RFs) (DOE, 1994) provides a compendium and analysis of experimental data from which airborne release fractions[1] (ARFs) and RFs[2] 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 a American National Standard for airborne release fractions at nonreactor nuclear facilities (ANS, 1998).

For materials in gaseous form, such as H-3, the recommended airborne release fraction is 1.0. All materials in the gaseous state can be transported and inhaled; therefore, the respirable fraction is also 1.0 (DOE, 1994).

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 temperature 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, 1994). 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 the building occupancy scenario air release fraction; therefore, a triangular distribution based on the above data is used to generate distribution. 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

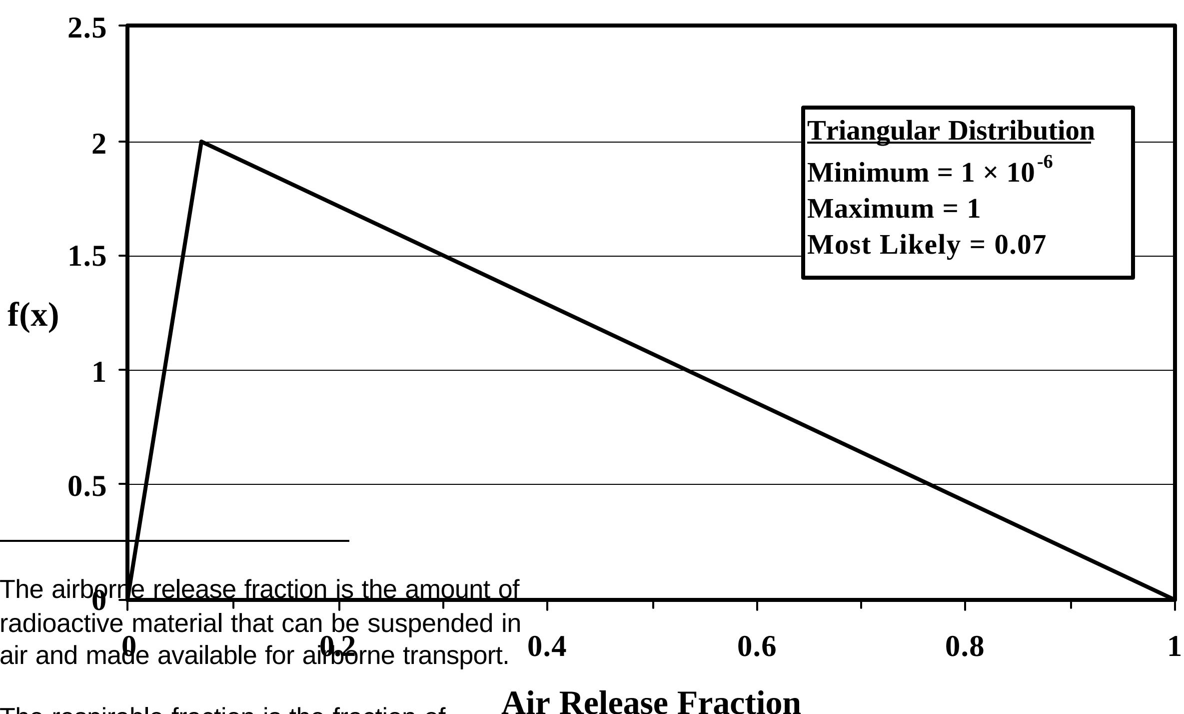

Figure A.10. Air Release Fraction Probability Density Function

[1] The airborne release fraction is the amount of radioactive material that can be suspended in air and made available for airborne transport.

[2] 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-:m aerodynamic equivalent diameter and less.

(0.1 × 0.7 = 0.07). Figure A.10 shows the probability density function.

A.2.5 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.

Unit: Centimeters (cm)

Probabilistic Input (allowed only for volume contamination with tritium):

Distribution: Uniform

Defining Values for Distribution:

Minimum: 5 Maximum: 30

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 porous nature. The high porosity of concrete materials makes them more vulnerable to the permeation of tritiated water, which can spread out 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 A.2.7).

The diffusion of HTO is assumed to proceed like a peeling process in which the HTO molecules closer to the concrete-atmosphere interface are 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) is formed, and its thickness increases 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 12 in. (30 cm). A low bound of 2 in. (5 cm) is selected because bulk contamination will not be extensive for a short exposure period. Figure A.11 shows the probability density function.

A.2.6 Source Thickness, Volume Source

Description: This parameter represents the thickness of each layer in an idealized volume source. This parameter does not apply to area, line, or point sources.

Unit: Centimeters (cm)

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 2.5 Maximum: 30
Most likely: 15

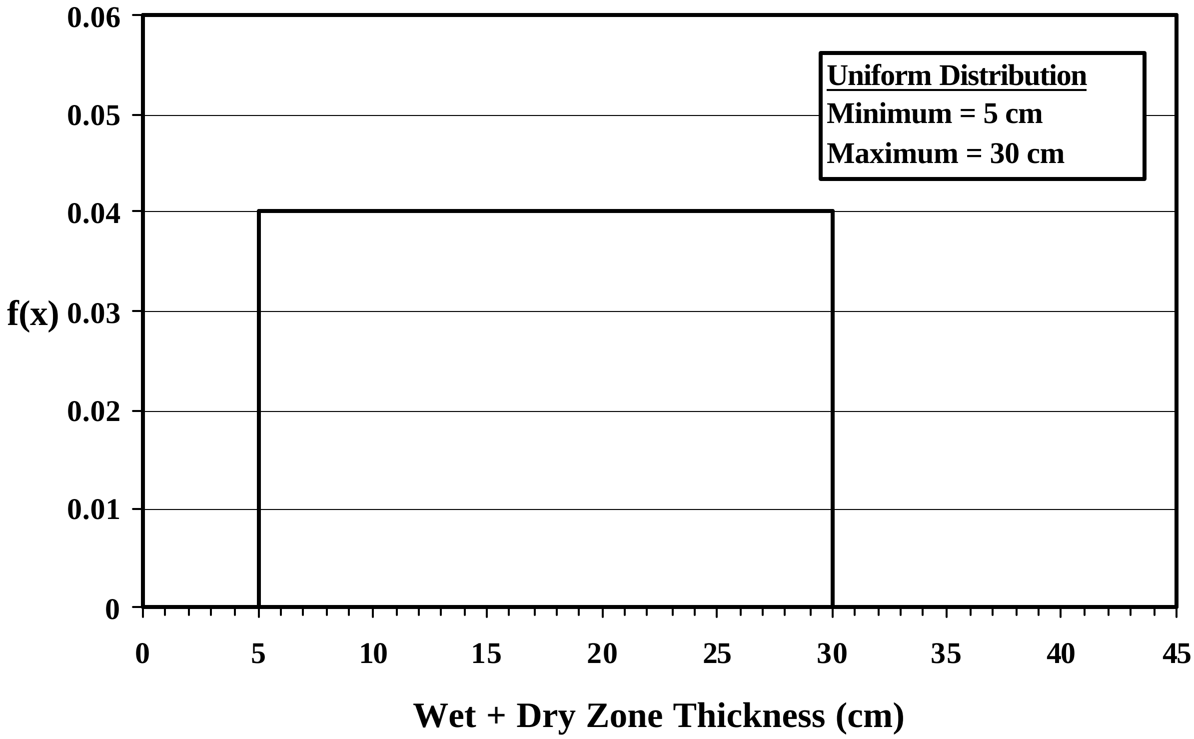

Figure A.11. Wet + Dry Zone Thickness Probability Density Function

Discussion: RESRAD-BUILD allows consideration of a total of five distinct regions (layers) in a volume source. The contamination is within these regions, and the total thickness of the volume source is the sum of the thicknesses of these regions. The code requires a source thickness (in centimeters) for every layer of each volume source. The source thickness depends on 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 2.5-cm (1-in.) depth and an average concrete thickness of 30 cm (12 in.) 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. The DandD and RESRAD-BUILD codes use 15 cm (6 in.) as the default source thickness for a volume source.

Little information is available for the source thicknesses in real D&D 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 (12 in.), the minimum value is chosen as 2.5 cm (1 in.), and the most likely value is the 15-cm (6-in.) default used in the DandD and RESRAD-BUILD codes for volume sources. Figure A.12 shows the probability density function for the source thickness.

A.2.7 Water Fraction Available for Evaporation

Description: This parameter is used in estimating the potential release rate of HTO vapor from a volume contamination source. It is the fraction of the total amount of HTO that will be released to the indoor air through the diffusion mechanism under room temperature.

Unit: Unitless

Probabilistic Input (allowed only for volume contamination with tritium)

Distribution: Triangular

Defining Values for Distribution:

Minimum: 0.5 Maximum: 1.0
Most likely: 0.75

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 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

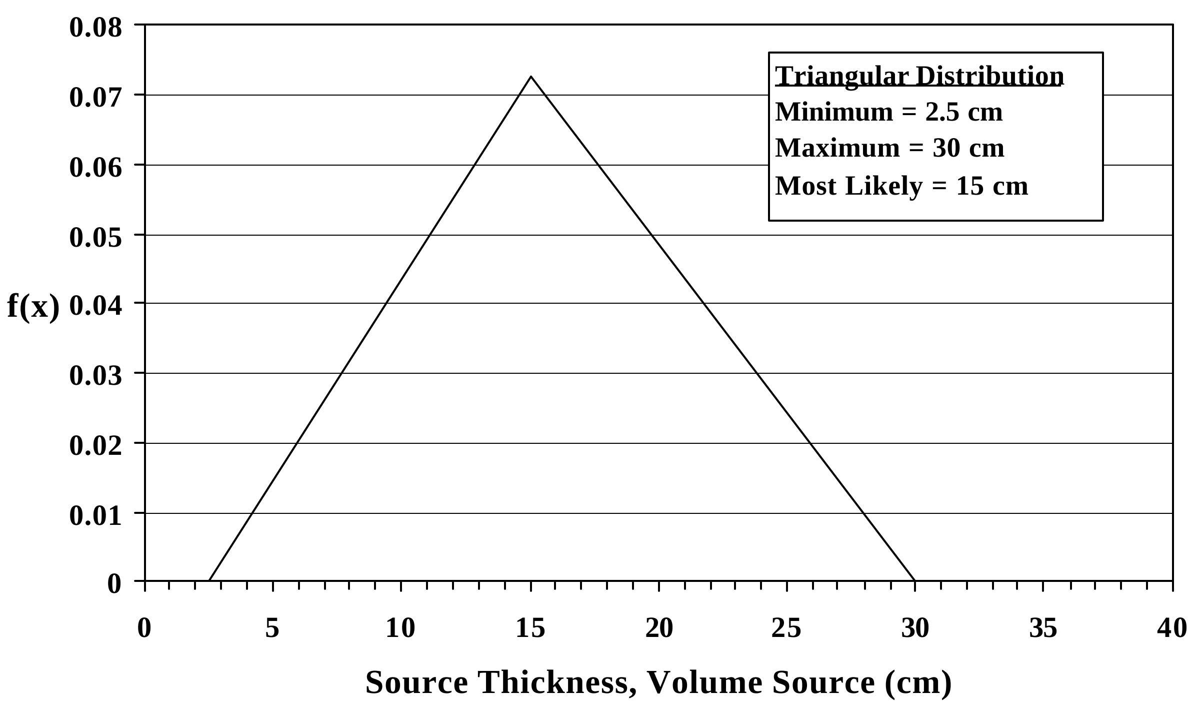

Figure A.12. Source Thickness Probability Density Function

showed that about 90% of the tritium desorbed from the 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 porous nature. The high porosity of concrete materials makes them more vulnerable to the permeation of HTO, which can spread out 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 information on 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 HTO available for evaporation 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 constituent 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 the 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 30EC (86EF). Residual tritium sorbed was recovered by heating up the samples up to 800EC (1,472EF). 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 HTO can form strong bounding 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 evaporate and diffuse to the indoor atmosphere.

Numata and Amano (1988) reported that the fraction of free HTO 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 HTO from concrete materials under accidental conditions that can cause the temperature to reach as high as 200ºC (392EF). In the DOE report (1994), it was assumed that tritiated water was 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, it can be concluded that (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 A.13.

A.3 HUMAN INTAKE PARAMETER DISTRIBUTIONS

A.3.1 Receptor Inhalation Rate

Description: This parameter reflects the rate at which a human receptor inhales air contaminated with resuspended airborne material.

Unit: cubic meters per day (m^3/d) (RESRAD-BUILD)

Probabilistic Input:

Distribution: Triangular

Defining Values for Distribution:

Minimum: 12 Maximum: 46
Most likely: 33.6

Discussion: The range of estimates of inhalation rate (Table A.10) 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 such a significant extent, it is preferable to derive a range of inhalation rates by using activity data specific to the population

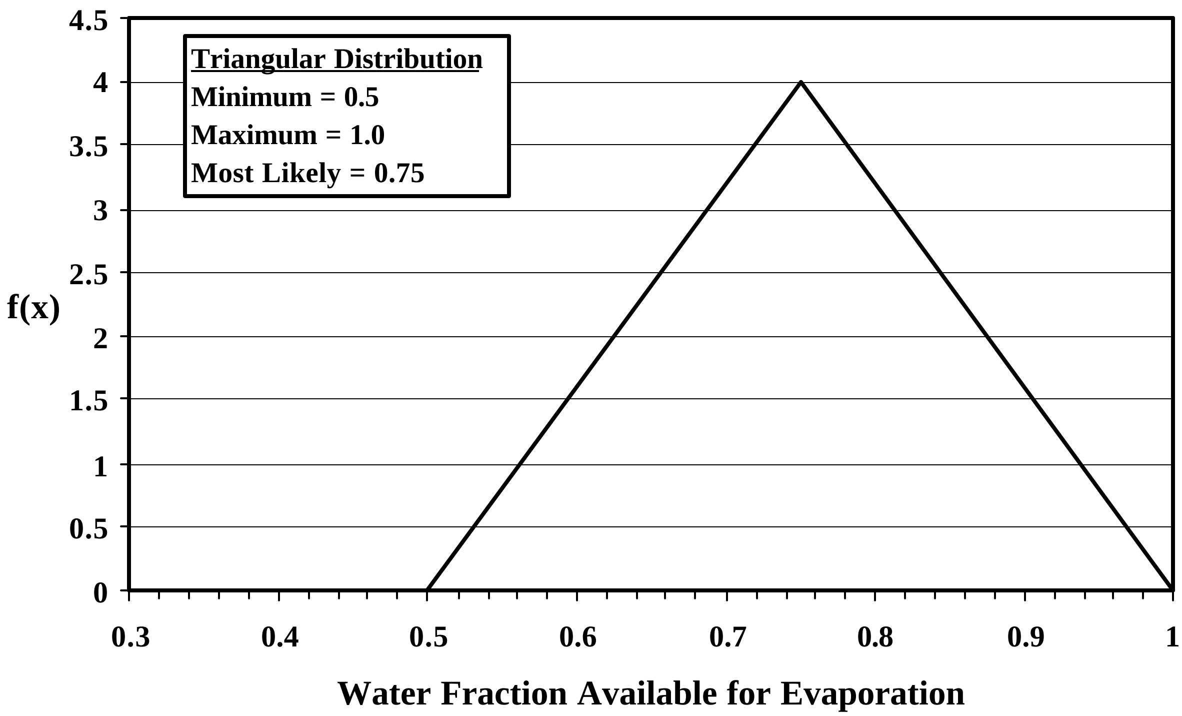

Figure A.13. Water Fraction Available for Evaporation

Table A.10. Inhalation Rate Distributions						
Basis	**Distribution Type**	**Inhalation Rate (m^3/d)**				**Reference**
		Min.	**Max.**	**Mean**	**Most Likely**	
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%.

under study. The hourly average inhalation rate in RESRAD-BUILD is intended 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 A.11 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.

For the building occupancy scenario, a triangular distribution is also used for input to RESRAD-BUILD. The most likely inhalation rate value was taken to be 33.6 m^3/d (1.4 m^3/h) as

recommended in Beyeler et al. (1999). The minimum value of 12 m^3/d (0.5 m^3/h) was selected on the basis of recommendations for sedentary adult activities. 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. (1999) for workers in light industry and falls within the range of moderate to heavy activities for both adults and outdoor workers (Table A.11).

A.3.2 Direct Ingestion Rate

Description: "Direct ingestion" refers to the incidental ingestion of contaminated material directly from the source.

Units: g/h for volume sources
1/h for point, line, and area sources

Probabilistic Input:

Distribution: None recommended

Discussion: The direct ingestion rate is included in the RESRAD-BUILD code to cover

Table A.11. Summary of EPA-Recommended Values for Inhalation

Population	Mean	Population	Mean
Long-Term Exposures		***Short-Term Exposures***	
Infants (<1 year)	4.5 m^3/d	Adults	
		Rest	0.4 m^3/h
Children		Sedentary activities	0.5 m^3/h
1-2 years	6.8 m^3/d	Light activities	1.0 m^3/h
3-5 years	8.3 m^3/d	Moderate activities	1.6 m^3/h
6-8 years	10 m^3/d	Heavy activities	3.2 m^3/h
9-11 years			
Males	14 m^3/d	Children	
Females	13 m^3/d	Rest	0.3 m^3/h
12-14 years		Sedentary activities	0.4 m^3/h
Males	15 m^3/d	Light activities	1.0 m^3/h
Females	12 m^3/d	Moderate activities	1.2 m^3/h
15-18 years		Heavy activities	1.9 m^3/h
Males	17 m^3/d		
Females	12 m^3/d	Outdoor workers	
		Hourly average[a]	1.3 m^3/h
Adults (19-65+yrs)		Slow activities	1.1 m^3/h
Females	11.3 m^3/d	Moderate activities	1.5 m^3/h
Males	15.2 m^3/d	Heavy activities	2.5 m^3/h

[a] Upper percentile = 3.3 m^3/h.

Source: EPA (1997).

the unlikely event that a receptor directly ingests source material. Such a receptor could be conducting a maintenance or renovation activity that involves 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 × thickness [Section A.2.6] × density [Section A.2.1]). In addition, the direct ingestion rate cannot exceed the amount removed per unit time as determined by the source erosion rate (Section 3.4). The soil ingestion rate could be used as a guide for this parameter. Indirect ingestion (Section A.3.3) 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 3.4).

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 3.5) and the source lifetime (Section 3.6) input parameters. If the direct ingestion rate is large enough to match the removal rate, then the air release fraction (Section A.2.4) input must be set to 0 to maintain mass balance.

A.3.3 Indirect Ingestion Rate

Description: 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.

Unit: Square meters per hour (m^2/h)

Probabilistic Input:

Distribution: Loguniform

Defining Values for Distribution:

Minimum: 2.8×10^{-5} Maximum: 2.9×10^{-4}

Discussion: Only limited information is available on the values for this parameter. As reported in Beyeler et al. (1999), 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 by adults in an occupational setting. A larger, secondary set of data from soil ingestion studies is available (Yu et al., 2000), but again, 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 in 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 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., 1999). 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., 1999). For this reason, Beyeler et al. (1999) 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 A.12) for the indirect ingestion rate parameter ranged from 4.4×10^{-4} to 4.6×10^{-3} m^2/d, with a mean of 1.8×10^{-3} m^2/d; and from 5.1×10^{-2} to 4.3×10^{-1} m^2/d, with a mean of 1.8×10^{-1} m^2/d. For use in RESRAD-BUILD, a 16-hour day was assumed, resulting in distributions with means of 1.1×10^{-4} and 1.1×10^{-2} for the low and high average ingestion rate distributions presented in Yu et al. (2000). As discussed in Beyeler et al. (1999), an ingestion rate corresponding to 1×10^{-2} m^2/h implies mouthing an area equivalent to the inner surface of the hand once each hour. Such an ingestion rate appears to be an upper bound for a commercial environment. Because 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 A.14 shows the probability density function.

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Table A.12. Indirect Ingestion Rates

Parameter	Mean	Lower Limit	Upper Limit
Dust loading (mg/m^2)[a]	320	10	5000
Low ingestion rate input (mg/d)[a]	0.50	0	200
High ingestion rate input (mg/d)[a]	50	0	200
Low ingestion rate estimate (m^2/d)[a]	1.8×10^{-3}	4.4×10^{-4}	4.6×10^{-3}
High ingestion rate estimate (m^2/d)[a]	1.8×10^{-1}	5.1×10^{-2}	4.3×10^{-1}
RESRAD-BUILD input[b] 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] Source: Beyeler et al. (1999).

[b] Assumes a 16-hour day using the results from Beyeler et al. (1999).

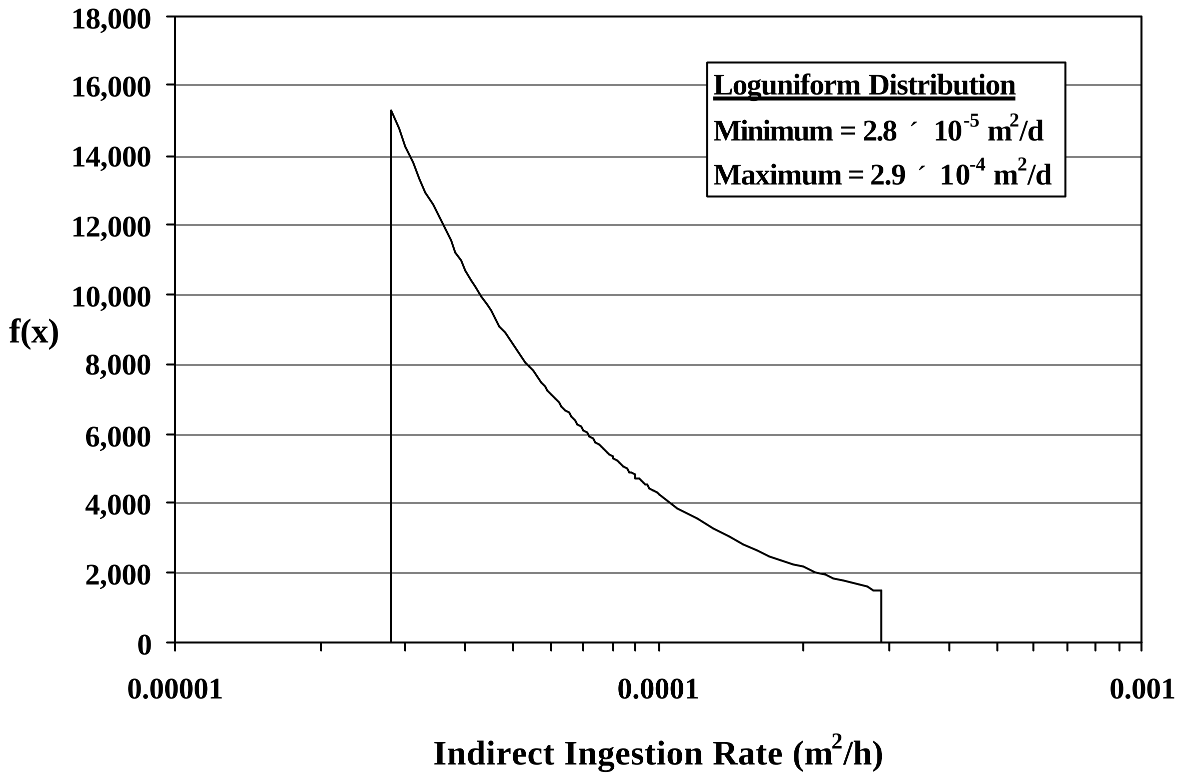

Figure A.14. Indirect Ingestion Rate Probability Density Function

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APPENDIX B:

PARAMETRIC DISTRIBUTION TYPES

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PARAMETRIC DISTRIBUTION TYPES

This appendix discusses the form and characteristics of each of the parametric distributions available in the Latin Hypercube Sampling (LHS) module that may be used to represent input parameters in the RESRAD-BUILD code. Table B.1 summarizes the continuous probability density distribution functions and the required input for the LHS module.

B.1 BETA DISTRIBUTION

The LHS code incorporates a four-parameter beta distribution that has the probability density function:

$$f(x) = \frac{1}{B(p,q)} \frac{(x-A)^{p-1}(B-x)^{q-1}}{(B-A)^{p+q-1}} , \qquad \text{(B.1)}$$

where *B(p,q)* is the beta function,

$$B(p,q) = \int_0^1 t^{p-1}(1-t)^{q-1} dt , \qquad \text{(B.2)}$$

p and *q* are shape parameters, and *A* and *B* are the endpoints of the distribution. This distribution is very flexible and is often used to fit empirical data. The shape of the distribution can vary widely depending on the relationship of *p* and *q* to one another. This flexibility also makes the beta distribution useful for approximating distributions when there are insufficient data.

As discussed below in the section on the maximum entropy distribution (Section B.7), the beta distribution may be used in cases where estimates for the minimum (*A*), maximum (*B*), mean (μ), and standard deviation (s) are available, but little else is known. In such a case, the shape parameters can be estimated according to Lee and Wright (1994):

$$p = (m - A)\left[\frac{(m-A)(B-m)/s^2 - 1}{B - A}\right] , \qquad \text{(B.3)}$$

and

$$q = \frac{(m-A)(B-m)}{s^2} - 1 - p . \qquad \text{(B.4)}$$

B.2 EXPONENTIAL DISTRIBUTION

The probability density function for the exponential distribution is:

$$f(x) = l\ e^{-l\,x} \quad \text{for } x \ \$\ 0, \qquad \text{(B.5)}$$

with the mean given by 1/ *l* . The variable *l* represents the average rate of occurrence of successive, independent, random events. Purely random Poisson processes exhibit such behavior. Examples include radioactive decay, accidents, and storm events.

B.3 GAMMA DISTRIBUTION

The gamma distribution represents the sum of a series of exponentially distributed random variables. The probability density function for the two-parameter form of the gamma distribution (sometimes referred to as "the incomplete gamma function") is:

$$f(x) = \frac{\beta^{\alpha} x^{(\alpha-1)} e^{-\beta x}}{\Gamma(\alpha)} \text{ with } x > 0,\ a > 0,\ ß > 0, \text{ and} \qquad \text{(B.6)}$$

$$\Gamma(\alpha) = \int_0^{\infty} y^{(\alpha-1)} e^{-y} dy \quad \text{or}$$

$$\Gamma(a) = (a - 1)! \ \text{ for integers,}$$

where *G*(*a*) is the gamma function. The *a* parameter determines the shape of the function, and the *ß* parameter controls the scale. If the shape parameter is set to 1, the gamma distribution becomes a scalable exponential distribution. The mean for the gamma distribution is *a/ß.* The gamma distribution is appropriate for representing the time required for a independent events to take place for

Table B.1. Continuous Probability Density Distribution Functions

Distribution	Input Variables			
Beta	A (minimum)	B (maximum)	p (shape factor)	q (shape factor)
Exponential Types				
Exponential	*?*			
Bounded exponential	*?*	A (minimum)	B (maximum)	
Truncated exponential	*?*	lower quantile value	upper quantile value	
Gamma	*a* (shape factor)	*ß* (scale factor)		
Inverse Gaussian	*µ*	*?*		
Lognormal Types				
Lognormal	*µ* (mean)	error factor		
Lognormal-b	value at 0.001 quantile	value at 0.999 quantile		
Lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution		
Bounded lognormal	*µ* (mean)	error factor	A (minimum)	B (maximum)
Bounded lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	A (minimum)	B (maximum)
Truncated lognormal	*µ* (mean)	error factor	lower quantile value	upper quantile value
Truncated lognormal-n	mean of underlying normal distribution	standard dev. of underlying normal distribution	lower quantile value	upper quantile value
Loguniform Types				
Loguniform	A (minimum)	B (maximum)		
Piecewise loguniform	number of intervals	# observations per interval 1…	# observations per interval n	first point, end point sequence
Maximum Entropy	A (minimum)	B (maximum)	*µ* (mean)	
Normal Types				
Normal	*µ* (mean)	*s* (standard deviation)		
Normal-b	value at 0.001 quantile	value at 0.999 quantile		
Bounded normal	*µ* (mean)	*s* (standard deviation)	A (minimum)	B (maximum)
Truncated normal	*µ* (mean)	*s* (standard deviation)	lower quantile value	upper quantile value
Pareto	*a*	*ß*		
Triangular	a (minimum)	b (most likely)	c (maximum)	
Uniform Types				

Uniform	A (minimum)	B (maximum)		
Piecewise uniform	number of intervals	# observations per interval 1…	# observations per interval n	first point, end point sequence
User Defined Types				
With linear interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
With logarithmic interpolation (CDF input)	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
With density function input	n (number of ordered pairs)	ordered pair 1	ordered pair 2 …	ordered pair n
Weibull	*a*	*ß*		

nonrandom events that occur at a constant arrival rate *ß*. This distribution is often used to describe system reliability (the length of life of industrial equipment).

B.4 INVERSE GAUSSIAN

The probability density function for the inverse Gaussian distribution is given by:

$$f(x) = \sqrt{\frac{\lambda}{2\pi x^3}}\, e^{-\left(\frac{\lambda (x-m)^2}{2m^2 x}\right)} \quad . \qquad \text{(B.7)}$$

The distribution was originally derived as a limiting form of distribution of sample size in certain sequential probability ratio tests. More information can be found in Johnson et al. (1994).

B.5 Lognormal Distribution

The lognormal distribution is defined by the logarithm of a normal distribution and is given by the following probability density function:

$$f(x) = \frac{1}{x s \sqrt{2p}}\, e^{-\left(\frac{(\ln x - m)^2}{2 s^2}\right)} \qquad \text{with } x > 0, \qquad \text{(B.8)}$$

where μ and s are the mean and standard deviation of the underlying normal distribution. One advantage of this two-parameter form is that it can take on only positive values. Whereas the normal distribution may be thought of as describing a random variable that is the sum of independent effects, the lognormal distribution may be thought of as describing a random variable that is the result of multiplicative processes. The lognormal distribution has the functional form that is often used for describing dilution of matter in water or air. Environmental concentrations of contaminants in air and water generally follow a lognormal distribution (Ott, 1995).

B.6 LOGUNIFORM DISTRIBUTION

The loguniform distribution is a variation on the uniform distribution. Similar to the uniform distribution, the loguniform distribution is useful when little is known about the distribution between the minimum and maximum values, but may be more appropriate when a large range exists between these values. The probability density function for the loguniform distribution is:

$$f(x) = \frac{1}{x(\ln b - \ln a)} \quad \text{for } a < x < b \;, \qquad \text{(B.9)}$$

with the mean given by

$$\frac{b-a}{\ln b - \ln a} . \qquad \text{(B.10)}$$

B.7 MAXIMUM ENTROPY DISTRIBUTION

The maximum entropy distribution implemented in the LHS code is a truncated exponential distribution where the user specifies the mean and the lower and upper bounds of the distribution. In general, the inference of maximum entropy produces broad distributions because it ensures that no mathematical possibility is ignored while using limited data. With knowledge of up to four properties of a distribution (lower and upper bounds, mean, standard deviation), a suitable maximum entropy distribution may be assigned (see Cullen and Frey [1999] for more information). A uniform distribution may be assigned using only estimates of the upper and lower bounds; a normal distribution may be assigned using only estimates of the mean and standard deviation; an exponential distribution may be assigned using only estimates of the lower (and upper) bound(s) in conjunction with the mean; and a beta distribution may be assigned using estimates of the lower and upper bounds, the mean, and the standard deviation.

B.8 NORMAL DISTRIBUTION

The normal distribution is defined by the following probability density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\left(\frac{(x-m)^2}{2\sigma^2}\right)}$$

with — 4 < x < 4 , (B.11)

where µ is the mean (– 4 < µ < 4) and *s* is the standard deviation (*s* > 0) of the random variable *x*. The normal distribution is also known as the Gaussian distribution and has the well-known bell-shaped curve, being symmetric about the mean with points of inflection at X = x ± *µ*. Thus, it is completely defined by the mean and standard deviation.

The theoretical basis for the application of the normal distribution lies in the central limit theorem. For a random variable x with mean *µ* and standard deviation *s*, this theorem states that the random variable Z has a distribution that approaches the standard normal distribution as $n \rightarrow \infty$ where *n* is the sample size and

$$Z = \frac{(\bar{x} - m)\sqrt{n}}{s}. \qquad \text{(B.12)}$$

The distribution of means of independent sample sets of a distribution or combination of distributions tends toward the normal distribution as the number of sample sets becomes large. The original distribution itself need not be a normal distribution. In summary, the central limit theorem suggests that any random variable representing the sum of a large number of independent processes or effects would tend to be normally distributed.

Because the normal distribution has infinite tails, the LHS module incorporated in RESRAD and RESRAD-BUILD provides three normal distribution options. Available are the normal distribution itself and two restricted versions, truncated normal (sampled between lower and upper quantile values input by the user) and bounded normal (sampled between lower and upper distribution values input by the user).

B.9 PARETO DISTRIBUTION

The Pareto distribution was originally developed to account for the distribution of income over a population. The probability density function for the Pareto distribution can be given as:

$$f(x) = \frac{ab^a}{x^{a+1}} \text{ for } x \text{ \$ } ß. \qquad \text{(B.13)}$$

The mean for the Pareto distribution is given by:

$$m = \frac{ab}{a-1} \text{ for } a > 1. \qquad \text{(B.14)}$$

B.10 TRIANGULAR DISTRIBUTION

The triangular distribution is used to model situations where there is an absence of data. The probability density function for the triangular distribution is:

$$f(x) = \begin{cases} \dfrac{2(x-a)}{(c-a)(b-a)} & a \le x \le b \\ \dfrac{2(c-x)}{(c-a)(c-b)} & b \le x \le c \end{cases}, \qquad \text{(B.15)}$$

with the mean given by:

$$\frac{a+b+c}{3}, \qquad \text{(B.16)}$$

where the minimum and maximum occur at *a* and *c*, respectively, and the most likely value at *b* (the apex of the triangle). The value of *b* must satisfy *a* # *b* # *c*.

B.11 UNIFORM DISTRIBUTION

All points within an interval having a uniform distribution, also known as the rectangular distribution, are equally likely. The probability density function for the uniform distribution is:

$$f(x) = \frac{1}{b-a} \text{ for } a \text{ \# } x \text{ \# } b, \qquad \text{(B.17)}$$

where *a* and *b* are the minimum and maximum values of the range of the random variable considered. The mean and variance of a uniform distribution are (*a* + *b*)/2 and $(b\ !\ a)^2/12$, respectively. If the only available data for a random variable are the minimum and maximum values, the maximum entropy distribution for such a case would be a uniform distribution. See the section above on maximum entropy distribution if the mean of the distribution is also known.

B.12 WEIBULL DISTRIBUTION

The Weibull distribution is often used as a time-to-failure model as an alternative to the exponential distribution. The Weibull distribution is also sometimes known as the Frechet distribution. The probability density function for the Weibull distribution is given as:

$$f(x) = \left(\frac{a}{b}\right)\left(\frac{x}{b}\right)^{(a-1)} e^{-\left(\frac{x}{b}\right)^{a}} \quad \text{for } a > 0 \qquad \text{(B.18)}$$

and $ß > 0$,

where *a* is the shape parameter and *ß* is the scale parameter. When *a* = 1, the Weibull distribution reduces to the exponential distribution. When *a* = 2, the Weibull distribution has the form of the Rayleigh distribution.

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