

DEVELOPMENT OF PROBABILISTIC RESRAD 6.0 AND RESRAD-BUILD 3.0 COMPUTER CODES

Prepared by

C. Yu, D. LePoire, E. Gnanapragasam, J. Arnish, S. Kamboj,
B.M. Biwer, J.-J. Cheng, A. Zielen, and S.Y. Chen
Environmental Assessment Division
Argonne National Laboratory

Submitted to

Tin Mo
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Radiation Protection, Environmental
Risk and Waste Management Branch

November 2000

ABSTRACT

The RESRAD and RESRAD-BUILD codes are part of the RESRAD family of codes developed by the U.S. Department of Energy. For many years, these deterministic codes have been used as dose assessment tools for cleanup of sites contaminated with radioactive materials. The RESRAD code applies to the cleanup of soils, and the RESRAD-BUILD code applies to the cleanup of buildings and structures.

This report is the third in a series documenting the procedures used to enhance the deterministic RESRAD and RESRAD-BUILD codes for probabilistic dose analysis. A six-step procedure was used in developing default parameter distributions and the probabilistic analysis modules. These six steps include (1) listing and categorizing parameters, (2) ranking parameters, (3) developing parameter distributions, (4) testing parameter distributions for probabilistic analysis, (5) developing probabilistic modules, and (6) testing probabilistic modules and integrated codes. These six steps are discussed and summarized in this report. Steps 4 and 5 are documented in separate NUREG/CR reports

(NUREG/CR-6676 [Kamboj et al., 2000] and NUREG/CR-6692 [LePaire et al., 2000]). The reports for steps 1, 2, 3, and 6 are included in this report as attachments.

The probabilistic versions of RESRAD and RESRAD-BUILD codes provide tools for studying the uncertainty in dose assessment caused by uncertain input parameters. The codes are designed to be user-friendly, but they can be misused. Therefore, it is important that potential users be trained in the proper use of the codes consistent with the guidance in NRC's Standard Review Plan (SRP) for Decommissioning (NRC, 2000) for dose modeling and analysis. Furthermore, it is important that the code users follow the guidance in the Multi-Agency Radiation Survey and Site Investigation Manual (NRC, 1997) on collecting site-specific data for developing probabilistic distributions of parameter values to be used in the RESRAD and RESRAD-BUILD codes. They need to collect enough data to develop values that are as close to real-world distributions of these values as possible to produce meaningful and technically defensible results.

CONTENTS

Abstract	iii
Executive Summary	vii
Foreword	xi
Acknowledgments	xii
Abbreviations	xiii
1 Introduction	1
2 Overview of the Deterministic RESRAD and RESRAD-BUILD Codes	5
2.1 RESRAD	5
2.2 RESRAD-BUILD	7
3 Procedures to Develop Probabilistic RESRAD and RESRAD-BUILD Codes	11
3.1 Listing and Categorizing Input Parameters	11
3.2 Selecting Parameters for Distribution Analysis	13
3.2.1 Attribute 1: Relevance in Dose Calculations	13
3.2.2 Attribute 2: Influence on Dose Variability	13
3.2.3 Attribute 3: Parameter Type	13
3.2.4 Attribute 4: Data Availability	13
3.3 Developing Default Parameter Distributions	14
3.4 Testing Parameter Distributions	14
3.5 Developing Probabilistic Modules	16
3.6 Testing Probabilistic Codes	17
4 Overview of the Probabilistic RESRAD and RESRAD-BUILD Codes	19
4.1 Sampling Method	19
4.2 Distribution of Parameters	21
4.3 Probabilistic Results	21
5 Summary and Discussion	25
6 References	27

Attachments

A	Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes	A-1
B	Selection of RESRAD and RESRAD-BUILD Input Parameters for Detailed Distribution Analysis	B-1
C	Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes	C-1
D	Testing of the RESRAD Probabilistic Modules	D-1

Figures

1.1	Project Scope for Developing Probabilistic RESRAD and RESRAD-BUILD Codes	3
2.1	Graphical Representation of Pathways Considered in RESRAD	6
2.2	Graphical Representation of Pathways Considered in RESRAD-BUILD	10
3.1	Flow Diagram of Steps in Developing Probabilistic RESRAD and RESRAD-BUILD Codes and the Report Locations for Each Step	12
4.1	Parameter Distribution Input Screen	20
4.2	An Example of a Help Screen Displaying Parameter Distribution	21

Tables

2.1	List of Principal Radionuclides in RESRAD and RESRAD-BUILD	8
3.1	Parameters Assigned Probability Density Functions	15
4.1	Listing of Input Data and Information Needed for Sample Generation	22
4.2	Comparison of Approaches for Correlating the Uncertainty in the Distribution of Doses to the Uncertainty in the Input Parameter	24

EXECUTIVE SUMMARY

In 1999, the U.S. Nuclear Regulatory Commission (NRC) tasked Argonne National Laboratory (Argonne) with adapting the existing RESRAD and RESRAD-BUILD codes for use in site-specific dose modeling and analysis in accordance with the NRC's guidance in the Standard Review Plan (SRP) for Decommissioning (NRC, 2000) to demonstrate compliance with the license termination rule. For this reason, Argonne revised and customized the codes to be consistent with the current NRC guidance for both deterministic and probabilistic dose modeling being developed in the SRP for Decommissioning. Thus, the primary objectives of Argonne's effort were to (1) develop distribution functions for the input parameters and parametric analyses for the RESRAD and RESRAD-BUILD codes and (2) develop necessary computer modules for conducting probabilistic dose analyses.

The RESRAD and RESRAD-BUILD codes have been developed by Argonne under U.S. Department of Energy (DOE) sponsorship for use in evaluating radioactively contaminated sites and structures, respectively. Both codes are used extensively for dose analysis in cleanup operations in the United States and abroad. The two codes incorporate pathway analysis models designed to evaluate the potential radiological dose to an average individual of the *critical group* who lives or works at a site or in a structure contaminated with residual radioactive materials.

As part of the ongoing effort to meet NRC's objectives, external modules equipped with probabilistic sampling and analytical capabilities were developed for RESRAD and RESRAD-BUILD. The modules are further equipped with user-friendly data input and output interface features to accommodate numerous distribution functions of input parameters and result-display requirements for dose modeling and analysis. The integrated system, consisting of the codes and the interface modules, is designed to operate on Microsoft Windows™ 95, 98, 2000, and NT platforms.

Three NUREG/CR reports have been prepared to document this effort. This, the third NUREG/CR document in the series, summarizes the procedure used in the development of probabilistic RESRAD and RESRAD-BUILD codes. The procedure consisted of six steps: (1) listing and categorizing parameters, (2) ranking parameters, (3) developing parameter distributions, (4) testing parameter distributions for probabilistic analysis, (5) developing probabilistic modules, and (6) testing probabilistic modules and integrated codes. A report for each step was prepared; NUREG/CR reports were prepared for Step 4 (NUREG/CR-6676 [Kamboj et al., 2000]) and Step 5 (NUREG/CR-6692 [LePoire et al., 2000]). This report is a final NUREG/CR report summarizing the project; it includes reports for Steps 1, 2, 3, and 6 as attachments.

NUREG/CR-6676 emphasizes probabilistic dose analysis using parameter distributions developed for the RESRAD and RESRAD-BUILD codes. The objective was to establish and demonstrate the process for site-specific analysis using the integrated code system and test the default parameter distributions. This site-specific approach is emphasized despite the fact that the parameter distributions have been compiled from national databases.

Results of the analysis indicated that no single correlation or regression coefficient can be used alone to identify sensitive parameters in all the cases, because the dependence of dose on the input parameter values is complex. The coefficients are useful guides but have to be used in conjunction with other aids, such as scatter plots and further analysis, to identify sensitive parameters.

The results indicated that all parameter distributions are reasonable and consistent for all cases and radionuclides analyzed. However, site-specific distributions should be used whenever available, especially for sensitive parameters such as shielding thickness and room area. RESRAD-BUILD dose variability for

the building occupancy scenario for both volume and area sources was much greater than the variability observed in RESRAD results for the residential scenario.

NUREG/CR-6692 documents the requirements, design, and operation of the probabilistic modules developed for the RESRAD and RESRAD-BUILD codes. The objective was to establish and demonstrate the features and functionality of the integrated system for site-specific dose analysis. The features incorporated include the previously identified parameter distributions, sampling with the stratified Latin hypercube sampling (LHS) method, an easily accessible probabilistic setup procedure, and a variety of formats (tabular, graphical, and database) for interpreting results. That report includes a user's guide for the probabilistic modules included in RESRAD version 6.0 and RESRAD-BUILD version 3.0. It should be used in conjunction with the technical reference manuals for RESRAD and RESRAD-BUILD codes (Yu et al., 1993b, 1994, or future updates), which describe the methods and parameters.

The software was designed with a user-centered approach. The result is an accessible, integrated package that leverages the user's familiarity with standard Windows tools and the family of RESRAD software tools. The probabilistic screens are tightly integrated with the previously identified default distributions for the input variables. However, the user also has the choice of entering site-specific distributions. The software offers feedback to quickly identify the default and site-specific distributions. The user can also graphically preview the distribution shape.

The LHS sampling method previously developed and accepted by NRC is used to perform the calculations. The user can specify details about this sampling method or accept the default method. The details of the sampling are stored in a report and database format to allow the user to review and query the input samples. Design considerations included methods to integrate the calculations efficiently into the standard deterministic software to ensure reasonable calculation times.

The output results are accessible through interactive tabular windows; interactive graphical windows; fixed tabular reports; and a complete, formatted database. The output results were chosen to support resultant dose distribution statistics, distributions, and correlations with the input variables. These results can be queried on the basis of environmental pathway, initial nuclide contamination, and time since contaminant placement. Special emphasis is placed on the analysis of both the "mean of the peaks" and the "peak of the means" doses. The "mean of the peaks" analysis is based on the time at which the dose is maximum for each sample. The "peak of the means" analysis is based on the time at which the average dose (averaged over all samples) is maximum.

This report documents the procedure used in developing parameter distributions and testing the integrated probabilistic code system. Development of parameter distributions contained in the modules entailed extensive data gathering and analysis to obtain the most up-to-date information. Relevant data were obtained from NRC-sponsored work (including NUREG/CR-5512 [Kennedy and Streng, 1992]) and results from an extensive literature search that made use of library and Internet resources. The focus of this data collection and analysis effort was to analyze the available data and to make the most plausible assignments of distributions for each selected parameter for use in dose calculations. A total of about 200 parameters are used in the RESRAD and RESRAD-BUILD codes to describe the exposure pathways and the associated exposure conditions. These parameters are listed, defined, and categorized as physical, behavioral, or metabolic parameters.

Any parameter that would not change if a different group of receptors was considered was classified as a physical parameter. Any parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. Any parameter representing the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered was classified as a metabolic parameter.

A strategy was developed to rank the input parameters according to their importance with regard to meeting the objective of the analysis. The parameter rankings were divided into three levels: 1 (high priority), 2 (medium priority), and 3 (low priority). The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations; (2) variability of the radiation dose as a result of changes in the parameter value; (3) parameter type (physical, behavioral, or metabolic); and (4) availability of data on the parameter in the literature. A composite scoring system was developed to rank the parameters.

Overall, 14 parameters were ranked as high priority, 59 were ranked as medium priority, and

the remaining 122 were ranked as low priority for RESRAD and RESRAD-BUILD combined.

Parameter distributions were developed for a total of 66 parameters identified as high or medium priority. The data were obtained from a variety of published sources representative of a national distribution. Because they are based on national average data, many of these distributions may not be appropriate for a site-specific assessment. However, their development was necessary for the testing of the probabilistic modules. Potential correlation among parameters was also studied.

FOREWORD

This contractor technical report, NUREG/CR-6697 was prepared by Argonne National Laboratory¹ 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 Risk Analysis and Applications, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the third in a series documenting the procedures used to enhance the deterministic RESRAD and RESRAD-BUILD computer codes (developed by DOE) for probabilistic dose analysis. The procedures for listing, categorizing, ranking of input parameters, and testing the integrated system of the probabilistic modules and the codes are included in this report as attachments. The procedures for testing of the parameter distributions for probabilistic analysis and for developing the probabilistic modules are documented in two other NUREG/CR reports (NUREG/CR- 6676 and NUREG/CR-6692).

The purpose of the NRC's probabilistic system of RESRAD codes is to provide a site-specific and probabilistic dose analysis approach for demonstrating compliance with the license termination rule, 10 CFR Part 20, Subpart E, in a risk informed manner. The codes may be used to demonstrate compliance with the dose criteria in 10 CFR Part 20, Subpart E, as described in NUREG-1727, "NMSS Decommissioning Standard Review Plan," and draft NUREG-1549, "Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination."

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.

Cheryl A. Trottier, Chief
Radiation Protection, Environmental Risk
& Waste Management Branch
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research

¹ Argonne National Laboratory is operated for the U.S. Department of Energy by the University of Chicago, under contract W-31-109-Eng-38.

ACKNOWLEDGMENTS

We would like to recognize Tin Mo, the U.S. Nuclear Regulatory Commission (NRC) Project Manager, for his effective project technical direction, his coordination of the work performed on this project with the NRC Standard Review Plan (SRP) Dose Modeling Working Group (DMWG), and his helpful guidance in ensuring the high quality and timeliness of the work and ensuring that it was performed as planned.

We also would like to thank three NRC staff members — Cheryl A. Trottier, Chief of the Radiation Protection, Environmental Risk and Waste Management Branch; Thomas King, Director, Division of Risk Analysis and Applications, Office of Nuclear Regulatory Research (RES); and John Greeves, Director, Division of Waste Management, Office of Nuclear Material Safety and Safeguards (NMSS) — for their managerial and financial support of the project.

The NRC SRP DMWG members made valuable contributions to the work performed, and their cooperation in reviewing, critiquing, and providing timely feedback on draft project reports and testing the beta versions of the probabilistic RESRAD and RESRAD-BUILD codes, as well as their effective participation at the numerous project review meetings and workshops, were of great value. We are especially thankful to Rateb (Boby) Abu-Eid, Mark Thaggard, James Danna, Duane Schmidt, Richard Clement, Richard Codell, and Timothy Harris of NMSS; to Thomas Nicholson, Philip Reed, Ralph Cady, and Stephen McGuire of RES; and to Patrick LaPlante and Michael Smith of the Center for Nuclear Waste Regulatory Analysis (CNWRA) for their helpful suggestions and recommendations.

We would like to thank Christine Daily of NRC RES for her timely initiation and coordination of the peer review of our work by Dr. F.O. Hoffman of SENES Oak Ridge, Inc. We thank

Dr. Hoffman for his valuable suggestions and effective contributions to this project. Thanks next go to Douglas Brosseau and Walter Beyeler of Sandia National Laboratories for providing the Latin hypercube sampling routines and for their helpful cooperation with the Argonne RESRAD Project Team in providing clarification on the general methodology and approaches developed by Sandia for performing parameter analysis for the DandD computer code.

Marianne Riggs and Margaret Farr, of NRC's Program Management, Policy Development and Analysis (RES/PMPDAS) staff, provided expeditious and effective contract administrative support, which contributed to the timely initiation of the project and the successful completion of this part of the project within the contract budget and schedule.

We appreciate the cooperation and support of this project shown by Alexander Williams, RESRAD project manager in the Office of Environmental Management (EM) of the U.S. Department of Energy (DOE); Andrew Wallo, Director of DOE's Air, Water and Radiation Division; and Harold Peterson in DOE's Office of Environmental Health (EH) for their cooperation and support of this project. We would also like to express special thanks to Anthony Dvorak, Director of the Environmental Assessment Division (EAD) at Argonne, for his support and encouragement, and to Halil Avci of Argonne for providing technical peer review.

Finally, we are grateful to Juanita Beeson and her staff at the NRC Publications Branch and John DePue and Marita Moniger, technical editors at Argonne, for their thorough review and helpful suggestions. We also thank B.J. Pruitte-Deal of EAD and the staff of the Document Processing Center of Argonne's Information and Publishing Division for preparing the manuscript.

ABBREVIATIONS

CD	compact disk
CEDE	committed effective dose equivalent
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
DCGL	derived concentration guideline level
DOE	U.S. Department of Energy
EDE	effective dose equivalent
g	gram(s)
GI	gastrointestinal
GUI	graphical user interface
h	hour(s)
ICRP	International Commission on Radiological Protection
kg	kilogram(s)
L	liter(s)
LHS	Latin hypercube sampling
m	meter(s)
m ²	square meter(s)
m ³	cubic meter(s)
MARSSIM	Multi-Agency Radiation Survey and Site Investigation Manual
μg	microgram(s)
NDD	normalized dose equivalent
NRC	U.S. Nuclear Regulatory Commission
PCC	partial correlation coefficient
pCi	picocurie(s)
PRCC	partial rank correlation coefficient
PRRC	partial rank regression coefficient
QA/QC	quality assurance/quality control
s	second(s)
SPRC	standardized partial regression coefficient
SPRRC	standardized partial rank regression coefficient
SRC	standardized regression coefficient
SRP	Standard Review Plan
SRRC	standardized rank regression coefficient
SRS	simple random sampling
TEDE	total effective dose equivalent
yr	year(s)

1 INTRODUCTION

On July 21, 1997, the U.S. Nuclear Regulatory Commission (NRC) published the License Termination Rule (Title 10, Code of Federal Regulations, Part 20 [10 CFR 20], Subpart E), which establishes regulatory requirements for nuclear facility licensees who are terminating their licensed operations. The NRC's approach to demonstrate compliance with the license termination rule is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary, using dose modeling to evaluate exposure to residual radioactivity in soil and structures. Such potential exposures are evaluated for two scenarios: building occupancy (for contamination on indoor building surfaces) and residential (for contaminated soil).

The objective of dose modeling is to assess the total effective dose equivalent (TEDE) to an average member of the *critical group*² from residual contamination, including any contamination that has reached ground sources of drinking water. The assessment offers a reasonable translation of residual contamination into estimated radiation doses to the public. Compliance with the NRC-prescribed dose criteria can then be assessed by the modeling results.

As part of the development of site-specific implementation guidance supporting the License Termination Rule and development of a Standard Review Plan (SRP) on Decommissioning (NRC, 2000), the NRC recognized the need to perform probabilistic analysis with codes that could be used for site-

specific modeling. Such modeling capabilities exist with the RESRAD (Yu et al., 1993b) and RESRAD-BUILD (Yu et al., 1994) codes. These two codes were developed at Argonne National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE). These DOE codes possess the following attributes: (1) the software has been widely accepted and there is already a large user base, (2) the models in the software were designed for and have been successfully applied at sites with relatively complex physical and contamination conditions, and (3) verification and validation of the codes are well documented (Camus et al., 1999; Cheng et al., 1995; Yu, 1999; Yu and Gnanapragasam, 1995; Halliburton NUS Corp., 1994; Faillace et al., 1994; IAEA, 1996; Laniak et al., 1997; Mills et al., 1997; Seitz et al., 1992; Seitz et al., 1994; Whelan et al., 1999a, 1999b; Gnanapragasam and Yu, 1997a, 1997b; BIOMOVs II, 1996; Regens, 1998; Yu et al., 1993a, 1993b, 1994; NUREG/CP-0163 [NRC, 1998]). The RESRAD codes have been used primarily to derive site-specific cleanup guidance levels (e.g., the derived concentration guideline levels, or DCGLs) with the deterministic method.

In 1999, the NRC tasked Argonne to modify the RESRAD and RESRAD-BUILD codes for use with the NRC's license termination compliance process and the SRP. For use in this NRC process, the codes must meet specifications consistent with the current NRC modeling guidelines. Thus, the primary objectives of this project were for Argonne to (1) develop parameter distribution functions that can be used with the RESRAD and RESRAD-BUILD computer codes to perform probabilistic analyses and (2) develop necessary computer modules that incorporate the parameter distribution functions for conducting the probabilistic analyses. These modules were equipped with user-friendly features based on a specially designed graphical user interface (GUI). They were tailored to use the RESRAD and RESRAD-BUILD codes to perform site-specific probabilistic dose assessments in support of decontamination and decommissioning of radioactively contaminated sites.

² The *critical group* is defined as an individual or relatively homogenous group of individuals expected to receive the highest exposure under the assumptions of the particular scenario considered (NUREG/CR-5512 [Kennedy and Strenge, 1992]). The average member of the critical group is an individual who is assumed to represent the most likely exposure situation on the basis of prudently conservative exposure assumptions and parameter values within the model calculations.

The task of developing probabilistic RESRAD and RESRAD-BUILD codes was carried out in six steps, as shown in Figure 1.1. Many of these steps, although they show a sequential logic, were carried out concurrently.

The first step was to list and categorize all the input parameters (about 200) used in the RESRAD and RESRAD-BUILD codes. The second step was to analyze and rank all the parameters and select parameters for development of parameter distributions. The third step was to collect data on the selected parameters and develop distributions for those parameters. The fourth step had dual purposes: (1) to test the parameter distributions developed in Step 3 and (2) to test the preliminary probabilistic module developed in Step 5. Step 5 was the development of the probabilistic modules, and this step was conducted concurrently with Steps 1 through 4. The last step, Step 6, was further testing of the probabilistic modules and the integrated codes.

The results of testing were used to further improve the codes (Step 5).

For each of these six steps, a report was generated to document the findings. For Steps 1, 2, 3, and 6, letter reports were prepared. For Steps 4 and 5, NRC NUREG/CR documents were prepared. This report, which is a NUREG/CR document, is the final report of this task, and it summarizes all subtasks (steps) performed. The four letter reports prepared for Steps 1, 2, 3, and 6 are included as attachments to this report for easy reference and distribution. This report is composed of six chapters and four attachments. Chapter 1 is an introduction. Chapter 2 is an overview of the deterministic RESRAD and RESRAD-BUILD codes. Chapter 3 summarizes the procedures used to develop probabilistic RESRAD and RESRAD-BUILD codes. An overview of the probabilistic codes is presented in Chapter 4. Chapter 5 is a summary and discussion. Chapter 6 lists all the references cited. The four letter reports are included as attachments.

Project Scope

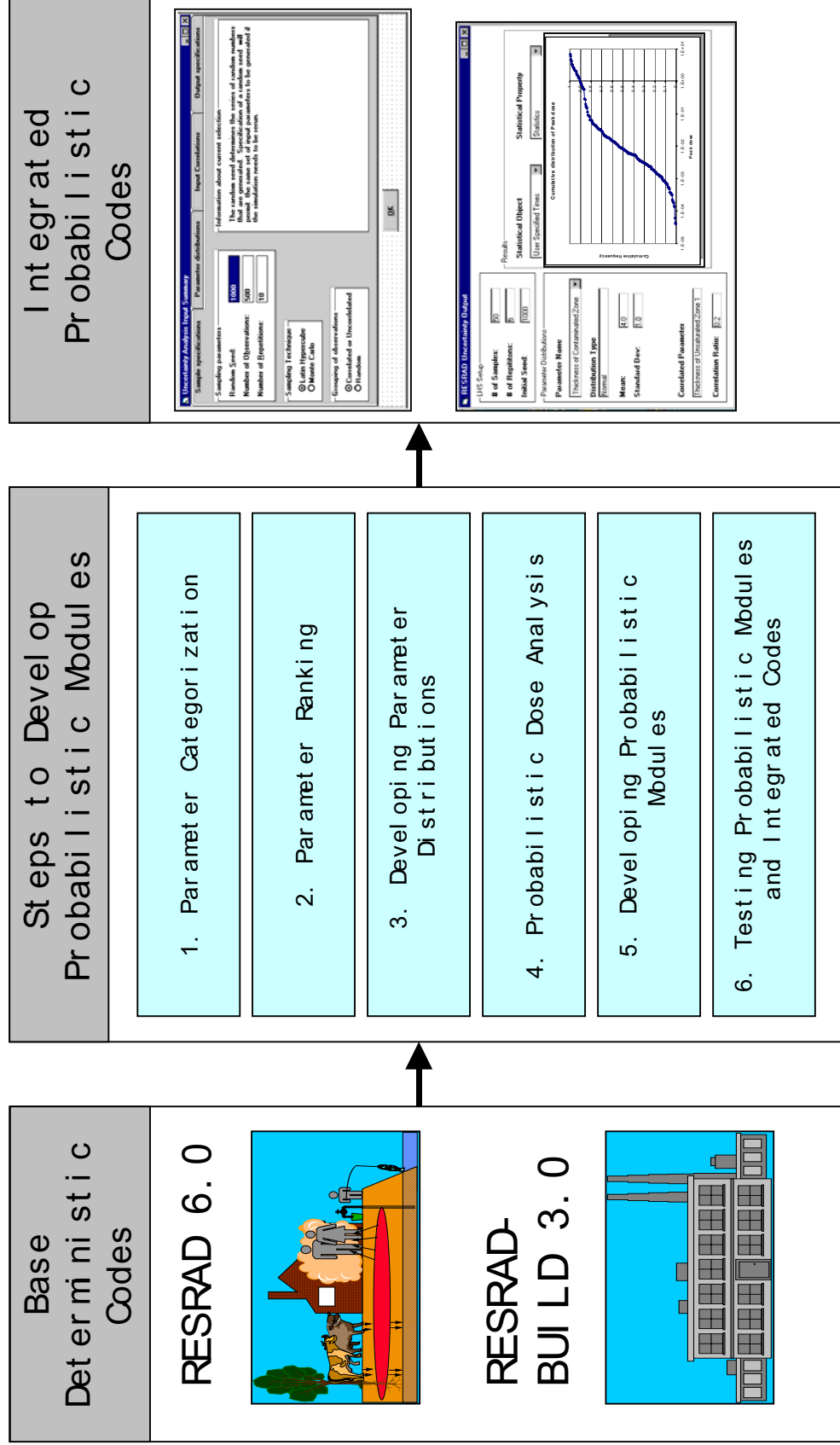


Figure 1.1 Project Scope for Developing Probabilistic RESRAD and RESRAD-BUILD Codes

2 OVERVIEW OF THE DETERMINISTIC RESRAD AND RESRAD-BUILD CODES

RESRAD (Yu et al., 1993b) and RESRAD-BUILD (Yu et al., 1994) computer codes have been developed by Argonne under sponsorship of DOE for use in evaluating radioactively contaminated sites and buildings, respectively, and are widely used in the United States and abroad (Yu, 1999). Both codes are pathway analysis models designed to evaluate the potential radiological dose incurred by an individual who lives at a site with radioactively contaminated soil or who works in a building containing residual radioactive material.

The radiation dose calculated by the codes from the resulting exposure is defined as the effective dose equivalent (EDE) from external radiation plus the committed effective dose equivalent (CEDE) from internal radiation. The total dose is the sum of the external radiation EDE and the internal radiation CEDE and is referred as the TEDE.

2.1 RESRAD

RESRAD (Yu et al., 1993b) implements the methodology described in DOE's manual for developing residual radioactive material guidelines and calculates radiation dose and excess lifetime cancer risk to a chronically exposed individual at a site with residual contamination.

The RESRAD code focuses on radioactive contaminants in soil and their transport in air, water, and biological media to a single receptor. Nine exposure pathways are considered in RESRAD: direct exposure, inhalation of particulates and radon, and ingestion of plant foods, meat, milk, aquatic foods, water, and soil. Figure 2.1 illustrates conceptually the exposure pathways considered in RESRAD.

The code uses a pathway analysis method in which the relation between radionuclide concentrations in soil and the dose to a member of a critical group is expressed as a pathway sum, which is the sum of products of "pathway

factors." Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or from which radiation can be emitted.

Radiation doses, health risks, soil guidelines, and media concentrations are calculated over user-specified time intervals. The source is adjusted over time to account for radioactive decay and ingrowth, leaching, erosion, and mixing. RESRAD uses a one-dimensional groundwater model that accounts for differential transport of parent and progeny radionuclides with different distribution coefficients. (A more versatile groundwater model has been implemented in another code in the RESRAD family — RESRAD-OFFSITE.)

RESRAD is designed to evaluate sites with soil that contains residual radioactive material. It can be used to derive cleanup criteria for a contaminated site, as well as for site screening and pre- and post-remediation dose/risk assessment. The initial source of contamination is assumed to be anthropogenic radionuclides in soil at a contaminated site; however, measured concentrations of radionuclides in a downgradient well can also be included in code calculations.

The RESRAD code is used to analyze doses to on-site individuals under current or plausible future land uses of the site. The default land use scenario in RESRAD assumes the presence of an on-site subsistence farmer with all exposure pathways active. By suppressing selected pathways and modifying applicable intake or occupancy parameter values, any number of potential scenarios and sets of conditions can be simulated.

RESRAD calculates time-integrated annual dose, soil guidelines, radionuclide concentrations, and lifetime cancer risks as a function of time. The user may request results for up to nine different times (time zero is

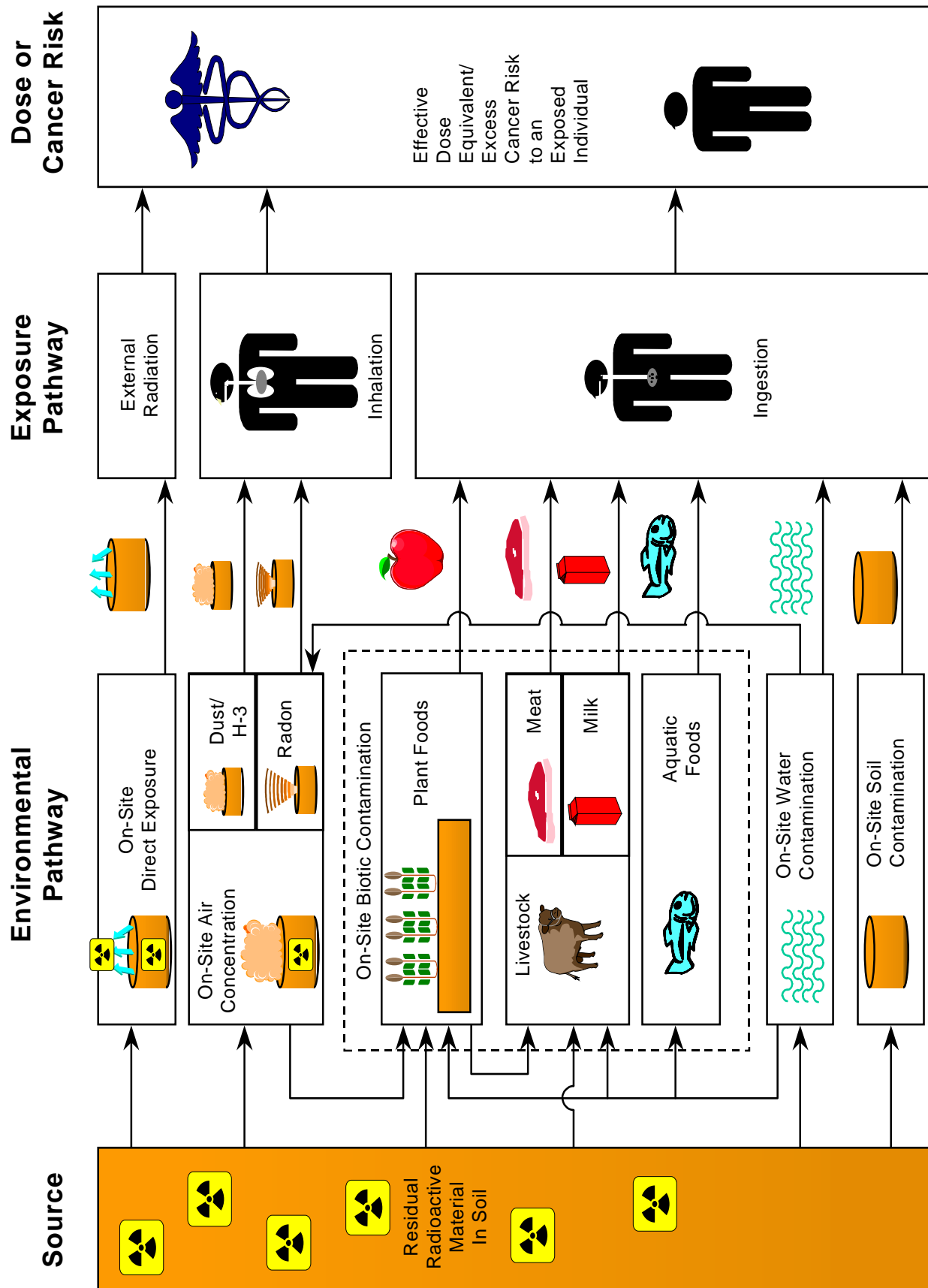


Figure 2.1 Graphical Representation of Pathways Considered in RESRAD

always calculated). Any time horizon up to 100,000 years may be selected. The code estimates at which time the peak dose occurs for each radionuclide and for all radionuclides summed.

It is assumed that the short-lived decay products with half-lives of 30 days or less, referred to as the associated radionuclides, are in secular equilibrium with their parent. The RESRAD database includes 91 principal radionuclides and more than 50 associated radionuclides in the decay chains. Table 2.1 lists principal radionuclides in RESRAD (and RESRAD-BUILD).

The chemical form of the radionuclide is considered in dose conversion factors (DCFs) for radionuclides taken up internally. For ingestion, the user may select the DCF for one or more gastrointestinal (GI) tract fractions. For inhalation, the user may select the DCF for one or more inhalation classes. RESRAD defaults are for the most conservative DCFs when more than one GI fraction or inhalation class is available. Short-lived radionuclides (with half-lives of less than 1 month) are considered to be in secular equilibrium with their parents. Thus, their DCF values and slope factors are added to the DCF values and slope factors of the parent radionuclide. Special models are developed that take into account the different chemical forms and transport of tritium (as tritiated water and water vapor) and carbon-14 (as organic carbon and carbon-dioxide) in the environment. A diffusion model is also developed for radon-222 and radon-220 transport in the environment.

The RESRAD methodology requires parameter values for the homogeneous layers (one optional cover layer, one contaminated zone, one to five optional unsaturated zones, and one optional saturated zone). The code can assess doses from small areas of contamination, and no constraints are placed on the area or thickness of any layer. In most cases, the receptor is assumed to be located on the site (outdoors and/or indoors, 1 m above the soil surface) and may obtain water from a well or pond located in the middle of the site (mass-balance model) or at the downgradient edge of the site (nondispersion model). For the external gamma pathway, the default source area is assumed to be circular, with the receptor

located above the center. However, the user may select a noncircular area, with the receptor located anywhere, including at off-site locations.

In the RESRAD computations, longer-lived progeny of all radionuclides are tracked separately from their parents. This procedure allows the user to account for the different properties of the decay products during transport from the contaminated zone through the unsaturated zone and into the saturated zone. The distribution coefficient for each long-lived radionuclide within each zone may be different and will depend on the chemical form of the radionuclide and the properties of the soil through which it is traveling. The distribution coefficient values may be entered by the user, or the code may be used to estimate these values by any of four separate methodologies: (1) concentration input for radionuclide in a downgradient well and time since material placement, (2) direct input of the leach rate from the contaminated zone, (3) input of solubility limit, and (4) correlation with the soil/plant transfer factor.

The RESRAD code permits sensitivity analysis for various parameters. Graphics are used to show the sensitivity analysis results. Five text reports are provided for users to view the deterministic analysis results through a text viewer.

2.2 RESRAD-BUILD

The RESRAD-BUILD code (Yu et al., 1994) 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. 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. It should be noted that certain default parameters and

Table 2.1. List of Principal Radionuclides^a in RESRAD and RESRAD-BUILD

ID	Radionuclide	ID	Radionuclide	ID	Radionuclide
1	Ac-227+D ^b	32	Fe-55	63	S-35 ^c
2	Ag-108m+D	33	Fe-59 ^c	64	Sb-124 ^c
3	Ag-110m+D	34	Gd-152	65	Sb-125+D ^e
4	Al-26	35	Gd-153	66	Sc-46 ^c
5	Am-241	36	Ge-68+D	67	Se-75 ^c
6	Am-243+D	37	H-3	68	Se-79 ^c
7	Au-195	38	I-125 ^c	69	Sm-147
8	Ba-133 ^c	39	I-129	70	Sm-151
9	Bi-207	40	Ir-192 ^c	71	Sn-113 ^c
10	C-14	41	K-40	72	Sr-85 ^c
11	Ca-41	42	Mn-54	73	Sr-89 ^c
12	Ca-45 ^c	43	Na-22	74	Sr-90+D
13	Cd-109	44	Nb-93m ^c	75	Ta-182 ^c
14	Ce-141 ^c	45	Nb-94	76	Tc-99
15	Ce-144+D	46	Nb-95 ^c	77	Te-125m ^c
16	Cf-252	47	Ni-59	78	Th-228+D
17	Cl-36	48	Ni-63	79	Th-229+D
18	Cm-243	49	Np-237+D	80	Th-230+D
19	Cm-244	50	Pa-231	81	Th-232
20	Cm-245 ^c	51	Pb-210+D ^d	82	Tl-204
21	Cm-246 ^c	52	Pm-147	83	U-232
22	Cm-247 ^c	53	Po-210 ^c	84	U-233
23	Cm-248	54	Pu-238	85	U-234
24	Co-57	55	Pu-239	86	U-235+D
25	Co-60	56	Pu-240	87	U-236
26	Cs-134	57	Pu-241+D	88	U-238+D
27	Cs-135	58	Pu-242	89	Zn-65
28	Cs-137+D	59	Pu-244+D	90	Zr-93 ^c
29	Eu-152	60	Ra-226+D	91	Zr-95 ^c
30	Eu-154	61	Ra-228+D		
31	Eu-155	62	Ru-106+D		

^a Associated radionuclides with half-lives of less than 30 days in RESRAD and of less than 6 months in RESRAD-BUILD are in secular equilibrium with their parent.

^b +D indicates that associated radionuclides are in secular equilibrium with the principal radionuclide.

^c Radionuclide is not in RESRAD-BUILD database.

^d For RESRAD-BUILD, associated radionuclide Po-210 is in secular equilibrium with Pb-210, whereas for RESRAD, Po-210 can be either a principal radionuclide or an associated radionuclide, depending on the cut-off half-life selected.

^e For RESRAD-BUILD, associated radionuclide Te-125m is in secular equilibrium with Sb-125 whereas for RESRAD, Te-125m can be either a principal radionuclide or an associated radionuclide, depending on the cut-off half-life selected.

model assumptions used in RESRAD-BUILD 3.0 may be incompatible or inconsistent with NRC's assumptions of scenarios and default parameters in NUREG/CR-5512 for the critical group of receptors. NRC staff is developing the template files for users to minimize such incompatibilities. NRC staff will inform users when these template files become available.

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. It should be noted that pathways 3, 5, and 7 are not included in the NUREG/CR-5512 building occupancy scenario. Figure 2.2 conceptually illustrates the exposure pathways considered in RESRAD-BUILD.

The air quality model in RESRAD-BUILD 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. With RESRAD-BUILD, the user can construct the exposure scenario by adjusting the input parameters. Typical building exposure

scenarios include long-term occupancy (resident and office worker) and short-term occupancy (remediation worker and visitor). It should be noted that the building occupancy scenario specified in NUREG/CR-5512 assumes occupancy by a typical light-industry worker.

RESRAD-BUILD can take into account the attenuation afforded by the shielding material between each source-receptor combination when calculating the external dose. The user can select the shielding material from eight material types and input the thickness and density of the material. The user can define the source as point, line, area, or volume source. (Note that NRC's building occupancy scenario assumes an area source only.) 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 decay products with half-lives of 6 months or less, referred to as the associated radionuclides, are in secular equilibrium with their parent. Table 2.1 lists radionuclides in both the RESRAD-BUILD and RESRAD databases. RESRAD-BUILD has a graphic (3-D display) interface to show the relative positions and shapes of sources and receptors. A text report is provided that contains the deterministic analysis results.

RESRAD-BUILD Pathways

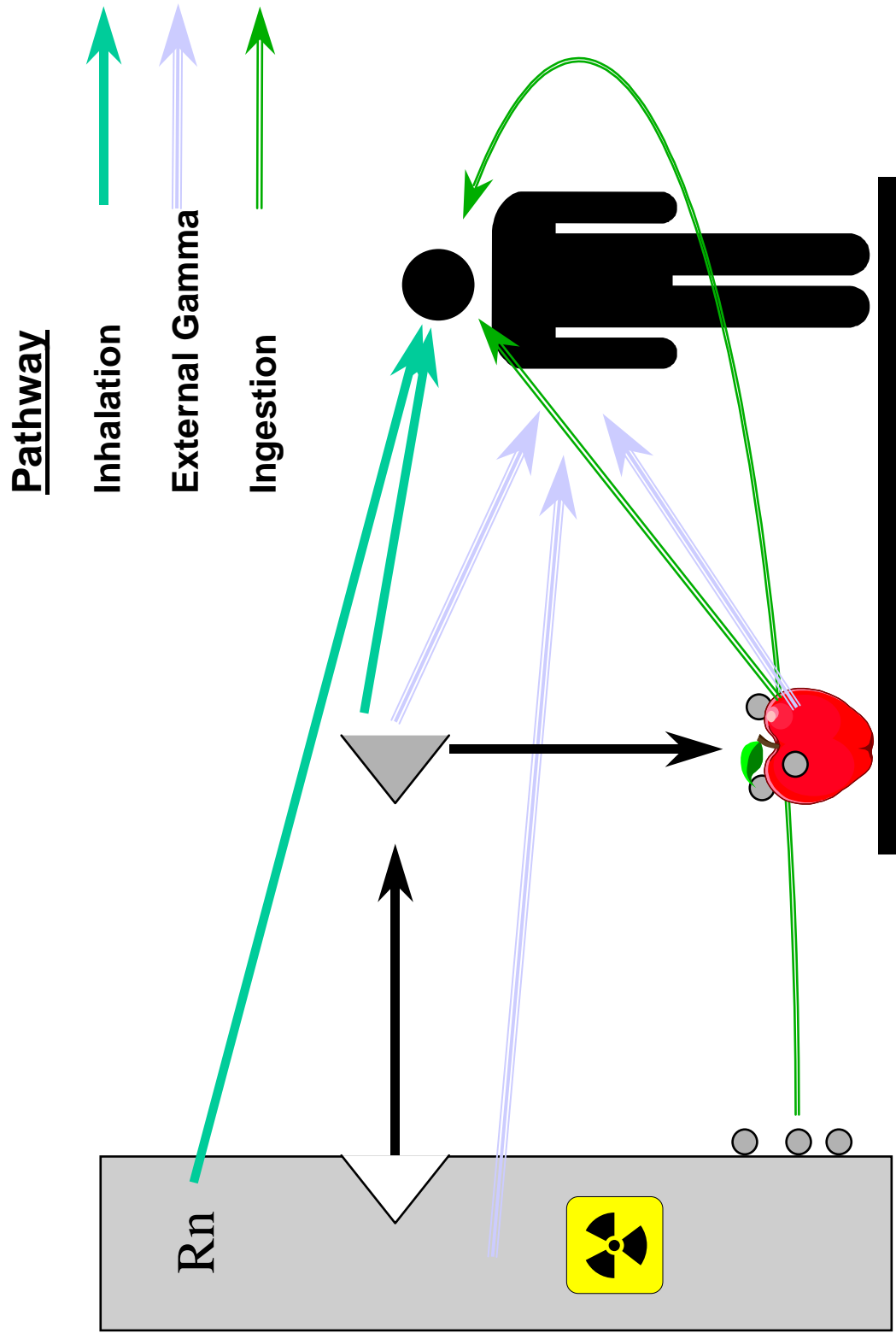


Figure 2.2 Graphical Representation of Pathways Considered in RESRAD-BUILD

3 PROCEDURES TO DEVELOP PROBABILISTIC RESRAD AND RESRAD-BUILD CODES

The deterministic RESRAD and RESRAD-BUILD codes have been widely used, and many supporting documents are available, including benchmarking, verification, and validation documents (Camus et al., 1999; Cheng et al., 1995; Yu, 1999; Yu and Gnanapragasam, 1995; Halliburton NUS Corp., 1994; Faillace et al., 1994; IAEA, 1996; Laniak et al., 1997; Mills et al., 1997; Seitz et al., 1992; Seitz et al., 1994; Whelan et al., 1999a, 1999b; Gnanapragasam and Yu, 1997a, 1997b; BIOMOVs II, 1996; Regens, 1998; Yu et al., 1993a, 1993b, 1994). One implicit requirement of developing the probabilistic RESRAD and RESRAD-BUILD codes was that the deterministic code results should not be affected by the probabilistic modules. This requirement is factored into the quality assurance/quality control (QA/QC) of the integrated probabilistic code systems.

The procedures for developing probabilistic RESRAD and RESRAD-BUILD codes are illustrated in Figure 3.1. Also shown in Figure 3.1 are the report numbers of the reports generated in each step. It can be seen that the steps are not sequential; some steps were carried out concurrently, and some steps were done iteratively pending the results of other steps. For example, Step 3 parameter distributions were generated and incorporated into Step 5 (the probabilistic module) and tested and analyzed in Step 4 (using the probabilistic module developed in Step 5), and the results of Step 4 were fed back to Step 3 for further refinement of parameter distributions. Each step is summarized in the following 6 sections. Full reports on each step are available, and the location or report numbers are indicated in Figure 3.1.

3.1 LISTING AND CATEGORIZING INPUT PARAMETERS

The first step in developing parameter distributions was listing all the input parameters used in the RESRAD and RESRAD-BUILD codes. RESRAD has 130 radionuclide-independent parameters, 10 radionuclide-

dependent parameters, and 5 element-dependent parameters. RESRAD-BUILD has 45 radionuclide-independent and 5 radionuclide-dependent parameters. For the radionuclide-dependent parameters, the distribution characteristics have to be generated for each radionuclide. A list of parameters and their definitions are included in Attachment A. Also included in the list is the classification of the parameters. The parameters are classified into three types: physical, behavioral, and metabolic. Some parameters may belong to more than one of these types. Additionally, if a parameter does not fit the definition of either physical or metabolic, it is classified as a behavioral parameter. Three RESRAD parameters are not classified because of their function in the code: "Basic radiation dose limit," "Use plant/soil ratio," check box, and "Accuracy for water soil computation."

Physical Parameter (P): Any parameter whose value would not change if a different group of receptors was considered is classified as a physical parameter. Physical parameters would be determined by the source, its location, and geological or physical characteristics of the site (i.e., these parameters are source- and site-specific).

Behavioral Parameter (B): Any parameter whose value would depend on the receptor's behavior and the scenario definition is classified as a behavioral parameter. For the same group of receptors, a parameter value could change if the scenario changed (e.g., parameters for recreational use could be different from those for residential use).

Metabolic Parameter (M): If a parameter represents the metabolic characteristics of the potential receptor and is independent of scenario, it is classified as a metabolic parameter. The parameter values may be different in different population age groups. According to the recommendations of the International Commission on Radiological Protection Report 43 (ICRP, 1984), parameters representing metabolic characteristics are

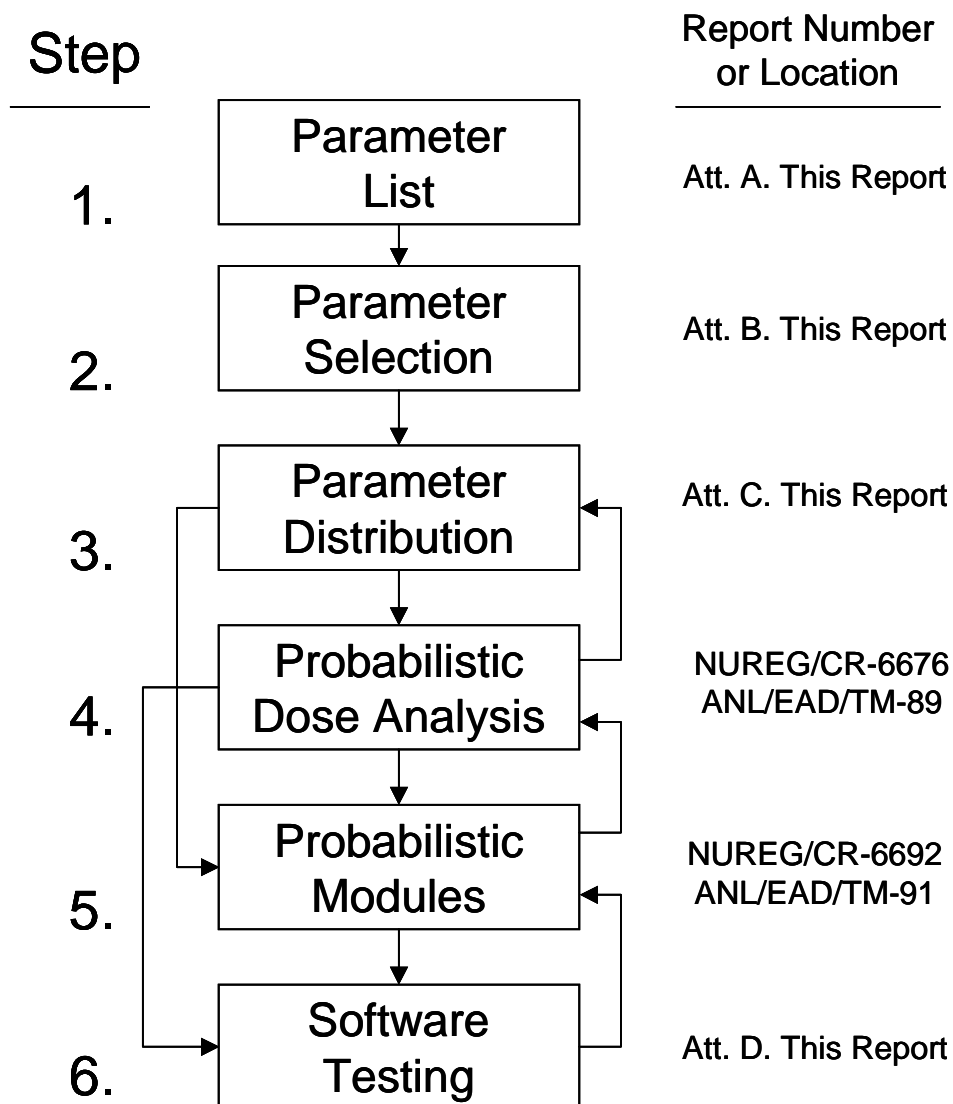


Figure 3.1 Flow Diagram of Steps in Developing Probabilistic RESRAD and RESRAD-BUILD Codes and the Report Locations for Each Step

defined by average values for the general population. These values are not expected to be modified for a site-specific analysis because the parameter values would not depend on site conditions.

Some parameters can be classified as more than one type. For example, inhalation rate is identified as M,B in Table 2.1 of Attachment A. This classification indicates that inhalation rate depends primarily on the metabolic characteristics of the potential receptor, but that

it also depends on the receptor behavior or exposure scenario.

The parameter classification results show that for RESRAD, there are 89 physical parameters, 16 behavioral parameters, 10 metabolic parameters, 27 dual-type parameters, and 3 unclassified parameters. For RESRAD-BUILD, there are 26 physical parameters, 11 behavioral parameters, 4 metabolic parameters, and 9 dual-type parameters.

3.2 SELECTING PARAMETERS FOR DISTRIBUTION ANALYSIS

The second step was to rank the parameters listed in Step 1 and select them for data collection and distribution analysis. The parameters were ranked into three priority levels: 1 (high priority), 2 (medium priority), and 3 (low priority). The assignment of priority was based on four attributes: (1) relevance of parameters in dose calculations, (2) variability of radiation dose as a result of changes in the parameter value, (3) parameter type, and (4) data availability. These four attributes are discussed in detail in Attachment B and are summarized below.

3.2.1 Attribute 1: Relevance in Dose Calculations

Irrelevant parameters are those used for selecting a mathematical model; those whose values can be derived by the code using other parameters; those whose values are normally set to 0 or 1; and those used for radon dose calculations. Irrelevant parameters received a score of 9. All other parameters are relevant parameters and received a score of 0.

3.2.2 Attribute 2: Influence on Dose Variability

The influence of the parameter on dose is gauged by using a sensitivity analysis approach. A quantity — normalized dose difference (NDD) — is calculated as
$$NDD = (D_{high} - D_{low}) / D_{base} \times 100\%$$
 where $(D_{high} - D_{low})$ is the potential range of the peak radiation dose and D_{base} is the peak dose calculated by setting the studied parameter to its base value. D_{base} is used as a normalization factor. D_{high} and D_{low} are the peak doses obtained by setting the parameter to its high and low values, respectively. The base case used was a subsistence farmer scenario for RESRAD and a building occupancy scenario for RESRAD-BUILD. The parameter values used for the base cases are presented in Attachment B. The representative radionuclides considered in this study are Co-60, Sr-90, Cs-137, Ra-226, Th-230, U-238, Pu-239, and Am-241. The largest NDD among those calculated for the

representative radionuclides was selected to represent each parameter's influence, and a numeric score of 1 to 7 was assigned to each parameter on the basis of the largest NDD.

3.2.3 Attribute 3: Parameter Type

Three parameter types were used in Step 1. Metabolic parameters usually are not expected to vary from site to site. Physical parameters are usually site specific. Behavioral parameters are in between, and they vary only when the critical group of the exposed population is different. Numeric scores of 1, 5, and 9 were assigned to physical parameters, behavioral parameters, and metabolic parameters, respectively. Some parameters were categorized as dual type; for those parameters, the lower numeric score was used.

3.2.4 Attribute 4: Data Availability

A literature search was conducted to determine data availability. Data were known to be available for analysis for some parameters, but other parameters had either less or little data available. Numeric scores of 1, 3, and 5 were assigned to parameters with known data availability, with less data availability, and with little data availability, respectively. Some parameters require site-specific values, and a numeric score of 5 was assigned to those parameters.

The numeric scores of the four attributes were summed for each parameter, and an overall rank of 1 to 3 was assigned on the basis of the sum of the scores. Among the 145 RESRAD parameters ranked, 10 were ranked at priority 1, 39 were ranked at priority 2, and 96 were ranked at priority 3. For RESRAD-BUILD, for which 50 parameters were ranked, 4 were at priority 1, 20 at priority 2, and 26 at priority 3. The ranking strategy provided a systematic way to evaluate the input parameters and enabled successful accomplishment of the objective of the project.

Detailed discussion on the ranking and the four attributes are included in Attachment B.

3.3 DEVELOPING DEFAULT PARAMETER DISTRIBUTIONS

In Step 2, parameters were ranked and placed in one of three priority categories (priorities 1 through 3). Priority 1 was assigned to the most relevant (high-priority) parameters and priority 3 to the least relevant (low-priority) parameters. Argonne and the NRC Dose Modeling Working Group agreed that priority 3 parameters would be excluded from distribution analysis at the present time because parameters in this category had already been determined to be of low priority and of insignificant impact on the overall results of dose estimation. The Parameter Distribution Report (Attachment C) assigned distributions to most priority 1 and 2 parameters in RESRAD and RESRAD-BUILD. However, a few directly measurable, site-specific-input parameters, such as radionuclide concentration, area of contamination, and thickness of contaminated zone, were not assigned distributions. Table 3.1 lists the parameters assigned distributions; it also lists the parameter type and assigned distribution type for each. Of the 66 parameters that were assigned distributions, 19 are log normal distribution, 9 are normal distribution, 19 are triangular distribution, 14 are uniform/log uniform distribution, and 5 are empirical distribution.

Assignment of an appropriate distribution to a RESRAD or RESRAD-BUILD input parameter was determined primarily by the quantity of relevant data available. Documented distributions were used whenever they were available. However, data were often lacking for environmental exposure pathways. As fewer data became available, secondary types of information were used in conjunction with existing sample data to assign the distribution.

Empirical distributions were available for some parameters within the context of the critical group or national average. For those parameters for which additional sampling was not expected to significantly change the distribution's shape (i.e., the variability of the parameter was well represented), direct use of the statistical data was made.

Sufficient relevant statistical data (data sets/matching function and parameter

characteristics) were available for some parameters to clearly show a distribution type. If the use of an empirical distribution was not appropriate, the data were fit to the identified distribution. In certain cases, probability plots or other graphical representations were used to determine goodness of fit.

Certain parameters had some data available, but those data were not sufficient to define a distribution type. These parameters were assigned a distribution on the basis of supporting information. If there was a mechanistic basis for assigning a given distribution to the data, such a distribution was used in the case of a sparse data set. In another case, surrogate data may have been used. If a distribution was well known for a parameter on a regional basis, the same distribution was used on a national basis. In either case, care was taken to ensure that the existing data for the target scenario were complemented.

In the case of a parameter for which sufficient data were not available, a distribution that fit a similar class of parameters or similar body of data was assigned. If an appropriate distribution was not found, a maximum entropy approach was used. In such a case, the distribution was restricted only by what was known. Examples included the use of a uniform distribution if only potential lower and upper bounds were available, or the use of a triangular distribution if a most likely value was known in addition to potential lower and upper bounds.

3.4 TESTING PARAMETER DISTRIBUTIONS

Testing of parameter distributions served two purposes — it not only was a test of the parameter distributions developed in Step 3 (Section 3.3), it was also a test of the probabilistic analysis methodology using the probabilistic modules developed in Step 5 (Section 3.5). A full report documenting the test results is provided in NUREG/CR-6676, ANL/EAD/TM-89 (Kamboj et al., 2000). A summary is provided below.

The parameter distributions developed in Step 3 were used in this analysis. This analysis used the residential scenario for the RESRAD code and the building occupancy scenario for the

Table 3.1. Parameters Assigned Probability Density Functions		
Parameter	Parameter Type ^a	Assigned Distribution Type
<i>RESRAD</i>		
Density of contaminated zone (g/cm ³)	P	Normal
Density of cover material (g/cm ³)	P	Normal
Density of saturated zone (g/m ³)	P	Normal
Depth of roots (m)	P	Uniform
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone)(cm ³ /g)	P	Lognormal
Saturated zone effective porosity	P	Normal
Saturated zone hydraulic conductivity (m/yr)	P	Lognormal
Saturated zone total porosity	P	Normal
Transfer factors for plants	P	Lognormal
Unsaturated zone thickness (m)	P	Lognormal
Aquatic food contaminated fraction	B, P	Triangular
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	P	Lognormal
C-14 evasion layer thickness in soil (m)	P	Triangular
Contaminated zone b parameter	P	Lognormal
Contaminated zone erosion rate (m/yr)	P, B	Empirical
Contaminated zone hydraulic conductivity (m/yr)	P	Lognormal
Contaminated zone total porosity	P	Normal
Cover erosion rate (m/yr)	P, B	Empirical
Depth of soil mixing layer (m)	P	Triangular
Drinking water intake (L/yr)	M, B	Lognormal
Evapotranspiration coefficient	P	Uniform
External gamma shielding factor	P	Lognormal
Fruit, vegetables, and grain consumption (kg/yr)	M, B	Triangular
Indoor dust filtration factor	P, B	Uniform
Mass loading for inhalation (μg/m ³)	P, B	Empirical
Milk consumption (L/yr)	M, B	Triangular
Runoff coefficient	P	Uniform
Saturated zone b parameter	P	Lognormal
Saturated zone hydraulic gradient	P	Lognormal
Soil ingestion rate (g/yr)	M, B	Triangular
Transfer factors for meat [(pCi/kg)/(pCi/d)]	P	Lognormal
Transfer factors for milk [(pCi/L)/(pCi/d)]	P	Lognormal
Unsaturated zone density (g/cm ³)	P	Normal
Unsaturated zone effective porosity	P	Normal
Unsaturated zone hydraulic conductivity (m/yr)	P	Lognormal
Unsaturated zone, soil-b parameter	P	Lognormal
Unsaturated zone total porosity	P	Normal
Weathering removal constant (1/yr)	P	Triangular
Well pump intake depth (below water table) (m)	P	Triangular
Wet foliar interception fraction for leafy vegetables	P	Triangular
Wet-weight crop yields for nonleafy vegetables (kg/m ²)	P	Lognormal

Table 3.1. Parameters Assigned Probability Density Functions (Continued)		
Parameter	Parameter Type^a	Assigned Distribution Type
Wind speed (m/s)	P	Lognormal
Humidity in air (g/m ³)	P	Lognormal
Indoor fraction	B	Empirical
Inhalation rate (m ³ /yr)	M, P	Triangular
<i>RESRAD-BUILD</i>		
Removable fraction	P, B	Uniform
Resuspension rate (1/s)	P, B	Loguniform
Shielding density (g/cm ³)	P	Uniform
Source density, volume source (g/cm ³)	P	Uniform
Air exchange rate for building and room (1/h)	B	Lognormal
Air release fraction ^c	B	Triangular
Deposition velocity (m/s)	P	Loguniform
Humidity (g/m ³)	P, B	Uniform
Indoor fraction	B	Empirical
Receptor indirect ingestion rate (m ² /h)	B	Loguniform
Receptor inhalation rate (m ³ /d)	M, B	Triangular
Room area (m ²)	P	Triangular
Room height (m)	P	Triangular
Shielding thickness (cm)	P, B	Triangular
Source erosion rate, volume source (cm/d)	P, B	Triangular
Source porosity	P	Uniform
Source thickness, volume source (cm)	P	Triangular
Time for source removal or source lifetime (d)	P, B	Triangular
Volumetric water content	P	Uniform
Water fraction available for evaporation	P	Triangular
Wet + dry zone thickness (cm)	P	Uniform
^a P = physical, B = behavioral, and M = metabolic; when more than one type is listed, the first is primary and the next is secondary.		

RESRAD-BUILD code. Three hundred samples were used with the Latin hypercube sampling method. For behavioral or metabolic parameters, single mean or median values were used. The results were the dose distribution quantile values based on unit source concentration. Use of regression analysis to identify sensitive parameters was explored. The results indicated that no single correlation or regression coefficient alone could be used to identify sensitive parameters for all cases. The dose variability for the RESRAD-BUILD results was much greater than that of RESRAD results. This test did not result in any significant

changes in the parameter distribution characteristics previously defined.

3.5 DEVELOPING PROBABILISTIC MODULES

The next step was to develop probabilistic modules for the RESRAD and RESRAD-BUILD codes. The requirements of the probabilistic modules were as follows: the deterministic results should not be changed; the parameter distributions identified in Step 3 should be used; the Latin hypercube sampling (LHS) method

should be supported; the modules should have a robust, user-friendly interface; they should provide graphical, interactive, and complete output; they should support “peak of the mean” as well as “mean of the peak” statistical dose analysis; they should be compatible with Windows (especially NT) operating systems; and they should be integrated into the RESRAD and RESRAD-BUILD codes.

Completion of this task resulted in development of the new (probabilistic) RESRAD code version 6.0 and the RESRAD-BUILD code version 3.0. The development of these codes followed the same stringent configuration and quality control/quality assurance methods originally used for the RESRAD family of codes. A user's guide for the integrated probabilistic RESRAD and RESRAD-BUILD codes is provided in Chapter 3 of NUREG/CR-6692, ANL/EAD/TM-91 (LePoire et al., 2000). An overview of the probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 is included in Chapter 4 of this report. The testing of the integrated codes is discussed in the next section.

The codes, user's guide, and other supporting documents can be downloaded from the ANL RESRAD web site (<http://web.ead.anl.gov/resrad>) and the NRC web site (<http://www.nrc.gov>).

3.6 TESTING PROBABILISTIC CODES

The next step in the process was comprehensive testing of the probabilistic RESRAD and RESRAD-BUILD codes. Testing of the codes is an ongoing process that started at the beginning of the development phase. The LHS program obtained from Sandia National Laboratories was first tested and compiled using a Lahey Fortran 77 compiler. The LHS program was successfully incorporated into RESRAD and RESRAD-BUILD with minor modifications (see Attachment D for details). The distributions generated by LHS were also verified, and the passing of distribution data to the deterministic RESRAD and RESRAD-BUILD codes was also successfully verified.

The post-processor program PCCSRC for correlation and regression analysis was also

improved with double precision to get more accurate results. The program was previously tested and verified.

The integrated probabilistic codes were tested to verify that they function as designed for all radionuclides and all pathways selected. The input parameter correlations were also tested and verified for proper function.

The calculational output was also tested. The percentile and statistics of the interactive tables and the report were compared and verified (with minor differences due to different calculational approach). The tables and graphs were compared and the results were the same.

The calculation, interface, and distribution aspects of the fully integrated system were tested with designed scenarios. The correlations of input parameters were tested. The results indicated that for some parameters, users need to specify correlations and must look at the LHS report to ensure that any adjustments to the rank correlation matrix suggested by the code are acceptable.

The test of the correlations indicated that the identification of sensitive parameters is not always straightforward. A number of analytical tools are provided by the RESRAD and RESRAD-BUILD codes. These tools include scatter plots, temporal plots of the mean dose and selected dose percentiles, and correlation and regression coefficients. Each of these tools is appropriate under different circumstances.

The testing of codes also included the testing of the distribution of codes via compact disks (CDs). The CD used for distribution was successfully tested on several computer systems, including Windows 95, 98, 2000, and NT 4.0 operating systems.

NRC also provided extensive testing of the integrated code system, as well as of the user's guide. NRC's testing resulted in enhancement and improvement of the operation of the code system. A detailed listing of NRC comments and Argonne responses to those comments is included in Appendices A and B of Attachment D.

4 OVERVIEW OF THE PROBABILISTIC RESRAD AND RESRAD-BUILD CODES

The probabilistic RESRAD and RESRAD-BUILD codes are extended and enhanced from the deterministic RESRAD and RESRAD-BUILD codes. The deterministic results produced by the two codes are not affected by this extension and enhancement. A pre-processor and a post-processor are incorporated into the RESRAD and RESRAD-BUILD codes to facilitate analysis of the effects of uncertainty in or the probabilistic nature of input parameters in the model. A standard Monte Carlo method or a modified Monte Carlo method, that is, Latin hypercube sampling (LHS) (McKay et al., 1979), can be applied to generate random samples of input parameters. Each set of input parameters is used to generate one set of output results. Figure 4.1 shows a typical parameter distribution input screen that allows the user to view and edit all currently specified parameter distributions for probabilistic analysis. Once the distribution statistics are specified, the user can click the help button and the distribution will be shown on the screen, as shown in Figure 4.2.

The results from all input samples are analyzed and presented in a statistical format in terms of the average value, standard deviation, minimum value, and maximum value. The cumulative probability distribution of the output is presented in tabular and graphic forms. Scatter plots of dose against the probabilistic inputs and temporal plots of dose statistics can be viewed. Further analysis using regression methods can be performed to find the correlation of the resultant doses with the input parameters. Partial correlation coefficients (PCC), partial rank correlation coefficients (PRCC), standardized partial regression coefficients (SPRC), and standardized partial rank regression coefficients (SPRRC) are computed and ranked to provide a tool for determining the relative importance of input parameters in influencing the resultant dose.

4.1 SAMPLING METHOD

Samples of the input parameters are generated with an updated version of the LHS computer

code (Iman and Shortencarier, 1984). The uncertainty input screen of the user interface collects all the data necessary for the sample generation and prepares the input file for the LHS code. When the code is executed (run), the LHS code will be called if the user has requested a probabilistic/uncertainty analysis. Table 4.1 lists the input data and information needed for sample generation.

The input data required for sample generation are divided in three categories: (1) sampling specifications data, (2) statistical distributions data, and (3) input rank correlation data. The input data and information needed for the sample generation include the initial seed value for the random number generator, the number of observations (N_{obs}), the number of repetitions (N_{rep}), the sampling technique, the method of grouping the samples generated for the different parameters, the type of statistical distribution for each input parameter, the parameters defining each of the distributions, and any correlations between input parameters.

Two sampling techniques are available, LHS and simple random (Monte Carlo) sampling (SRS). The LHS technique is an enhanced, stratified sampling scheme developed by McKay et al. (1979). It divides the distribution of each input parameter into N_{obs} nonoverlapping regions of equal probability. One sample value is obtained at random (using the current random seed) from each region on the basis of the probability density function for that region. Each time a sample is obtained, a new random seed for use in the next region is also generated by using the current random seed. The sequence of random seeds generated in this manner can be reproduced if there is ever a need to regenerate the same set of samples. After a complete set of N_{obs} samples of one probabilistic/uncertain parameter has been generated, the same procedure is repeated to generate the samples for the next parameter.

The Monte Carlo sampling, or SRS, technique also obtains the N_{obs} samples at random; however, it picks out each sample from the

Uncertainty Analysis Input Summary			
Sample specifications	Parameter distributions	Input Rank Correlations	Output specifications

Variable Description	Statistics of Uncertain variable
Kd of U-238 in Contaminated Zone	Plant transfer factor for U Distribution LOGNORMAL-N Default Mean (Mu) of underlying normal -6.21 Standard deviation (Sigma) of underlying normal .916291
Kd of U-238 in Unsaturated Zone 1	
Kd of U-238 in Saturated Zone	
Plant transfer factor for U	
	<div style="display: flex; justify-content: space-between; margin-top: 20px;"> Previous parameter ▲ Next parameter ▼ </div> <div style="display: flex; justify-content: space-around; margin-top: 10px;"> Remove parameter Help Restore Default </div>

☒ Perform uncertainty analysis
☐ Suppress uncertainty analysis this session

OK

Figure 4.1 Parameter Distribution Input Screen

entire distribution using the probability density function for the whole range of the parameter. Report No. 100 of the International Atomic Energy Agency safety series (IAEA, 1989) discusses the advantages of the two sampling techniques.

The N_{obs} samples generated for each probabilistic/uncertain parameter must be combined to produce N_{obs} sets of input parameters. Two methods of grouping (or combining) are available — random grouping or correlated/uncorrelated grouping. Under random grouping, the N_{obs} samples generated for each of the parameters are combined randomly to produce (N_{obs}) sets of inputs. For N_{var} probabilistic/uncertain parameters, there are $(N_{obs})^{N_{var}}$ ways of combining the samples. It is possible that some pairs of parameters may be correlated to some degree in the randomly

selected grouping, especially if N_{obs} is not sufficiently larger than N_{var} .

In the correlated/uncorrelated grouping, the user specifies the degree of correlation between each correlated parameter by inputting the correlation coefficients between the ranks of the parameters. The pairs of parameters for which the degree of correlation is not specified are treated as being uncorrelated. The code checks whether the user-specified rank correlation matrix is positive definite and suggests an alternative rank correlation matrix if necessary. The code then groups the samples so that the rank correlation matrix is as close as possible to the one specified. Both matrices are saved in the LHS.REP file (which is generated by the RESRAD or RESRAD-BUILD code after the probabilistic analysis is executed. Hence, the

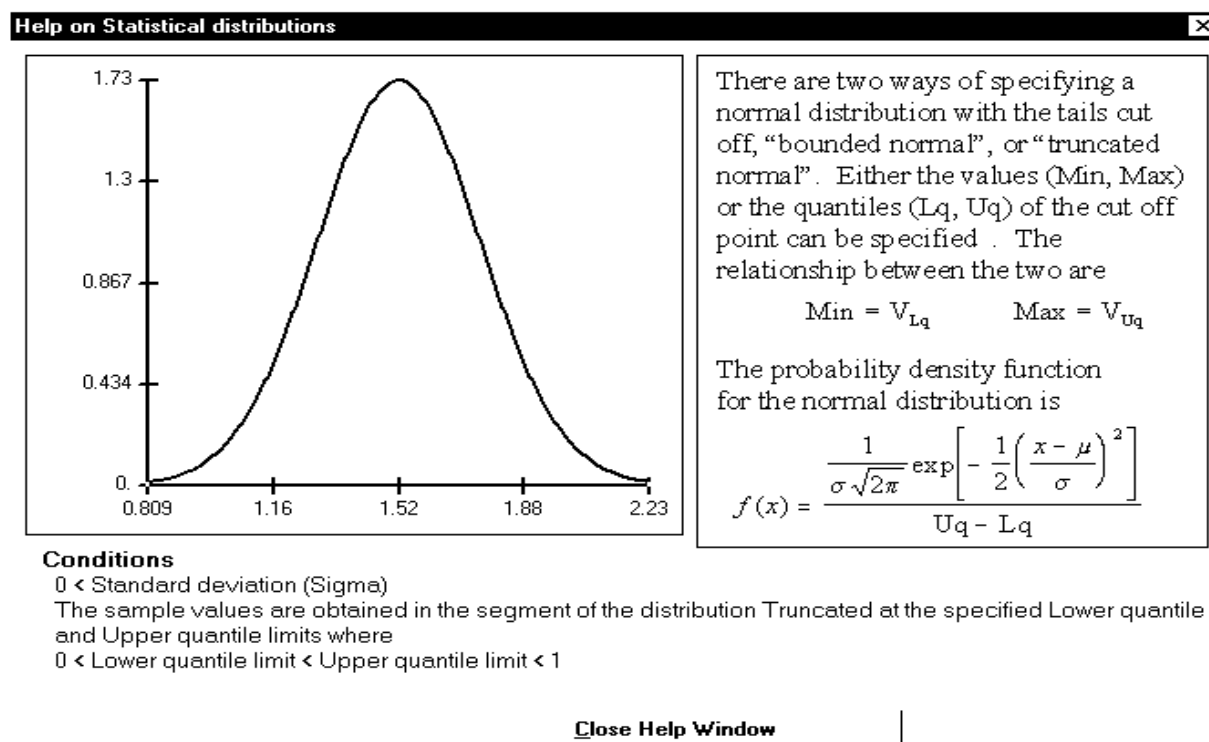


Figure 4.2 An Example of a Help Screen Displaying Parameter Distribution

user should examine the matrices to verify that the grouping is acceptable.

Iman and Helton (1985) suggest ways of choosing the number of samples for a given situation. The minimum and maximum values of estimated doses or risks vary with the number of samples chosen. The accuracies of the mean dose and of the dose values for a particular percentile are dependent on the percentile of interest and on the number of samples. The confidence interval or the confidence limit (upper or lower) of the mean can be determined from the results of a single set of samples. Distribution-free upper (u%, v%) statistical tolerance limits can be computed by using the SRS technique according to the methodology outlined in IAEA Report No. 100 (IAEA, 1989).

4.2 DISTRIBUTION OF PARAMETERS

A set of input parameters for uncertainty analysis is chosen through the code's interface. Each parameter chosen must have a probability distribution assigned to it and may be correlated

with other input parameters included in the uncertainty analysis. A total of 34 distribution types are available for selection. The statistical parameters required depend on the distribution, and the appropriate input fields are displayed when a specific distribution is selected. The conditions to be satisfied by these statistical parameters are given in the help screen (Figure 4.2). The interface module checks if the selected statistical parameters satisfy the conditions when the user inputs them, and it simultaneously red flags any statistical parameters that violate the conditions. Table A.1 in the Parameter Distribution Report (Attachment C) lists the different distribution types and the required distribution data. The input parameters can be correlated by specifying a pairwise rank correlation matrix. The induced correlation is applied to the ranks of the parameters; hence, the name "rank correlation."

4.3 PROBABILISTIC RESULTS

The results of the probabilistic analysis handled by the post-processor are presented in the summary text files MCSUMMAR.REP in

Table 4.1. Listing of Input Data and Information Needed for Sample Generation	
Input Data	Description
<i>Sampling Parameters</i>	
Random Seed	Determines the sequence of random numbers generated. This ensures that the same set of observations is produced when the given input file is run on different computers, or when an input file is run at different times on the same computer.
Number of Observations	Number of sample values to be generated for each input variable for each repetition. The maximum number allowed is 2001.
Number of Repetitions	Number of times probabilistic analysis is repeated.
<i>Sampling Techniques</i>	
Latin Hypercube	The distribution to be sampled is split into a number of equally probable distribution segments, the number being equal to the desired number of observations. A single observation is obtained from each segment.
Simple Random	The desired number of observations are obtained at random from the whole distribution.
<i>Grouping of Observations</i>	
Correlated or Uncorrelated	The samples of each variable are grouped together according to the specified correlations. The grouping ensures that the variables for which correlations were not specified are uncorrelated.
Random	The samples of each variables are grouped together at random. Some pairs of variables may be correlated just by chance.
<i>Statistical Distributions</i>	
Statistical Distribution and Statistical Parameters	The statistical distribution and its parameters define the set of observations to be generated for a probabilistic variable. The statistical distribution has to be one of the 34 distributions available in the code. The parameters that have to be specified depend on the selected distribution and have to satisfy the conditions of the distribution. These conditions are given in the help screen (Figure 4.2). The input interface will check that these are satisfied when the user completes inputting the parameters.
<i>Input Rank Correlations</i>	
Variable 1, Variable 2	Two variables for which rank correlation is specified.
Rank Correlation Coefficient	The specified input rank correlation coefficient between two variables.

RESRAD and RESBMC.RPT in RESRAD-BUILD.

The interactive output provides graphical and tabular results for peak pathway doses, for peak nuclide doses, and for doses at user-specified times for any pathway-nuclide combination in RESRAD. In RESRAD-BUILD, the output provides results for dose to each receptor via each or all pathways from each or all nuclides in each source at each user time, and for dose to each receptor via each or all pathways from all sources at each user-specified time. The tabular results provided are the minimum, maximum, mean, standard deviation, and the percentile values in steps of 5%, as well as their 95% confidence range where appropriate. Scatter plots associated with the probabilistic inputs and cumulative probability are available in both RESRAD and RESRAD-BUILD. In addition, RESRAD has temporal plots of the mean, 90% and 95% of total dose.

Printable results are available in the text files. In each case, the file contains statistical data for a collection of resultant doses as a function of user time, pathway, radionuclide, source, and receptor, as appropriate. The statistical data provided for the resultant dose include the average value, standard deviation, minimum value, and maximum value. The cumulative probability distribution of the resultant dose is presented in a tabular form in terms of percentile values in steps of 2.5%. Separate tables provided for each repetition in RESRAD give the minimum, maximum, mean, median, the 90th%, 95th%, 97.5th%, and the 99th% of total dose (summed over nuclides and pathways) at graphical times. A single table summarizes the peak of the mean total dose for all observations, and the time of the same for each repetition.

The results include tabulations of the correlation of the resultant doses with the input parameters calculated with regression methods. The input parameters are ranked according to their relative importance and their contribution to the overall uncertainty. The parameter ranks are presented in the correlation tables.

The correlation analyses of the input parameters and the resultant doses (e.g., peak total dose, peak pathway doses, peak nuclide doses, and the dose at the time of the peak of

the mean total dose at graphical times for RESRAD, and total dose, pathway doses, dose for each source, and dose to each receptor at all times for RESRAD-BUILD) are based on the methodology of Iman et al. (1985). The correlation results in RESRAD 6.0 and RESRAD-BUILD 3.0 are summarized in a table. The correlating statistical data provided include partial correlation coefficients (PCCs), standardized regression coefficients (SRCs), partial rank correlation coefficients (PRCCs), and the standardized rank regression coefficient (SRRC), as well as their associated correlation ranks. The coefficients of determination are provided at the end of the table. If the correlation and rank are desired for a dose resulting from a specific radionuclide and pathway, it is suggested that the user run the code for the same problem with only the radionuclide and pathway of interest.

The coefficient of determination varies between 0 and 1 and presents a measure of the variation in the peak dose explained by the regression on the input parameters involved in the analysis. Thus, a value of 0 is displayed if the selected input parameters do not influence the calculated dose, and regression on these parameters does not yield an estimate of the output. The coefficient of determination is set to 0 in the code if the resultant correlation matrix is singular.

The correlation ranking of the parameters is based on the absolute value of the correlation coefficients; rank 1 is assigned to the parameter with the highest value. Thus, a parameter with a correlation rank of 1 has the strongest relationship with the total dose. The correlation rank is set to 0 in the code if the correlation of the resultant doses is 0, or if the resulting correlation matrix is singular.

The PCC is calculated in the code by using the actual values of the input parameter and the resultant dose. It provides a measure of the linear relationship between the input parameter and the dose. The SRC is calculated by using the standardized values (i.e., [actual value-mean]/standard deviation) of the input parameter and the dose. It provides a direct measure of the relative importance of the input parameter independent of the units being used to measure the different parameters.

When nonlinear relationships are involved, it is often more revealing to calculate SRCs and PCCs on parameter ranks than on the actual values for the parameters; such coefficients are the SRRCs and PRCCs. The smallest value of each parameter is assigned rank 1, the next smallest value is assigned rank 2, and so on up to the largest value, which is assigned rank n , where n denotes the number of samples. The standardized regression coefficients and partial correlation coefficients are then calculated on these ranks. In general, use of PRCC and SRRC is recommended over PCC and SRC when nonlinear relationships, widely disparate

scales, or long tails are present in the inputs and outputs.

Table 4.2 compares the approaches available for correlating the uncertainty in the distribution of doses to the uncertainty in the input parameter. Additional information on input and output of the probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 codes can be found in the user's guide (NUREG/CR-6692, ANL/EAD/TM-91) of the probabilistic RESRAD and RESRAD-BUILD codes (LePaire et al., 2000). A quick tour of these codes is also included in Appendix C of that guide.

Table 4.2. Comparison of Approaches for Correlating the Uncertainty in the Distribution of Doses to the Uncertainty in the Input Parameter		
Approach	Advantages	Disadvantages
PCC	Measures linear relationship and gives the unique contribution of an input parameter to the resultant dose.	Large variations in scale distort PCC values, and PCC not of much use when the relationships are nonlinear.
SRC	Measures linear relationship without influence of scale between input parameter and resultant dose. It provides "shared" contribution of an input parameter to the resultant dose.	Less useful when the relationship between input parameter and resultant dose is nonlinear and the input parameters are highly correlated.
PRCC	Estimates nonlinear monotonic relationship and gives the unique contribution of an input parameter to the resultant dose.	Not useful when the relationship between input parameter and resultant dose is nonmonotonic.
SRRC	Estimates nonlinear monotonic relationship and provides "shared" contribution of an input parameter to the resultant dose.	Less useful when input parameters are highly correlated.
Source: Based in part on information from Cullen and Frey (1999).		

5 SUMMARY AND DISCUSSION

The deterministic RESRAD and RESRAD-BUILD codes have been extended and enhanced with probabilistic analysis capability. The procedure for adding the probabilistic analysis capability consisted of six steps. These steps are discussed in Chapter 3, and reports were prepared documenting each of the six steps. This six-step procedure can be used to develop probabilistic analysis capability for other computer codes. The following is a brief summary of these six steps:

- **Step 1: Listing and Categorizing Parameters**

All the input parameters used in the RESRAD and RESRAD-BUILD codes (totaling about 200 parameters) were listed, categorized, and defined. The parameters were classified relative to physical, behavioral, or metabolic attributes. Any parameter that would not change if a different group of receptors was considered was classified as a physical parameter. Any parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. Any parameter representing the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered was classified as a metabolic parameter.

- **Step 2: Ranking Parameters**

A strategy was developed to rank the input parameters and identify them according to their importance in meeting the objective of the analysis. The parameter rankings were divided into three levels: 1 (high priority), 2 (medium priority), and 3 (low priority). The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations; (2) variability of the radiation dose as a result of changes in the parameter value; (3) parameter type (physical, behavioral, or metabolic); and (4) availability of data on the parameter in the literature. A composite scoring system was developed to rank the parameters. Overall, 14 parameters were ranked as high priority, 59 were ranked as medium priority,

and the remaining 122 were ranked as low priority for RESRAD and RESRAD-BUILD combined.

- **Step 3: Developing Parameter Distributions**

Parameter distributions were developed for a total of 66 parameters identified in Step 2 as high or medium priority. The data were obtained from a variety of published sources representative of a national distribution. Because they are based on national average data, many of these distributions may not be appropriate for a site-specific assessment. However, their development was necessary for testing of the probabilistic modules in Step 4. Potential correlation among parameters was also studied and discussed.

- **Step 4: Testing Parameter Distributions for Probabilistic Analysis**

The analysis fully demonstrated the process of using the integrated RESRAD and RESRAD-BUILD codes and the probabilistic modules, together with the parameter distributions, for dose assessment at a relatively complex site. This analysis indicated that a site-specific application could be implemented in cases where pertinent site data could be developed.

- **Step 5: Developing Probabilistic Modules**

A preprocessor and a post-processor were developed for the RESRAD and RESRAD-BUILD codes for probabilistic dose and risk analysis. The parameter distributions developed in Step 3 were incorporated into the codes as default distributions. Both conventional Monte Carlo sampling and LHS methods are used in both codes. Text reports, interactive output, and graphic output are provided for viewing the results of analysis. A user's guide for the probabilistic code is available as a NUREG/CR document (LePoire et al., 2000).

- **Step 6: Testing Probabilistic Modules and Integrated Codes**

Testing of the probabilistic codes was the sixth step. It was initiated early in the process when the probabilistic modules were being developed. All components of software modules (such as LHS sampling routine, input interface, output interface, graphic viewer, interactive output viewer) were tested when developed. Finally the integrated code system was tested extensively by Argonne, NRC, and others.

The development of the probabilistic RESRAD and RESRAD-BUILD codes has implemented the above six steps and has met stringent QA requirements. The integrated codes have been extensively tested internally and externally by NRC staff and NRC contractors. These codes are released for field testing, and any bugs identified should be reported to Argonne through NRC.

The probabilistic version of the RESRAD and RESRAD-BUILD codes provides a tool for studying the parameter uncertainty in dose assessment. Other types of uncertainties, such as model uncertainty and scenario uncertainty, also exist. These uncertainties should be considered in the beginning stage of modeling (i.e., in the selection of models and exposure scenarios). For parameter uncertainty study, there are also other methods, such as bounding analysis and sensitivity studies. The probabilistic approach used in RESRAD and RESRAD-BUILD codes is more widely used and represents the current trend in the study of uncertainties.

Although the RESRAD and RESRAD-BUILD codes provide an easy-to-use interface for probabilistic analysis, users need to

employ this feature with caution. The saying “garbage in, garbage out” is not only true for the deterministic codes, it is especially true for the probabilistic codes. As a matter of fact, because there are more parameters (such as distribution characteristics parameters) in the probabilistic codes, users need to obtain more information on the site and perhaps need to better characterize the site to properly model the site with the probabilistic codes.

The probabilistic modules use the Monte Carlo method (and a varied Monte Carlo method – LHS) to study uncertainty. Like most methods based on probability theory, Monte Carlo methods are data-intensive, and they usually cannot produce reliable results unless a considerable amount of empirical information has been collected (or unless assumptions are made in place of such empirical information) (Ferson, 1996).

The probabilistic versions of the RESRAD 6.0 and RESRAD-BUILD 3.0 codes provide a tool for studying the uncertainty in dose assessment caused by uncertainty in the input parameters. Although the codes are designed to be user-friendly, it is important that users be properly trained; also, a sufficient amount of site-specific (probabilistic) data must be collected for input into the codes for a meaningful probabilistic dose assessment to be conducted. Furthermore, it is important that the code users follow the guidance in the Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM [NRC, 1997]) on collecting data for inputting into RESRAD and RESRAD-BUILD codes if they are to produce results that more accurately reflect a specific site’s radiological conditions.

6 REFERENCES

- BIOMOVs II Steering Committee. "Long-Term Contaminant Migration and Impacts from Uranium Mill Tailings – Comparison of Computer Models Using a Realistic Dataset." Stockholm, Sweden: Swedish Radiation Protection Institute; BIOMOVs II Technical Report No. 5. Aug. 1996.
- Biwer, B.M., et al. "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes, Revision 1." Letter report prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, DC. March 2000. (This report is included in this document as Attachment C.)
- Camus, H., et al. "Long-Term Contaminant Migration and Impacts from Uranium Mill Tailings." *J. Environ. Rad.*, 42:289-304. 1999.
- Cheng, J.-J., et al. "Benchmarking Analysis of Three Multimedia Models: RESRAD, MMSOILS, and MEPAS." Washington, DC: U.S. Department of Energy; DOE/ORO-2033. 1995.
- Cullen, A.C. and H.C. Frey. *Probabilistic Techniques in Exposure Assessment*. Plenum Press: New York. 1999.
- Faillace, E.R., J.-J. Cheng, and C. Yu. "RESRAD Benchmarking against Six Radiation Exposure Pathway Models." Argonne, IL: Argonne National Laboratory. ANL/EAD/TM-24. 1994.
- Ferson, S. "What Monte Carlo Methods Cannot Do." *Human and Ecological Risk Assessment*, 2(4):990-1007. 1996.
- Gnanapragasam, E.K. and C. Yu. "Analysis of BIOMOVs II Uranium Mill Tailings Scenario 1.07 with the RESRAD Computer Code." Argonne, IL: Argonne National Laboratory. ANL/EAD/TM-66. 1997a.
- Gnanapragasam, E.K. and C. Yu. "Application of the RESRAD Computer Code to VAMP Scenario S." Argonne, IL: Argonne National Laboratory. ANL/EAD/TM-70. 1997b.
- Halliburton NUS Corporation. "Verification of RESRAD. A Code for Implementing Residual Radioactive Material Guidelines, Version 5.03." Gaithersburg, MD. HNUS-ARPD-94-174. June 1994.
- International Commission on Radiological Protection. "Principles of Monitoring for the Protection of the Population." ICRP Publication 43. Pergamon Press: New York. 1984.
- Iman, R.L. and J.C. Helton. NUREG/CR-3904, SAND84-1461 RG, "A Comparison of Uncertainty and Sensitivity Analysis Techniques for Computer Models." Prepared by Sandia National Laboratories, Albuquerque, NM, for the U.S. Nuclear Regulatory Commission, Washington, DC. March 1985.
- Iman, R.L. and M.J. Shortencarier. NUREG/CR-3624, SAND83-2365 RG, "A FORTRAN 77 Program and User's Guide for the Generation of Latin Hypercube and Random Samples for Use with Computer Models." Prepared by Sandia National Laboratories, Albuquerque, NM, for U.S. Nuclear Regulatory Commission, Washington, DC. March 1984.
- Iman, R.L., et al. NUREG/CR-4122, SAND85-0044 RG, "A FORTRAN 77 Program and User's Guide for the Calculation of Partial Correlation and Standard Regression Coefficients." Prepared by Sandia National Laboratories, Albuquerque, NM, for U.S. Nuclear Regulatory Commission, Washington, DC. June 1985.
- International Atomic Energy Agency. "Evaluating Reliability of Predictions Made Using Environmental Transfer Models." IAEA Report No. 100. Vienna: IAEA. 1989.
- International Atomic Energy Agency. "Validation of Models Using Chernobyl Fallout Data from Southern Finland, Scenario S." Vienna: Second report of the VAMP Multiple Pathways Assessment Working Group. IAEA-TECDOC-904. Sept. 1996.

Kamboj, S., et al. NUREG/CR-6676, ANL/EAD/TM-89, "Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes." Washington, DC: U.S. Nuclear Regulatory Commission, prepared by Argonne National Laboratory, Argonne, IL. 2000.

Kennedy, W.E. and Strenge, D.L. NUREG/CR-5512, "Residual Radioactive Contamination from Decommissioning; Volume 1; Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent." Washington, DC: U.S. Nuclear Regulatory Commission, prepared by Pacific Northwest Laboratory, Richland, WA. 1992.

Laniak, G.F., et al. "An Overview of a Multimedia Benchmarking Analysis for Three Risk Assessment Models: RESRAD, MMSOILS, and MEPAS." *Risk Anal.*, 17(2):203-214. 1997.

LePoire, D., et al. NUREG/CR-6692, ANL/EAD/TM-91, "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes." Washington, DC: U.S. Nuclear Regulatory Commission, prepared by Argonne National Laboratory, Argonne, IL. 2000.

McKay, M.D., et al. "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code." *Technometrics*, 21:239-245. 1979.

Mills, W.B., et al. "Multimedia Benchmarking Analysis for Three Risk Assessment Models: RESRAD, MMSOILS, and MEPAS." *Risk Anal.* 17(2):187-201. 1997.

Regens, J.L., et al. "Multimedia Modeling and Risk Assessment." Washington, DC: U.S. Department of Energy, Consortium for Environmental Risk Evaluation. May 1998.

Seitz, R.R., et al. "Comparison of Computer Codes and Approaches Used at DOE Sites to Model Intrusion Scenarios." *Proceedings of the Symposium on Waste Management*. Tucson, AZ; March 1-5; vol. 1; p. 509. 1992.

U.S. Nuclear Regulatory Commission. NUREG-1575, "Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM)." Washington, DC: U.S. Nuclear Regulatory Commission. December 1997.

U.S. Nuclear Regulatory Commission. NUREG/CP-0163, "Proceedings of the Workshop on Review of Dose Modeling Methods for Demonstration of Compliance with Radiological Criteria for License Termination." Washington, DC: Nuclear Regulatory Commission. May 1998.

U.S. Nuclear Regulatory Commission. NUREG-1727, "NMSS Decommissioning Standard Review Plan," Washington, DC: U.S. Nuclear Regulatory Commission. September 2000.

Seitz, R.R. "Benchmarking of Computer Codes and Approaches for Modeling Exposure Scenarios." U.S. Department of Energy; DOE/LLW-188. Prepared by Radioactive Waste Technical Support Program, Idaho National Engineering Laboratory, Idaho Falls, ID. Aug. 1994.

Whelan, G., et al. "Benchmarking of the Saturated-Zone Module Associated with Three Risk Assessment Models: RESRAD, MMSOILS, and MEPAS." *Environ. Eng. Sci.* 16(1):67-80. 1999a.

Whelan, G., et al. "Benchmarking of the Vadose-Zone Module Associated with Three Risk Assessment Models: RESRAD, MMSOILS, and MEPAS." *Environ. Eng. Sci.*, 16(1):81-91. 1999b.

Yu, C. "RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities," Chapter 11, pp. 207-231. Health Physics Society 1999 Summer School Textbook, M.J. Slobodien (Ed.). Medical Physics Publishing, Madison, WI. 1999.

Yu, C. and E. Gnanapragasam. "Testing RESRAD Predictions with Chernobyl Data." International Symposium on the Environmental Impact of Radioactive Releases; Vienna, Austria: IAEA-SM-339/129. May 1995.

Yu, C., et al. "Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil." Argonne, IL: Argonne National Laboratory. ANL/EAIS-8. 1993a.

Yu, C., et al. "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0: Working Draft for Comment." Argonne, IL: Argonne National Laboratory. ANL/EAD/LD-2. 1993b.

Yu, C., et al. "RESRAD-BUILD: A Computer Model for Analyzing the Radiological Dose Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material," Argonne, IL: Argonne National Laboratory. ANL/EAD/LD-3. 1994.

ATTACHMENT A

PARAMETERS AND PARAMETER TYPES IN RESRAD AND RESRAD-BUILD CODES

Prepared by

S. Kamboj, C. Yu, J.-J. Cheng, E. Gnanapragasam,
B. Biwer, D. LePoire, J. Arnish, and S.Y. Chen
Environmental Assessment Division
Argonne National Laboratory

CONTENTS

NOTATION	v
1 INTRODUCTION	1
1.1 Purpose and Scope	2
1.2 Model Descriptions	2
1.2.1 RESRAD	2
1.2.2 RESRAD-BUILD	3
1.3 Parameter Classification	3
2 MODEL PARAMETERS IN RESRAD AND RESRAD-BUILD	5
2.1 RESRAD Parameters	5
2.2 RESRAD-BUILD Parameters	6
3 TREATMENT OF SHORT-LIVED RADIONUCLIDES AND PARAMETER TYPES	55
3.1 Treatment of Short-Lived Radionuclides	55
3.2 Parameter Types and Default Values	55
4 REFERENCES	70

TABLES

2.1 Parameters and Their Default Values Used in Version 6.0 of RESRAD	7
2.2 Default Dose Conversion Factors for External, Inhalation, and Ingestion Pathways in RESRAD	32
2.3 Radionuclide Slope Factors for External, Inhalation, and Ingestion Pathways in RESRAD	35
2.4 Default Distribution Coefficients Used in RESRAD	38
2.5 Transfer Factors for Plants, Meat, and Milk in RESRAD	40
2.6 Bioaccumulation Factors for Fish and Crustacea and Mollusks in RESRAD	42
2.7 Parameters and Their Default Values Used in Version 3.0 of RESRAD-BUILD	43

TABLES (Cont.)

2.8 Default Dose Conversion Factors for the Air Submersion Pathway in RESRAD-BUILD	54
3.1 List of Principal Radionuclides in RESRAD and Equivalent Primary Radionuclides in DandD	56
3.2 Parameter Types and Their Default Values in RESRAD and DandD for Residential Scenario	59
3.3 Parameter Types and Their Default Values in RESRAD-BUILD and DandD for Occupancy Scenario	67

NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Some acronyms used only in tables or equations are defined in the respective tables or equations.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ALARA	as low as reasonably achievable
ANL	Argonne National Laboratory
CFR	Code of Federal Regulations
DG	draft guide
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
GI	gastrointestinal
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
NRC	U.S. Nuclear Regulatory Commission
SNL	Sandia National Laboratories

UNITS OF MEASURE

cm	centimeter(s)	m	meter(s)
cm ³	cubic centimeter(s)	m ²	square meter(s)
d	day(s)	m ³	cubic meter(s)
dpm	disintegrations per minute	mol	mole(s)
g	gram(s)	mrem	millirem(s)
h	hour(s)	pCi	picocurie(s)
kg	kilogram(s)	s	second(s)
L	liter(s)	yr	year(s)

PARAMETERS AND PARAMETER TYPES IN RESRAD AND RESRAD-BUILD CODES

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has taken steps to ensure that residual radioactive contamination remaining after licensed facilities are decontaminated and decommissioned meets acceptable levels and that risks to the exposed “critical group” of the public are within prescribed limits.

NRC Draft Regulatory Guide DG-4006 (NRC 1998a) presents NRC’s regulatory positions on dose modeling, final status surveys, ALARA (as low as reasonably achievable) compliance, and restricted use for both buildings and soil. The dose modeling section describes NRC positions on demonstrating compliance with the dose criteria in Subpart E to 10 CFR Part 20. In particular, the section addresses dose modeling methods to relate concentrations of residual radioactivity to dose to the average member of the critical group in order to demonstrate that the dose criteria of 10 CFR 20.1402 and 20.1403 have been met. NUREG-1549, *Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination* (NRC 1998b), provides an acceptable methodology for calculating dose.

NRC has developed a generic modeling approach (presented in NUREG/CR-5512 [Kennedy and Streng 1992]) to translate residual contamination levels into potential radiation doses to the public. The NUREG/CR-5512 approach is based on use of “prudently conservative” scenarios with simple, “prudently conservative” models in a multilevel screening process. Level 1 modeling uses generic screening factors (i.e., default parameter values) in the models to represent those scenarios. Level 2 involves substitution of site-specific parameter values for some of the default values and elimination of pathways to more closely approximate conditions at a particular site. Level 3 modeling is based on even more realistic models that use site-specific data. Level 3 modeling is required when an even more site-specific approach is needed than can be provided by the generic screening methods. As a licensee proceeds through iterations from one level to the next, the conservatism is reduced and the dose estimates decrease.

The RESRAD (Yu et al. 1993a) and RESRAD-BUILD (Yu et al. 1994) codes are currently designed to address Level 2 and Level 3 objectives entailing site-specific analysis. (RESRAD can also be used for Level 1 screening calculations provided a default dataset is developed.) The RESRAD and RESRAD-BUILD codes permit user input of site-specific data to model doses for various exposure scenarios. They have been developed by Argonne National Laboratory and approved by the U.S. Department of Energy (DOE) for evaluation of radioactively contaminated sites and buildings, respectively. These two

codes are widely used in the United States and abroad to estimate doses from residual radioactive material and to set site-specific cleanup levels for radioactive contaminants. The RESRAD codes complement NRC's licensing efforts in developing methods for demonstrating compliance with decontamination and decommissioning rules.

1.1 PURPOSE AND SCOPE

This report provides the descriptions and the default values of the parameters used in the RESRAD and RESRAD-BUILD codes. This presentation is the initial step in the overall project for Argonne National Laboratory to develop detailed descriptions, ranges, and probability distributions for parameters used in RESRAD and RESRAD-BUILD and to develop necessary interfacing modules. These interfacing modules will incorporate the information developed under this project and make it possible for the revised codes to be used by NRC staff and licensees to perform site-specific and probabilistic radiation dose assessments. The code versions to be used in this project are RESRAD version 6.0 and RESRAD-BUILD version 3.0.

Tables listing parameters used in the RESRAD and RESRAD-BUILD computer codes and their current default values are provided in Section 2. The parameters are classified as physical, behavioral, or metabolic. Definitions applied to identify parameter types are included in Section 1.3. The tables listing parameters and default values also provide references for additional sources of information for some of the parameters. Section 3 compares some aspects of the RESRAD, RESRAD-BUILD, and DandD (Wernig et al. undated) codes. The treatment of short-lived radionuclides is compared in Section 3.1. Section 3.2 compares the parameter types and default values.

1.2 MODEL DESCRIPTIONS

1.2.1 RESRAD

The RESRAD computer code (Yu et al. 1993a) implements the methodology described in DOE's manual for developing residual radioactive material guidelines for remediation sites. It calculates radiation dose and excess lifetime cancer risk to a chronically exposed on-site resident for different land use and exposure scenarios. The RESRAD code focuses on radioactive contaminants in soil and their transport in air, water, and biological media to a single receptor. Nine exposure pathways are considered in RESRAD: direct exposure, inhalation of particulates and radon, and ingestion of plant foods, meat, milk, aquatic foods, water, and soil. RESRAD uses a pathway analysis approach in which the relation between radionuclide concentrations in soil and the dose to a member of a critical population group is expressed as a pathway sum (the sum of

products of “pathway factors”). Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or from which radiation can be emitted. Radiation doses, health risks, soil guidelines, and media concentrations of radionuclides are calculated for user-specified time intervals. The source is adjusted over time to account for radioactive decay and ingrowth, leaching, erosion, and mixing. RESRAD uses a one-dimensional groundwater model that accounts for differential transport of parent radionuclides and progeny with different distribution coefficients. (A three-dimensional groundwater model has been implemented in RESRAD-OFFSITE, which is currently being developed by Argonne National Laboratory.)

1.2.2 RESRAD-BUILD

The RESRAD-BUILD code (Yu et al. 1994) 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. A single run of the RESRAD-BUILD code can model a building with up to 3 rooms or compartments, 10 distinct 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.

In both RESRAD and RESRAD-BUILD, the user can construct exposure scenarios by suppressing exposure pathways and by adjusting the input parameters. Default values are provided for most of the parameters used in the codes.

1.3 PARAMETER CLASSIFICATION

This report classifies RESRAD version 6.0 and RESRAD-BUILD version 3.0 parameters into three types: physical, behavioral, or metabolic, as described below. Some parameters may belong to more than one of these types (e.g., the mass loading factor). Additionally, if a parameter does not fit the definition of either physical or metabolic, it is classified as a behavioral parameter.

Physical Parameter: Any parameter whose value would not change if a different group of receptors were considered is classified as a physical parameter. Physical parameters would be determined by the source, its location, and geological characteristics of the site (i.e., these parameters are source- and site-specific).

Behavioral Parameter: Any parameter whose value would depend on the receptor's behavior and the scenario definition is classified as a behavioral parameter. For the same group of receptors, a parameter value could change if the scenario changed (e.g., parameters for recreational use could be different from those for residential use).

Metabolic Parameter: If a parameter represents the metabolic characteristics of the potential receptor and is independent of scenario, it is classified as a metabolic parameter. The parameter values may be different in different population age groups. According to the recommendations of the International Commission on Radiological Protection, Report 43 (ICRP 1985), parameters representing metabolic characteristics are defined by average values for the general population. These values are not expected to be modified for a site-specific analysis because the parameter values would not depend on site conditions.

2 MODEL PARAMETERS IN RESRAD AND RESRAD-BUILD

This section presents tables listing characteristics of the parameters used in RESRAD and RESRAD-BUILD. These tables include parameter name, default value, code-accepted range of values for the parameter, parameter type (based on the definitions given in Section 1.3), references for more information, and the general description of the parameter.

2.1 RESRAD PARAMETERS

Table 2.1¹ lists user changeable parameters in the RESRAD code. Additional information about these parameters can be obtained from the RESRAD User's Manual (Yu et. al. 1993a). Parameters are arranged according to the input window in which they appear. The number of parameters that a user can change will depend on the pathways and radionuclides selected. In RESRAD, a pathway can be turned on or off. Parameters pertaining to suppressed pathways are blanked out in the data entry screens because they would not be used in the calculations. Radon parameters can only be changed if radon precursor is selected in the radionuclide list and the radon pathway is on. Similarly, a user will have access to carbon-14 parameters only if carbon-14 is selected as a contaminant. Some parameters are nuclide or element specific. Table 2.1 mentions that characteristic of the parameter but does not provide details. Separate tables of nuclide- or element-specific data are also provided for the parameters (Tables 2.2 through 2.6). The code-accepted values are not provided for element- or nuclide-specific parameters. Table 2.1 also identifies the parameter types: physical (P), metabolic (M), and behavioral (B). For some parameters, more than one type is listed; the first one listed is the primary type and the next one is secondary. For example, inhalation rate is identified as M, B, which indicates that it depends primarily on the metabolic characteristics of the potential receptor, but that it also depends on the receptor behavior or exposure scenario.

Table 2.2 lists dose conversion factors for all radionuclides included in the RESRAD database. For the inhalation dose conversion factor, the default inhalation class used is also listed. For the ingestion dose conversion factor, the default fraction of a stable element entering the gastrointestinal (GI) tract that reaches body fluid is also listed. Table 2.3 lists slope factors for external exposure, inhalation, and ingestion used in the RESRAD code for all radionuclides. Table 2.4 provides default distribution coefficients used in the code for all radionuclides (values are nuclide specific); Table 2.5 lists element-specific transfer factors for plants, meat, and milk. Table 2.6 provides element-specific

¹To maintain the continuity of the text, the tables have been placed at the end of the section.

bioaccumulation factors for fish and for crustacea and mollusks.

2.2 RESRAD-BUILD PARAMETERS

Computation of the radiation doses for the generic screening or site-specific calculation for residual radioactive contamination in buildings relies on numerous parameters and data values. Table 2.7 lists the parameters used in the RESRAD-BUILD code, the pathways in which they are used, and their description. Additional information about these parameters can be obtained from Yu et al. (1994). Dose conversion factors for direct external exposure, inhalation, and ingestion pathways used in the RESRAD-BUILD code are the same as those used in RESRAD (see Table 2.2). Table 2.7 also lists the RESRAD-BUILD parameter types identified. As was the case for RESRAD (Table 2.1), more than one attribute may be identified for some parameters, with the first one being primary and second one secondary. For example, shielding thickness is identified as P, B, meaning that it depends primarily on the source or site-specific conditions; but that it also can be modified by receptor behavior. The air submersion external dose conversion factors used in the RESRAD-BUILD code are listed in Table 2.8.

TABLE 2.1 Parameters and Their Default Values Used in Version 6.0 of RESRAD

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Source						
Radionuclide concentration	pCi/g	100 (Nuclide specific)	Site specific	P	Yu et al. 1993b	Average radionuclide concentration in the contaminated zone. The contaminated zone is treated as a uniformly contaminated volume with the same radionuclide concentration.
Transport Factors						
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zones)	cm ³ /g	Nuclide specific (Table 2.4)		P	Yu et al. 1993b-c; EPA 1996; IAEA 1994; Sheppard and Thibault 1990; Sheppard et al. 1991	Site-specific values should be used everywhere for each radionuclide. Default values are provided by the code for most radionuclides. However, these values should be used with care because distribution coefficients can vary over many orders of magnitude.
Number of unsaturated zones	— ^c	1	0–5 (integer value)	P	Yu et al. 1993a-b	Number of unsaturated zones. An unsaturated zone is defined as a horizontal uncontaminated layer located between the contaminated zone and the aquifer. The code allows maximum of five unsaturated zones.
Time since placement of material	yr	0	0–100	P	Yu et al. 1993b	The duration between the placement of radioactive material on-site and the performance of a radiological survey. A non-zero value for this parameter is necessary to activate the groundwater concentration input box. The non-zero value of this parameter is used along with groundwater concentration to calculate the water/soil concentration ratio and effective distribution coefficient.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Groundwater concentration	pCi/L	0 ^d (Nuclide specific)	0–1E+34	P	Yu et al. 1993b	The measured groundwater concentration of principal radionuclides. The groundwater concentration should be measured at the same time the soil concentrations are measured. Groundwater concentration can be input only if time since placement of material is > 0.
Leach rate ^e	1/yr	0 (Nuclide specific)	0–1E+34	P	Yu et al. 1993b; Snyder et al. 1994	The fraction of the available radionuclide leached from the contaminated zone per unit of time. Radionuclide leach rates should be used if known. The nonzero leach rate is used to calculate the leaching of the radionuclide from the contaminated zone and to derive the water/soil concentration ratio and distribution coefficient. If the derived distribution coefficient is greater than zero, the input distribution coefficient would be replaced by these values.
Solubility limit	mol/L	0 (Nuclide specific)	0–1E+34	P	Yu et al. 1993a	The solubility limit provides an additional option for calculating the distribution coefficient in the code. The solubility limit serves as an upper bound on the amount of a radionuclide released from the soil particles.
Use plant/soil ratio	check box	Yes/No	NA ^f	NA	Yu et al. 1993a	The code allows distribution coefficients to be calculated from the plant root uptake factors (plant/soil concentration ratio). This option becomes active if the plant/soil ratio box is checked.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Calculation Parameters						
Basic radiation dose limit	mrem/yr	30	1E-2–1E+4	NA	Yu et al. 1993b	The annual radiation dose limit in mrem/yr used to derive all site-specific guidelines.
Times for calculations	yr	1, 3, 10, 30, 100, 300, 1000	0–1E+5	P	Yu et al. 1993a	The times in years following the radiological survey for which tabular values for single-radionuclide soil guidelines and mixture sums will be obtained. The code calculates dose at time zero and up to nine user specified times.
Contaminated Zone Parameters						
Area of contaminated zone	m ²	10,000	1E-4–1E+15	P	Yu et al. 1993b	Total area of the site that is homogeneously contaminated.
Thickness of contaminated zone	m	2	1E-5–1E+3	P	Yu et al. 1993b	The distance between the uppermost and lowermost soil samples that have radionuclide concentration clearly above background.
Length parallel to aquifer flow	m	100	1E-4–1E+6	P	Yu et al. 1993b	The distance between two parallel lines perpendicular to the direction of aquifer flow, one at the upgradient edge of the contaminated zone and the other at the downgradient edge.
Cover and Contaminated Zone Hydrological Data						
Cover depth	m	0	0–100	P	Yu et al. 1993b	Distance from the ground surface to the contaminated zone.
Density of cover material	g/cm ³	1.5	1E-3–22.5	P	Yu et al. 1993b; Snyder et al. 1994	Bulk density of the cover material.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Cover erosion rate	m/yr	0.001	0-5	P, B	Yu et al. 1993b	The average volume of cover material that is removed per unit of ground surface area and per unit of time. Erosion rates can be estimated by means of the universal soil loss equation.
Density of contaminated zone	g/cm ³	1.5	1E-3-22.5	P	Yu et al. 1993b; Snyder et al. 1994	Bulk density of the contaminated zone.
Contaminated zone total porosity	-	0.4	1E-5-1	P	Yu et al. 1993b-c; EPA 1996	Ratio of the pore volume to the total volume of the contaminated zone.
Contaminated zone field capacity	-	0.2	1E-34-1	P	Yu et al. 1993b; EPA 1996	Volumetric moisture content of soil at which (free) gravity drainage ceases. This is the amount of moisture that will be retained in a column of soil against the force of gravity. The field capacity is one of several hydrogeological parameters used to calculate water transport through the unsaturated part of the soil. The user can use this input to specify a minimum moisture content for each partially saturated region. It is also called specific retention, irreducible water content, or residual water content.
Contaminated zone erosion rate	m/yr	0.001	0-5	P, B	Yu et al. 1993b	The average volume of source material that is removed per unit of ground surface area and per unit of time.
Contaminated zone hydraulic conductivity	m/yr	10	1E-3-1E+10	P	Yu et al. 1993b-c; EPA 1996	The measure of the soil's ability to transmit water when submitted to a hydraulic gradient. The hydraulic conductivity depends on the soil grain size, the structure of the soil matrix, the type of soil fluid, and the relative amount of soil fluid (saturation) present in the soil matrix.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Contaminated zone b parameter	–	5.3	0–15	P	Yu et al. 1993b; EPA 1996; Clapp and Hornberger 1978	An empirical and dimensionless parameter that is used to evaluate the saturation ratio (or the volumetric water saturation) of the soil according to a soil characteristic function called the conductivity function.
Humidity in air	g/m ³	8	0–1,000	P	Yu et al. 1993a; Etnier 1980	Average absolute humidity in air. It is used in the tritium model to calculate tritium concentration in air.
Evapotranspiration coefficient	–	0.5	0–0.999	P	Yu et al. 1993b-c; EPA 1996	The ratio of the total volume of water leaving the ground via evapotranspiration to the total volume of water available within the root zone of the soil during a fixed period of time.
Wind speed	m/s	2	1E-4–20	P	Yu et al. 1993b	The overall average of the wind speed, measured near the ground.
Precipitation rate	m/yr	1.0	0–10	P	Yu et al. 1993b	The average volume of water in the form of rain, snow, hail, or sleet that falls per unit of area per unit of time at the site.
Irrigation rate	m/yr	0.2	0–10	B	Yu et al. 1993b-c	The average volume of water that is added to the soil at the site, per unit of surface area and per unit of time. Irrigation is the practice of supplying water artificially to the soil in order to permit agricultural use of the land in an arid region or to compensate for occasional droughts in semiarid or semihumid regions. It is the average annual irrigation rate. The code has two irrigation modes: overhead and ditch irrigation.
Irrigation mode	–	Overhead	Overhead/ditch	B	Yu et al. 1993a	Method of irrigation; it could be overhead or ditch.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Runoff coefficient	–	0.2	0–1	P	Yu et al. 1993b-c	The fraction of the average annual precipitation that does not infiltrate into the soil and is not transferred back to the atmosphere through evapotranspiration.
Watershed area for nearby stream or pond	m ²	1,000,000	1E-4–1E+34	P	Yu et al. 1993b	The site-specific area that drains into the nearby pond.
Accuracy for water soil computation	–	0.001	0–0.1	NA	Yu et al. 1993a	The fractional accuracy desired (convergence criterion) in the Romberg integration used to obtain water/soil concentration ratios.
Saturated Zone Hydrological Data						
Density of saturated zone	g/cm ³	1.5	1E-3–22.5	P	Yu et al. 1993b-c	See density of contaminated zone (above).
Saturated zone total porosity	–	0.4	1E-5–1	P	Yu et al. 1993b-c; EPA 1996	See contaminated zone total porosity (above).
Saturated zone effective porosity	–	0.2	1E-34–1	P	Yu et al. 1993b; EPA 1996	The effective porosity is the ratio of the pore volume where water can circulate to the total volume. It is used along with other hydrological parameters to calculate the water transport breakthrough times.
Saturated zone field capacity	–	0.2	1E-34–1	P	Yu et al. 1993b; EPA 1996	See contaminated zone field capacity (above). (The field capacity and b parameter of the saturated zone are used only if the water table drop rate is positive.)
Saturated zone hydraulic conductivity	m/yr	100	1E-3–1E+10	P	Yu et al. 1993b-c; EPA 1996	See contaminated zone hydraulic conductivity (above).

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Saturated zone hydraulic gradient	–	0.02	1E-10–10	P	Yu et al. 1993b	The change in hydraulic head per unit of distance in the groundwater flow direction. In an unconfined (water table) aquifer, the horizontal hydraulic gradient of groundwater flow is approximately the slope of the water table. In a confined aquifer, it represents the difference in potentiometric surfaces over a unit distance.
Saturated zone b parameter	–	5.3	1E-34–15	P	Yu et al. 1993b; EPA 1996; Clapp and Hornberger 1978	See contaminated zone b parameter (above).
Water table drop rate	m/yr	0.001	0–5	P	Yu et al. 1993b	The rate at which the depth of the water table is lowered. If the water table drop rate is greater than zero, the unsaturated zone thickness will be created or increased. The saturation of this newly created unsaturated zone is estimated by the hydrological parameters of the saturated zone. The code does not allow negative water table drop rate.
Well pump intake depth (below water table)	m	10.0	1E-5–1,000	P	Yu et al. 1993b	The screened depth of a well within the aquifer (the saturated zone).

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Model: nondispersion (ND) or mass-balance (MB)	–	ND	ND/MB	P	Yu et al. 1993a	Two models are used in the code for calculating the water/soil concentration ratio for the groundwater pathway: a mass-balance (MB) model and a nondispersion (ND) model. The MB model assumes that a well is located at the center of the contaminated zone, and the ND model assumes that the well is located at the downgradient edge of the contaminated zone. In the MB model, it is assumed that all of the radionuclides released from the contaminated zone are withdrawn through the well. In the ND model, it is assumed that the saturated zone is a single homogeneous stratum, and the water withdrawn introduces only a minor perturbation in the water flow.
Well pumping rate	m ³ /yr	250	0–1E+10	B, P	Yu et al. 1993a	The volume of water removed from the groundwater aquifer annually for all domestic purposes.
Uncontaminated Unsaturated Zone Parameters						
Unsaturated zone thickness	m	4	0–10,000	P	Yu et al. 1993b	The thickness of the uncontaminated unsaturated zone that lies below the bottom of the contaminated zone and above the groundwater table. The code has provisions for up to five different horizontal strata within this zone. Each stratum is characterized by six radionuclide independent parameters: thickness, density, total porosity, effective porosity, b parameter, and hydraulic conductivity.
Unsaturated zone density	g/cm ³	1.5	1E–3–22.5	P	Yu et al. 1993b-c; Snyder et al. 1994	Bulk density of the unsaturated zone soil.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Unsaturated zone total porosity	–	0.4	1E-5–1	P	Yu et al. 1993b-c; EPA 1996	See contaminated zone total porosity (above).
Unsaturated zone effective porosity	–	0.2	1E-34–1	P	Yu et al. 1993b; EPA 1996	See saturated zone effective porosity (above).
Unsaturated zone field capacity	–	0.2	1E-34–1	P	Yu et al. 1993a	See contaminated zone field capacity (above).
Unsaturated zone, soil-specific b parameter	–	5.3	0–15	P	Yu et al. 1993b; EPA 1996; Clapp and Hornberger 1978	See contaminated zone b parameter (above).
Unsaturated zone hydraulic conductivity	m/yr	10	1E-3–1E+10	P	Yu et al. 1993b-c; EPA 1996	See contaminated zone hydraulic conductivity (above).
Occupancy, Inhalation, and External Gamma Parameters						
Inhalation rate	m ³ /yr	8,400	0–20,000	M, B	Yu et al. 1993b-c; EPA 1997; Sprung et al. 1990	The annual air intake in m ³ /yr. The default value of 8,400 m ³ /yr is recommended by the International Commission on Radiological Protection (1975).
Mass loading for inhalation	g/m ³	1E-4	0–2	P, B	Yu et al. 1993b; Snyder et al. 1994; Gilbert et al. 1983	The air/soil concentration ratio or average mass loading of airborne contaminated soil particles. The code uses this parameter along with area factor for inhalation pathway dose estimation. This average mass loading factor includes short periods of high mass loading and sustained periods of normal activity on a typical farm.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Exposure duration	yr	30	1–1,000	B	Yu et al. 1993a	The exposure duration is the span of time, in years, during which an individual is expected to spend time on the site. This value is used in calculating lifetime cancer risk from exposure to radionuclide contamination. It is also used to calculate time-integrated dose if exposure duration is less than a year.
Indoor dust filtration factor	–	0.4	0–1	P, B	Yu et al. 1993b-c; Snyder et al. 1994; Sprung et al. 1990; Alzona et al. 1979	Describes the effect of the building structure on the level of contaminated dust existing indoors. This is the fraction of the outdoor contaminated dust that will be available indoors.
External gamma shielding factor	–	0.7	0–1	P	Yu et al. 1993b; Snyder et al. 1994; Sprung et al. 1990	Describes the effect of building structure on the level of gamma radiation existing indoors. It is the fraction of the outdoor gamma radiation that will be available indoors. The shielding factor value is used in calculating the occupancy factor.
Indoor time fraction	–	0.5	0–1	B	Yu et al. 1993b; EPA 1997; Sprung et al. 1990	The average fraction of time during which an individual stays inside the house.
Outdoor time fraction	–	0.25	0–1	B	Yu et al. 1993b; Sprung et al. 1990; EPA 1997; Snyder et al. 1994	The average fraction of time during which an individual stays outdoors on the site.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Shape of the contaminated zone (shape factor flag)	–	Circular	Circular/non-circular	P	Yu et al. 1993b	The code has the capability to handle any shape of contaminated zone. If the shape factor flag has been set, the 12 annular area fields comprising shape factor data are input. The shape factor data are calculated by RESRAD by drawing 2 to 12 concentric circles emanating from the receptor location inside (or possibly outside) the contaminated area. The outermost circle circumscribes the entire contaminated zone. For each annular ring, the outer radius and fraction of the ring within the contaminated zone should be entered. For simple shapes (square, rectangle, triangle, doughnut), two circles are sufficient. For complicated shapes, all 12 concentric circles can be used.
<i>Ingestion Pathway, Dietary Data</i>						The code has yearly average consumption for six food categories: fruit, vegetable, and grain; leafy vegetables; milk; meat and poultry; fish; and other seafood.
Fruit, vegetable, and grain consumption	kg/yr	160	0–1,000	M, B	Yu et al. 1993b-c; EPA 1997; Sprung et al. 1990	The dietary factor for fruit, vegetable, and grain consumption by humans. The default is based on national averages.
Leafy vegetable consumption	kg/yr	14	0–100	M, B	Yu et al. 1993b-c; EPA 1997; Sprung et al. 1990	The dietary factor for leafy vegetable consumption by humans. The default is based on national averages.
Milk consumption	L/yr	92	0–1,000	M, B	Yu et al. 1993b-c; EPA 1997; Sprung et al. 1990	The dietary factor for milk consumption by humans. The default is based on national averages.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Meat and poultry consumption	kg/yr	63	0–300	M, B	Yu et al. 1993b-c; EPA 1997; Sprung et al. 1990; USDA 1992	The dietary factor for meat and poultry consumption by humans. The default is based on national averages.
Fish consumption	kg/yr	5.4	0–1,000	M, B	Yu et al. 1993b; EPA 1997	The dietary factor for fish consumption by humans. The default is based on national averages.
Other seafood consumption	kg/yr	0.9	0–100	M, B	Yu et al. 1993b-c; Rupp et al. 1980	The dietary factor for other seafood consumption by humans. The default is based on national averages.
Soil ingestion rate	g/yr	36.5	0–10,000	M, B	Yu et al. 1993b-c; EPA 1997	The average annual quantity of soil ingested for the soil ingestion pathway.
Drinking water intake	L/yr	510	0–10,000	M, B	Yu et al. 1993b; EPA 1997	The drinking water ingestion rate.
Drinking water contaminated fraction	–	1	0–1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake for the drinking water pathway. The remaining balance (if value <1) of the drinking water is from off-site sources, which are assumed to be uncontaminated. Setting the value to zero will turn off the drinking water pathway entirely.
Household water contaminated fraction	–	1	0–1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated household water for use in calculating radon exposure. The remaining balance (if value <1) of the household water is from off-site sources, which are assumed to be uncontaminated. The default value of 1 indicates that all household water is from an on-site source.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Livestock water contaminated fraction	–	1	0–1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake of livestock water for the meat and milk pathway. The remaining balance (if value <1) of the livestock water is from off-site sources, which are assumed to be uncontaminated. The default value of 1 indicates that all livestock water is from an on-site source.
Irrigation water contaminated fraction	–	1	0–1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake of irrigation water for the plant, meat and milk pathways. The remaining balance (if value <1) of the irrigation water is from off-site sources, which are assumed to be uncontaminated. The default value of 1 indicates that all irrigation water is from an on-site source.
Aquatic food contaminated fraction	–	0.5	0–1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake for the fish pathway. The remaining balance is from off-site sources, which are assumed to be uncontaminated. The default value of 0.5 indicates that 50% of aquatic food is being obtained from on-site sources. Setting the value to 0 will turn off the fish pathway entirely.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Plant food contaminated fraction	–	-1	0 to 1 or -1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake for the plant pathway. The appropriate values range from 0 to 1, although a negative value can be input. The remaining balance is from off-site sources, which are assumed to be uncontaminated. The default value of -1 specifies that the contaminated fraction of plant food will be calculated from the appropriate area factor in the code. Setting the value to 0 will turn off the plant pathway entirely.
Meat contaminated fraction	–	-1	0 to 1 or -1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake for the meat pathway. The appropriate values range from 0 to 1, although a negative value can be input. The remaining balance is from off-site sources, which are assumed to be uncontaminated. The default value of -1 specifies that the contaminated fraction of meat will be calculated from the appropriate area factor in the code. Setting the value to 0 will turn off the meat pathway entirely.
Milk contaminated fraction	–	-1	0 to 1 or -1	B, P	Yu et al. 1993a	Allows specification of the fraction of contaminated intake for the milk pathway. The appropriate values range from 0 to 1, although a negative value can be input. The remaining balance is from off-site sources, which are assumed to be uncontaminated. The default value of -1 specifies that the contaminated fraction of milk will be calculated from the appropriate area factor in the code. Setting the value to 0 will turn off the milk pathway entirely.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
<i>Ingestion Pathway, Nondietary Data</i>						
Livestock fodder intake for meat	kg/d	68	0–300	M	Sprung et al. 1990	The daily intake of fodder by livestock kept for meat consumption. The code uses the area factor to calculate the contaminated intake.
Livestock fodder intake for milk	kg/d	55	0–300	M	Sprung et al. 1990	The daily intake of fodder by livestock kept for milk consumption. The code uses the area factor to calculate the contaminated intake.
Livestock water intake for meat	L/d	50	0–500	M	Yu et al. 1993b; Sprung et al. 1990	The daily intake of water by livestock kept for meat consumption. The code uses the area factor to calculate the contaminated intake.
Livestock water intake for milk	L/d	160	0–500	M	Yu et al. 1993b; Sprung et al. 1990	The daily intake of water by livestock kept for milk consumption. The code uses the area factor to calculate the contaminated intake.
Livestock intake of soil	kg/d	0.5	0–10	M	Yu et al. 1993a	The daily intake of soil by livestock kept for meat or milk consumption.
Mass loading for foliar deposition	g/m ³	1E-4	0–1	P	Gilbert et al. 1983	The average mass loading of airborne contaminated soil particles in a garden during the growing season.
Depth of soil mixing layer	m	0.15	0–1	P	Yu et al. 1993a	Used in calculating the depth factor for dust inhalation and soil ingestion pathways and for foliar deposition for the plant, meat, and milk ingestion pathways. The depth factor is the fraction of the resuspendable soil particles at the ground surface that are contaminated. It is calculated by assuming that mixing of soil will occur in the soil mixing layer.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Depth of roots	m	0.9	0–100	P	Yu et al. 1993b-c	The maximum root depth below the ground surface.
Groundwater fractional usage for drinking water	–	1	0–1	B, P	Yu et al. 1993a	The four groundwater fractional usage parameters (drinking water, household water, livestock water, and irrigation water) are included primarily for all groundwater (well or spring) and surface water (pond or river) scenarios. Hence, the fractions will usually be set at 1 or 0. A value of 1 specifies 100% groundwater usage and 0 selects 100% surface water usage.
Groundwater fractional usage for household water	–	1	0–1	B, P	Yu et al. 1993a	The four groundwater fractional usage parameters (drinking water, household water, livestock water, and irrigation water) are included primarily for all groundwater (well or spring) and surface water (pond or river) scenarios. Hence, the fractions will usually be set at 1 or 0. A value of 1 specifies 100% groundwater usage and 0 selects 100% surface water usage.
Groundwater fractional usage for livestock water	–	1	0–1	B, P	Yu et al. 1993a	The four groundwater fractional usage parameters (drinking water, household water, livestock water, and irrigation water) are included primarily for all groundwater (well or spring) and surface water (pond or river) scenarios. Hence, the fractions will usually be set at 1 or 0. A value of 1 specifies 100% groundwater usage and 0 selects 100% surface water usage.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Groundwater fractional usage for irrigation water	–	1	0–1	B, P	Yu et al. 1993a	The four groundwater fractional usage parameters (drinking water, household water, livestock water, and irrigation water) are included primarily for all groundwater (well or spring) and surface water (pond or river) scenarios. Hence, the fractions will usually be set at 1 or 0. A value of 1 specifies 100% groundwater usage and 0 selects 100% surface water usage.
Plant Factors						
Wet-weight crop yields	kg/m ²	0.7 (non-leafy) 1.5 (leafy) 1.1 (fodder)	0.01–3	P	USDA 1997; Beyeler et al. 1998b	The weight of the edible portion of plant food produced per unit land area for different food classes. The code has wet weight crop yield for non-leafy, leafy, and fodder. Non-leafy and leafy vegetables are for human consumption; fodder is for animal consumption.
Length of growing season	yr	0.17 (non-leafy) 0.25 (leafy) 0.08 (fodder)	0.01–1	P	USDA 1997; Beyeler et al. 1998b	The exposure time to contamination for the plant food during the growing season. The contamination can reach the edible portion of the plant food through foliar deposition, root uptake, and water irrigation. The code has length of growing season for non-leafy vegetables, leafy vegetables, and fodder.
Translocation factor	–	0.1 (non-leafy) 1 (leafy vegetable and fodder)	0–1	P	IAEA 1994; Snyder et al. 1994	The fraction of the contamination that is retained on the foliage that is transferred to the edible portion of the plant. The code has three food categories, non-leafy (includes non-leafy vegetables, fruit, and grain) and leafy vegetables for human and fodder for animal consumption (in all three values).

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Weathering removal constant	1/yr	20	1–40	P	IAEA 1994; Snyder et al. 1994	The weathering process would remove contaminants from foliage of the plant food. The process is characterized by a removal constant and reduces the amount of contaminants on foliage exponentially during the exposure period.
Wet foliar interception fraction	–	0.25 (non-leafy, leafy, and fodder)	0–1	P	IAEA 1994	The fraction of deposited radionuclides that is retained on the foliage of the plant food. Both dry deposition (from airborne particulates) and the wet deposition processes (from irrigation) are considered. The code has wet as well as dry foliar interception fraction for non-leafy, leafy (for human consumption), and fodder (for animal consumption).
Dry foliar interception fraction	–	0.25 (non-leafy, leafy, and fodder)	0–1	P	IAEA 1994; Snyder et al. 1994	The fraction of deposited radionuclides that is retained on the foliage of the plant food. Both the dry deposition (from airborne particulates) and the wet deposition processes (from irrigation) are considered. The code has wet as well as dry foliar interception fraction for non-leafy, leafy (for human consumption), and fodder (for animal consumption).
Radon Parameters						
Cover total porosity	–	0.4	0–1	P	Yu et al. 1993b-c	The ratio of the void space volume to the total volume of the porous medium.
Cover volumetric water content	–	0.05	0–1	P	Yu et al. 1993b-c; EPA 1996	The fraction of the total volume of the porous medium that is occupied by water.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Cover radon diffusion coefficient	m ² /s	2.0E-6	0–1 or -1	P	Yu et al. 1993a	The effective (or interstitial) radon diffusion coefficient is the ratio of the diffusive flux density of radon activity across the pore area to the gradient of the radon activity concentration in the pore space. Entering –1 for any diffusion coefficient will cause the code to calculate the diffusion coefficient based on the porosity and water content of the medium.
Building foundation thickness	m	0.15	0–10	P	Yu et al. 1993b	Average thickness of the building shell structure in the subsurface of the soil.
Building foundation density	g/cm ³	2.4	0–100	P	Yu et al. 1993b-c; Sprung et al. 1990	The solid phase of mass to the total volume.
Building foundation total porosity	–	0.1	1E-4–1	P	Yu et al. 1993b-c	See cover total porosity (above).
Building foundation volumetric water content	–	0.03	0–1	P	Yu et al. 1993b-c; EPA 1996	See cover volumetric water content (above).
Building foundation radon diffusion coefficient	m ² /s	3.0E-7	0–1 or -1	P	Yu et al. 1993b	See cover radon diffusion coefficient (above).
Contamination radon diffusion coefficient	m ² /s	2.0E-6	0–1 or -1	P	Yu et al. 1993b	See cover radon diffusion coefficient (above).
Radon vertical dimension of mixing	m	2	1E-4–1,000	P	Yu et al. 1993b	The height into which the plume of radon is uniformly mixed in the outdoor air (above).
Building air exchange rate	1/h	0.5	0–1,000	P, B	Yu et al. 1993b-c; EPA 1997	The building exchange rate (or ventilation) is defined as the number of the total volumes of air contained in the building being exchanged with outside air per unit of time.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Building height	m	2.5	1E-4–100	P	Yu et al. 1993b; EPA 1997	The average height of rooms in the building.
Building indoor area factor	–	0	0–100	P	Yu et al. 1993b	The fraction of the area built on the contaminated soil. Values greater than 1 indicate contribution from adjacent walls. A default value of zero is assumed, which forces the code to calculate this time dependent area factor by assuming floor area of 100 m ² and walls extending into the contaminated area. This factor is time dependent because of erosion.
Foundation depth below ground surface	m	-1	0–100 or -100	P	Yu et al. 1993b	The vertical distance in the soil immediately from the bottom of the basement floor slab to the ground surface. A default value of –1 is used in the code; in this case the code adjusts the depths so that the foundation depth will not extend into the contaminated zone at each of the times at which dose is computed.
Radon-222 emanation coefficient	–	0.25	0.01–1	P	Yu et al. 1993b-c	The fraction of the total radon generated by radium decay that escapes soil. (Depends on such parameters as porosity, particle size distribution, mineralogy, and moisture content.)
Radon-220 emanation coefficient	–	0.15	0.01–1	P	Yu et al. 1993b-c	See radon-222 emanation coefficient (above).

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
<i>Storage Times before Use Data</i>						
Storage times for fruits, non-leafy vegetables, and grain	d	14	0–1E+34	B	Snyder et al. 1994	The storage times are used to calculate radioactive ingrowth and decay adjustment factors for food and feed due to storage. The code has values for fruits, non-leafy vegetables, and grain (one category), leafy vegetables, milk, well and surface water, livestock fodder, meat, fish and crustacea; and mollusks.
Storage times for leafy vegetables	d	1	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for milk	d	1	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for meat	d	20	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for fish	d	7	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for crustacea and mollusks	d	7	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for well water	d	1	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for surface water	d	1	0–1E+34	B	Snyder et al. 1994	See above.
Storage times for livestock fodder	d	45	0–1E+34	B	Snyder et al. 1994	For livestock fodder the storage time is an annual average. The default value is obtained by assuming 6 months of outside grazing and 6 months of silage fodder with an average silo time of 3 months.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Carbon-Model Parameters						
C-12 concentration in local water	g/cm ³	2E-5	0–100	P	Yu et al. 1993a	The stable carbon concentration in water.
C-12 concentration in contaminated soil	g/g	0.03	1E-4–1	P	Yu et al. 1993a	The stable carbon concentration in contaminated soil.
Fraction of vegetation carbon absorbed from soil	–	0.02	1E-4–1	P	Yu et al. 1993a	The fraction of total vegetation carbon obtained by direct root uptake from the soil.
Fraction of vegetation carbon absorbed from air	–	0.98	0–1	P	Yu et al. 1993a	The fraction of total vegetation carbon assimilated from the atmosphere through photosynthesis.
C-14 evasion layer thickness in soil	m	0.3	0–10	P	Yu et al. 1993a	The maximum soil thickness layer through which C-14 can escape to the air by conversion to CO ₂ . C-14 below this depth is assumed to be trapped.
C-14 evasion flux rate from soil	1/s	7E-07	0–1	P	Sheppard et al. 1991	The fraction of the soil inventory of C-14 that is lost to the atmosphere per unit time.
C-12 evasion flux rate from soil	1/s	1E-10	0–1	P	Amiro et al. 1991	The fraction of C-12 in soil that escapes to the atmosphere per unit time.
Grain fraction in livestock feed	–	0.8 (beef cattle) 0.2 (cow)	0–1 0–1	B	Amiro et al. 1991	The fraction of grain (non-leafy) vegetation in the livestock diet. The balance is assumed to be leafy vegetation: hay or fodder.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Inhalation dose conversion factors	mrem/pCi	Nuclide specific (Table 2.2)		M	Eckerman et al. 1988	Radionuclide-specific values from FGR-11. Usually values for more than one inhalation class are listed per radionuclide. The three classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days; respectively. For some gaseous radionuclides (e.g., H-3, C-14, Ni-59, and Ni-63), inhalation classes other than D, W, Y are also listed. The most conservative dose conversion factor is chosen as the default. The values can be changed if chemical forms are known or more appropriate data are available.
Ingestion dose conversion factors	mrem/pCi	Nuclide specific (Table 2.2)		M	Eckerman et al. 1988	Radionuclide-specific values from FGR-11. Ingestion dose conversion factors depend on the chemical form, which determines the fraction of a radionuclide entering the gastrointestinal tract that reaches body fluids. The code lists these fractions along with the dose conversion factor. The most conservative values are chosen as the default for the dose conversion factor. The values can be changed if chemical forms are known or more appropriate data are available.
Slope factor- external	(risk/yr)/ (pCi/g)	Nuclide specific (Table 2.3)		M	EPA 1995	The ratio of cancer risk per year to the radionuclide concentration in the soil. The slope factors are based on the EPA methodology of calculating cancer risk.
Slope factor - inhalation	risk/pCi	Nuclide specific (Table 2.3)		M	EPA 1995	The ratio of cancer risk to the radionuclide activity inhaled.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Slope factor - ingestion	risk/pCi	Nuclide specific (Table 2.3)		M	EPA 1995	The ratio of cancer risk to the radionuclide activity ingested.
Plant transfer factor	–	Element specific (Table 2.5)		P	IAEA 1994; Snyder et al. 1994; Sprung et al. 1990; Yu et al. 1993c	The ratio of radionuclide concentration in edible portions of the plant at harvest time to the dry soil radionuclide concentration. It is assumed that the same root uptake transfer factors can be used for leafy and non-leafy vegetables. The code has element-specific values and the user is allowed to change these values.
Meat transfer factor	(pCi/kg)/(pCi/d)	Element specific (Table 2.5)		P	IAEA 1994; Snyder et al. 1994; Sprung et al. 1990; Yu et al. 1993c	The ratio of radionuclide concentration in beef to the daily intake of the same radionuclide in livestock feed or water. The code has element-specific values for meat. The code allows the user to change these values.
Milk transfer factor	(pCi/L)/(pCi/d)	Element specific (Table 2.5)		P	IAEA 1994; Snyder et al. 1994; Sprung et al. 1990; Yu et al. 1993c	The ratio of radionuclide concentration in milk to the daily intake of the same radionuclide in livestock feed or water. The code has element-specific values for milk. The code allows the user to change these values.
Bioaccumulation factor for fish	(pCi/kg)/(pCi/L)	Element specific (Table 2.6)		P	IAEA 1994; Snyder et al. 1994; Yu et al. 1993c	The ratio of radionuclide concentration in the aquatic food to the concentration of the same radionuclide in water. The code has the element-specific aquatic bioaccumulation factors for fish and crustacea and mollusks. The user can change these values.

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values ^a	Type ^b	References	Description
Bioaccumulation factor for crustacea and mollusks	(pCi/kg)/ (pCi/L)	Element specific (Table 2.6)		P	IAEA 1994; Yu et al. 1993c	The ratio of radionuclide concentration in the aquatic food to the concentration of the same radionuclide in water. The code has the element-specific aquatic bioaccumulation factors for fish and crustacea and mollusks. The user can change these values.

^a Code-accepted values are not provided for element- or nuclide-specific parameters.

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

^c “_” indicates that the parameter is dimensionless.

^d Groundwater concentration can be input only if time since placement of material is >0.

^e This parameter should be used only if radionuclide leach rates are known.

^f NA = not applicable.

TABLE 2.2 Default Dose Conversion Factors (DCFs) for External, Inhalation, and Ingestion Pathways in RESRAD^{a,b}

Radionuclide ^c	External DCFs (mrem/yr)/ (pCi/g)	Class ^d	Inhalation DCFs (mrem/pCi)	f ₁ ^e	Ingestion DCF (mrem/pCi)
H-3	0.0	(H ₂ O)	6.40E-08	1	6.40E-08
C-14	1.34E-05	(ORGANIC)	2.09E-06	1	2.09E-06
Na-22	1.37E+01	D	7.66E-06	1	1.15E-05
Al-26	1.74E+01	D	7.96E-05	1.00E-02	1.46E-05
S-35	1.49E-05	W	2.48E-06	8.00E-01	7.33E-06
Cl-36	2.39E-03	W	2.19E-05	1	3.03E-06
K-40	1.04E-00	D	1.24E-05	1	1.86E-05
Ca-41	0.0	W	1.35E-06	3.00E-01	1.27E-06
Ca-45	6.26E-05	W	6.62E-06	3.00E-01	3.16E-06
Sc-46	1.27E+01	Y	2.96E-05	1.00E-04	6.40E-06
Mn-54	5.16E-00	W	6.70E-06	1.00E-01	2.77E-06
Fe-55	0.0	D	2.69E-06	1.00E-01	6.07E-07
Fe-59	7.64E-00	D	1.48E-05	1.00E-01	6.70E-06
Co-57	5.01E-01	Y	9.07E-06	3.00E-01	1.18E-06
Co-60	1.62E+01	Y	2.19E-04	3.00E-01	2.69E-05
Ni-59	0.0	(VAPOR)	2.70E-06	5.00E-02	2.10E-07
Ni-63	0.0	(VAPOR)	6.29E-06	5.00E-02	5.77E-07
Zn-65	3.70E-00	Y	2.04E-05	5.00E-01	1.44E-05
Ge-68+D	5.62E-00	W	5.19E-05	1	1.41E-06
Se-75	1.98E-00	W	8.47E-06	8.00E-01	9.62E-06
Se-79	1.86E-05	W	9.84E-06	8.00E-01	8.70E-06
Sr-85	2.97E-00	Y	5.03E-06	3.00E-01	1.98E-06
Sr-89	9.08E-03	Y	4.14E-05	1.00E-02	9.25E-06
Sr-90+D	2.46E-02	Y	1.31E-03	3.00E-01	1.53E-04
Zr-93	0.0	D	3.21E-04	2.00E-03	1.66E-06
Zr-95+D	4.52E-00	D	2.36E-05	2.00E-03	3.79E-06
Nb-93m	1.04E-04	Y	2.92E-05	1.00E-02	5.21E-07
Nb-94	9.68E-00	Y	4.14E-04	1.00E-02	7.14E-06
Nb-95	4.69E-00	Y	5.81E-06	1.00E-02	2.57E-06
Tc-99	1.26E-04	W	8.33E-06	8.00E-01	1.46E-06
Ru-106+D	1.29E-00	Y	4.77E-04	5.00E-02	2.74E-05
Ag-108m+D	9.65E-00	Y	2.83E-04	5.00E-02	7.62E-06
Ag-110m+D	1.72E+01	Y	8.03E-05	5.00E-02	1.08E-05
Cd-109	1.47E-02	D	1.14E-04	5.00E-02	1.31E-05

TABLE 2.2 (Cont.)

Radionuclide ^c	External DCFs (mrem/yr)/ (pCi/g)	Class ^d	Inhalation DCFs (mrem/pCi)	f ₁ ^e	Ingestion DCF (mrem/pCi)
Sn-113+D	1.46E-00	W	1.07E-05	2.00E-02	3.19E-06
Sb-124	1.17E+01	W	2.52E-05	1.00E-02	1.01E-05
Sb-125	2.45E-00	W	1.22E-05	1.00E-01	2.81E-06
Te-125m	1.51E-02	W	7.29E-06	2.00E-01	3.67E-06
I-125	1.66E-02	D	2.42E-05	1	3.85E-05
I-129	1.29E-02	D	1.74E-04	1	2.76E-04
Cs-134	9.47E-00	D	4.63E-05	1	7.33E-05
Cs-135	3.83E-05	D	4.55E-06	1	7.07E-06
Cs-137+D	3.41E-00	D	3.19E-05	1	5.00E-05
Ba-133	1.98	D	7.86E-06	1.00E-01	3.40E-06
Ce-141	3.18E-01	Y	8.95E-06	3.00E-04	2.90E-06
Ce-144+D	3.20E-01	Y	3.74E-04	3.00E-04	2.11E-05
Pm-147	5.01E-05	Y	3.92E-05	3.00E-04	1.05E-06
Sm-147	0.0	W	7.47E-02	3.00E-04	1.85E-04
Sm-151	9.84E-07	W	3.00E-05	3.00E-04	3.89E-07
Eu-152	7.01E-00	W	2.21E-04	1.00E-03	6.48E-06
Eu-154	7.68E-00	W	2.86E-04	1.00E-03	9.55E-06
Eu-155	1.82E-01	W	4.14E-05	1.00E-03	1.53E-06
Gd-152	0.0	D	2.43E-01	3.00E-04	1.61E-04
Gd-153	2.45E-01	D	2.38E-05	3.00E-04	1.17E-06
Ta-182	7.94E-00	Y	4.48E-05	1.00E-03	6.51E-06
Ir-192	4.61E-00	Y	2.82E-05	1.00E-02	5.74E-06
Au-195	2.07E-01	Y	1.30E-05	1.00E-01	1.06E-06
Tl-204	4.05E-03	D	2.41E-06	1	3.36E-06
Pb-210+D	6.05E-03	D	1.38E-02	2.00E-01	5.37E-03
Bi-207	9.38E-00	W	2.00E-05	5.00E-02	5.48E-06
Po-210	5.23E-05	W	9.40E-03	1.00E-01	1.90E-03
Ra-226+D	1.12E+01	W	8.60E-03	2.00E-01	1.33E-03
Ra-228+D	5.98E-00	W	5.08E-03	2.00E-01	1.44E-03
Ac-227+D	2.01E-00	D	6.72	1.00E-03	1.48E-02
Th-228+D	1.02E+01	Y	3.45E-01	2.00E-04	8.08E-04
Th-229+D	1.60E-00	W	2.16	2.00E-04	4.03E-03
Th-230	1.21E-03	W	3.26E-01	2.00E-04	5.48E-04
Th-232	5.21E-04	W	1.64	2.00E-04	2.73E-03

TABLE 2.2 (Cont.)

Radionuclide ^c	External DCFs (mrem/yr)/ (pCi/g)	Class ^d	Inhalation DCFs (mrem/pCi)	f ₁ ^e	Ingestion DCF (mrem/pCi)
Pa-231	1.91E-01	W	1.28	1.00E-03	1.06E-02
U-232	9.02E-04	Y	6.59E-01	5.00E-02	1.31E-03
U-233	1.40E-03	Y	1.35E-01	5.00E-02	2.89E-04
U-234	4.02E-04	Y	1.32E-01	5.00E-02	2.83E-04
U-235+D	7.57E-01	Y	1.23E-01	5.00E-02	2.67E-04
U-236	2.15E-04	Y	1.25E-01	5.00E-02	2.69E-04
U-238+D	1.37E-01	Y	1.18E-01	5.00E-02	2.69E-04
Np-237+D	1.10E-00	W	5.40E-01	1.00E-03	4.44E-03
Pu-238	1.51E-04	W	3.92E-01	1.00E-03	3.20E-03
Pu-239	2.95E-04	W	4.29E-01	1.00E-03	3.54E-03
Pu-240	1.47E-04	W	4.29E-01	1.00E-03	3.54E-03
Pu-241+D	1.89E-05	W	8.25E-03	1.00E-03	6.85E-05
Pu-242	1.28E-04	W	4.11E-01	1.00E-03	3.36E-03
Pu-244+D	7.73E-00	W	4.03E-01	1.00E-03	3.32E-03
Am-241	4.37E-02	W	4.44E-01	1.00E-03	3.64E-03
Am-243+D	8.95E-01	W	4.40E-01	1.00E-03	3.63E-03
Cm-243	5.83E-01	W	3.07E-01	1.00E-03	2.51E-03
Cm-244	1.26E-04	W	2.48E-01	1.00E-03	2.02E-03
Cm-245	3.40E-01	W	4.55E-01	1.00E-03	3.74E-03
Cm-246	1.16E-04	W	4.51E-01	1.00E-03	3.70E-03
Cm-247+D	1.86	W	4.14E-01	1.00E-03	3.42E-03
Cm-248	8.78E-05	W	1.65	1.00E-03	1.36E-02
Cf-252	1.76E-04	Y	1.57E-01	1.00E-03	1.08E-03

^a External dose conversion factors taken from Eckerman and Ryman (1993), and inhalation and ingestion dose conversion factors are from Eckerman et al. (1988).

^b Same values of external, inhalation, and ingestion dose conversion factors are used in the RESRAD-BUILD code.

^c +D indicates that the dose conversion factors of associated radionuclides (half-life less than 30 days) are included along with the principal radionuclide.

^d The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively. (H₂O) indicates water; (ORGANIC) indicates an organic material; and (VAPOR) indicates a gaseous material.

^e Fraction of a stable element entering the GI tract that reaches body fluids.

TABLE 2.3 Radionuclide Slope Factors^a for External, Inhalation, and Ingestion Pathways in RESRAD

Radionuclide	External (Risk/yr)/(pCi/g)	Inhalation (Risk/pCi)	Ingestion (Risk/pCi)
H-3	0.0	9.60E-14	7.20E-14
C-14	1.0E-11 ^b	7.00E-15	1.00E-12
Na-22	8.20E-06	4.90E-12	8.00E-12
Al-26	1.3E-05 ^b	6.0E-11 ^b	9.9E-12 ^b
S-35	1.1E-11 ^b	1.90E-13	4.20E-13
Cl-36	1.8E-09 ^b	1.30E-12	2.20E-12
K-40	6.10E-07	7.50E-12	1.30E-11
Ca-41	0.0 ^b	9.1E-12 ^b	9.1E-13 ^b
Ca-45	3.90E-18	2.50E-12	2.00E-12
Sc-46	7.90E-06	1.30E-11	5.70E-12
Mn-54	3.30E-06	3.70E-12	2.00E-12
Fe-55	0.0	5.60E-13	3.50E-13
Fe-59	4.60E-06	7.10E-12	5.90E-12
Co-57	2.10E-07	2.90E-12	9.70E-13
Co-60	9.80E-06	6.90E-11	1.90E-11
Ni-59	0.0	4.00E-13	1.90E-13
Ni-63	0.0	1.00E-12	5.50E-13
Zn-65	2.30E-06	1.00E-11	9.90E-12
Ge-68+D	4.30E-06 ^b	2.6E-13 ^b	1.1E-12 ^b
Se-75	8.90E-07	4.90E-12	6.50E-12
Se-79	1.40E-11 ^b	7.50E-12 ^b	6.60E-12 ^b
Sr-85	1.50E-06	1.10E-12	1.40E-12
Sr-89	5.40E-10	3.70E-12	1.00E-11
Sr-90+D	1.90E-08 ^b	6.90E-11	5.60E-11
Zr-93	0.0	5.30E-12	5.20E-12
Zr-95+D	2.80E-06	6.50E-12	3.90E-12
Nb-93m	3.60E-11	4.30E-13	6.60E-13
Nb-94	6.10E-06	8.20E-11	6.90E-12
Nb-95	2.90E-06	3.10E-12	2.30E-12
Tc-99	6.20E-13	2.90E-12	1.40E-12
Ru-106+D	7.60E-07	1.20E-10	3.50E-11
Ag-108m+D	5.60E-06	7.00E-11	6.10E-12
Ag-110m+D	1.10E-05	3.20E-11	8.40E-12
Cd-109	5.60E-10	1.90E-11	8.00E-12
Sn-113+D	7.9E-07 ^c	7.00E-15 ^c	1.00E-12 ^c
Sb-124	7.40E-06	1.30E-11	1.10E-11
Sb-125	1.30E-06	5.20E-12	3.00E-12
Te-125m	2.20E-09	2.90E-12	2.50E-12

TABLE 2.3 (Cont.)

Radionuclide	External (Risk/yr)/(pCi/g)	Inhalation (Risk/pCi)	Ingestion (Risk/pCi)
I-125	2.40E-09	1.70E-11	2.60E-11
I-129	2.70E-09	1.20E-10	1.80E-10
Cs-134	5.90E-06	2.90E-11	4.70E-11
Cs-135	2.9E-11 ^b	2.70E-12	4.50E-12
Cs-137+D	2.10E-06	1.90E-11	3.20E-11
Ba-133	9.20E-07	4.00E-12	2.70E-12
Ce-141	1.40E-07	4.30E-12	3.90E-12
Ce-144+D	1.60E-07	1.10E-10	3.00E-11
Pm-147	6.40E-12	7.50E-12	1.40E-12
Sm-147	0.0	6.90E-09	2.50E-11
Sm-151	2.90E-13	4.60E-12	4.60E-13
Eu-152	4.10E-06	7.90E-11	5.70E-12
Eu-154	4.70E-06	9.20E-11	9.40E-12
Eu-155	6.10E-08	9.60E-12	1.70E-12
Gd-152	0.0 ^b	1.8E-07 ^b	1.1E-10 ^b
Gd-153	7.20E-08	3.20E-12	1.30E-12
Ta-182	4.70E-06	1.70E-11	7.00E-12
Ir-192	2.70E-06	1.10E-11	6.40E-12
Au-195	1.6E-06 ^b	9.1E-12 ^b	8.4E-13 ^b
Tl-204	8.70E-10	1.20E-12	2.00E-12
Pb-210+D	1.1E-10 ^c	1.7E-09 ^c	6.8E-10 ^c
Bi-207	5.50E-06	9.40E-12	5.10E-12
Po-210	3.30E-11	2.10E-09	3.30E-10
Ra-226+D	6.70E-06	2.70E-09	3.00E-10
Ra-228+D	3.30E-06	9.90E-10	2.50E-10
Ac-227+D	9.30E-07	7.90E-08	6.30E-10
Th-228+D	6.20E-06	9.70E-08	2.30E-10
Th-229+D	7.70E-07	8.30E-08	3.60E-10
Th-230	4.40E-11	1.70E-08	3.80E-11
Th-232	2.00E-11	1.90E-08	3.30E-11
Pa-231	2.70E-08	2.40E-08	1.50E-10
U-232	3.40E-11	5.30E-08	8.10E-11
U-233	3.50E-11	1.40E-08	4.50E-11
U-234	2.10E-11	1.40E-08	4.40E-11
U-235+D	2.70E-07	1.30E-08	4.70E-11
U-236	1.70E-11	1.30E-08	4.20E-11
U-238+D	6.60E-08	1.20E-08	6.20E-11
Np-237+D	4.60E-07	3.50E-08	3.00E-10
Pu-238	1.90E-11	2.70E-08	3.00E-10

TABLE 2.3 (Cont.)

Radionuclide	External (Risk/yr)/(pCi/g)	Inhalation (Risk/pCi)	Ingestion (Risk/pCi)
Pu-239	1.30E-11	2.80E-08	3.20E-10
Pu-240	1.90E-11	2.80E-08	3.20E-10
Pu-241+D	3.4E-12 ^c	2.8E-10 ^c	5.2E-12 ^c
Pu-242	1.60E-11	2.60E-08	3.00E-10
Pu-244+D	1.10E-06	2.70E-08	3.20E-10
Am-241	4.60E-09	3.90E-08	3.30E-10
Am-243+D	2.70E-07	3.80E-08	3.30E-10
Cm-243	1.70E-07	2.90E-08	2.50E-10
Cm-244	2.10E-11	2.40E-08	2.10E-10
Cm-245	5.50E-08	3.90E-08	3.40E-10
Cm-246	1.80E-11	3.90E-08	3.30E-10
Cm-247	1.00E-06 ^c	3.60E-08 ^c	3.10E-10 ^c
Cm-248	1.50E-11	1.50E-07	1.30E-09
Cf-252	1.80E-11	2.60E-08	1.80E-10

^a Values for slope factors are taken from EPA (1995) except where marked.

^b Calculated by using dose conversion factor and risk coefficient.

^c Calculated by using individual slope factors values given in EPA (1995).

TABLE 2.4 Default Distribution Coefficients Used in RESRAD

Radionuclide	Distribution Coefficient ^a (cm ³ /g)	Radionuclide	Distribution Coefficient ^a (cm ³ /g)
Ac-227	2.000E+01	Ir-192	0.0
Ag-108m	0.0	K-40	5.500E+00
Ag-110m	0.0	Mn-54	2.000E+02
Al-26	0.0	Na-22	1.000E+01
Am-241	2.000E+01	Nb-93m	0.0
Am-243	2.000E+01	Nb-94	0.0
Au-195	0.0	Nb-95	0.0
Ba-133	5.000E+01	Ni-59	1.000E+03
Bi-207	0.0	Ni-63	1.000E+03
C-14	0.0	Np-237	1.0
Ca-41	5.000E+01	Pa-231	5.000E+01
Ca-45	5.000E+01	Pb-210	1.000E+02
Cd-109	0.0	Pm-147	-1.0
Ce-141	1.000E+03	Po-210	1.000E+01
Ce-144	1.000E+03	Pu-238	2.000E+03
Cf-252	-1.0	Pu-239	2.000E+03
Cl-36	1.000E-01	Pu-240	2.000E+03
Cm-243	-1.0	Pu-241	2.000E+03
Cm-244	-1.0	Pu-242	2.000E+03
Cm-245	-1.0	Pu-244	2.000E+03
Cm-246	-1.0	Ra-226	7.000E+01
Cm-247	-1.0	Ra-228	7.000E+01
Cm-248	-1.0	Ru-106	0.0
Co-57	1.000E+03	S-35	0.0
Co-60	1.000E+03	Sb-124	0.0
Cs-134	1.000E+03	Sb-125	0.0
Cs-135	1.000E+03	Sc-46	0.0
Cs-137	1.000E+03	Se-75	0.0
Eu-152	-1.0	Se-79	0.0
Eu-154	-1.0	Sm-147	-1.0
Eu-155	-1.0	Sm-151	-1.0
Fe-55	1.000E+03	Sn-113	0.0
Fe-59	1.000E+03	Sr-85	3.000E+01
Gd-152	-1.0	Sr-89	3.000E+01
Gd-153	-1.0	Sr-90	3.000E+01
Ge-68	0.0	Ta-182	0.0
H-3	0.0	Tc-99	0.0
I-125	1.000E-01	Te-125m	0.0
I-129	1.000E-01	Th-228	6.000E+04

TABLE 2.4 (Cont.)

Radionuclide	Distribution Coefficient ^a (cm ³ /g)	Radionuclide	Distribution Coefficient ^a (cm ³ /g)
Th-229	6.000E+04	U-235	5.000E+01
Th-230	6.000E+04	U-236	5.000E+01
Th-232	6.000E+04	U-238	5.000E+01
Tl-204	0.0	Zn-65	0.0
U-232	5.000E+01	Zr-93	-1.0
U-233	5.000E+01	Zr-95	-1.0
U-234	5.000E+01		

^a -1.0 indicates that the code will calculate the default distribution coefficient on the basis of a correlation with the plant root uptake transfer factor.

Sources: Baes and Sharp (1983); Nuclear Safety Associates (1980); Isherwood (1981); NRC (1980); Gee et al. (1980); Staley et al. (1979); Yu et al. (1993a).

TABLE 2.5 Transfer Factors for Plants, Meat, and Milk in RESRAD

Element	Plant	Meat (pCi/kg)/(pCi/d)	Milk (pCi/L)/(pCi/d)
H	4.8	1.20E-02	1.00E-02
C	5.5	3.10E-02	1.20E-02
Na	5.00E-02	8.00E-02	4.00E-02
Al	4.00E-03	5.00E-04	2.00E-04
S	6.00E-01	2.00E-01	2.00E-02
Cl	20	6.00E-02	2.00E-02
K	3.00E-01	2.00E-02	7.00E-03
Ca	5.00E-01	1.60E-03	3.00E-03
Sc	2.00E-03	1.50E-02	5.00E-06
Mn	3.00E-01	5.00E-04	3.00E-04
Fe	1.00E-03	2.00E-02	3.00E-04
Co	8.00E-02	2.00E-02	2.00E-03
Ni	5.00E-02	5.00E-03	2.00E-02
Zn	4.00E-01	1.00E-01	1.00E-02
Ge	4.00E-01	2.00E-01	1.00E-02
Se	1.00E-01	1.00E-01	1.00E-02
Sr	3.00E-01	8.00E-03	2.00E-03
Zr	1.00E-03	1.00E-06	6.00E-07
Nb	1.00E-02	3.00E-07	2.00E-06
Tc	5	1.00E-04	1.00E-03
Ru	3.00E-02	2.00E-03	3.30E-06
Ag	1.50E-01	3.00E-03	2.50E-02
Cd	3.00E-01	4.00E-04	1.00E-03
Sn	2.50E-03	1.00E-02	1.00E-03
Sb	1.00E-02	1.00E-03	1.00E-04
Te	6.00E-01	7.00E-03	5.00E-04
I	2.00E-02	7.00E-03	1.00E-02
Cs	4.00E-02	3.00E-02	8.00E-03
Ba	5.00E-03	2.00E-04	5.00E-04
Ce	2.00E-03	2.00E-05	3.00E-05
Pm	2.50E-03	2.00E-03	2.00E-05
Sm	2.50E-03	2.00E-03	2.00E-05
Eu	2.50E-03	2.00E-03	2.00E-05
Gd	2.50E-03	2.00E-03	2.00E-05
Ta	2.00E-02	5.00E-06	5.00E-06
Ir	3.00E-02	2.00E-03	2.00E-06
Au	1.00E-01	5.00E-03	1.00E-05
Tl	2.00E-01	2.00E-03	3.00E-03

TABLE 2.5 (Cont.)

Element	Plant	Meat (pCi/kg)/(pCi/d)	Milk (pCi/L)/(pCi/d)
Pb	1.00E-02	8.00E-04	3.00E-04
Bi	1.00E-01	2.00E-03	5.00E-04
Po	1.00E-03	5.00E-03	3.40E-04
Ra	4.00E-02	1.00E-03	1.00E-03
Ac	2.50E-03	2.00E-05	2.00E-05
Th	1.00E-03	1.00E-04	5.00E-06
Pa	1.00E-02	5.00E-03	5.00E-06
U	2.50E-03	3.40E-04	6.00E-04
Np	2.00E-02	1.00E-03	5.00E-06
Pu	1.00E-03	1.00E-04	1.00E-06
Am	1.00E-03	5.00E-05	2.00E-06
Cm	1.00E-03	2.00E-05	2.00E-06
Cf	1.00E-03	6.00E-05	7.50E-07

Source: Yu et al. (1993a, Tables D.3 and D.4).

TABLE 2.6 Bioaccumulation Factors for Fish and Crustacea and Mollusks in RESRAD

Element	Fish (pCi/kg)/(pCi/L)	Crustacea and Mollusks (pCi/kg)/(pCi/L)	Element	Fish (pCi/kg)/(pCi/L)	Crustacea and Mollusks (pCi/kg)/(pCi/L)
H	1	1	I	4.00E+01	5
C	5.00E+04	9.10E+03	Cs	2.00E+03	1.00E+02
Na	2.00E+01	2.00E+02	Ba	4	2.00E+02
Al	5.00E+02	1.00E+03	Ce	3.00E+01	1.00E+03
S	1.00E+03	2.40E+02	Pm	3.00E+01	1.00E+03
Cl	1.00E+03	1.90E+02	Sm	2.50E+01	1.00E+03
K	1.00E+03	2.00E+02	Eu	5.00E+01	1.00E+03
Ca	1.00E+03	3.30E+02	Gd	2.50E+01	1.00E+03
Sc	1.00E+02	1.00E+03	Ta	1.00E+02	3.00E+01
Mn	4.00E+02	9.00E+04	Ir	1.00E+01	2.00E+02
Fe	2.00E+02	3.20E+03	Au	3.50E+01	1.00E+03
Co	3.00E+02	2.00E+02	Tl	1.00E+04	1.50E+04
Ni	1.00E+02	1.00E+02	Pb	3.00E+02	1.00E+02
Zn	1.00E+03	1.00E+04	Bi	1.50E+01	1.00E+01
Ge	4.00E+03	2.00E+04	Po	1.00E+02	2.00E+04
Se	2.00E+02	2.00E+02	Ra	5.00E+01	2.50E+02
Sr	6.00E+01	1.00E+02	Ac	1.50E+01	1.00E+03
Zr	3.00E+02	6.7	Th	1.00E+02	5.00E+02
Nb	3.00E+02	1.00E+02	Pa	1.00E+01	1.10E+02
Tc	2.00E+01	5	U	1.00E+01	6.00E+01
Ru	1.00E+01	3.00E+02	Np	3.00E+01	4.00E+02
Ag	5	7.70E+02	Pu	3.00E+01	1.00E+02
Cd	2.00E+02	2.00E+03	Am	3.00E+01	1.00E+03
Sn	3.00E+03	1.00E+03	Cm	3.00E+01	1.00E+03
Sb	1.00E+02	1.00E+01	Cf	2.50E+01	1.00E+03
Te	4.00E+02	7.50E+01			

Source: Yu et al. (1993a, Table D.5).

TABLE 2.7 Parameters and Their Default Values Used in Version 3.0 of RESRAD-BUILD

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
External dose conversion factor	External	(mrem/yr)/(pCi/g)	Nuclide specific (Table 2.2)		M	Eckerman and Ryman 1993	FGR-12's nuclide-specific values adjusted for shielding, source material size, shape, and exposure distance. The user is not allowed to change these values.
Air submersion dose conversion factor	Air submersion	(mrem/yr)/(pCi/m ³)	Nuclide specific (Table 2.8)		M	Eckerman and Ryman 1993	FGR-12's nuclide-specific values. The user is not allowed to change these values.
Inhalation dose conversion factor	Inhalation	mrem/pCi	Nuclide specific (Table 2.2)		M	Eckerman et al. 1988	Largest nuclide-specific values from FGR-11. The user is not allowed to change these values.
Ingestion dose conversion factors	Ingestion	mrem/pCi	Nuclide specific		M	Eckerman et al. 1988	Largest nuclide-specific values from FGR-11. The user is not allowed to change these values.
Exposure duration	All	d	365	>0	B	Yu et al. 1994	The time spanned by the dose assessment, including intervals during which receptors may be absent from the building. It is used to calculate the amount of time at each receptor location as: time at receptor location = exposure duration x fraction of time inside x fraction of time at receptor location.
Indoor fraction	All	^c —	0.5	0–1	B	EPA 1997; Yu et al. 1997	The fraction of total time spent by one or more receptors inside a building.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Number of evaluation times	All	–	2	2–10	P	Yu et al. 1997	The number of time periods that the dose calculations are performed. The sources will be calculated for the evaluation time by way of mechanical erosion and radionuclide decay and ingrowth.
Time	All	yr	1	0–10,000	P	Yu et al. 1997	The time at which the dose assessment is performed (other than time zero). Dose can be calculated at nine user specified times. Dose is always calculated at time zero.
Number of rooms	All except direct external	–	1	1, 2, 3	P	Yu et al. 1997	The maximum number of distinct air flow regions in the building being modeled. Maximum regions allowed are three.
Deposition velocity	All except direct external	m/s	0.01	≥ 0	P	Yu et al. 1997	An empirical rate constant that relates the concentration of a radionuclide in air to that on a horizontal surface.
Resuspension rate	All except direct external	1/s	5E-7	≥ 0	P, B	Yu et al. 1997	The fraction of the deposited particles resuspended into the air per unit of time.
Room height	All except direct external	m	2.5	> 0	P	EPA 1997; Yu et al. 1997	The height of each distinct air flow volume.
Room area	All except direct external	m ²	36	> 0	P	EPA 1997; Yu et al. 1997	The floor area of each distinct air flow volume.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Air exchange rate for building and room	All except direct external	1/h	0.8 (building) 1.0 (room)	≥ 0	B	EPA 1997; Yu et al. 1993c; Mueller 1996	The rate at which the total amount of air contained within the building or room is replaced or renewed per unit time.
Net flow	All except direct external	m ³ /h	0 ^d	Unlimited	B	Yu et al. 1997	The net volume of air exchanged between two rooms per unit of time. This parameter has a strong and complex dependency on other air parameters.
Outdoor inflow	All except direct external	m ³ /h	60 ^d	Unlimited	B, P	Yu et al. 1997	The outdoor air flow into each of three rooms in a building.
Number of receptors	All	–	1	1–10	B	Yu et al. 1997	The number of locations, time fractions, and intake characteristics for one or more individuals who are subject to dose assessment.
Receptor room	All except direct external	–	1	1–3	B	Yu et al. 1997	The room in which an individual receptor is located. This number could also represent the number of points necessary to characterize one exposed individual.
Receptor location	Direct external	m	1,1,1 (Cartesian coordinates)	-1,000–1,000	B	Yu et al. 1997	The spatial coordinates of the point occupied by a receptor.
Receptor time fraction	All	–	1	>0	B	Yu et al. 1997; EPA 1997	The fraction of time spent by one or more receptors at a given location while inside the building.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Receptor inhalation rate	Inhalation and radon	m ³ /d	18	0–200	M, B	Yu et al. 1993c; EPA 1997	The rate at which an individual inhales air at the receptor location. The dose could be zero from these pathways if the inhalation rate is zero or the injection rate is zero.
Receptor indirect ingestion rate	Ingestion	m ² /h	0.0001	0–1	B	Yu et al. 1997; Beyeler et al. 1998a	The rate at which an individual ingests deposited dust after it has transferred to hands, foods, or other items at each receptor location. This parameter is used in one of two ingestion pathways. The other pathway is direct ingestion of the contaminated material. The dose from indirect ingestion could be zero if the ingestion rate is zero or the deposition velocity is zero. Unlike the direct ingestion rate, the dose from this pathway might be nonzero when the source of contamination and the receptor points are in different rooms.
Number of sources	All	–	1	1–10	P	Yu et al. 1997	The number of sources at different locations, or of different geometrical, physical, and radiological characteristics of sources entered. Each source can have up to 10 radionuclides.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Source type	All	–	Volume	1, 2, 3, 4	P	Yu et al. 1997	It could be one of four source types – volume, area, line, or point. Different assumptions and input parameters are required for the different types of sources. The volume source has a circular exposed area with some finite depth perpendicular to this area. Details of the five different regions and contamination need to be specified. The area source has a circular exposed area with no thickness. There is a distinction between the volume type and the other sources in the air quality model. The injection and radon release models are different.
Source room or primary room	All except direct external	–	1	1, 2, 3	P	Yu et al. 1997	It could be one of up to a maximum of three rooms allowed in which each source must be located. It is the primary room location of the contamination source.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Source direction	Direct external	–	X direction	X, Y, Z	P	Yu et al. 1997	The direction of a source relative to the three axes. For the volume and area sources it is the direction perpendicular to the exposed area. For the line source it is the direction of the line. No direction required for point source. The source direction is used for external dose calculations only, and it determines the geometry of the source and receptor.
Source location	Direct external	–	0,0,0	-1,000–1,000	P	Yu et al. 1997	The geometric coordinates to define the location of the source center in 3-d space relative to the origin.
Source length or area	All	m or m ²	36 ^e	> 0	P	Yu et al. 1997	The measure of the extent of contamination from the center point of the source. It is assumed that the contamination is distributed evenly along these dimensions.
Air release fraction	All except direct external	–	0.1	0–1	B	Yu et al. 1997	The amount of contaminated material removed from the source that is in the respirable particulate range. It is assumed that the remainder of the material is removed immediately from the site.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Direct ingestion rate	Ingestion	g/h (volume) and 1/h (other)	0	≥ 0	B	Yu et al. 1997; EPA 1997	The incidental ingestion rate of contaminated material directly from the source by any receptor in the room. Each receptor will ingest the source at a rate determined by the product of the ingestion rate and the amount of contamination in the source at that time.
Removable fraction	All	-	0.5 ^f	0–1	P, B	Yu et al. 1997; Beyeler 1998a	The fraction of a point, line, or area source that is subject to removal. This fraction of the source will be linearly removed between time 0 and time for source removal.
Time for source removal or source lifetime	All	d	365	>0	P, B	Yu et al. 1997	The time period during which the removable fraction of an area, line, or point source linearly erodes. If the source is fixed nothing will erode; the removable fraction should be set to zero, and the source lifetime would be immaterial.
Radon release fraction	Radon	–	0.1 ^g	0–1	P, B	Yu et al. 1997	The fraction of the total amount of radon produced by radium decay that escapes the surface of a contaminated material and is released to air.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Radionuclide concentration	All	pCi/g; ² pCi/m ² , pCi/m, pCi	1 (Co-60)	> 0	P	Yu et al. 1997	The activity (for a point source) or activity concentration of radionuclides distributed in a source. The units of measure depend on the type of source (volume: pCi/g; area: pCi/m ² ; line: pCi/m; point: pCi).
Number of regions in volume source	All	–	1	1, 2, 3, 4, 5	P	Yu et al. 1997	The number of distinct cylindrical layers in a volume source. The contamination is within these regions and the thickness of the volume source is the sum of the thickness of these regions.
Contaminated region-volume source	All	–	1	1, 2, 3, 4, 5	P	Yu et al. 1997	One of up to five cylindrical layers in an idealized volume source that contains radionuclide contamination.
Source thickness, volume source	All	cm	15	0 – ∞	P	Yu et al. 1997	The thickness of each cylindrical layer in an idealized volume source.
Source density, volume source	Direct external	g/cm ³	2.4	0 – 22.5	P	Yu et al. 1993b, 1997; Sprung et al. 1990	The effective density of each cylindrical layer in an idealized volume source.
Source erosion rate, volume source	All	cm/d	2.4E-8	0 – ∞	P, B	Yu et al. 1993b, 1997; EPA 1996	The erosion rate of each cylindrical layer in an idealized volume source when each layer is exposed.
Source porosity	Radon	–	0.1 ⁹	> 0 – < 1	P	Yu et al. 1993b, 1997; EPA 1996	The ratio of the pore volume to the total volume.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Radon effective diffusion coefficient	Radon	m ² /s	3E-7 ^g	0 – 2E-5	P	Yu et al. 1993b, 1997	The diffusivity of radon source materials.
Radon emanation coefficient	Radon	–	0.2 ^g	0 – 1	P	Yu et al. 1993b, 1997	The fraction of the total amount of radon produced by radium decay that escapes the contaminated material and gets into the pores of the medium.
Shielding thickness	Direct external	cm	0	0 – ∞	P, B	Yu et al. 1997	The effective (line-of-sight) thickness of shielding between a receptor and a source.
Shielding density	Direct external	g/cm ³	2.4	0 – 22.4	P	Yu et al. 1993b, 1997; Sprung et al. 1990	The effective density of shielding between a receptor and a source.
Shielding material	Direct external	–	Concrete	Concrete, water, aluminum, iron, copper, tungsten, lead, uranium	P	Yu et al. 1997	The type of material used in the shield between the receptor and source. The code can handle concrete, water, aluminum, iron, copper, tungsten, lead, or uranium.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Dry zone thickness	Tritium volume source	cm	0	≥ 0	P	Thibodeaux and Hwang 1982	RESRAD-BUILD has a specific model ⁿ to consider the volatilization of tritiated water (HTO) from the contaminated material. A contaminated layer with HTO can be located within the material. The dry zone thickness is the thickness between the uppermost plane of the contaminated zone and the surface of the material (or the interface of the material and the indoor atmosphere). As water molecules evaporate, H-3 is released to the indoor air and results in potential radiation exposure. To estimate the release rate of H-3, the values of several additional parameters are required.
Wet + dry zone thickness	Tritium volume source	cm	10	>dry zone thickness	P	Thibodeaux and Hwang 1982	The thickness between the surface of the contaminated material and the bottom of the contaminated zone.
Volumetric water content	Tritium volume source	–	0.03	0–1	P	Yu et al. 1993b-c; EPA 1996	The volume of water per unit volume of the porous material. This value should be less than the total porosity of the solid material.

TABLE 2.7 (Cont.)

Parameter Name	Pathways Used	Unit	Default Value	Code-Accepted Values ^a	Type ^b	Reference	Description
Water fraction available for evaporation	Tritium volume source	–	1	0–1	P	Yu et al. 1993b	The fraction of the amount of water in the contaminated zone that will volatilize to the total amount of water in the contaminated zone. This parameter is used to account for potential binding between the water molecule and the solid matrix of the contaminated zone, which prohibits volatilization of the water molecule.
Humidity	Tritium volume source	g/m ³	8	0–1,00	P, B	Yu et al. 1993a; Etnier 1980	The average humidity in the building. The value is dependent on the air conditioning and ventilation in the building.

^a Code-accepted values are not provided for nuclide-specific parameters.

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

^c “–” indicates that the parameter is dimensionless.

^d Value for this parameter will appear only if more than one room is selected in the “number of rooms” parameter.

^e Value for this parameter will not appear if the selected source type is a point source.

^f Value for this parameter will appear only if the selected source type is other than a volume source.

^g Value for this parameter will appear only if at least one of the selected radionuclides is a radon precursor.

^h The tritium evaporation model implemented in the RESRAD-BUILD code was adapted from the landfarming model developed by Thibodeaux and Hwang (1982) to consider evaporation of hydrocarbons from contaminated soils.

TABLE 2.8 Default Dose Conversion Factors for the Air Submersion Pathway in RESRAD-BUILD

Nuclide ^a	Submersion	Nuclide ^a	Submersion
H-3	0.0	Gd-152	0.0
C-14	2.62E-08	Gd-153	4.34E-04
Na-22	1.26E-02	Au-195	3.76E-04
Al-26	1.59E-02	Tl-204	6.54E-06
Cl-36	2.61E-06	Pb-210+D	1.43E-05
K-40	9.42E-04	Bi-207	8.82E-03
Ca-41	0.0	Ra-226+D	1.04E-02
Mn-54	4.79E-03	Ra-228+D	5.59E-03
Fe-55	0.0	Ac-227+D	2.16E-03
Co-57	6.56E-04	Th-228+D	9.41E-03
Co-60	1.47E-02	Th-229+D	1.72E-03
Ni-59	0.0	Th-230	2.04E-06
Ni-63	0.0	Th-232	1.02E-06
Zn-65	3.39E-03	Pa-231	2.01E-04
Ge-68+D	5.36E-03	U-232	1.66E-06
Sr-90+D	2.31E-05	U-233	1.91E-06
Nb-94	9.01E-03	U-234	8.93E-07
Tc-99	1.90E-07	U-235+D	9.03E-04
Ru-106+D	1.22E-03	U-236	5.86E-07
Ag-108m+D	9.14E-03	U-238+D	1.60E-04
Ag-110m+D	1.59E-02	Np-237+D	1.21E-03
Cd-109	3.44E-05	Pu-238	5.71E-07
Sb-125	2.36E-03	Pu-239	4.96E-07
I-129	4.45E-05	Pu-240	5.56E-07
Cs-134	8.86E-03	Am-241	9.57E-05
Cs-135	6.61E-08	Pu-241+D	2.56E-08
Cs-137+D	3.19E-03	Pu-242	4.69E-07
Ce-144+D	3.29E-04	Pu-244+D	1.90E-03
Pm-147	8.11E-08	Am-243+D	1.15E-03
Sm-147	0.0	Cm-243	6.88E-04
Sm-151	4.22E-09	Cm-244	5.74E-07
Eu-152	6.61E-03	Cm-248	3.97E-07
Eu-154	7.18E-03	Cf-252	5.92E-07
Eu-155	2.91E-04		

^a +D indicates that the dose conversion factors of associated radionuclides with half-life less than 6 months are included along with the principal radionuclide.

Source: Eckerman and Ryman (1993).

3 TREATMENT OF SHORT-LIVED RADIONUCLIDES AND PARAMETER TYPES

3.1 TREATMENT OF SHORT-LIVED RADIONUCLIDES

The short-lived radionuclides are treated differently in the RESRAD family of codes (RESRAD and RESRAD-BUILD) than they are in the DandD code. RESRAD version 6.0 uses a library of 91 principal radionuclides with half-lives of 30 days or longer. RESRAD-BUILD version 3.0 uses a library of 67 principal radionuclides with half-lives of 6 months or longer. Both consider any progeny with a half-life shorter than 30 days in RESRAD and 6 months in RESRAD-BUILD to be in equilibrium with the principal radionuclide. The DandD version 1.0 library includes 249 primary radionuclides. The half-lives of all primary radionuclides in the DandD code library are 10 minutes or longer. DandD always assumes a short-lived decay product to be in equilibrium with its parent when both of the following conditions are met: the decay product has a half-life that is less than 9 hours and that is less than one-tenth of the half-life of the parent. Table 3.1 lists all the principal radionuclides in the RESRAD code and the equivalent primary radionuclides in the DandD code. Percentages for the radionuclides are listed when a mixture of radionuclides are involved.

Table 3.1 shows that several principal radionuclides included in the RESRAD code (Ge-68+D, Ag-108m+D, Sn-113+D, Ba-133, Gd-152, Ta-182, Au-195, and Tl-204) are not included in DandD code. In addition, for some radionuclides (Sr-90, Zr-95, Pb-210, Ra-226, Ac-227, Th-228, Th-229, U-235, U-238, Np-237, Pu-241, Pu-244, and Am-243) if users want to compare the results in two codes, they may have to select more than one radionuclide in the DandD code. For example, to compare the dose results for U-235 obtained with the RESRAD code to the corresponding results for the DandD code, it is necessary to sum the DandD results for U-235 and Th-231 and compare that total to the RESRAD U-235 dose results.

3.2 PARAMETER TYPES AND DEFAULT VALUES

Information in this section compares the RESRAD and RESRAD-BUILD parameter types and default values with those of the DandD code for the NUREG-5512 residential and occupancy scenarios. RESRAD default parameters are compared with the DandD default residential scenario parameters (Table 3.2), and RESRAD-BUILD default parameters are compared with the DandD default occupancy scenario parameters (Table 3.3).

TABLE 3.1 List of Principal Radionuclides in RESRAD and Equivalent Primary Radionuclides in DandD

RESRAD Principal Radionuclide ^a	Equivalent Primary Radionuclides in DandD Code	All Radionuclides with Percentages
H-3	H-3	H-3
C-14	C-14	C-14
Na-22	Na-22	Na-22
Al-26	Al-26	Al-26
S-35	S-35	S-35
Cl-36	Cl-36	Cl-36
K-40	K-40	K-40
Ca-41	Ca-41	Ca-41
Ca-45	Ca-45	Ca-45
Sc-46	Sc-46	Sc-46
Mn-54	Mn-54	Mn-54
Fe-55	Fe-55	Fe-55
Fe-59	Fe-59	Fe-59
Co-57	Co-57	Co-57
Co-60	Co-60	Co-60
Ni-59	Ni-59	Ni-59
Ni-63	Ni-63	Ni-63
Zn-65	Zn-65	Zn-65
Ge-68+D	– ^b	Ge-68 + Ga-68 ^c
Se-75	Se-75	Se-75
Se-79	Se-79	Se-79
Sr-85	Sr-85	Sr-85
Sr-89	Sr-89	Sr-89
Sr-90+D	Sr-90+Y-90	Sr-90 + Y-90
Zr-93	Zr-93	Zr-93
Zr-95+D	Zr-95 + (0.7%) Nb-95m	Zr-95 + (0.7%) Nb-95m
Nb-93m	Nb-93m	Nb-93m
Nb-94	Nb-94	Nb-94
Nb-95	Nb-95	Nb-95
Tc-99	Tc-99	Tc-99
Ru-106+D	Ru-106	Ru-106 + Rh-106
Ag-108m+D	–	Ag-108m + (8.9%) Ag-108
Ag-110m+D	Ag-110m	Ag-110m + (1.33%) Ag-110
Cd-109	Cd-109	Cd-109
Sn-113+D	–	Sn-113 + In-113m
Sb-124	Sb-124	Sb-124
Sb-125	Sb-125	Sb-125
Te-125m	Te-125m	Te-125m
I-125	I-125	I-125
I-129	I-129	I-129

TABLE 3.1 (Cont.)

RESRAD Principal Radionuclide ^a	Equivalent Primary Radionuclides in DandD Code	All Radionuclides with Percentages
Cs-134	Cs-134	Cs-134
Cs-135	Cs-135	Cs-135
Cs-137+D	Cs-137	Cs-137 + (94.6%) Ba-137 m
Ba-133	—	Ba-133
Ce-141	Ce-141	Ce-141
Ce-144+D	Ce-144+D	Ce-144 + (98.22%) Pr-144 + (1.78%) Pr-144m
Pm-147	Pm-147	Pm-147
Sm-147	Sm-147	Sm-147
Sm-151	Sm-151	Sm-151
Eu-152	Eu-152	Eu-152
Eu-154	Eu-154	Eu-154
Eu-155	Eu-155	Eu-155
Gd-152	—	Gd-152
Gd-153	Gd-153	Gd-153
Ta-182	—	Ta-182
Ir-192	Ir-192	Ir-192
Au-195	—	Au-195
Tl-204	—	Tl-204
Pb-210+D	Pb-210 + Bi-210	Pb-210 + Bi-210
Bi-207	—	Bi-207
Po-210	Po-210	Po-210
Ra-226+D	Ra-226 + Rn-222	Ra-226 + Rn-222 + Po-218 + (99.98%) Pb-214 + (0.02%) At-218 + Bi-214 + (99.98%) Po-214 + (0.02%) Tl-210
Ra-228+D	Ra-228	Ra-228 + Ac-228
Ac-227+D	Ac-227 + (98.62%)Th-227 + Ra-223	Ac-227 + (98.6%) Th-227 + (1.4%) Fr-223 + Ra-223 + Rn-219 + Po-215 + Pb-211 + Bi-211 + (99.72%) Tl-207 + (0.28%) Po-211
Th-228+D	Th-228 + Ra-224 + Pb-212	Th-228 + Ra-224 + Rn-220 + Po-216 + Pb-212 + Bi-212 + (64%) Po-212 + (36%) Tl-208
Th-229+D	Th-229 + Ra-225 + Ac-225	Th-229 + Ra-225 + Ac-225 + Fr-221 +At-217 + Bi-213 + (97.8%) Po-213 + (2.2%) Tl-209 + Pb- 209
Th-230	Th-230	Th-230
Th-232	Th-232	Th-232
Pa-231	Pa-231	Pa-231
U-232	U-232	U-232
U-233	U-233	U-233
U-234	U-234	U-234
U-235+D	U-235 + Th-231	U-235 + Th-231
U-236	U-236	U-236

TABLE 3.1 (Cont.)

RESRAD Principal Radionuclide ^a	Equivalent Primary Radionuclides in DandD Code	All Radionuclides with Percentages
U-238+D	U-238 + Th-234	U-238 + Th-234 + (99.8%) Pa-234m + (0.02%) Pa-234
Np-237+D	Np-237 + Pa-233	Np-237 + Pa-233
Pu-238	Pu-238	Pu-238
Pu-239	Pu-239	Pu-239
Pu-240	Pu-240	Pu-240
Pu-241+D	Pu-241 + (0.00245%) U-237	Pu-241 + (0.00245%) U-237
Pu-242	Pu-242	Pu-242
Am-241	Am-241	Am-241
Am-243+D	Am-243 + Np-239	Am-243 + Np-239
Cm-243	Cm-243	Cm-243
Cm-244	Cm-244	Cm-244
Cm-245	Cm-245	Cm-245
Cm-246	Cm-246	Cm-246
Cm-247+D	Cm-247	Cm-247 + Pu-243
Cm-248	Cm-248	Cm-248
Cf-252	Cf-252	Cf-252

^a “+D” indicates that the dose conversion factors of associated radionuclides (half-life less than 30 days) are included along with the principal radionuclide.

^b “—” indicates that radionuclide is not available in the database.

^c Percentages are listed only when the contribution is less than 100%.

TABLE 3.2 Parameter Types and their Default Values in RESRAD and DandD for Residential Scenario

Parameter Name	RESRAD Parameter		DandD Parameter		
	Unit	Default Value	Type ^a	Default value	Type ^a
Source					
Nuclide concentration	pCi/g	100	P	1	P
Transport Factors					
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zones)	cm ³ /g	Nuclide specific (Table 2.4)	P	Element specific	P
Number of unsaturated zones	– ^b	1	P	1	NA ^c
Time since placement of material	yr	0	P	NA	NA
Groundwater concentration	pCi/L	0 ^d	P	NA	NA
Leach rate	(/yr)	0 ^e	P	NA	NA
Solubility limit	mol/L	0	P	NA	NA
Use plant/soil ratio	check box	Yes/No	NA	NA	NA
Calculation Parameters					
Basic radiation dose limit	mrem/yr	30	NA	NA	NA
Times for calculations ^f	yr	1, 3, 10, 30, 100, 300, 1,000	P	–	NA
Contaminated Zone Parameters					
Area of contaminated zone ^g	m ²	10,000	P	2,400	B
Thickness of contaminated zone	m	2	P	0.15	P
Surface layer ratio	–	NA	NA	0.1626	P
Length parallel to aquifer flow	m	100	P	NA	NA
Cover^h and Contaminated Zone Hydrological Data					
Cover depth	m	0	P	NA	NA
Density of cover material	g/cm ³	1.5	P	NA	NA
Cover erosion rate	m/yr	0.001	P, B	NA	NA
Density of contaminated zone ⁱ	g/cm ³	1.5	P	1.4312	P
Contaminated zone total porosity	–	0.4	P	0.4599	P
Contaminated zone field capacity	–	0.2	P	NA	NA
Contaminated zone erosion rate	m/yr	0.001	P, B	NA	NA
Contaminated zone hydraulic conductivity	m/yr	10	P	NA	NA

TABLE 3.2 (Cont.)

Parameter Name	Unit	RESRAD Parameter		DandD Parameter	
		Default Value	Type ^a	Default value	Type ^a
Contaminated zone b parameter	–	5.3	P	NA	NA
Humidity in air	g/m ³ (RESRAD) L/m ³ (DandD)	8	P	0.008	P
Evapotranspiration coefficient	–	0.5	P	NA	NA
Wind speed	m/s	2	P	NA	NA
Precipitation rate ^j	m/yr	1.0	P	NA	NA
Irrigation rate ^k	m/yr	0.2	B	1.29	B
Infiltration rate	m/yr	NA	NA	0.2526	P
Irrigation mode	–	Overhead	B	NA	NA
Runoff coefficient	–	0.2	P	NA	NA
Watershed area ^l for nearby stream or pond	m ²	1,000,000	P	1,300,000	P
Accuracy for water soil computation	–	0.001	NA	NA	NA
Saturated Zone Hydrological Data^m					
Density of saturated zone	g/cm ³	1.5	P	NA	NA
Saturated zone total porosity	–	0.4	P	NA	NA
Saturated zone effective porosity	–	0.2	P	NA	NA
Saturated zone field capacity	–	0.2	P	NA	NA
Saturated zone hydraulic conductivity	m/yr	100	P	NA	NA
Saturated zone hydraulic gradient	–	0.02	P	NA	NA
Saturated zone b parameter	–	5.3	P	NA	NA
Water table drop rate	m/yr	0.001	P	NA	NA
Well pump intake depth (below water table)	m	10.0	P	NA	NA
Model: nondispersion (ND) or mass-balance (MB)	–	ND	P	NA	NA
Well pumping rate ⁿ	m ³ /yr	250	B, P	11,8000	B
Uncontaminated Unsaturated Zone^o Parameters					
Unsaturated zone thickness	m	4	P	1.2288	P
Unsaturated zone density	g/cm ³	1.5	P	1.4312	P
Unsaturated zone total porosity	–	0.4	P	0.4599	P
Unsaturated zone effective porosity	–	0.2	P	NA	NA
Unsaturated zone field capacity	–	0.2	P	NA	NA
Unsaturated zone, soil-specific b parameter	–	5.3	P	NA	NA

TABLE 3.2 (Cont.)

Parameter Name	Unit	RESRAD Parameter		DandD Parameter	
		Default Value	Type ^a	Default value	Type ^a
Unsaturated ratio	–	NA	NA	0.1626	P
Unsaturated zone hydraulic conductivity	m/yr	10	P	NA	NA
Occupancy, Inhalation, and External Gamma Parameters					
Inhalation rate ^p	m ³ /yr	8,400	M, B	NA	NA
Indoor breathing rate	m ³ /h	NA	NA	0.9	M
Outdoor breathing rate	m ³ /h	NA	NA	1.4	M
Gardening breathing rate	m ³ /h	NA	NA	1.7	M
Mass loading for inhalation ^q	g/m ³	1E-4	P, B		P
Exposure duration	yr	30	B	NA	NA
Indoor dust filtration factor	–	0.4	P, B	NA	NA
Floor dust	g/m ²	NA	NA	0.1599	P
Resuspension factor	m ⁻¹	NA	NA	2.82E-6	P
Indoor dust	g/m ³	NA	NA	1.41E-6	P
Outdoor dust	g/m ³	NA	NA	3.14E-6	P
Gardening dust	g/m ³	NA	NA	4.0E-4	P
External gamma shielding factor ^r	–	0.7	P	0.552	B
Indoor time fraction ^s	–	0.5	B	NA	NA
Outdoor time fraction	–	0.25	B	NA	NA
Time indoor	d/yr	NA	NA	240	B
Time outdoor	d/yr	NA	NA	40.2	B
Time gardening	d/yr	NA	NA	2.92	B
Exposure period	d	NA	NA	365.25	B
Garden period	d	NA	NA	90	B
Shape of the contaminated zone (shape factor flag)	–	Circular	P	NA	NA
Ingestion Pathway, Dietary Data					
Fruit, vegetables, and grain consumption	kg/yr	160	M, B	52.8 + 44.6 + 14.4	B
Leafy vegetable consumption	kg/yr	14	M, B	21.4	B
Milk consumption	L/yr	92	M, B	233	B
Meat and poultry consumption	kg/yr	63	M, B	39.8 + 25.3	B
Fish consumption	kg/yr	5.4	M, B	20.6	B
Other seafood consumption	kg/yr	0.9	M, B	NA	NA

TABLE 3.2 (Cont.)

Parameter Name	Unit	RESRAD Parameter		DandD Parameter	
		Default Value	Type ^a	Default value	Type ^a
Soil ingestion rate	g/yr (RESRAD) g/d (DandD)	36.5	M, B	0.05	B
Drinking water intake	L/yr (RESRAD) L/d (DandD)	510	M, B	1.31	B
Water period	d	NA	NA	365.25	P
Drinking water contaminated fraction ^t	–	1	B, P	1	B
Household water contaminated fraction	–	1	B, P	1	B
Livestock water contaminated fraction	–	1	B, P	1	B
Irrigation water contaminated fraction	–	1	B, P	1	B
Aquatic food contaminated fraction	–	0.5	B, P	1	B
Plant food contaminated fraction	–	-1	B, P	1	B
Meat contaminated fraction	–	-1	B, P	1	B
Milk contaminated fraction	–	-1	B, P	1	B
Ingestion Pathway, Nondietary Data					
Livestock fodder intake for meat ^u	kg/d	68	M	8.133 forage 2.41877 grain 16.2535 hay	P
Livestock fodder intake for milk ^v	kg/d	55	M	35.1654 forage 1.94662 grain 26.1089 hay	P
Livestock water intake for meat	L/d	50	M	50	P
Livestock water intake for milk	L/d	160	M	60	P
Livestock intake of soil ^w	kg/d	0.5	M	NA	P
Mass loading for foliar deposition ^x	g/m ³	1E-4	P	NA	P
Depth of soil mixing layer	m	0.15	P	NA	NA
Depth of roots	m	0.9	P	NA	NA
Groundwater fractional usage for drinking water	–	1	B, P	1	B
Groundwater fractional usage for household water	–	1	B, P	1	B
Groundwater fractional usage for livestock water	–	1	B, P	1	B
Groundwater fractional usage for irrigation water	–	1	B, P	1	B

TABLE 3.2 (Cont.)

Parameter Name	RESRAD Parameter		DandD Parameter		
	Unit	Default Value	Type ^a	Default value	Type ^a
Plant Factors					
Wet-weight crop yields	kg/m ² (RESRAD) kg/m ³ (DandD)	0.7 (nonleafy) 1.5 (leafy) 1.1 (fodder)	P	1.88921 leafy 2.40002 root 2.36732 fruit 0.390429 grain-human 1.8868 forage and hay 0.656769 grain-animal	P
Length of growing season	yr	0.17 (nonleafy) 0.25 (leafy) 0.08 (fodder)	P	30 days (forage) 90 days (grains, fruits, other vegetables) 45 days (leafy vegetables, stored hay)	P
Translocation factor	–	0.1 (nonleafy) 1 (leafy vegetable and fodder)	P	1 (leafy, forage, and hay) 0.1 (non-leafy, fruit, grain)	P
Weathering removal constant	1/yr	20	P	NA	NA
Weathering rate ^y	d	NA	NA	0.0495	P
Wet foliar interception fraction	–	0.25 (nonleafy, leafy, and fodder)	P	0.35 (leafy, non-leafy, fruit, grain)	P
Dry foliar interception fraction	–	0.25 (nonleafy, leafy, and fodder)	P	0.349 (forage and hay) NA	NA
Radon Parameters^z					
Cover total porosity	–	0.4	P	NA	NA
Cover volumetric water content	–	0.05	P	NA	NA
Cover radon diffusion coefficient	m ² /s	2.0E-6	P	NA	NA
Building foundation thickness	m	0.15	P	NA	NA
Building foundation density	g/cm ³	2.4	P	NA	NA
Building foundation total porosity	–	0.1	P	NA	NA
Building foundation volumetric water content	–	0.03	P	NA	NA
Building foundation radon diffusion coefficient	m ² /s	3.0E-7	P	NA	NA
Contamination radon diffusion coefficient	m ² /s	2.0E-6	P	NA	NA
Radon vertical dimension of mixing	m	2	P	NA	NA
Building air exchange rate	1/h	0.5	P, B	NA	NA
Building height	m	2.5	P	NA	NA

TABLE 3.2 (Cont.)

Parameter Name	Unit	RESRAD Parameter		DandD Parameter	
		Default Value	Type ^a	Default value	Type ^a
Building indoor area factor	–	0	P	NA	NA
Foundation depth below ground surface	m	-1	P	NA	NA
Radon-222 emanation coefficient	–	0.25	P	NA	NA
Radon-220 emanation coefficient	–	0.15	P	NA	NA
Storage Times^{aa} Before Use Data					
Storage times for fruits, non-leafy vegetables, and grain	d	14	B	14	B
Storage times for leafy vegetables	d	1	B	1	B
Storage times for milk	d	1	B	1	B
Storage times for meat	d	20	B	20	B
Storage times for fish	d	7	B	NA	NA
Storage times for crustacea and mollusks	d	7	B	NA	NA
Storage times for well water	d	1	B	NA	NA
Storage times for surface water	d	1	B	NA	NA
Storage times for livestock fodder	d	45	B	NA	NA
Carbon-Model Parameters^{bb}					
C-12 concentration in local water	g/cm ³	2E-5	P	NA	NA
C-12 concentration in contaminated soil	g/g	0.03	P	NA	NA
Fraction of vegetation carbon absorbed from soil	–	0.02	P	NA	NA
Fraction of vegetation carbon absorbed from air	–	0.98	P	NA	NA
C-14 evasion layer thickness in soil	m	0.3	P	NA	NA
C-14 evasion flux rate from soil	1/s	7E-07	P	NA	NA
C-12 evasion flux rate from soil	1/s	1E-10	P	NA	NA
Grain fraction in livestock feed	–	0.8 (beef cattle) 0.2 (cow)	B	NA	NA
Inhalation dose conversion factors	mrem/pCi	Nuclide specific (Table 2.2)	M	Nuclide specific	P
Ingestion dose conversion factors	mrem/pCi	Nuclide specific (Table 2.2)	M	Nuclide specific	P
Slope factor ^{cc} - external	(risk/yr)/ (pCi/g)	Nuclide specific (Table 2.3)	M	NA	NA
Slope factor - inhalation	risk/pCi	Nuclide specific (Table 2.3)	M	NA	NA

TABLE 3.2 (Cont.)

Parameter Name	Unit	RESRAD Parameter		DandD Parameter	
		Default Value	Type ^a	Default value	Type ^a
Slope factor - ingestion	risk/pCi	Element specific (Table 2.3)	M	NA	NA
Plant transfer factor	–	Element specific (Table 2.5)	P	Element specific	P
Meat transfer factor	(pCi/kg)/(pCi/d)	Element specific (Table 2.5)	P	Element specific	P
Milk transfer factor	(pCi/L)/(pCi/d)	Element specific (Table 2.5)	P	Element specific	P
Bioaccumulation factor for fish	(pCi/kg)/(pCi/L)	Element specific (Table 2.6)	P	Element specific	P
Bioaccumulation factor for crustacea and mollusks	(pCi/kg)/(pCi/L)	Element specific (Table 2.6)	P	NA	NA

^a Parameter types, P = physical, B = behavioral, M = metabolic.

^b Hyphen indicates that the parameter is dimensionless.

^c NA = not applicable (code does not require this value).

^d Groundwater concentration can be input into the code only if time since placement of material is greater than 0.

^e This value should only be used if radionuclide leach rates are known.

^f The DandD code has start time (default value of 0 days), end time (default value 365,250 days), and time step size (default value of 365.25 days).

^g This parameter is called "area of land cultivated" in the DandD code.

^h The DandD code does not include cover in dose calculations.

ⁱ This parameter is called "surface soil density" in the DandD code.

^j The DandD code has an infiltration rate of 0.2526 m/yr instead of precipitation rate, evapotranspiration coefficient, and runoff coefficient.

^k The irrigation rate in DandD has the unit of L/m²* day.

^l The DandD code uses volume of water in surface-water pond (in liters).

^m The DandD code does not require any parameter for saturated zone.

ⁿ The DandD code uses volume of water removed annually (in liters) from the groundwater aquifer.

^o The unsaturated zone parameters required in DandD code are thickness of unsaturated zone, number of layers in the unsaturated zone, porosity of unsaturated zone soil, degree of saturation for the unsaturated zone soil (P), and bulk density of the unsaturated zone.

^p The DandD code uses indoor, outdoor, and gardening breathing rate; all are metabolic parameters with constant value.

Footnotes continue on next page

TABLE 3.2 (Cont.)

Footnotes (continued)

- ^q In the DandD code, floor dust, resuspension factor, indoor dust, outdoor dust, and gardening dust are used to calculate inhalation doses.
- ^r In the DandD code this parameter is called indoor shielding factor. DandD also has a outdoor shielding factor for external exposure with the default set at 1.
- ^s Instead of the indoor and outdoor time fractions, the DandD code uses time indoors, time outdoors, time gardening, exposure period, and garden period. Time indoors, time outdoors, and time gardening are behavioral parameters. Exposure period and garden period are behavioral parameters with constant value.
- ^t The DandD code uses the fraction of human diet grown on-site. The default value for this parameter is 1, i.e., 100% is grown on-site.
- ^u DandD uses separate animal feed intake rates for forage, grain, and hay for beef cattle, poultry, and layer hens. Default values listed in this table are for beef cattle.
- ^v DandD uses separate animal feed intake rates for forage, grain, and hay for milk cows.
- ^w DandD uses animal intake mass fraction of soil in dry fresh forage; the values are 0.02 for beef cattle and milk cows and 0.1 for layer hens and poultry.
- ^x DandD uses plant mass loading (0.1 g/g) for leafy vegetables, other vegetables, fruit, grain, and also forage, grain, stored hay consumed by beef cattle, poultry, milk cows, and layer hens.
- ^y In the DandD code this parameter is the weathering rate for activity removal of radionuclides from plants.
- ^z The DandD code does not include the radon inhalation pathway in dose calculations.
- ^{aa} This parameter is called the holdup period in the DandD code, and values are not provided for fish and water.
- ^{bb} The DandD code has different carbon-model parameters. The parameters are mass fractions for beef, poultry, milk, eggs, forage, grain, hay, soil and animal activity. All parameters are physical with constant value.
- ^{cc} The DandD code does not calculate risk.

TABLE 3.3 Parameter Types and Their Default Values in RESRAD-BUILD and DandD for Occupancy Scenario

Parameter	Unit	RESRAD-BUILD Parameter		DandD Parameter	
		Default Value	Type ^a	Default Value	Type ^a
External dose conversion factor	(mrem/yr)/(pCi/g)	Nuclide specific (Table 2.2)	M	Nuclide specific	P
Inhalation dose conversion factor	mrem/pCi	Nuclide specific (Table 2.2)	M	Nuclide specific	P
Ingestion dose conversion factors	mrem/pCi	Nuclide specific (Table 2.2)	M	Nuclide specific	P
Air submersion dose conversion factors	(mrem/yr)/(pCi/m ³)	Nuclide specific (Table 2.8)	M	NA ^b	NA
Exposure duration	d	365	B	NA	NA
Indoor fraction	— ^c	0.5	B	NA	NA
Number of evaluation times	—	2	P	NA	NA
Time	yr	1	P	NA	NA
Number of rooms	—	1	P	NA	NA
Deposition velocity	m/s	0.01	P	NA	NA
Resuspension rate	1/s	5E-7	P, B	NA	NA
Room height	m	2.5	P	NA	NA
Room area	m ²	36	P	NA	NA
Air exchange rate for building and room	1/h	0.8 (building) 1.0 (room)	B	NA	NA
Net flow	m ³ /h	0	B	NA	NA
Outdoor inflow	m ³ /h	60	B, P	NA	NA
Number of receptors	—	1	B	NA	NA
Receptor room	—	1	B	NA	NA
Receptor location	m	1,1,1 (Cartesian coordinates)	B	NA	NA
Receptor time fraction	—	1	B	NA	NA
Receptor inhalation rate	m ³ /d	18	M, B	NA	NA
Receptor indirect ingestion rate	m ² /h	0.0001	B	NA	NA
Number of sources	—	1	P	NA	NA
Source type	—	Volume	P	NA	NA
Source room or primary room	—	1	P	NA	NA
Source direction	—	X	P	NA	NA
Source location	—	0,0,0	P	NA	NA
Source length or area	m or m ²	36	P	NA	NA
Air release fraction	—	0.1	B	NA	NA

TABLE 3.3 (Cont.)

Parameter	Unit	RESRAD-BUILD Parameter		DandD Parameter	
		Default Value	Type ^a	Default Value	Type ^a
Direct ingestion rate	g/h (volume) and 1/h (other)	0	B	NA	NA
Removable fraction	—	0.5	P, B	NA	NA
Time for source removal or source lifetime	d	365	P, B	NA	NA
Radon release fraction	—	0.1	P, B	NA	NA
Radionuclide concentration	pCi/g, pCi/m ² , pCi/m, pCi	1 (Co-60)	P	1 dpm/100 cm ²	P
Number of regions in volume source	—	1	P	NA	NA
Contaminated region-volume source	—	1	P	NA	NA
Source thickness, volume source	cm	15	P	NA	NA
Source density, volume source	g/cm ³	2.4	P	NA	NA
Source erosion rate, volume source	cm/d	2.4E-8	P, B	NA	NA
Source porosity	—	0.1	P	NA	NA
Radon effective diffusion coefficient	m ² /s	3E-7	P	NA	NA
Radon emanation coefficient	—	0.2	P	NA	NA
Shielding thickness	cm	0	P, B	NA	NA
Shielding density	g/cm ³	2.4	P	NA	NA
Shielding material	—	Concrete	P	NA	NA
Dry zone thickness	cm	0	P	NA	NA
Wet + dry zone thickness	cm	10	P	NA	NA
volumetric water content	—	0.03	P	NA	NA
Water fraction available for evaporation	—	1	P	NA	NA
Humidity	g/m ³	8	P, B	NA	NA
Time in building ^d	d/yr	NA	NA	97.46	B
Occupancy period ^e	d	NA	NA	365.25	P
Breathing rate ^f	m ³ /h	NA	NA	1.4	M
Resuspension factor ^g	m ⁻¹	NA	NA	1.42E-5	P
Ingestion rate ^h	m ² /h	NA	NA	1.11E-5	B

See next page for footnotes.

TABLE 3.3 (Cont.)

- ^a Parameter types, P = physical, B = behavioral, M = metabolic.
- ^b NA = not applicable (parameter is not required in the code).
- ^c A hyphen indicates that the parameter is dimensionless.
- ^d Time in building in DandD is related to total time and indoor fraction in RESRAD-BUILD
- ^e Occupancy period in DandD is the same as total time in RESRAD-BUILD.
- ^f Breathing rate in DandD and receptor inhalation rate in RESRAD-BUILD.
- ^g DandD uses resuspension factor and RESRAD-BUILD uses resuspension rate.
- ^h DandD uses the direct ingestion rate in m^2/h ; whereas RESRAD-BUILD requires both direct and indirect ingestion rates. Direct ingestion rate has units of g/h or $1/\text{h}$, and indirect ingestion rate has units of m^2/h .

4 REFERENCES

Alzona, J., et al., 1979, "Indoor-Outdoor Relationships for Airborne Particulate Matter of Outdoor Origin," *Atmospheric Environment* 13:55-60.

Amiro, B.D., et al., 1991, "Relative Importance of Atmospheric and Root Uptake Pathways for $^{14}\text{CO}_2$ Transfer from Contaminated Soil to Plants," *Health Physics* 61:825-829.

Baes, C.F., and R.D. Sharp, 1983, "A Proposal for Estimation of Soil Leaching and Leaching Constants for Use in Assessment Models," *Journal of Environmental Quality* 12(1):17-28.

Beyeler, W.E., et al. 1998a, *Review of Parameter Data for the NUREG/CR-5512 Building Occupancy Scenario and Probability Distributions for the DandD Parameter Analysis*, NUREG/CR-5512, Vol.3, prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Jan.

Beyeler, W.E., et al. 1998b, Letter Report, *Review of Parameter Data for the NUREG/CR-5512 Residential Farmer Scenario and Probability Distributions for the DandD Parameter Analysis*, prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission, Jan.

Clapp, R.B., and G.M. Hornberger, 1978, "Empirical Equations for Some Soil Hydraulic Properties," *Water Resources Research* 14:601-604.

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

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

EPA: See U.S. Environmental Protection Agency.

Etnier, E.L., 1980, "Regional and Site-Specific Absolute Humidity Data for Use in Tritium Dose Calculations," *Health Physics* 39:318-320.

Gee, G.W., et al., 1980, *Interaction of Uranium Mill Tailings Leachate with Soils and Clay Liners*, NUREG/CR-1494, PNL-3381, prepared by Pacific Northwest Laboratory, Richland, Wash., for U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C.

Gilbert, T.L., et al., 1983, *Parameters Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites*, ORO-832 (Rev.), prepared by Division of Environmental Impact Studies, Argonne National Laboratory, Argonne, Ill., for U.S. Department of Energy, Oak Ridge Operations, Oak Ridge, Tenn., March (reprinted with corrections January 1984).

IAEA: See International Atomic Energy Agency.

ICRP: See International Commission on Radiological Protection.

International Atomic Energy Agency, 1994, *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments*, Technical Reports Series No. 364, Vienna, Austria.

International Commission on Radiological Protection, 1985, *Principles of Monitoring for the Radiation Protection of the Population*, ICRP No. 43, New York, N.Y.

Isherwood, D., 1981, *Geoscience Data Base Handbook for Modeling a Nuclear Waste Repository*, NUREG/CR-0912, Vols. 1 and 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Kennedy, W.E., and Streng, D.L., 1992, *Residual Radioactive Contamination from Decommissioning; A Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent*, NUREG/CR-5512, PNL 7994, Vol. 1, prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, Washington, D.C..

Mueller Associates, Inc. 1986, *Indoor Air Quality Environmental Information Handbook: Radon*, DOE/PE/72013-2, prepared by Mueller Associates, Inc., Baltimore, Md., for U.S. Department of Energy, Washington, D.C.

NRC: See U.S. Nuclear Regulatory Commission.

Nuclear Safety Associates, Inc., 1980, *Comparison of Alternatives for Long-Term Management of High-Level Radioactive Waste at the Western New York Nuclear Service Center*, prepared by Nuclear Safety Associates, Inc., Bethesda, Md., for Argonne National Laboratory, Argonne, Ill.

Rupp, E.M., et al., 1980, "Some Results of Recent Surveys of Fish and Shellfish Consumption by Age and Region of U.S. Residents," *Health Physics* 39:165-175.

Sheppard, M.I., and D.H. Thibault, 1990, "Default Soil/Liquid Partition Coefficients, K_{ds}, for Four Soil Types: A Compendium," *Health Physics* 59(4):471-482.

Sheppard, M.I., et al., 1991, "Mobility and Plant Uptake of Inorganic C-14 and C-14 Labeled PCB in Soils of High and Low Retention," *Health Physics* 61(4):481-492.

Snyder, S.F., et al., 1994, *Parameters Used in the Environmental Pathways and Radiological Dose Modules (DESCARTES, CIDER, and CRD Codes) of the Hanford Environmental Dose Reconstruction Integrated Codes (HEDRIC)*, PNWD-2023, HEDR Rev. 1, letter report for the Technical Steering Panel and the Centers for Disease Control and Prevention, by Pacific Northwest Laboratories, Richland, Wash., May.

Sprung, J.L., et al., 1990, *Evaluation of Severe Accident Risks: Quantification of Major Input Parameters, MACCS Input*, NUREG/CR-4551, Vol. 2, Rev. 1, Pt. 7, prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission, Division of Systems Research, Office of Nuclear Regulatory Research, Washington, D.C., Dec.

Staley, G.B., et al., 1979, "Radionuclide Migration from Low-Level Waste: A Generic Overview," pp. 1041-1072 in: M.W. Carter et al. (eds.), *Management of Low-Level Radioactive Waste*, Pergamon Press, New York, N.Y.

Thibodeaux, L.J., and S.T. Hwang, 1982, "Landfarming of Petroleum Wastes — Modeling the Air Emission Problem," *Environmental Progress* 1(1):42.

USDA: See U.S. Department of Agriculture.

U.S. Department of Agriculture, 1992, *Food Consumption, Prices, and Expenditures, 1970-90*, Statistical Bulletin Number 840, Economic Research Service, Washington, D.C.

U.S. Department of Agriculture, 1997, *Crop Production Annual Survey*, National Agricultural Statistics Service (NASS), Agricultural Statistics Board, Washington, D.C., Jan.

U.S. Environmental Protection Agency, 1995, *Health Effects Summary Tables (HEAST), FY-1995 Supplement*, EPA/540/R-95/142, Washington, D.C., Nov.

U.S. Environmental Protection Agency, 1996, *Documenting Ground-Water Modeling at Sites Contaminated with Radioactive Substances*, EPA 540-R-96-003, Cooperative effort by U.S. EPA, Office of Solid Waste and Emergency Response, Office of Radiation and Indoor Air, Washington, D.C.; U.S. Department of Energy, Office of Environmental Restoration, Washington, D.C.; and U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, Washington, D.C., Jan.

U.S. Environmental Protection Agency, 1997, *Exposure Factors Handbook, Volume 1 — General Factors*, EPA/600/P-95/002Fa, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C., Aug.

U.S. Nuclear Regulatory Commission, 1980, *Final Generic Environmental Impact Statement on Uranium Milling*, NUREG-0706, Vols. 1-3, Office of Nuclear Material Safety and Safeguards, Washington, D.C.

U.S. Nuclear Regulatory Commission, 1998a, *Demonstrating Compliance with the Radiological Criteria for License Termination*, Draft Regulatory Guide DG 4006, Office of Nuclear Regulatory Research, Washington, D.C., Aug.

U.S. Nuclear Regulatory Commission, 1998b, *Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination*, Draft Report for Comment, NUREG-1549, Division of Regulatory Applications, Office of Nuclear Regulatory Research, Washington, D.C., July.

Wernig, M.A., et al., undated, *Residual Radioactive Contamination from Decommissioning; User's Manual*, NUREG/CR-5512, Vol. 2, prepared for U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C.

Yu, C., et al., 1993a, *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0*, ANL/EAD/LD-2, Argonne National Laboratory, Argonne, Ill., Sept.

Yu, C., et al., 1993b, *Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil*, ANL/EAIS-8, Argonne National Laboratory, Argonne, Ill., April.

Yu, C., et al., 1993c, unpublished information, Argonne National Laboratory, Argonne, Ill., Sept.

Yu, C., et al., 1994, *RESRAD-BUILD: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material*, ANL/EAD/LD-3, Argonne National Laboratory, Argonne, Ill.

Yu, C., et al. 1997, unpublished information, Argonne National Laboratory, Argonne, Ill.

ATTACHMENT B

SELECTION OF RESRAD AND RESRAD-BUILD INPUT PARAMETERS FOR DETAILED DISTRIBUTION ANALYSIS

Prepared by

J.-J. Cheng, S. Kamboj, C. Yu, B. Biwer, J. Arnish,
D. LePoire, E. Gnanapragasam, and S.Y. Chen
Environmental Assessment Division
Argonne National Laboratory

CONTENTS

NOTATION	v
1 INTRODUCTION	1
2 RANKING STRATEGY FOR INPUT PARAMETERS	3
2.1 Criterion 1: Relevance of Parameters in Dose Calculations	4
2.2 Criterion 2: Variability of Radiation Dose as a Result of Changes in the Parameter Value	5
2.3 Criterion 3: Parameter Type	7
2.4 Criterion 4: Data Availability	7
2.5 Final Ranking	9
3 DOSE VARIABILITY ANALYSES FOR CRITERION 2	10
3.1 Analyses for the RESRAD Parameters	10
3.2 Analyses for the RESRAD-BUILD Parameters	10
4 OVERALL RANKING RESULTS	11
4.1 Ranking Results for RESRAD	11
4.2 Ranking Results for RESRAD-BUILD	11
APPENDIX: Critical Pathways for the Representative Radionuclides	12
REFERENCES	15

TABLES

2.1 Corresponding Ranges of NDD Values for the Seven Numeric Scores (1-7) Assigned for the Dose Variability Ranking Criterion	18
3.1 Dose Variability Analysis Results for the RESRAD Input Parameters	19
3.2 Transport and Transfer Factors Used in the RESRAD Dose Variability Analysis	34
3.3 Dose Variability Analysis Results for the RESRAD-BUILD Parameters	38
4.1 Ranking Results for the RESRAD Parameters	45

TABLES

4.2	Summary of the Overall Ranking Results for RESRAD	55
4.3	Overall Ranking Results for the RESRAD-BUILD Parameters	57
4.4	Summary of the Overall Ranking Results for RESRAD-BUILD	60
A.1	Peak Radiation Doses for the Base Case in the RESRAD Code	61
A.2	Maximum Radiation Doses for the Base Case of Volume Contamination in the RESRAD-BUILD Code	62
A.3	Maximum Radiation Doses for the Base Case of Surface Contamination in the RESRAD-BUILD Code	63

NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in the document. Some acronyms used only in tables or equations are defined in the respective tables or equations.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

DOE	U.S. Department of Energy
max.	maximum
min.	minimum
NDD	normalized dose difference
NRC	U.S. Nuclear Regulatory Commission

UNITS OF MEASURE

cm	centimeter(s)	m	meter(s)
cm ³	cubic centimeter(s)	m ²	square meter(s)
d	day(s)	m ³	cubic meters(s)
g	gram(s)	mol	mole(s)
h	hour(s)	mrem	millirem(s)
kg	kilogram(s)	pCi	picocurie(s)
L	liter(s)	s	second(s)
yr	year(s)		

SELECTION OF RESRAD AND RESRAD-BUILD INPUT PARAMETERS FOR DETAILED DISTRIBUTION ANALYSIS

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC 1998a,b) has taken steps to ensure that residual radioactive contamination remaining after licensed nuclear facilities are decontaminated and decommissioned meets acceptable levels (Subpart E to 10 CFR Part 20) and that risks to the exposed "critical group" of the public will be within prescribed limits (10 CFR 20.1402 and 20.1403). In addition, the NRC has developed a generic modeling approach (presented in NUREG/CR-5512 [Kennedy and Streng 1992] and coded in DandD [Wernig et al. undated]) to translate residual contamination levels into potential radiation doses to the public. In that approach, a multilevel screening process is used to assess potential radiation exposure to the public. Level 1 modeling uses generic screening factors. Level 2 modeling involves substitution of site-specific parameter values for some of the default values and elimination of pathways to more closely approximate the exposure conditions at a particular site. Level 3 modeling involves using an even more site-specific approach that is not provided by the generic screening methods. The RESRAD (Yu et al. 1993) and RESRAD-BUILD (Yu et al. 1994) computer codes are currently designed to address Level 2 and Level 3 objectives entailing site-specific analysis and can also be used for Level 1 screening calculations, provided a default data set is developed. These two codes have been developed by Argonne National Laboratory and approved by the U.S. Department of Energy (DOE) for use in evaluating radioactively contaminated sites and buildings, respectively, and are widely used in the United States and abroad. The RESRAD codes complement NRC's licensing efforts in developing methods for demonstrating compliance with decontamination and decommissioning rules.

Argonne has been contracted by the NRC to evaluate the input parameters used in the RESRAD and RESRAD-BUILD dose calculations. The objective is to collect information and develop generic values for characterizing distributions of the input parameters so that distributions of the potential end doses can be better understood. The project was divided into several subtasks, with a deliverable to be produced under each subtask. The subtasks are: (1) listing parameters and parameter types, (2) selecting parameters for detailed distribution analysis, (3) analyzing the selected parameters and developing distribution data, (4) analyzing distribution of the end doses by using distribution data developed for the parameters, (5) developing an interface module for the RESRAD and RESRAD-BUILD computer codes to perform uncertainty analysis on input parameters, (6) testing the two computer codes for the added capability, and (7) documenting project results. In the previous letter report to the NRC on subtask 1 (Kamboj et al. 1999)¹, all the input parameters used in the two codes were listed, categorized, and defined. In subtask 2, a strategy was developed to rank the input parameters and identify parameters for detailed distribution analysis. This report documents the ranking strategy used and the results from

¹ This letter report is included as Attachment A of the main document.

implementation of that strategy. It is the second of a series of letter reports for the first four subtasks discussed above. Results in this report will be used as the basis for prioritizing efforts in subtask 3² to conduct detailed analysis for parameter distributions.

² The report has been completed and is included as Attachment C of the main document.

2 RANKING STRATEGY FOR INPUT PARAMETERS

There are about 200 parameters in the RESRAD and RESRAD-BUILD codes. To make the most effective use of available project resources, it is necessary to establish priorities about which parameters to collect data for and use for distribution analysis. To accomplish this objective, the RESRAD and RESRAD-BUILD parameters were ranked into three levels of priority: 1 (high priority), 2 (medium priority), and 3 (low priority). Priority 1 parameters are those for which detailed distributions will be developed in subtask 3. Priority 3 parameters are those for which parameter distributions will not be developed until all distributions for priority 2 parameters have been developed. Not all priority 2 parameters will be analyzed for distribution in subtask 3. Parameters in priority 2 will be selected jointly by Argonne and NRC staff.

Generally speaking, parameters ranked as priority 1 have a greater potential of affecting radiation doses, tend to vary more from site to site, and can be characterized more easily because data on them can be found in readily available literature. Parameters ranked as priority 3 have less impact on radiation doses, vary less from site to site, cannot be easily characterized because little or no data on them are available, or are irrelevant within the scope of this project. As a result, the collection and analysis of data need to focus first on priority 1 parameters, then on priority 2 parameters, and finally on priority 3 parameters. In case a parameter is not analyzed for detailed distribution, a default value or a method for obtaining a site-specific value will be suggested so that screening dose assessments can be conducted.

The method used to prioritize parameters takes into account the following four criteria: (1) relevance of the parameter in dose calculations, (2) variability of the radiation dose as a result of changes in the parameter value, (3) parameter type (physical, behavioral, or metabolic), and (4) availability of data in the literature. For each of these four criteria, a numeric score is assigned to each parameter. The numeric score ranges from 0 to 9, with a low score assigned to parameters with a higher priority and a high score assigned to parameters with lower priority under the considered criterion. Selection of the scale for the numeric scores is somewhat arbitrary; however, the relatively large range is used to provide a distinct differentiation between the important and the unimportant parameters, so that the unimportant parameters receive a high score and an overall low ranking. After numeric scores are assigned to all of the four criteria, the four numeric scores received by a parameter are added. The sums for each parameter are then compared with those for the other parameters, and an overall rank is determined for each individual parameter.

At the current stage of the project, detailed information on the input parameters has not yet been developed. Therefore, ranking of the parameters has had to rely on existing data and certain assumptions. The strategy described in this report is for screening purposes only. More detailed sensitivity or uncertainty analyses can be conducted to rank the input parameters after subtask 3 is completed. More detailed discussion on each of the four ranking criteria used in the screening process is provided in the following sections.

2.1 CRITERION 1: RELEVANCE OF PARAMETERS IN DOSE CALCULATIONS

The "relevance" of a parameter in dose calculations was determined by considering the actual use of that parameter in the mathematical equations, the necessity of having an assigned value to complete the calculations, and the appropriateness of having a distribution for its value. Parameters determined as irrelevant were assigned a numerical score of 9 for this criterion. A numerical score of 9 for the irrelevant parameters, which include three different categories as discussed below, was chosen to ensure these parameters would be assigned the lowest priority in the overall ranking. The remaining parameters were defined as relevant and received a numerical score of 0.

The first category of irrelevant parameters are those used in RESRAD and RESRAD-BUILD for selecting calculation methods but are not used in the actual dose calculations. An example is the irrigation mode parameter in RESRAD.

Because of the various parameter correlations and relationships, some parameters in the RESRAD code can be derived from the values of other parameters. As a result, assigning numerical values to these parameters was not as critical as it was for other parameters. Therefore, such parameters were classified as irrelevant, too. Examples of this category of parameters are the leach rate constant and the plant, meat, and milk contaminated fractions in RESRAD.

The last category of irrelevant parameters are those whose values are normally set to one of the extremes (0 or 1), depending on site-specific conditions. These parameters include household, livestock, and irrigation water contaminated fraction and groundwater usage fractions for drinking water, household water, livestock water, and irrigation water. Assigning distributions to these parameters would not be appropriate; therefore, they were also classified as irrelevant parameters.

In addition to the above three categories, some parameters were determined to be of low priority for distribution analysis on the basis of a decision of a joint technical working group formed by Argonne and the NRC (NRC 1999). Parameters in this category include age-dependent parameters, such as inhalation and ingestion dose conversion factors and slope factors, and parameters that are used exclusively to assess potential exposure to radon. According to the decision, constant values will be used for the dose conversion factors and slope factors (NRC 1999). Although both RESRAD and RESRAD-BUILD consider radiation exposure from radon, radon doses are currently excluded from the dose limit set in the decontamination and decommissioning rules. Because of their low priority within the scope of this project, these parameters are also classified as irrelevant and receive a numerical score of 9.

2.2 CRITERION 2: VARIABILITY OF RADIATION DOSE AS A RESULT OF CHANGES IN THE PARAMETER VALUE

The impact on the radiation dose resulting from a change in a parameter value is a major factor in selecting parameters for detailed distribution analysis. Parameters with the potential to have a high impact can alter the radiation dose greatly when they have different values. Therefore, to obtain a more accurate estimate of the radiation dose, values of parameters with the potential to have a high impact should be more accurately determined.

At the present stage of project, detailed parameter distribution data (subtask 3) have not yet been developed and exact ranges of parameters are largely unavailable. Therefore, traditional sensitivity or uncertainty analyses cannot be performed for evaluating the parameter ranking. The approach described below instead relies on a gross indicator of dose variability. The purpose is to establish a basis for parameter screening that uses existing available data.

To study the potential of a particular parameter to affect the radiation dose, a calculated variable, defined as the normalized dose difference (NDD) in this report, is used as an indicator. The value of NDD is proportional to the range of the peak radiation dose resulting from a change in the value of an input parameter. In general, the NDD of a parameter can be obtained by gauging the change in the peak radiation dose by setting the parameter to its low value and high value, respectively. However, because the relationship between the radiation dose and the input parameters is often nonlinear, the range of the peak dose cannot always be obtained by using the above method. In such instances, several calculations have to be conducted to explore the full range of the peak dose by varying the value of the input parameter over the entire possible range obtained with the existing data. The variable NDD can be expressed by the following equation:

$$\text{NDD} = (D_{\text{high}} - D_{\text{low}})/D_{\text{base}} \times 100\% \quad (1)$$

where $(D_{\text{high}} - D_{\text{low}})$ is the potential range of the peak radiation dose and D_{base} is the peak dose calculated by setting the studied parameter to its base value. In the equation, D_{base} is used as a normalization factor. To obtain the NDD value associated with a specific parameter, the values of the other parameters are kept constant at their base values.

Base scenarios were selected for the RESRAD and RESRAD-BUILD codes. For the RESRAD code, the base scenario involved a subsistence farmer who lives on a contaminated site, grows plant food and raises livestock on the site, catches fish and other aquatic food in a nearby pond, and withdraws water from a well located on the site. For the RESRAD-BUILD code, the base scenario was a building occupancy scenario in which full-time adult workers from a light industry were assumed to work in a contaminated building. The two base scenarios used for the RESRAD and RESRAD-BUILD codes were the same as the default scenarios considered in the DandD code. Therefore, the default parameter values for the DandD code were used, to the extent practical, as the base values for the various RESRAD and RESRAD-BUILD parameters. All the exposure pathways included

in the RESRAD code were applicable to the subsistence farmer scenario, and all the exposure pathways included in the RESRAD-BUILD code were applicable to the building occupancy scenario.

Depending on the characteristics of radionuclides, critical exposure pathways for the peak radiation doses can be different for different radionuclides. As a result, the dose variability (defined by the NDD value) associated with a specific parameter will change for different radionuclides. To avoid obtaining biased NDD values from a single radionuclide, a group of radionuclides were used in the analyses. These radionuclides had different critical pathways. Relative contributions from the critical pathways to the total radiation doses were also different. Each of the selected radionuclides was considered when the NDD values for a specific parameter were calculated. The largest NDD value among the radionuclides was selected as the representative value for that parameter, and it was used for comparison with the other parameters. Therefore, assignment of a final numeric score under this dose variability criterion for each parameter was based on the largest NDD value, obtained by considering the group of representative radionuclides.

The representative radionuclides used for the RESRAD and RESRAD-BUILD codes were Co-60, Sr-90, Cs-137, Ra-226, Th-230, U-238, Pu-239, and Am-241. In general, they were selected because of their various critical pathways in dose calculations, which is discussed in the Appendix. Because of the unique environmental transport mechanisms, exposure pathways, and dosimetry for C-14 and H-3, the dose variability analyses of the input parameters used to calculate the doses that could result from exposure and uptake of these two radionuclides had to be performed individually. For the storage time parameters in the RESRAD code, dose variability analyses were conducted for the following radionuclides: Ca-45, Ra-228, and Cf-252. These three radionuclides were selected because they have shorter half-lives and the significant contributions to the radiation doses are from the ingestion pathways. These two characteristics allowed changes in radiation doses to be observed while storage time parameters were varied from their low values to their high values.

The dose variability associated with a parameter was gauged by the upper and lower peak dose values recorded for the representative radionuclides when the parameter value was varied within its possible range between the low and the high values. For many of the parameters, the low and high values were obtained from the two DandD reports (Beyeler et al. 1997, 1998) documenting the probability distributions of the DandD input parameters. For cases in which probability information was not available in the two reports (some parameters are used in the RESRAD and RESRAD-BUILD codes but not in the DandD code), selection of the low and high values was based on data from previously searched literature and professional judgments. Note that the low and high values were not the absolute lower bound and upper bound values for a parameter but the values thought to represent a parameter in terms of revealing the potential range of radiation doses under likely conditions.

The time at which the peak doses would occur in the future varied among the representative radionuclides. To observe the potential dose contributions from the

groundwater-related pathways (which, for many contaminated sites, might be the critical pathways), the calculation time frame was extended to 3,000 years in the RESRAD code. Such an extension of the calculation time beyond 1,000 years (the time frame used in decontamination and decommissioning dose assessments) was necessary to fully explore the impact potential of the soil and water transport parameters on the radiation doses.

Dose variability analyses were carried out for relevant parameters identified by the first ranking criterion (relevance of parameters). Numerous runs of the RESRAD and RESRAD-BUILD codes were performed, and the NDD values for the relevant parameters were recorded. Detailed calculation results for the NDD values are provided in Section 3. The numeric scores, assigned according to the NDD values, under this ranking criterion ranged from 1 through 7. Parameters with large NDD values were characterized as having a high potential for affecting the radiation doses and were assigned a lower numeric score. Parameters with small NDD values were characterized as having a small potential for affecting the radiation doses and were assigned a higher numeric score. Table 2.1 lists the corresponding ranges of NDD values for the seven numeric scores. (All tables appear at the end of this document.)

2.3 CRITERION 3: PARAMETER TYPE

Parameters were ranked according to the three categories assigned to them in subtask 1: physical, behavioral, and metabolic. NRC decontamination and decommissioning guidance requires radiation dose assessments to be performed for the average member of the critical population group. Therefore, the metabolic and behavioral parameters used in dose assessments need to be typical for the average member and are not expected to vary much from site to site. This is especially true for the metabolic parameters such as dose conversion factors, which are considered reasonably well defined for the average member of the critical group. On the other hand, physical parameters are usually site-specific and can vary widely from site to site. Therefore, in terms of developing detailed distribution information, physical parameters should be assigned a higher priority than the behavioral and metabolic parameters.

Because of the above considerations, a numeric score of 1 was assigned to physical parameters, 5 was assigned to behavioral parameters, and 9 to metabolic parameters. If a parameter was categorized as a dual type (e.g., both behavioral and metabolic), the lower numeric score was assigned to it. For example, inhalation rate was both behavioral and metabolic, so it was given a numeric score of 5.

2.4 CRITERION 4: DATA AVAILABILITY

The availability of data from the open literature varies, depending on the parameter being considered. Previous efforts resulted in the publication of several reports that compile and analyze probabilistic distributions for some input parameters. These reports include the ones published by the NRC for the DandD code (Beyeler et al. 1997 and 1998)

and the one prepared by the Pacific Northwest National Laboratory for the soil/water distribution coefficient parameter (K_d) (Krupka et al. 1999). In addition, Argonne had compiled distribution information for some of the RESRAD parameters. Therefore, data for the parameters included in these reports are available, so less effort would be required to conduct further literature searches, and detailed analyses of probabilistic distributions could be undertaken in a shorter period of time. For the purpose of analyzing more parameters within the scope of this project, parameters included in the mentioned documents should be given a higher priority in the ranking process.

The availability of data on the remaining parameters is less certain. However, on the basis of reviews of currently available literature on modeling for environmental risk assessments as well as professional judgment and past experience, the remaining parameters can be roughly categorized into two groups. For the first group, some effort is needed to locate data sources and to compile and analyze data. For the second group, little or no information is available, and extensive effort would be needed to collect data. In fact, obtaining data might even require making some assumptions and conducting experiments. Therefore, the remaining parameters should be given lower priority than the parameters with known data availability; furthermore, within the remaining parameters, those judged as belonging to the second group should be assigned the lowest priority under this ranking criterion. Nevertheless, the joint Argonne/NRC technical working group may decide, at a later time, to reprioritize certain parameters if they are determined to be very important to dose assessments.

There is an exception for parameters with known data availability. For some, developing generic distribution information for dose calculations would not be appropriate, either because their values can be measured easily or because their values have to be measured to obtain a fundamental understanding of the contamination situation. Furthermore, their values have profound impacts on radiation doses. For these parameters, site-specific information should always be used in dose calculations. Therefore, even though data from existing or past contaminated sites were available for these parameters, they were given a numeric score that was the same as that given to parameters with little or no information in order to lower their priority for distribution analysis. Such parameters include radionuclides concentration, area of source or contaminated zone, contamination depth or thickness, thickness of cover material, building height, and shielding material.

A numeric score of 1 was assigned to the parameters with known data availability. A score of 3 was assigned to those with limited data but for which some search effort could probably yield additional data. A score of 5 was assigned to the remaining parameters: those with little or no data available and judged as requiring extensive effort to develop distribution information, and those for which generic distribution information is considered inappropriate for dose calculations.

2.5 FINAL RANKING

The final rankings of parameters were assigned on the basis of their total numeric scores under the four ranking criteria. Parameters with a lower total score were assigned a higher priority. The high-priority parameters (Priority 1) have a total score between 3 and 6, the medium-priority parameters (Priority 2) have a total score between 7 and 10, and the low-priority parameters (Priority 3) have a score above 10. Summaries of the final ranking results are provided in Section 4.

3 DOSE VARIABILITY ANALYSES FOR CRITERION 2

Dose variability analyses were conducted for the RESRAD and RESRAD-BUILD parameters according to the strategy laid out in Section 2.2. The following sections provide more detailed discussions on implementation of the dose variability analyses.

3.1 Analyses for the RESRAD Parameters

Table 3.1 (at the end of this document) lists dose variability analysis results for the RESRAD parameters. Peak radiation doses corresponding to the low, base, and high values of each parameter are included. The last column lists the maximum value of the NDD variable selected among the representative radionuclides for each parameter. The maximum NDD value is the basis used for assigning the numeric score to each parameter under the dose variability ranking criterion.

The peak radiation doses reported for the RESRAD parameters include contributions from the decay products (progeny radionuclides). For most of the parameters, the values are not nuclide-dependent; therefore, the same low, base, and high values were used for both parent and decay products to obtain the low, base, and high values for the peak radiation doses. However, for the distribution coefficient parameters, transfer factor parameters (for plant, meat, and milk), and bioaccumulation factor parameters (for fish and other aquatic food), the values are nuclide-dependent. Therefore, nuclide-specific low values for the parent and decay products were used to obtain the low values for the peak radiation doses. Likewise, nuclide-specific base and high values were used, respectively, to obtain the base and high values of the peak radiation doses. The nuclide-specific values used in the analyses are listed in Table 3.2.

Originally, in the base case used for the RESRAD code, there was no cover material on top of the contaminated area. As a result, the cover density and cover erosion rate parameters could not be assigned values and could not be used in dose calculations. To study the potential dose variability associated with these two parameters, a layer of cover material has to be assumed. Therefore, the base case was modified to include a layer of cover material with a thickness of 30 cm.

3.2 Analyses for the RESRAD-BUILD Parameters

Table 3.3 lists dose variability analysis results for the RESRAD-BUILD parameters. In the analyses, both a volume contamination source and a surface contamination source were considered. In case a parameter was used in the dose calculations for both types of contamination sources, the maximum NDD value associated with that parameter was selected from among the individual NDD values calculated by considering a volume source and from among the individual NDD values calculated by considering a surface source. The one-compartment model incorporated in the RESRAD-BUILD code was used for dose calculations.

Therefore, the "net flow" and "outdoor inflow" parameters were not analyzed because they are used for a two- or three-compartment model.

Although RESRAD-BUILD considers potential attenuation of radiation doses resulting from shielding materials, in the base case used to study most of the parameters, such attenuation was not considered. The attenuation was considered only when the shielding density parameter was studied, for which the base case was modified to include a shielding material with a thickness of 15 cm.

Unlike the RESRAD code, in RESRAD-BUILD, the relative distance between the radiation source and the receptors can be specified. To study the dose variability potential of the exposure distance parameter, the location of the receptor was varied while the location of the radiation source was fixed.

4 OVERALL RANKING RESULTS

Implementation of the ranking strategy with four ranking criteria, as discussed in Section 2, categorized the RESRAD and RESRAD-BUILD parameters, respectively, into three priority levels for detailed distribution analysis. Efforts in subtask 3 to develop probabilistic distribution information will focus first on priority 1 parameters, then shift to lower priority parameters. Because there are many priority 2 parameters, further prioritization of the priority 2 parameters may be necessary and will be determined by the joint ANL/NRC technical working group. The exact number of parameters subjected to distribution analysis will not be known until subtask 3 is completed. For those parameters not analyzed, a default value or a method for obtaining a site-specific value will be suggested so that screening dose assessments can be conducted. The following sections provide more discussion on the overall ranking results.

4.1 Ranking Results for RESRAD

Table 4.1 (at the end of this document) lists the numeric scores assigned for each ranking criterion, the sum of the numeric scores, and the final priority ranking for each parameter. In addition, a brief discussion on the effect of the individual parameter on the total radiation dose is provided in the table. Table 4.2 summarizes the overall ranking results. Among the 145 parameters ranked, 10 were ranked at priority 1, 39 were ranked at priority 2, and 96 were ranked at priority 3. The final priority rankings of 1, 2, and 3 were assigned to parameters with a total numeric scores of 3-6, 7-10, and above 10, respectively.

4.2 Ranking Results for RESRAD-BUILD

Tables 4.3 and 4.4 list results for the RESRAD-BUILD parameters. Of the 50 parameters ranked, 4 were at priority 1, 20 were at priority 2, and 26 were at priority 3. The final priority rankings of 1, 2, and 3 corresponded to a total numeric score of 3-6, 7-10, and above 10, respectively.

APPENDIX: CRITICAL PATHWAYS FOR THE REPRESENTATIVE RADIONUCLIDES

As mentioned in Section 2.2, an individual parameter's potential impact on the radiation dose could vary for different radionuclides because their critical pathways are different. For some radionuclides, the external radiation pathway is the most critical one in terms of contribution to the total dose. As a result, potential dose variability associated with the external pathway parameters would be greater for these radionuclides than for other radionuclides for which the inhalation or ingestion pathway is critical. To avoid obtaining biased dose variability results, a group of representative radionuclides was used in the analysis. The critical pathways for these representative radionuclides are different, but together the radionuclides cover all the pathways considered by the RESRAD and RESRAD-BUILD codes.

Nine exposure pathways are considered by the RESRAD code: external radiation, inhalation of dust particles, inhalation of radon, and ingestion of water, plant food, meat, milk, soil, and aquatic food. Among the considered pathways, radiation doses for the plant, meat, milk, and radon pathways can result from both residual contamination in the soil and contamination in water, resulting from leaching of radionuclides from the contaminated soil. To differentiate dose contributions from these two media, the exposure pathways are divided into two categories: water-dependent and water-independent. The inhalation of radon and ingestion of plant food, meat, and milk pathways are listed under both categories. The exposure pathways considered in the RESRAD-BUILD code include external radiation directly from the source, from contaminated dust particles deposited on the floor, and from immersion in contaminated air; ingestion of dust particles; inhalation of radon; and inhalation of dust particles and gas (for H-3 only).

Table A.1 (at the end of this document) lists the peak radiation doses for the RESRAD base case for each of the representative radionuclides. For Co-60 and Cs-137, external radiation is the most critical pathway because the external dose conversion factors are large. For Sr-90, the water-independent plant pathway is the most critical pathway, followed by the water-independent milk pathway. The amount of Sr-90 that is ingested is greater than the amount that is inhaled, and the milk transfer factor is large for Sr-90. For Ra-226, the water-independent radon inhalation pathway makes the largest contribution to the total dose, followed by the external radiation pathway. The water-independent plant ingestion pathway also accounts for some of the total dose. The most critical pathway for Th-230 is the water-independent radon pathway, followed by the external pathway and water-independent plant ingestion pathway. The radon dose results from the decay of Th-230 to Ra-226 and subsequently to the radon progeny nuclides. The drinking water pathway accounts for most of the radiation dose for U-238 because the soil-water distribution coefficient (K_d) used for uranium in the calculations is small ($2 \text{ cm}^3/\text{g}$, the default value used in the DandD code). Therefore, U-238 would reach the groundwater table in a shorter period of time (65.4 yr). For Pu-239, the most critical pathway is the drinking water pathway, too. This is true also because of the smaller K_d values used in the dose calculations ($14 \text{ cm}^3/\text{g}$, the DandD default value). For Am-241, the water-independent plant ingestion pathway and the soil ingestion pathway are the most critical because the ingestion amount is larger than the inhalation amount for Am-241.

For H-3, drinking water is the most critical pathway, followed by the water-dependent milk and plant pathways because H-3 would leach to the groundwater table quickly. For C-14, the fish pathway makes the largest contribution to the total dose, and the drinking water pathway makes the second largest contribution. The bioaccumulation factor for fish used in the calculations is large. For Cf-252, Ca-45, and Ra-228, which were used to study the storage parameters, plant ingestion is either the most critical or one of the most critical pathways. In general, the significance of the plant ingestion pathway results from the larger plant transfer factors.

Tables A.2 and A.3 lists the maximum doses for the two base cases — volume contamination and surface contamination — used in the RESRAD-BUILD code. The H-3 evaporation model is applicable only to the volume contamination source; therefore, it is not included in the table for the surface contamination source. The external radiation pathway is more critical for a volume contamination source than for a surface contamination source. Generally speaking, potential radiation doses from the inhalation pathway are greater than those from the ingestion pathway (direct ingestion and secondary ingestion).

REFERENCES

- Alzona, J., et al., 1979, "Indoor-Outdoor Relationships for Airborne Particulate Matter of Outdoor Origin," *Atmospheric Environment* 13:55-60.
- Baes, C.F., and R.D. Sharp, 1983, "A Proposal for Estimation of Soil Leaching and Leaching Constants for Use in Assessment Models," *Journal of Environmental Quality* 12(1):17-28.
- Bair, F.E. (editor), 1992, *Weather of U.S. Cities*, 4th ed., Gale Research Inc., Detroit, Mich.
- Beyeler, W.E., et al., 1997, *Review of Parameter Data for the NUREG/CR-5512 Building Occupancy Scenario and Probability Distributions for the DandD Parameter Analysis*, Letter Report, prepared by Sandia National Laboratory for U.S. Nuclear Regulatory Commission, January.
- Beyeler, W.E., et al., 1998, *Review of Parameter Data for the NUREG/CR-5512 Residential Farmer Scenario and Probability Distributions for the DandD Parameter Analysis*, Letter Report, prepared by Sandia National Laboratory for U.S. Nuclear Regulatory Commission, January.
- Clapp, R.B., and G.M. Hornberger, 1978, "Empirical Equations for Some Soil Hydraulic Properties," *Water Resources Research* 14:601-604.
- EPA, 1997, *General Factors Exposure Factors Handbook, Update to Exposure Factors Handbook*, EPA/600/8-89/043—May 1989, EPA/600/P-95/002Fa, U.S. Environmental Protection Agency, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C., August.
- Etnier, E.L., 1980, "Regional and Site-Specific Absolute Humidity Data for Use in Tritium Dose Calculations," *Health Physics* 39:318-320.
- Gilbert, T.L., et al., 1983, *Parameters Analysis and Radiation Dose Estimates for Radioactive Residues at Formerly Utilized MED/AEC Sites*, ORO-832 (Rev.), prepared by Division of Environmental Impact Studies, Argonne National Laboratory, Argonne, Ill., for U.S. Department of Energy, Oak Ridge Operations, Oak Ridge, Tenn., March (reprinted with corrections January 1984).
- Hoffman, F.O., and C.F. Baes, 1979, *A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides*, ORNL-NUREG/TM-282, Oak Ridge National Laboratory, Oak Ridge, Tenn.
- Kamboj, S., et al., 1999, *Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes*, Letter Report, prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, September.

- Kamboj, S., E. Faillace, and C. Yu, 1997, *Radiological Dose Assessment for the Decontaminated Concrete Removed from 183-H Solar Evaporation Basins at the Hanford Site, Richland, Washington*, ANL/EAD/TM-67, Argonne National Laboratory, Argonne, Ill., January.
- Kennedy, W.E., and Streng, D.L., 1992, *Residual Radioactive Contamination from Decommissioning: A Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent*, NUREG/CR-5512, PNL 7994, Vol. 1, prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission.
- Krupka, K.M., et al., 1999, *Understanding Variation in Partitioning Coefficient, K_d , Values*, Vols. I and II, EPA 402-R-99-004A and B, a cooperative effort by: Office of Radiation and Indoor Air, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, and Office of Environmental Restoration, U.S. Department of Energy, Washington, D.C., August.
- Mueller Associates, Inc., 1986, *Indoor Air Quality Environmental Information Handbook: Radon*, DOE/PE/72013-2, prepared by Mueller Associates, Inc., Baltimore, Md., for U.S. Department of Energy, Washington, D.C.
- Ng, Y.C., et al., 1982, *Soil-to-Plant Concentration Factors for Radiological Assessments*, NUREG/CR-2975, UCID-19463, Lawrence Livermore National Laboratory, Livermore, Calif.
- NRC (U.S. Nuclear Regulatory Commission), 1977, *Calculation of Annual Doses to Man from Routine Release of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix 2, Regulatory Guide 1.109, Rev. 1*, Office of Standards Development, Washington, D.C., October.
- NRC (U.S. Nuclear Regulatory Commission), 1998a, *Demonstrating Compliance with the Radiological Criteria for License Termination*, Draft Regulatory Guide, DG 4006, Office of Nuclear Regulatory Research, U.S. Nuclear Commission, Washington, D.C., August.
- NRC (U.S. Nuclear Regulatory Commission), 1998b, *Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination, Division of Regulatory Applications*, Draft Report for Comment, NUREG-1549, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C. July.
- NRC (U.S. Regulatory Commission), 1999, unpublished information provided in monthly teleconference between NRC and Argonne National Laboratory for project entitled Development of Risk-Based (Probabilistic) Default Parameters for RESRAD and RESRAD-BUILD Computer Codes (Job Code Y6112), July.
- Rupp, E.M., et al., 1980, "Some Results of Recent Surveys of Fish and Shellfish Consumption by Age and Region of U.S. Residents," *Health Physics* 39:165-175.

- Sheppard, M.I., and D.H. Thibault, 1990, "Default Soil Solid/Liquid Partition Coefficients, K_{ds}, for Four Major Soil Types: A Compendium," *Health Physics* 59(4):471-482.
- USDA (U.S. Department of Agriculture), 1992, *Food Consumption, Prices, and Expenditures, 1970-90*, Economic Research Service, Statistical Bulletin Number 840, Washington, D.C.
- USDA (U.S. Department of Agriculture), 1997, *Crop Production Annual Survey*, National Agricultural Statistics Service (NASS), Agricultural Statistics Board, U.S. Department of Agriculture, January.
- Wallace, L.A. 1996, "Indoor Particles: A Review," *J. Air and Waste Management Assoc.* 46(2):98-126.
- Wernig, M.A., et al., undated, *Residual Radioactive Contamination from Decommissioning; User's Manual*, NUREG/CR-5512, Vol. 2, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Yu, C., et al., 1993, *Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0*, ANL/EAD/LD-2, Argonne National Laboratory, Argonne, Ill., September.
- Yu, C., et al., 1994, *RESRAD-BUILD: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material*, ANL/EAD/LD-3, Argonne National Laboratory, Argonne, Ill., November.

Table 2.1 Corresponding Ranges of NDD Values for the Seven Numeric Scores (1-7) Assigned for the Dose Variability Ranking Criterion¹

Numeric Score	1	2	3	4	5	6	7
Range of NDD Values	>1,000	300 - 1,000	100 - 300	50 - 100	10 - 50	3 - 10	<= 3

¹ When both upper and lower bounds are listed, the value of the upper bound is included in the range. For example, 10 - 50 means >10 but <= 50.

Table 3.1 Dose Variability Analysis Results for the RESRAD Input Parameters

Source	Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
		Low	Base	High			Low	Base	High		
Nuclide concentration (pCi/g)	Base value corresponds to the default value used in the DandD code. Low and high values were 1/10 of and 10 times, respectively, the base value. They were selected to observe change in radiation doses.	0.1	1	10		Co-60	5.803E-01	5.803E+00	5.803E+01	990.00	990.00
						Si-90	1.396E-01	1.396E+00	1.396E+01	990.00	
						Cs-137	1.465E-01	1.465E+00	1.465E+01	990.00	
						Ra-226	3.615E+00	3.615E+01	3.615E+02	990.00	
						Th-230	5.420E-02	5.420E+00	5.420E+01	990.00	
						U-238	1.736E-01	1.736E+00	1.736E+01	990.00	
						Pu-239	3.252E-01	3.252E+00	3.252E+01	990.00	
						Am-241	1.659E-02	1.659E-01	1.659E+00	990.00	
Transport Factors (contaminated zone, unsaturated zones, and saturated zone)(cm ³ /g)	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2.	Co-60	5.752E+00	5.803E+00	5.803E+00	0.88	95.45
						Si-90	1.372E+00	1.396E+00	1.414E+00	3.01	
						Cs-137	1.465E+00	1.465E+00	1.546E+00	5.53	
						Ra-226	3.611E+01	3.615E+01	3.615E+01	0.11	
						Th-230	5.032E-01	5.420E-01	7.814E-01	51.33	
						U-238	1.736E+00	1.736E+00	9.829E-02	94.34	
						Pu-239	3.252E+00	3.252E+00	1.480E-01	95.45	
						Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Contaminated Zone Parameters Area of contaminated zone (m ²)	100	2400	10000		Base value corresponds to the default value used in the DandD code. Low and high values were selected to observe change in radiation doses.	Co-60	4.832E+00	5.803E+00	5.959E+00	19.42	117.48
						Si-90	1.393E+00	1.396E+00	1.396E+00	0.21	
						Cs-137	1.254E+00	1.465E+00	1.496E+00	16.52	
						Ra-226	3.532E+01	3.615E+01	3.638E+01	2.93	
						Th-230	5.211E-01	5.420E-01	5.465E-01	4.69	
						U-238	7.234E-02	1.736E+00	2.098E+00	116.69	
						Pu-239	1.355E-01	3.252E+00	3.956E+00	117.48	
						Am-241	1.156E-01	1.659E-01	1.680E-01	31.59	
Thickness of contaminated zone (m)	0.15	0.15	4		Base value corresponds to the default value used in the DandD code. Low and high values were selected to observe change in radiation doses.	Co-60	5.803E+00	5.803E+00	7.029E+00	21.13	6156.46
						Si-90	1.396E+00	1.396E+00	8.095E+00	479.87	
						Cs-137	1.465E+00	1.465E+00	2.147E+00	46.55	
						Ra-226	3.615E+01	3.615E+01	8.167E+01	125.92	
						Th-230	5.420E-01	5.420E-01	3.391E+01	6156.46	
						U-238	1.736E+00	1.736E+00	3.079E+01	1673.62	
						Pu-239	3.252E+00	3.252E+00	6.020E+01	1751.17	
						Am-241	1.659E-01	1.659E-01	5.706E-01	243.94	
Length parallel to aquifer flow (m)	10	48.99	100		Values correspond to square roots of the "area of contaminated zone" parameter.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	71.32
						Si-90	1.396E+00	1.396E+00	1.396E+00	0.00	
						Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
						Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
						Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
						U-238	2.090E+00	1.736E+00	8.518E-01	71.32	
						Pu-239	3.914E+00	3.252E+00	1.600E+00	71.16	
						Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Cover and Contaminated Zone Hydrological Data Cover depth (m)	0	0	0.3		High value was selected to observe potential reduction in radiation doses.	Co-60	5.803E+00	5.803E+00	2.568E-01	95.57	158.86
						Si-90	1.396E+00	1.396E+00	1.314E+00	5.87	
						Cs-137	1.465E+00	1.465E+00	1.165E-01	92.05	
						Ra-226	3.615E+01	3.615E+01	3.212E+01	11.15	
						Th-230	5.420E-01	5.420E-01	1.403E+00	158.86	
						U-238	1.736E+00	1.736E+00	1.758E+00	1.27	
						Pu-239	3.252E+00	3.252E+00	3.548E+00	9.10	
						Am-241	1.659E-01	1.659E-01	8.132E-02	50.98	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
	Low	Base	High			Low	Base	High		
Density of cover material (g/cm ³) ²	0.86	1.4312	1.76	Low and high values are from Baes and Sharp (1983). Base value corresponds to the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	7.934E-01 1.314E+00 1.314E+00 1.165E-01 3.254E+01 1.404E+00 1.758E+00 3.548E+00 8.140E-02	2.568E-01 1.314E+00 1.314E+00 1.165E-01 3.212E+01 1.403E+00 1.758E+00 3.548E+00 8.132E-02	1.545E-01 1.314E+00 1.037E-01 3.204E+01 1.403E+00 1.758E+00 3.548E+00 8.130E-02	248.79 0.00 84.64 1.56 0.07 0.00 0.00 0.12	248.79
Cover erosion rate (m/yr) ²	0	0.001	0.001	Judging from previously searched literature data, the RESRAD default value of 0.001 m/yr is the high end of the erosion rate. Therefore, it was used as the high value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.558E-01 1.314E+00 1.164E-01 3.208E+01 1.222E+00 1.758E+00 3.548E+00 8.078E-02	2.568E-01 1.314E+00 1.165E-01 3.212E+01 1.403E+00 1.758E+00 3.548E+00 8.132E-02	2.568E-01 1.314E+00 1.165E-01 3.212E+01 1.403E+00 1.758E+00 3.548E+00 8.132E-02	0.39 0.00 0.09 0.12 12.90 0.00 0.00 0.66	12.90
Density of contaminated zone (g/cm ³)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	4.664E+00 1.380E+00 1.202E+00 2.324E+01 2.899E-01 1.033E+00 2.027E+00 1.656E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	6.185E+00 1.400E+00 1.546E+00 4.337E+01 6.897E-01 2.104E+00 3.915E+00 1.660E-01	26.21 1.43 23.48 55.68 73.76 61.69 58.06 0.24	73.76
Contaminated zone total porosity	0.34	0.4599	0.68	Low and high values were calculated by using the equation $\theta = 1 - \rho_s / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_s is the bulk soil density. Base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.971E+01 5.739E-01 1.737E+00 3.253E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.125E+01 4.944E-01 1.728E+00 3.250E+00 1.659E-01	0.00 0.00 0.14 23.40 14.67 0.52 0.09 0.00	23.40
Contaminated zone field capacity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.734E+00 3.251E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.12 0.03 0.00	0.12
Contaminated zone erosion rate (m/yr)	0	0.001	0.001	Judging from previously searched literature data, the RESRAD default value of 0.001 m/yr is at the high end of the erosion rate. Therefore, it was used as the high value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.810E+00 1.400E+00 1.467E+00 3.672E+01 1.404E+00 1.758E+00 3.548E+00 1.664E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.12 0.29 0.14 1.58 159.04 1.27 9.10 0.30	159.04

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD	
	Low	Base	High			Low	Base	High			
Contaminated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1e-5 to 1e+7. The high and low values were selected to observe the max. variation in potential radiation exposure.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.35	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00		
					Cs-137	1.465E+00	1.465E+00	1.464E+00	0.07		
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00		
					Th-230	5.421E-01	5.420E-01	5.419E-01	0.04		
					U-238	1.731E+00	1.736E+00	1.737E+00	0.35		
					Pu-239	3.250E+00	3.252E+00	3.253E+00	0.09		
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00		0.23
Contaminated zone b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayey soil. Both limit values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	0.23	
					Cs-137	1.464E+00	1.465E+00	1.465E+00	0.07		
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00		
					Th-230	5.418E-01	5.420E-01	5.420E-01	0.04		
					U-238	1.737E+00	1.736E+00	1.733E+00	0.23		
					Pu-239	3.254E+00	3.252E+00	3.251E+00	0.09		
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00		
					H-3	3.348E-03	3.348E-03	3.348E-03	0.00		0.00
					Co-60	5.802E+00	5.803E+00	5.805E+00	0.05		44.19
Humidity in air (g/m³)	0.5	0.7	0.9	High value from Kamboj et al. (1997) for the Hanford site. Base value was selected, in conjunction with the value for the runoff coefficient, to approximate an infiltration rate of 0.2526 m/yr, the default value used in the DandD code.	Sr-90	1.381E+00	1.396E+00	1.411E+00	2.15	44.19	
					Cs-137	1.414E+00	1.465E+00	1.518E+00	7.10		
					Ra-226	3.614E+01	3.615E+01	3.615E+01	0.03		
					Th-230	4.452E-01	5.420E-01	6.847E-01	44.19		
					U-238	1.744E+00	1.736E+00	1.676E+00	3.92		
					Pu-239	3.379E+00	3.252E+00	2.663E+00	22.02		
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00		7.29
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00		7.29
Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00							
Ra-226	3.627E+01	3.615E+01	3.609E+01	0.50							
Th-230	5.448E-01	5.420E-01	5.406E-01	0.77							
U-238	1.736E+00	1.736E+00	1.736E+00	0.00							
Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00							
Am-241	1.743E-01	1.659E-01	1.622E-01	7.29							
Co-60	5.805E+00	5.803E+00	5.802E+00	0.05	43.84						
Precipitation rate (m/yr)	0.161	1	1.617	High value from Bair (1992). Low value from Kamboj et al. (1997) for the Hanford site. The base value is the RESRAD default value.	Sr-90	1.412E+00	1.396E+00	1.384E+00	2.01	43.84	
					Cs-137	1.523E+00	1.465E+00	1.424E+00	6.76		
					Ra-226	3.615E+01	3.615E+01	3.614E+01	0.03		
					Th-230	6.997E-01	5.420E-01	4.621E-01	43.84		
					U-238	1.651E+00	1.736E+00	1.743E+00	5.30		
					Pu-239	2.503E+00	3.252E+00	3.359E+00	26.32		
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00		15.50
					Sr-90	1.398E+00	1.396E+00	1.390E+00	0.57		15.50
Cs-137	1.472E+00	1.465E+00	1.444E+00	1.91							
Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00							
Th-230	5.580E-01	5.420E-01	4.989E-01	10.90							
U-238	1.668E+00	1.736E+00	1.937E+00	15.50							
Pu-239	3.128E+00	3.252E+00	3.605E+00	14.67							
Am-241	1.660E-01	1.659E-01	1.659E-01	0.06							
Irrigation rate (m/yr)	0.0396	0.1125	0.33	Data from Table 3.71 of Beyeler et al. (1998). The reported values in L/m²/d were converted to give values in m/yr with the assumption that duration for gardening activities was 90 days/yr.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	15.50	
					Sr-90	1.398E+00	1.396E+00	1.390E+00	0.57		
					Cs-137	1.472E+00	1.465E+00	1.444E+00	1.91		

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Runoff coefficient	0.03	0.3	0.7	High value from Gilbert et al. (1983). Low value from Kamboj et al. (1997). The base value was selected, in conjunction with the value for the evapotranspiration coefficient, to approximate an infiltration rate of 0.2526 m/yr, the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.802E+00 1.388E+00 1.439E+00 3.615E+01 4.894E-01 1.741E+00 3.329E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.804E+00 1.407E+00 1.504E+00 3.615E+01 6.414E-01 1.715E+00 2.958E+00 1.600E-01	0.03 1.36 4.44 0.00 28.04 1.50 11.41 0.06	28.04
Watershed area for nearby stream or pond (m ²)	10000	1,000,000	1,000,000	Low value set to be 1/100 of the base value. The base value is the default value used in the RESRAD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.985E+00 4.561E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 14.34 40.25 0.00	40.25
Saturated Zone Hydrological Data										
Density of saturated zone (g/m3)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 2.598E+00 5.333E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.449E+00 2.656E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 66.19 82.32 0.00	82.32
Saturated zone total porosity	0.34	0.4599	0.68	Low and high values were calculated by using the equation $\theta = 1 - \rho_s / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_s is the bulk soil density. The base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.332E+00 2.418E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 2.368E+00 4.758E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 59.68 71.96 0.00	71.96
Saturated zone effective porosity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 3.402E+00 6.505E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 8.686E-01 1.626E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 145.93 150.03 0.00	150.03
Saturated zone field capacity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Saturated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1E-5 to 1E7. The high and low values were set to observe the max. variation in potential radiation exposure.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 7.746E-02 1.425E-01 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 2.052E+00 3.923E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 113.80 116.93 0.00	116.93
Saturated zone hydraulic gradient	0.002	0.02	0.2	Low and high values taken to be 1/10 of and ten times, respectively, the base value, which is the RESRAD default value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.759E-01 3.371E-01 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 2.052E+00 3.923E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 108.07 110.27 0.00	110.27
Saturated zone b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayey soil. Both the limit values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00
Water table drop rate (m/yr)	0.0005	0.001	0.002	Low and high values were taken to be 1/2 of and twice, respectively, the base value, which is the default value used in the RESRAD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00
Well pump intake depth (below water table) (m)	5	10	20	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.704E+00 3.265E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.046E+00 1.957E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 37.90 40.22 0.00	40.22
Well pumping rate (m ³ /yr)	54.884	118	276	Table 3.8.1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 2.090E+00 3.914E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 7.437E-01 1.398E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 77.55 77.37 0.00	77.55

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Uncontaminated Unsaturated Zone Parameters										
Unsaturated zone thickness (m)	0.3	1.2288	316	The base value is the default value used in the DandD code. The low and high are from page 5.2-4, Beyeler et al. (1998)	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 7.746E-02 1.425E-01 1.659E-01	0.00 0.00 0.00 0.00 0.00 95.54 95.71 0.00	95.71
Unsaturated zone density (g/cm ³)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.09 0.00	0.09
Unsaturated zone total porosity	0.34	0.4599	0.68	The low and high values were calculated by using the equation $\theta = 1 - \rho_s / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_s is the bulk soil density. The base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.06 0.00	0.06
Unsaturated zone effective porosity	0.1	0.2	0.4	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.248E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.18 0.00	0.18
Unsaturated zone field capacity	0.1	0.2	0.4	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00
Unsaturated zone, soil-b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayed soil. Both the limits values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Unsaturated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1E-5 to 1E7. The high and low values were set to observe the maximal variation in potential radiation exposure.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00
Occupancy, Inhalation, and External Gamma Parameters										
Inhalation rate (m ³ /yr)	4200	8578	16400	The base value was calculated by using the default inhalation rates (for outdoor, indoor, and gardening activities) and time fractions (for outdoor, indoor, and gardening activities) in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.35 0.00 0.00 0.00 5.91	5.91
Mass loading for inhalation (g/m ³)	1E-7	3.014E-5	2.54E0-4	The base value was calculated by using the mass loading values (for outdoor and gardening activities) and time fractions (for outdoor and gardening activities) in the DandD code. The low value is from Beyeler et al. (1998). The high value is from Gilbert et al. (1989).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.406E-01 1.736E+00 3.252E+00 1.591E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.521E-01 1.736E+00 3.252E+00 2.170E-01	0.00 0.00 0.00 0.00 0.00 2.12 0.00 0.00 34.90	34.90
Indoor dust filtration factor	0.05	0.449	0.7	The low and high values are from Alzona et al. (1979). The base value was the ratio of dust loading factor indoors to dust loading factor outdoors in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.411E-01 1.736E+00 3.252E+00 1.616E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.425E-01 1.736E+00 3.252E+00 1.687E-01	0.00 0.00 0.00 0.00 0.00 0.26 0.00 0.00 4.28	4.28
Exposure duration (yr)	1	30	70	High value set to the average life span. The base value is the RESRAD default value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	0.00
External gamma shielding factor	0.43	0.552	0.837	Figure 3.4.3 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	4.857E+00 1.394E+00 1.253E+00 3.544E+01 5.304E-01 1.736E+00 3.252E+00 1.627E-01	4.857E+00 1.394E+00 1.253E+00 3.544E+01 5.304E-01 1.736E+00 3.252E+00 1.659E-01	4.857E+00 1.394E+00 1.253E+00 3.544E+01 5.304E-01 1.736E+00 3.252E+00 1.659E-01	54.40 0.43 48.26 6.56 7.14 0.00 0.00 6.51	54.40

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
	Low	Base	High			Low	Base	High		
Indoor time fraction	0.518	0.65	0.781	Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	4.933E+00 1.394E+00 1.270E+00 2.934E+01 4.432E-01 1.736E+00 3.252E+00 1.533E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	6.666E+00 1.398E+00 1.658E+00 4.290E+01 6.400E-01 1.736E+00 3.252E+00 1.785E-01	29.86 0.29 26.48 37.51 36.31 0.00 0.00 15.19	37.51
Outdoor time fraction	0.055	0.12	0.2405	Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.027E+00 1.394E+00 1.291E+00 3.566E+01 5.320E-01 1.736E+00 3.252E+00 1.579E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	7.241E+00 1.399E+00 1.787E+00 3.723E+01 5.605E-01 1.736E+00 3.252E+00 1.808E-01	38.15 0.36 33.86 4.62 5.26 0.00 0.00 13.80	38.15
Ingestion Pathway, Dietary Data Fruit, vegetables, and grain consumption (kg/yr)	56	111.8	844	The high value is from EPA (1997). The base value was calculated by using the default values in the DandD code. The low value is set to 1/2 of the base value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.784E+00 9.823E-01 1.447E+00 3.564E+01 5.300E-01 1.721E+00 3.223E+00 1.320E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	6.048E+00 6.822E+00 1.693E+00 4.331E+01 6.999E-01 1.936E+00 3.638E+00 6.118E-01	4.55 418.32 16.79 21.22 31.35 12.38 12.76 289.21	418.32
Leafy vegetable consumption	7	21.4	64	The low value is from Hoffman and Baes (1979) for children. The high value is from NRC (1977) for adults. The base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.798E+00 1.289E+00 1.460E+00 3.602E+01 5.388E-01 1.706E+00 3.194E+00 1.567E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.817E+00 1.711E+00 1.478E+00 3.653E+01 5.512E-01 1.711E+00 3.423E+00 1.933E-01	0.33 30.23 1.23 1.41 2.29 0.29 7.04 22.06	30.23
Milk consumption (L/yr)	112	233	778	The high value is from EPA (1997). The base value is the default value used in the DandD code. The low value is 1/2 of the base value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.795E+00 1.264E+00 1.423E+00 3.600E+01 5.390E-01 1.709E+00 3.252E+00 1.655E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.840E+00 1.989E+00 1.653E+00 3.683E+01 5.552E-01 1.860E+00 3.252E+00 1.680E-01	0.78 51.93 15.70 2.30 2.99 8.70 0.00 1.51	51.93
Meat and poultry consumption (kg/yr)	51	65.1	178	The low value is from the reported min. for meat consumption by the USDA (1992). The high value is from EPA (1997). The base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.797E+00 1.365E+00 1.451E+00 3.613E+01 5.414E-01 1.735E+00 3.251E+00 1.647E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.852E+00 1.643E+00 1.573E+00 3.626E+01 5.466E-01 1.745E+00 3.257E+00 1.763E-01	0.95 19.91 8.33 0.36 0.96 0.58 0.18 6.99	19.91

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Fish consumption (kg/yr)	2.66	20.6	29.41	Low and high values are from Rupp et al. (1980) for the consumption rate of freshwater finfish. The base value is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.734E+00 3.242E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.737E+00 3.257E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.737E+00 3.257E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.17 0.46 0.00	0.46
Other seafood consumption (kg/yr)	0	0.9	11.52	Low and high values are from Rupp et al. (1980) for the consumption of shellfish. The base value is the RESRAD default value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.250E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.35 0.88 0.00	0.68
Soil Ingestion rate (g/yr)	0	18.25	36.5	Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.394E+00 1.464E+00 3.613E+01 5.390E-01 1.736E+00 3.252E+00 1.150E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.804E+00 1.398E+00 1.465E+00 3.617E+01 5.450E-01 1.736E+00 3.252E+00 2.169E-01	0.02 0.29 0.07 0.11 1.11 0.00 0.00 61.42	61.42
Drinking water intake (L/yr)	154.45	478.5	1468	The base value is the mean value reported in Beyeler et al. (1998). The low and high values correspond to the values one standard deviation lower and higher, respectively, than the mean value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 6.523E-01 1.159E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 6.523E-01 1.159E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 6.523E-01 1.159E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 253.09 260.92 0.00	260.92
Aquatic food contaminated fraction	0	1	1	The base value is based on the assumption that all the ingested aquatic food is contaminated.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.734E+00 3.239E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 0.12 0.40 0.00	0.40
Ingestion Pathway, Non-dietary Data										
Livestock fodder intake for meat (kg/d)	13.4	26.81	53.6	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated fodder that is ingested.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.797E+00 1.344E+00 1.456E+00 3.614E+01 5.418E-01 1.735E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.815E+00 1.500E+00 1.481E+00 3.616E+01 5.423E-01 1.738E+00 3.253E+00 1.660E-01	0.31 11.17 1.71 0.06 0.09 0.17 0.03 0.06	11.17

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Livestock fodder intake for milk (kg/d)	31.6	63.22	126	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated fodder that is ingested.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.798E+00 1.286E+00 1.446E+00 3.608E+01 5.410E-01 1.724E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.813E+00 1.613E+00 1.502E+00 3.628E+01 5.439E-01 1.761E+00 3.252E+00 1.660E-01	0.26 23.42 3.82 0.55 0.54 2.13 0.00 0.06	23.42
Livestock water intake for meat (L/d)	25	50	100	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated water that is ingested.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.660E-01	0.00 0.00 0.00 0.00 0.00 0.35 0.09 0.00	0.35
Livestock water intake for milk (L/d)	30	60	120	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated water that is ingested.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.764E+00 3.252E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 2.42 0.00 0.00	2.42
Livestock intake of soil (kg/d)	0.25	0.5	1	The low and high values are 1/2 of and 2 times, respectively, the RESRAD base value, which is the default value used in the DandD code.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.792E+00 1.359E+00 1.420E+00 3.605E+01 5.389E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.825E+00 1.469E+00 1.554E+00 3.635E+01 5.481E-01 1.736E+00 3.252E+00 1.727E-01	0.57 7.88 9.15 0.83 1.70 0.00 0.00 6.09	9.15
Mass loading for foliar deposition (g/m ³)	1E-7	4E-4	7E-4	Base value and high value are from page 5.4-7 of Beyeler et al. (1998). The low value was set to the low value for the "dust loading for inhalation" parameter to observe potential variation in radiation dose.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.419E-01 1.736E+00 3.252E+00 1.646E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.670E-01	0.00 0.00 0.00 0.00 0.02 0.00 0.00 1.45	1.45
Depth of soil mixing layer (m)	0.075	0.15	0.3	The low value is 1/2 of the RESRAD default value and the high value is twice the RESRAD default value.	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.516E-01 1.736E+00 3.252E+00 1.662E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.792E+00 1.358E+00 1.420E+00 3.603E+01 5.367E-01 1.736E+00 3.252E+00 1.330E-01	0.19 2.72 3.07 0.33 2.75 0.00 0.00 20.01	20.01

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD	
	Low	Base	High			Low	Base	High			
Depth of roots (m)	0.3	0.9	3	Based on previously collected data.	Co-60	5.936E+00	5.803E+00	5.757E+00	3.08	253.37	
					Sr-90	4.016E+00	1.396E+00	4.789E-01	253.37		
					Cs-137	1.655E+00	1.465E+00	1.398E+00	17.54		
					Ra-226	3.885E+01	3.615E+01	3.520E+01	10.10		
					Th-230	6.037E-01	5.420E-01	5.204E-01	15.37		
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00		
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00		
					Am-241	3.270E-01	1.659E-01	1.096E-01	131.04		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00		12.58
Wet-weight crop yields for non-leafy vegetables (kg/m ²)	0.31	2.4	3	USDA (1997) is the source for the low value, which corresponds approximately to the average yields of asparagus, lima beans, and peas. The high value is the upper limit set in the RESRAD code and is close to the reported max. value (4) in USDA (1997) for the average yields of onions, carrots, strawberries, and grapefruits. The base value is from Beyeler et al. (1998).	Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00		
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00		
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.04		
					U-238	1.941E+00	1.736E+00	1.730E+00	12.15		
					Pu-239	3.649E+00	3.252E+00	3.240E+00	12.58		
					Am-241	1.696E-01	1.659E-01	1.658E-01	2.29		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00		0.28
					Wet-weight crop yields for leafy vegetables (kg/m ²)	2.7	2.9	3.0	Low and base values are from Table 5.5.1.5 of Beyeler et al. (1998). The high value is the upper limit that can be accepted by the RESRAD code.		Sr-90
Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00							
Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00							
Th-230	5.420E-01	5.420E-01	5.420E-01	0.00							
U-238	1.739E+00	1.736E+00	1.735E+00	0.23							
Pu-239	3.258E+00	3.252E+00	3.249E+00	0.28							
Am-241	1.660E-01	1.659E-01	1.659E-01	0.06							
Co-60	5.803E+00	5.803E+00	5.803E+00	0.00						1.04	
Wet-weight crop yields for fodder (kg/m ²)	1.259	1.8868	2.36	Table 5.5.2.2 of Beyeler et al. (1998).						Sr-90	1.396E+00
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00		
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00		
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00		
					U-238	1.749E+00	1.736E+00	1.731E+00	1.04		
					Pu-239	3.253E+00	3.252E+00	3.252E+00	0.03		
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06		
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.34	
					Length of growing season for non-leafy vegetables (yr)	0.085	0.2466	0.4932	Beyeler et al. (1998).	Sr-90	1.396E+00
Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00							
Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00							
Th-230	5.420E-01	5.420E-01	5.420E-01	0.00							
U-238	1.731E+00	1.736E+00	1.736E+00	0.29							
Pu-239	3.242E+00	3.252E+00	3.253E+00	0.34							
Am-241	1.659E-01	1.659E-01	1.660E-01	0.06							
Co-60	5.803E+00	5.803E+00	5.803E+00	0.00						0.81	
Length of growing season for leafy vegetables (yr)	0.062	0.123	0.246	Base value is from Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.						Sr-90	1.396E+00
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00		
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00		
					Th-230	5.419E-01	5.420E-01	5.420E-01	0.02		
					U-238	1.726E+00	1.736E+00	1.740E+00	0.81		
					Pu-239	3.233E+00	3.252E+00	3.259E+00	0.80		
					Am-241	1.658E-01	1.659E-01	1.660E-01	0.12		

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Length of growing season for fodder (yr)	0.04	0.082	0.16	Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.75
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.728E+00	1.736E+00	1.741E+00	0.75	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
Translocation factor for non-leafy vegetables	0.05	0.1	0.2	The low value is 1/2 of the RESRAD default value and the high value is twice the RESRAD default value.	Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	2.71
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.721E+00	1.736E+00	1.767E+00	2.65	
Translocation factor for leafy vegetables	0.5	1	1	The low value is 1/2 of the RESRAD default value. The high value is the largest value the parameter can assume.	Pu-239	3.223E+00	3.252E+00	3.311E+00	2.71	1.32
					Am-241	1.657E-01	1.659E-01	1.665E-01	0.48	
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
Translocation factor for fodder	0.5	1	1	The low value is 1/2 of the RESRAD default value. The high value is the largest value the parameter can assume.	U-238	1.714E+00	1.736E+00	1.736E+00	1.27	0.75
					Pu-239	3.209E+00	3.252E+00	3.252E+00	1.32	
					Am-241	1.656E-01	1.659E-01	1.659E-01	0.18	
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
Weathering removal constant (1/yr)	10	20	40	The low value is 1/2 of the RESRAD default value, and the high value is twice the RESRAD default value.	Th-230	5.419E-01	5.420E-01	5.420E-01	0.02	6.11
					U-238	1.723E+00	1.736E+00	1.736E+00	0.75	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
Wet foliar interception fraction for non-leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	2.58
					Th-230	5.420E-01	5.420E-01	5.419E-01	0.02	
					U-238	1.796E+00	1.736E+00	1.690E+00	6.11	
					Pu-239	3.349E+00	3.252E+00	3.183E+00	5.10	
					Am-241	1.688E-01	1.659E-01	1.653E-01	2.11	
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
Wet foliar interception fraction for non-leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	2.53
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.714E+00	1.736E+00	1.758E+00	2.53	
					Pu-239	3.210E+00	3.252E+00	3.294E+00	2.58	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
					Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Wet foliar interception fraction for leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.704E+00 3.191E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.768E+00 3.313E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 3.69 3.75 0.00	3.75
Wet foliar interception fraction for fodder	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.717E+00 3.251E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.755E+00 3.253E+00 1.659E-01	0.00 0.00 0.00 0.00 0.00 2.19 0.06 0.00	2.19
Dry foliar interception fraction for non-leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.419E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.663E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.663E-01	0.00 0.00 0.00 0.00 0.02 0.00 0.00 0.42	0.42
Dry foliar interception fraction for leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.419E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.663E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.663E-01	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.66	0.66
Dry foliar interception fraction for fodder	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.419E-01 1.736E+00 3.252E+00 1.659E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.665E-01	5.803E+00 1.396E+00 1.465E+00 3.615E+01 5.420E-01 1.736E+00 3.252E+00 1.665E-01	0.00 0.00 0.00 0.00 0.02 0.00 0.00 0.86	0.86
Storage Times for Fruits, Non-leafy Vegetables, and Grain³										
Storage times for fruits, non-leafy vegetables, and grain (d)	0	14	28	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.						
Storage times for leafy vegetables (d)	0	1	7	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.						

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Storage times for milk (d)	0	1	7	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Storage times for meat (d)	7	20	30	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.913E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.02 0.00	0.02
Storage times for fish (d)	1	7	14	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Storage times for crustacea	1	7	14	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Storage times for well water (d)	0.5	1	2	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Storage times for surface water (d)	0.5	1	2	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Storage times for livestock fodder (d)	15	45	90	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45 Ra-228 Cf-252	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	2.470E-02 4.914E+00 3.870E-02	0.00 0.00 0.00	0.00
Carbon-Model Parameters										
C-12 concentration in local water (g/cm ³)	0.000002	0.00002	0.0002	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.327E-02	5.327E-02	5.326E-02	0.02	0.02
C-12 concentration in contamination soil (g/g)	0.003	0.03	0.3	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.383E-02	5.327E-02	5.310E-02	1.37	1.37
Fraction of vegetation carbon absorbed from soil	0.002	0.02	0.2	The low and high are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.321E-02	5.327E-02	5.382E-02	1.15	1.15
Fraction of vegetation carbon adsorbed from air	0.8	0.98	0.998	The low and high were determined by using the high and low values, respectively, of the previous parameter.	C-14	5.293E-02	5.327E-02	5.330E-02	0.69	0.69
C-14 evasion layer thickness in soil (m)	0.2	0.3	1	Values were selected to observe potential variation in doses.	C-14	5.265E-02	5.327E-02	1.254E-01	136.57	136.57
C-14 evasion flux rate from soil (l/s)	0.00000035	0.0000007	0.0000014	Values were selected to observe potential variation in doses.	C-14	5.235E-02	5.327E-02	5.510E-02	5.16	5.16
C-12 evasion flux rate from soil (l/s)	5E-11	1E-10	0.0000000002	Values were selected to observe potential variation in doses.	C-14	5.327E-02	5.327E-02	5.327E-02	0.00	0.00
Grain fraction in livestock feed for beef cattle	0.125	0.25	0.5	Base value from page 5.6-5 of Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.	C-14	5.397E-02	5.327E-02	5.252E-02	2.72	2.72
Grain fraction in livestock feed for milk cow	0.05	0.1	0.2	Base value from page 5.6-5 of Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.	C-14	5.352E-02	5.327E-02	5.291E-02	1.15	1.15

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD ¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Transfer Factors for plants	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.738E+00	5.803E+00	5.803E+00	1.12	480.55
					Si-90	1.602E-01	1.396E+00	1.396E+00	88.52	
					Cs-137	1.371E+00	1.465E+00	1.555E+00	12.56	
					Ra-226	3.493E+01	3.615E+01	5.001E+01	41.72	
					Th-230	5.143E-01	5.420E-01	8.202E-01	56.44	
					U-238	1.736E+00	1.736E+00	1.737E+00	0.06	
					Pu-239	3.252E+00	3.252E+00	3.253E+00	0.03	
					Am-241	9.347E-02	1.659E-01	8.907E-01	480.55	
					Co-60	5.778E+00	5.803E+00	6.056E+00	4.79	
					Si-90	1.267E+00	1.396E+00	2.680E+00	101.22	
Transfer factors for meat [(pCi/kg)/(pCi/d)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Cs-137	1.409E+00	1.465E+00	2.026E+00	42.12	179.80
					Ra-226	3.609E+01	3.615E+01	3.671E+01	1.72	
					Th-230	5.396E-01	5.420E-01	5.660E-01	4.87	
					U-238	1.731E+00	1.736E+00	1.784E+00	3.05	
					Pu-239	3.249E+00	3.252E+00	3.279E+00	0.92	
					Am-241	1.606E-01	1.659E-01	2.196E-01	35.56	
					Co-60	5.789E+00	5.803E+00	5.945E+00	2.69	
					Si-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
Transfer factors for milk [(pCi/L)/(pCi/d)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	30.13
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
					Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	
					Co-60	5.803E+00	5.803E+00	5.945E+00	2.69	
					Si-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
					Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
Bioaccumulation Factors for fish [(pCi/kg)/(pCi/L)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	3.51
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	
					Co-60	5.803E+00	5.803E+00	5.945E+00	2.69	
					Si-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
					Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
					Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	
Bioaccumulation factors for crustacea and mollusks [(pCi/kg)/(pCi/L)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.803E+00	5.803E+00	5.945E+00	2.69	0.49
					Si-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
					Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
					Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	
					Co-60	5.803E+00	5.803E+00	5.945E+00	2.69	
					Si-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
					Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
					Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	

¹ NDD is defined as $ABS [(D_{high} - D_{low})/D_{def} \times 100\%]$, where ABS is the absolute value operator, D_{high} is the peak dose calculated with the parameter value listed under the "high" column, D_{low} is the peak dose calculated with the parameter value listed under the "low" column, D_{def} is the peak dose calculated with the base value of the parameter.

² For "cover density" and "cover erosion rate" parameters, the base case was modified to include a layer of cover material on top of the contaminated zone. Thickness of the cover material was assumed to be 30 cm. The base case used for all other parameters did not have a layer of cover material.

³ To study the storage time parameters, Ca-45, Ra-228, and Cf-252 were selected. Kd values used are shown as the base values in Table 3.2 and transfer factors were set to the RESRAD default values for these radionuclides.

Table 3.2 Transport and Transfer Factors Used in the RESRAD Dose Variability Analysis

Parameter	Radionuclides		Parameter Value			Source
	Parent	Decay Chain	Low	Base	High	
Distribution coefficients (contaminated zone, unsaturated zone, and saturated zone)(cm ³ /g)	H-3	H-3	-	0	-	The base values are the DandD default values. The low and high values are from Sheppard and Thibault (1990). They were selected among the reported geometric mean values from 4 different types of soil: sand, loam, clay, and organic. For some radionuclides, the low value was set to the base value so that the base value was included in the range.
	C-14	C-14	-	4	-	
	Ca-45	Ca-45	-	1,468	-	
	Co-60	Co-60	60	1,515	1,515	
	Sr-90	Sr-90	15	31	150	
	Cs-137	Cs-137	10	10	4,600	
	Ra-226	Ra-226	500	3,529	36,000	
	Pb-210	Pb-210	270	2,377	22,000	
	Ra-228	Ra-228	-	3,529	-	
	Th-228	Th-228	-	119	-	
	Th-230	Th-230	119	119	89,000	
	Ra-226	Ra-226	500	3,529	36,000	
	Pb-210	Pb-210	270	2,377	22,000	
	U-238	U-238	2	2	1,600	
	U-234	U-234	2	2	1,600	
	Th-230	Th-230	119	119	89,000	
	Ra-226	Ra-226	500	3,529	36,000	
	Pb-210	Pb-210	270	2,377	22,000	
	Pu-239	Pu-239	14	14	5,100	
	U-235	U-235	2	2	1,600	
	Pa-231	Pa-231	5	5	2,600	
	Ac-227	Ac-227	450	1,726	5,400	
	Am-241	Am-241	1,432	1,432	11,200	
	Np-237	Np-237	5	14	1,200	
	U-233	U-233	2	2	1,600	
	Th-229	Th-229	119	119	89,000	
Cf-252	Cf-252	Cf-252	-	158	-	
	Cm-248	Cm-248	-	109,084	-	
	Pu-244	Pu-244	-	14	-	
	Pu-240	Pu-240	-	14	-	
	U-236	U-236	-	2	-	
	Th-232	Th-232	-	119	-	
	Ra-228	Ra-228	-	3,529	-	
	Th-228	Th-228	-	119	-	

Table 3.2 (Continued)

Parameter Transfer Factors	Radionuclides		Parameter Value			Source
	Parent	Decay Chain	Low	Base	High	
Transfer factors for plants ¹	Co-60	Co-60 Sr-90 Cs-137 Ra-226	1.00E-03	8.00E-02	8.00E-02	The base values are the RESRAD default values. The low and high values are from Ng et al. (1982), if available. Otherwise, they were set to 1/10 of and 10 times, respectively, the base values.
	Sr-90		1.70E-02	3.00E-01	3.00E-01	
	Cs-137	Cs-137 Ra-226	6.40E-04	4.00E-02	7.80E-02	
	Ra-226		4.00E-03	4.00E-02	4.00E-01	
	Th-230	Pb-210 Th-230 Ra-226	1.00E-03	1.00E-02	1.00E-01	
			1.00E-04	1.00E-03	1.00E-02	
		Pb-210 Th-230	4.00E-03	4.00E-02	4.00E-01	
			1.00E-03	1.00E-02	1.00E-01	
	U-238	U-238 U-234	2.50E-04	2.50E-03	2.50E-02	
			2.50E-04	2.50E-03	2.50E-02	
		Th-230 Ra-226	1.00E-04	1.00E-03	1.00E-02	
			4.00E-03	4.00E-02	4.00E-01	
		Pb-210 Pu-239	1.00E-03	1.00E-02	1.00E-01	
			1.00E-04	1.00E-03	1.00E-02	
	Pu-239	U-235 Pa-231	2.50E-04	2.50E-03	2.50E-02	
			1.00E-03	1.00E-02	1.00E-01	
		Ac-227 Am-241	2.50E-04	2.50E-03	2.50E-02	
			1.00E-04	1.00E-03	1.00E-02	
	Am-241	Np-237 U-233	1.00E-06	2.00E-02	2.00E-02	
			2.50E-04	2.50E-03	2.50E-02	
		Th-229	1.00E-04	1.00E-03	1.00E-02	
Transfer factors for meat ¹ [(pCi/kg)/(pCi/d)]	Co-60	Co-60 Sr-90 Cs-137 Ra-226	2.00E-03	2.00E-02	2.00E-01	High and low values were selected to be 10 times and 1/10 of, respectively, the base values. The base values are the RESRAD default values.
	Sr-90		8.00E-04	8.00E-03	8.00E-02	
	Cs-137	Cs-137 Ra-226	3.00E-03	3.00E-02	3.00E-01	
	Ra-226		1.00E-04	1.00E-03	1.00E-02	
	Th-230	Pb-210 Th-230 Ra-226	8.00E-05	8.00E-04	8.00E-03	
			1.00E-05	1.00E-04	1.00E-03	
		Pb-210 Th-230	1.00E-04	1.00E-03	1.00E-02	
			8.00E-05	8.00E-04	8.00E-03	
	U-238	U-238 U-234	3.00E-05	3.00E-04	3.00E-03	
			3.00E-05	3.00E-04	3.00E-03	
		Th-230 Ra-226	1.00E-06	1.00E-05	1.00E-04	
			1.00E-04	1.00E-03	1.00E-02	
		Pb-210 Pu-239	8.00E-05	8.00E-04	8.00E-03	
			1.00E-05	1.00E-04	1.00E-03	
	Pu-239	U-235 Pa-231	3.00E-05	3.00E-04	3.00E-03	
			3.00E-05	3.00E-04	3.00E-03	
		Ac-227 Am-241	2.00E-06	2.00E-05	2.00E-04	
			5.00E-06	5.00E-05	5.00E-04	
	Am-241	Np-237 U-233	1.00E-04	1.00E-03	1.00E-02	
			3.40E-05	3.40E-04	3.40E-03	
		Th-229	1.00E-05	1.00E-04	1.00E-03	

Table 3.2 (Continued)

Parameter	Radionuclides		Parameter Value			Source
	Parent	Decay Chain	Low	Base	High	
Transfer factors for milk ¹ [(pCi/kg)/(pCi/d)]	Co-60	Decay Chain	2.00E-04	2.00E-03	2.00E-02	High and low values were selected to be 10 times and 1/10 of, respectively, the base values. The base values are the RESRAD default values.
	Sr-90	Co-60	2.80E-04	2.80E-03	2.80E-02	
	Cs-137	Sr-90	8.00E-04	8.00E-03	8.00E-02	
	Ra-226	Cs-137	2.00E-05	2.00E-04	2.00E-03	
		Ra-226	3.00E-05	3.00E-04	3.00E-03	
		Pb-210	5.00E-07	5.00E-06	5.00E-05	
	Th-230	Th-230	2.00E-05	2.00E-04	2.00E-03	
		Ra-226	3.00E-05	3.00E-04	3.00E-03	
		Pb-210	4.00E-05	4.00E-04	4.00E-03	
	U-238	U-238	4.00E-05	4.00E-04	4.00E-03	
		U-234	5.00E-07	5.00E-06	5.00E-05	
		Th-230	2.00E-05	2.00E-04	2.00E-03	
		Ra-226	3.00E-05	3.00E-04	3.00E-03	
		Pb-210	1.10E-07	1.10E-06	1.10E-05	
	Pu-239	Pu-239	4.00E-05	4.00E-04	4.00E-03	
		U-235	5.00E-07	5.00E-06	5.00E-05	
		Pa-231	2.00E-06	2.00E-05	2.00E-04	
		Ac-227	2.00E-07	2.00E-06	2.00E-05	
	Am-241	Am-241	5.00E-07	5.00E-06	5.00E-05	
		Np-237	6.00E-05	6.00E-04	6.00E-03	
		U-233	5.00E-07	5.00E-06	5.00E-05	
		Th-229				
Bioaccumulation Factors Bioaccumulation factors for fish ¹ [(pCi/kg)/(pCi/L)]	Parent	Decay Chain	30	300	3,000	High and low values were selected to be 10 times and 1/10 of, respectively, the base values. The base values are the RESRAD default values.
	Co-60	Co-60	6	60	600	
	Sr-90	Sr-90	200	2,000	20,000	
	Cs-137	Cs-137	5	50	500	
	Ra-226	Ra-226	30	300	3,000	
		Pb-210	10	100	1,000	
	Th-230	Th-230	5	50	500	
		Ra-226	30	300	3,000	
		Pb-210	1	10	100	
	U-238	U-238	1	10	100	
		U-234	10	100	1,000	
		Th-230	5	50	500	
		Ra-226	30	300	3,000	
	Pu-239	Pu-239	3	30	300	
		U-235	1	10	100	
		Pa-231	1	10	100	
		Ac-227	2	15	150	
	Am-241	Am-241	3	30	300	
		Np-237	3	30	300	
		U-233	1	10	100	
		Th-229	10	100	1,000	

Table 3.2 (Continued)

Parameter	Radionuclides		Parameter Value		Source	
	Parent	Decay Chain	Low	Base		High
Bioaccumulation factors for crustacea and mollusks ¹ [(pCi/kg)/(pCi/L)]	Co-60	Decay Chain	20	200	2,000	High and low values were selected to be 10 times and 1/10 of, respectively, the base values. The base values are the RESRAD default values.
	Sr-90		10	100	1,000	
	Cs-137		10	100	1,000	
	Ra-226		25	250	2,500	
	Pb-210	30	300	3,000		
	Th-230	50	500	5,000		
	Ra-226	25	250	2,500		
	Pb-210	30	300	3,000		
	U-238	6	60	600		
	U-234	6	60	600		
	Th-230	50	500	5,000		
	Ra-226	25	250	2,500		
	Pb-210	30	300	3,000		
	Pu-239	10	100	1,000		
	U-235	6	60	600		
	Pa-231	11	110	1,100		
	Ac-227	100	1,000	10,000		
	Am-241	100	1,000	10,000		
	Np-237	40	400	4,000		
	U-233	6	60	600		
	Th-229	50	500	5,000		

High and low values were selected to be 10 times and 1/10 of, respectively, the base values. The base values are the RESRAD default values.

¹ The transfer factors (for plant, meat, and milk) and the bioaccumulation factors (for fish, crustacea and mollusks) used for H-3, C-14, Ca-45, Ra-228, and Cf-252, and their respective progeny radionuclides in the dose variability analyses are the RESRAD default values.

Table 3.3 Dose Variability Analysis Results for the RESRAD-BUILD Parameters

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Indoor fraction	0.205	0.267	0.383	The base value is the default value used in the DandD code. The low and high values are from Fig. 5.1 of Beyeler et al. (1997).	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.910E+00 3.150E-03 4.460E-01 2.360E+00 1.640E-03 1.740E-02 1.390E-03 5.810E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	3.570E+00 5.880E-03 8.330E-01 4.400E+00 3.053E-03 3.250E-02 2.600E-03 1.090E-02	66.67 66.59 66.61 66.45 66.21 66.81 66.85 67.24	67.25
Deposition velocity (m/s)	0	0.01	0.01	The low value was selected for considering radionuclides in the gas form.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.100E-03 5.810E-01 9.400E+00 3.490E-03 2.260E-02 1.740E-03 7.500E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	0.00 0.00 0.00 206.19 63.54 0.00 3.87 0.92	206.19
Resuspension rate (1/s)	1.2E-10	1.42E-07	4.00E-04	The base value was obtained by multiplying the DandD resuspension factor by the base value of the deposition velocity. The low and high values are from the reported data for resuspension factor/rate listed in Table 5.10 of Beyeler et al. (1997).	Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.460E-05 2.530E-06 3.610E-06 3.750E-05 6.090E-04 2.210E-04 8.020E-04 8.290E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	3.31 32.53 14.25 15.16 0.98 1.34 4.30 3.72	11969.23
					Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.130E-03 5.810E-01 3.080E+00 1.557E-02 2.960E-02 8.110E-02 1.640E-02	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 3.410E+00 2.187E-03 2.260E-02 1.740E-03 7.500E-03	0.00 0.73 0.00 10.75 627.13 30.97 4384.53 117.57	
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.580E-05 1.570E-05 1.030E-05 5.320E-03 7.000E-03 3.520E-03 3.860E-02 5.050E-03	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.460E-05 2.530E-06 3.610E-06 2.960E-05 6.090E-04 2.210E-04 8.020E-04 8.290E-04	7.95 351.20 158.91 11969.23 1039.19 1472.77 4510.50 490.24	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Room height (m)	1.67	2.5	3.75	The low and high values are 2/3 of and 1.5 times, respectively, the base value, which is the default value used in the RESRAD code.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.110E-03 5.810E-01 3.250E+00 2.810E-03 2.290E-02 2.690E-03 8.460E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 2.910E+00 1.669E-03 2.250E-02 1.77 1.230E-03 6.970E-03	0.00 0.24 0.00 11.07 53.47 1.77 80.66 19.68	83.09
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.530E-05 5.330E-06 4.500E-06 6.010E-05 9.210E-04 3.350E-04 1.250E-03 1.290E-03	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.490E-05 2.610E-06 4.000E-06 3.340E-05 4.100E-04 1.490E-04 5.590E-04 5.760E-04	2.65 72.53 11.88 60.41 83.09 83.04 82.46 82.93	
Room area (m ²)	3.6	36	360	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.170E-03 5.810E-01 1.400E+01 1.610E-02 2.690E-02 1.770E-02 2.390E-02	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.090E-03 5.810E-01 1.980E+00 7.310E-04 2.220E-02 2.270E-04 5.940E-03	0.00 1.95 0.00 391.53 720.20 20.80 965.36 237.25	990.00
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.970E-05 3.640E-05 9.170E-06 3.420E-04 6.150E-03 2.230E-03 8.380E-03 8.610E-03	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.440E-05 4.780E-07 3.630E-06 1.420E-05 6.150E-05 2.250E-05 8.380E-05 8.640E-05	35.10 957.92 131.59 741.63 990.00 985.49 990.00 989.97	
Air exchange rate for building and room (1/h)	0.18	0.8	1.5	The high value is from Mueller Associates (1986); the low value is from EPA (1997). The base value is the RESRAD default value.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.120E-03 5.810E-01 7.240E+00 2.490E-03 2.420E-02 7.880E-03 1.360E-02	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 2.480E+00 1.401E-04 2.240E-02 9.910E-04 6.730E-03	0.00 0.49 0.00 155.05 344.42 7.96 380.61 90.75	390.57
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.590E-05 1.250E-05 5.820E-06 1.560E-04 2.730E-03 9.930E-04 3.720E-03 3.750E-03	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.480E-05 2.130E-06 3.910E-06 2.870E-05 3.280E-04 1.190E-04 4.470E-04 4.610E-04	7.28 276.53 45.37 288.01 390.57 390.18 390.57 382.00	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Receptor inhalation rate (m ³ /d)	12	33.6	45.6	The base value corresponds to an inhalation rate of 1.4 m ³ /hr, the default value used in the DandD code. The low and high values are from Table 5.9 of Beyeler et al. (1997).	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	99.19
						Sr-90	4.100E-03	4.100E-03	4.100E-03	0.00	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.070E+00	3.070E+00	3.070E+00	0.00	
						Th-230	1.307E-03	2.134E-03	2.584E-03	59.84	
						U-238	2.230E-02	2.260E-02	2.280E-02	2.21	
						Pu-239	7.300E-04	1.810E-03	2.420E-03	93.37	
						Am-241	6.450E-03	7.570E-03	8.190E-03	22.99	
						Co-60	1.490E-05	1.510E-05	1.510E-05	1.32	
						Sr-90	2.330E-06	3.750E-06	4.540E-06	58.93	
				The location of the receptor was varied to change the exposure distance. The variation considered a room area of 36 m ² (the RESRAD default value) and the assumption that it was 6 m x 6 m.	Volume	Cs-137	4.170E-06	4.210E-06	4.230E-06	1.43	94.83
						Ra-226	3.350E-05	4.420E-05	5.010E-05	37.56	
						Th-230	2.230E-04	6.150E-04	8.330E-04	99.19	
						U-238	8.170E-05	2.240E-04	3.020E-04	98.35	
						Pu-239	3.230E-04	8.380E-04	1.120E-03	95.11	
						Am-241	3.320E-04	8.610E-04	1.160E-03	96.17	
Receptor location (m)	1,1,1	1,1,1	5.5,1			Co-60	2.490E+00	2.490E+00	2.810E-01	88.71	
						Sr-90	4.100E-03	4.100E-03	2.120E-04	94.83	
						Cs-137	5.810E-01	5.810E-01	6.660E-02	88.54	
						Ra-226	3.070E+00	3.070E+00	1.420E-00	53.75	
				The low and high values are from information provided on page 5-17 of Beyeler et al. (1997).	Surface	Th-230	2.134E-03	2.134E-03	1.618E-03	24.18	
						U-238	2.260E-02	2.260E-02	3.000E-03	86.73	
						Pu-239	1.810E-03	1.810E-03	1.770E-03	2.21	
						Am-241	7.570E-03	7.570E-03	2.450E-03	67.64	
						Co-60	1.510E-05	1.510E-05	2.150E-06	85.76	
						Sr-90	3.750E-06	3.750E-06	3.640E-06	2.93	
						Cs-137	4.210E-06	4.210E-06	9.930E-07	76.41	
						Ra-226	4.420E-05	4.420E-05	3.440E-05	22.17	
						Th-230	6.150E-04	6.150E-04	6.150E-04	0.00	
						U-238	2.240E-04	2.240E-04	2.230E-04	0.45	
Receptor indirect ingestion rate (m ² /h)	0.00011	0.00011	0.011	The low and high values are from information provided on page 5-17 of Beyeler et al. (1997).	Volume	Pu-239	8.380E-04	8.380E-04	8.380E-04	0.00	3740.00
						Am-241	8.610E-04	8.610E-04	8.610E-04	0.00	
						Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	
						Sr-90	4.100E-03	4.100E-03	4.400E-03	7.32	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.070E+00	3.070E+00	3.070E+00	0.00	
						Th-230	2.134E-03	2.134E-03	3.315E-03	55.34	
						U-238	2.260E-02	2.260E-02	2.320E-02	2.65	
						Pu-239	1.810E-03	1.810E-03	9.430E-03	420.99	
						Am-241	7.570E-03	7.570E-03	1.530E-02	102.11	
				The low and high values are from information provided on page 5-17 of Beyeler et al. (1997).	Surface	Co-60	1.510E-05	1.510E-05	3.160E-05	109.27	
						Sr-90	3.750E-06	3.750E-06	1.440E-04	3740.00	
						Cs-137	4.210E-06	4.210E-06	5.030E-05	1094.77	
						Ra-226	4.420E-05	4.420E-05	1.500E-03	3293.67	
						Th-230	6.150E-04	6.150E-04	1.180E-03	91.87	
						U-238	2.240E-04	2.240E-04	4.990E-04	122.77	
						Pu-239	8.380E-04	8.380E-04	4.460E-03	432.22	
						Am-241	8.610E-04	8.610E-04	4.560E-03	429.62	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Source length or area (m or m ²)	3.6	36	360	The low and high values were set to 1/10 of and 10 times, respectively, the RESRAD default value.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	4.610E-01 7.880E-04 1.080E-01 4.660E-01 2.630E-04 4.180E-03 1.860E-04 1.270E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	3.480E+00 4.990E-03 7.950E-01 1.470E+01 1.638E-02 3.490E-02 1.770E-02 2.560E-02	121.24 102.49 118.24 463.65 755.25 135.93 967.62 321.40	990.00
Air release fraction	0.01	0.1	1	The low and high values were set to 1/10 of and 10 times, respectively, the default value.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.090E-03 5.810E-01 3.070E+00 9.670E-04 2.220E-02 2.270E-04 5.940E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.170E-03 5.810E-01 3.070E+00 1.370E-02 2.690E-02 1.770E-02 2.390E-02	0.00 1.95 0.00 0.00 596.67 20.80 965.36 237.25	990.00
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.430E-05 4.770E-07 3.610E-06 1.560E-05 6.150E-05 2.250E-05 8.380E-05 8.640E-05	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	2.240E-05 3.650E-05 1.020E-05 3.310E-04 6.150E-03 2.230E-03 8.380E-03 8.610E-03	53.64 960.61 156.53 713.57 990.00 985.49 990.00 989.97	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.990E-03 5.810E-01 3.080E+00 5.136E-03 2.420E-02 2.250E-02 2.880E-02	0.00 21.71 0.00 0.33 140.67 7.08 1143.09 280.45	1143.09
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
						Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	0	0	0.0025	The low/high value was obtained by using 1/10 of the upper/lower limit of the ingestion rate (0/200 mg/d) in the DandD code and the assumption that the exposure time was 8 hr/d.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.990E-03 5.810E-01 3.080E+00 5.136E-03 2.420E-02 2.250E-02 2.880E-02	0.00 21.71 0.00 0.33 140.67 7.08 1143.09 280.45	1143.09
	0	3.08E-07	0.00005	The high value corresponds to an ingestion rate that would consume the entire source in 10 years, assuming an exposure time of 8 hours per day and 250 days per year. It was selected to observe variation in radiation doses.	Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Removable fraction	0.01	0.1	0.5	The base value was set to the assumed value used in the DandD code. The low value and high value were selected to observe variation in radiation doses.	Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.500E-05 4.830E-07 3.780E-06 1.620E-05 6.150E-05 2.250E-05 8.380E-05 8.640E-05	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.530E-05 1.830E-05 6.110E-06 1.690E-04 3.070E-03 1.120E-03 4.190E-03 4.310E-03	1.99 475.12 55.34 345.70 489.19 489.96 490.00 490.55	490.55
Time for source removal or source lifetime (d)	365	365	36500	The low and high values were set to 1/10 of and 10 times, respectively, the RESRAD default value.	Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.500E-05 1.560E-07 3.740E-06 1.340E-05 6.190E-06 2.430E-06 8.390E-06 8.880E-06	0.66 95.84 11.16 69.68 98.99 98.92 99.00 98.97	99.00
Radionuclide concentration (pCi/g for volume source, pCi/m ² for surface source)	0.1	1	10	Values were varied to observe change in radiation doses.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E-01 4.100E-04 5.810E-02 3.070E-01 2.134E-04 2.260E-03 1.810E-04 7.570E-04	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+01 4.100E-02 5.810E+00 3.070E+01 2.134E-02 2.260E-01 1.810E-02 7.570E-02	990.00 990.00 990.00 990.00 990.00 990.00 990.00 990.00	990.00
Source thickness, volume source (cm)	0.1	1	10	Values were varied to observe change in radiation doses.	Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-06 3.750E-07 4.210E-07 4.420E-06 6.150E-05 2.240E-05 8.380E-05 8.610E-05	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-04 3.750E-05 4.210E-05 4.420E-04 6.150E-03 2.240E-03 8.380E-03 8.610E-03	990.00 990.00 990.00 990.00 990.00 990.00 990.00 990.00	94.46
Source density, volume source (g/cm ³)	2	2.4	4	The low and high values were varied from the RESRAD default value, which is the average value for concrete, to observe change in radiation doses.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.390E+00 3.260E-03 3.570E-01 1.480E+00 1.770E-03 1.490E-02 1.800E-03 7.680E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.650E+00 4.150E-03 5.920E-01 4.380E+00 2.417E-03 2.340E-02 1.810E-03 7.570E-03	50.60 21.71 40.45 94.46 30.32 37.61 0.55 1.45	81.22

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Source erosion rate, volume source (cm/d)	2.4E-10	2.4E-08	2.4E-06	The low and high values were set to 1/100 and 100 times of the RESRAD default value.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.090E-03 5.810E-01 3.070E+00 8.500E-04 2.220E-02 6.880E-05 5.780E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.860E-03 5.810E-01 3.070E+00 1.300E-01 6.910E-02 1.760E-01 1.870E-01	0.00 18.78 0.00 0.00 6052.01 207.52 9719.96 2393.92	9719.96
Shielding thickness (cm) ²	0	0	15	The low and high value were selected to observe variation in radiation doses.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.490E+00 4.100E-03 5.810E-01 3.070E+00 2.134E-03 2.260E-02 1.810E-03 7.570E-03	2.140E-01 8.500E-05 2.720E-02 1.340E+00 1.580E-03 1.610E-03 1.760E-03 1.810E-03	91.41 97.93 95.32 56.35 25.96 92.88 2.76 76.09	97.93
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	1.510E-05 3.750E-06 4.210E-06 4.420E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	2.470E-06 3.630E-06 9.100E-07 3.450E-05 6.150E-04 2.230E-04 8.380E-04 8.610E-04	83.64 3.20 78.38 21.95 0.00 0.45 0.00 0.00	
Shielding density (g/cm ³)	2	2.4	7.6	The low and high value were selected to observe variation in radiation doses.	Volume	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	3.370E-01 1.670E-04 4.750E-02 1.430E+00 1.599E-03 2.410E-03 1.760E-03 1.810E-03	2.140E-01 8.500E-05 2.720E-02 1.340E+00 1.580E-03 1.610E-03 1.760E-03 1.810E-03	5.250E-04 7.650E-06 1.920E-05 1.210E+00 1.552E-03 4.700E-04 1.760E-03 1.810E-03	157.23 187.47 174.56 16.42 2.97 120.50 0.00 0.00	187.47
					Surface	Co-60 Sr-90 Cs-137 Ra-226 Th-230 U-238 Pu-239 Am-241	3.390E-06 3.640E-06 1.090E-06 3.520E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	2.470E-06 3.630E-06 9.100E-07 3.450E-05 6.150E-04 2.230E-04 8.380E-04 8.610E-04	8.250E-07 3.630E-06 6.610E-07 3.340E-05 6.150E-04 2.240E-04 8.380E-04 8.610E-04	103.85 0.28 47.14 5.22 0.00 0.00 0.00 0.00	41.89
Dry zone thickness (cm) ³	0	0	5	The low and high value were selected to observe variation in radiation doses.	Volume	H-3	3.700E-03	3.700E-03	2.150E-03	41.89	41.89
Wet + dry zone thickness (cm) ³	5	10	30	The low and high value were selected to observe variation in radiation doses.	Volume	H-3	1.860E-03	3.700E-03	5.660E-03	102.70	102.70
Volumetric water content ³	0.02	0.03	0.06	The low and high value were selected to observe variation in radiation doses.	Volume	H-3	3.690E-03	3.700E-03	3.710E-03	0.54	0.54
Water fraction available for evaporation ³	0	1	1	The low and high value were selected to observe variation in radiation doses.	Volume	H-3	3.670E-10	3.700E-03	3.700E-03	100.00	100.00

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			Max. of NDD
	Low	Base	High				Low	Base	High	
Humidity (g/m ³) ³	3	8	16.5	Einier (1985).	Volume	H-3	3.710E-03	3.700E-03	2.220E-03	40.27
Source porosity ³	0.05	0.1	0.2	The low and high value were selected to observe variation in radiation doses.	Volume	H-3	3.570E-03	3.700E-03	3.720E-03	4.05

¹ NDD is defined as $ABS [(D_{high} - D_{low})/D_{def} \times 100\%]$, where ABS is the absolute value operator, D_{high} is the peak dose calculated with the parameter value listed under the "high" column, D_{low} is the peak dose calculated with the parameter value listed under the "low" column, D_{def} is the peak dose calculated with the base value of the parameter.

² When the shielding density parameter was being studied, the base case was modified to include a shielding material.

³ When the parameters used in the tritium model were being studied, the deposition velocity value was set to zero.

Table 4.1 Ranking Results for the RESRAD Parameters

Source	Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵	Sum of Ranking Scores ⁶	Final Ranking ⁷
Nuclide concentration (pCi/g)		Affects all pathways. Radiation doses are linearly proportional to the value.	990	1	0	5	2	8	2
	Transport Factors Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone)(cm ³ /g)	Account for partitioning of radionuclides between soil particles and soil water. The larger the value, the greater the partitioning to soil particles. In the contaminated zone, the coefficient affects the amount of radionuclides leaching out to the deeper soil. In the unsaturated zone, it affects the transport speed of radionuclides toward the groundwater table. In the saturated zone, it affects the transport speed of radionuclides toward the downgradient well. Value not used directly in dose calculation.	95.45	1	0	1	4	6	1
Time since placement of material (yr)	Number of unsaturated zones	Value not used directly in dose calculation.		1	9			> 10	3
	Time since placement of material (yr)	Used together with input groundwater concentrations to calculate the distribution coefficients. However, the distribution coefficients can be input directly for dose calculations.		1	9			> 10	3
Groundwater concentration (pCi/L)		Used together with the "time since placement of material" parameter to calculate the distribution coefficients. However, the distribution coefficients can be input directly for dose calculations.		1	9			> 10	3
	Leach rate (yr)	Used to calculate the distribution coefficients, however, the distribution coefficients can be input directly for dose calculations.		1	9			> 10	3
Solubility limit (mol/L)		Used to calculate distribution coefficients for the contaminated zone; however, the distribution coefficients can be input directly for dose calculations.		1	9			> 10	3
	Use plant/soil ratio	Check box to determine whether the root uptake transfer factors should be used to derive the distribution coefficients, which can be directly input for dose calculations.			9			> 10	3
Calculation Parameters Basic radiation dose limit (mrem/yr)		Used to derive soil cleanup objectives. A fixed value should be used.			9			> 10	3
	Time for calculations (yrs)	Can be of any value not exceeding 1,000, the time limit for DandD dose calculations.		1	9			> 10	3

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Contaminated Zone Parameters Area of contaminated zone (m ²)	The lateral size of the contamination source that affects every pathway. When the value is small (<25), it has strong impact on the external radiation dose. In the default case, it is used to determine the fractions of contaminated plant, meat, and milk that are consumed. As a general rule, "the length parallel to aquifer flow" is taken to be the square root of this parameter, which then impacts the dose of the water-dependent pathways.	117.48	1	0	5	3	9	2
Thickness of contaminated zone (m)	The vertical extent of the contamination source. The external radiation dose is quite sensitive to this parameter when its value is small (e.g., less than 15 cm). The amount of radionuclides leaching out from the contaminated zone is also dependent on this parameter. It affects the uptake amount of radionuclides by plant roots and the amount of contaminated dust particles getting into the atmosphere.	6156.46	1	0	5	1	7	2
Length parallel to aquifer flow (m)	As a general rule, the value is taken to be the square root of the contaminated area. It is the maximum distance traveled by radionuclides in the saturated zone from the upgradient edge of the contaminated zone to a well located at the downgradient edge of the contaminated zone. Affects the amount of radionuclides screened by the well and therefore the water concentration.	71.32	1	0	5	4	10	2
Cover and Contaminated Zone Hydrological Data Cover depth (m)	Attenuates the external radiation doses. Impacts the root uptake of radionuclides by plants by making the source radionuclides farther from the ground surface and farther for roots to reach. Radionuclides in the contaminated zone are less likely to suspend to the air with the existence of cover material. The foundation of a house is also less likely to extend to the contaminated zone, which reduces the surface area available for radon to diffuse into the building.	158.86	1	0	5	3	9	2
Density of cover material (g/cm ³)	Affects the degree of attenuation to the external radiation dose provided by the cover material.	248.79	1	0	1	3	5	1

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria			Dose Variability ⁵	Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴			
Contaminated Zone Parameters								
Cover erosion rate (m/yr)	Affects the thickness of cover material over time, and thereby affects the external dose, the inhalation dose, and the ingestion dose.	12.9	1	0	3	5	9	2
Density of contaminated zone (g/cm ³)	Determines the total mass of soil within a specified source volume. Since the radionuclide concentrations are specified in pCi/g, it also determines the total amount of radionuclides within the volume. It is used to calculate the leach rate of radionuclides. It has the potential of affecting all the pathways.	73.76	1	0	1	4	6	1
Contaminated zone total porosity	Used with the saturation ratio in determining the moisture content in soil, which then is used to determine the retardation factor and the transport speed of water in the soils. Affects mainly the water-dependent pathways.	23.4	1	0	1	5	7	2
Contaminated zone field capacity	Used as the lower limit to the moisture content in unsaturated soils.	0.12	1	0	3	7	11	3
Contaminated zone erosion rate (m/yr)	Affects the thickness of contaminated zone over time.	159.04	1	0	3	3	7	2
Contaminated zone hydraulic conductivity (m/yr)	Used along with the water infiltration rate and soil b parameter to determine the water saturation ratio in soil, which is then used in determining the transport speed of water and affects doses for the water-dependent pathways.	0.35	1	0	1	7	9	2
Contaminated zone b parameter	A soil-specific parameter used in determining the water saturation ratio of soil.	0.23	1	0	1	7	9	2
Humidity in air (g/m ³)	Used in the tritium-model to determine the average equilibrium concentration of hydrogen in air. Assuming the transport of tritium generally follows that of stable hydrogen, the concentration of hydrogen in air then helps set the upper limit of tritium concentration in air.	0	1	0	3	7	11	3
Evapotranspiration coefficient	Affects the water infiltration rate, which is used in determining the transport speed of water. Affects mainly the water-dependent pathways.	44.19	1	0	1	5	7	2
Wind speed (m/s)	Used in the inhalation pathway to determine the atmospheric dilution of suspended dust particles from the contaminated area. Affects the inhalation pathway.	7.29	1	0	3	6	10	2
Irrigation mode	Used to select method for calculating plant concentrations.		5	9			> 14	3
Precipitation rate (m/yr)	Affect the water infiltration rate, which is used in determining the transport speed of water. Affect mainly the water-dependent pathways.	43.84	1	0	1	5	7	2
Irrigation rate (m/yr)		15.5	5	0	1	5	11	3
Runoff coefficient		28.04	1	0	1	5	7	2

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵	Sum of Ranking Scores ⁶	Final Ranking ⁷
Watershed area for nearby stream or pond (m ²)	Used to determine the dilution factor in surface water. The larger the watershed area, the larger the dilution factor and the smaller the radionuclide concentrations in water.	40.25	1	0	5	5	11	3
Accuracy for water soil computation	Used as a convergence criterion in the calculations of water/soil concentration ratios. Does not directly affect the potential radiation doses.			9			> 10	3
Saturated Zone Hydrological Data	Parameters affect radiation doses from the water-dependent pathways.							
Density of saturated zone (g/m ³)	Used to calculate the retardation factor, which is then used in determining the time required for radionuclides to transport with groundwater from the upgradient edge to the downgradient edge of the contaminated zone.	82.32	1	0	1	4	6	1
Saturated zone total porosity	Used in determining the time required for radionuclides to transport with groundwater from the upgradient edge to the downgradient edge of the saturated zone, i.e., the rise time.	71.96	1	0	1	4	6	1
Saturated zone effective porosity	Used as the lower limit to the moisture content of the unsaturated zone created by dropping of the water table.	150.03	1	0	1	3	5	1
Saturated zone field capacity	Used to determine the groundwater flow rate, which affects the rise time as well as the dilution factor of radionuclides in well water.	0	1	0	3	7	11	3
Saturated zone hydraulic conductivity (m/yr)	Used to calculate the moisture content of the unsaturated zone created by dropping of the water table.	116.93	1	0	1	3	5	1
Saturated zone hydraulic gradient	Used to calculate the moisture content of the unsaturated zone created by dropping of the water table.	110.27	1	0	3	3	7	2
Saturated zone b parameter	Used to calculate the thickness of the unsaturated zone created by dropping of water table.	0	1	0	1	7	9	2
Water table drop rate (m/yr)	Used to determine the dilution factor of radionuclides in the well water.	0	1	0	5	7	13	3
Well pump intake depth (below water table) (m)	Used to select method for calculating groundwater concentrations.	40.22	1	0	3	5	9	2
Model: nondispersion (ND) or mass-balance (MB)	Affects the dilution factor of radionuclides in the well water.	77.55	1	9	3	4	> 10	3
Well pumping rate (m ³ /yr)	Parameters affect radiation doses from the water-dependent pathways.						8	2
Uncontaminated Unsaturated Zone Parameters	The distance for the radionuclides to travel from the contaminated zone to the groundwater table. The larger the thickness, the longer the travel time (breakthrough time). The breakthrough time affects the ingrowth and decay of radionuclides, which then affect the amounts of radionuclides reaching the groundwater table.							
Uncontaminated zone thickness (m)	Used to calculate the retardation factor, which is then used to calculate the breakthrough time.	95.71	1	0	1	4	6	1
Uncontaminated zone density (g/cm ³)		0.09	1	0	1	7	9	2
Uncontaminated zone total porosity		0.06	1	0	1	7	9	2

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵	Sum of Ranking Scores ⁶	Final Ranking ⁷
Unsaturated zone effective porosity	Used to calculate the breakthrough time. The larger the porosity, the longer the breakthrough time.	0.18	1	0	1	7	9	2
Unsaturated zone field capacity	Used as the lower limit to the moisture content in soil.	0	1	0	3	7	11	3
Unsaturated zone, soil-b parameter	Used in determining the moisture content in soil, which affects the retardation factor and the breakthrough time.	0	1	0	1	7	9	2
Unsaturated zone hydraulic conductivity (m/yr)			1	0	1	7	9	2
Occupancy, Inhalation, and External Gamma Parameters								
Inhalation rate (m ³ /yr)	Directly affects the inhalation dose, including inhalation of radon.	5.91	5	0	1	6	12	3
Mass loading for inhalation (g/m ³)	Used in determining the on-site outdoor air concentration resulting from dust suspension. Impacts the inhalation dose.	34.9	1	0	3	5	9	2
Exposure duration (yr)	Unless the value is smaller than 1 year, it will not impact the radiation doses.	0	5	0	1	7	13	3
Indoor dust filtration factor	Used to determine the on-site indoor air concentration resulting from dust suspension outdoors. Affects the inhalation pathway.	4.28	1	0	1	6	8	2
External gamma shielding factor	Used to account for attenuation in external radiation provided by buildings.	54.4	1	0	3	4	8	2
Indoor time fraction	Impact the radiation doses from the external, inhalation, and radon inhalation pathways.	37.51	5	0	3	5	13	3
Outdoor time fraction	Not used directly in dose calculations.	38.15	5	0	3	5	13	3
Shape of the contaminated zone (shape factor flag)			1	9			> 10	3
Ingestion Pathway, Dietary Data								
Fruit, vegetables, and grain consumption (kg/yr)	Parameters affect radiation doses from the ingestion pathways. Affect the ingestion of plant pathway directly. Since the ingestion rate of this food category is greater than that of leafy vegetable, it also contributes a larger radiation dose to the ingestion pathway than that from the ingestion of leafy vegetables.	418.32	5	0	1	2	8	2
Leafy vegetable consumption (kg/yr)	Affects the ingestion of plant pathway directly. However, the dose contribution is less than that from the non-leafy category (fruit, vegetables, and grain).	30.23	5	0	1	5	11	3
Milk consumption (L/yr)	Affects the radiation dose from the milk pathway.	51.93	5	0	1	4	10	2

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Meat and poultry consumption (kg/yr)	Affects the radiation dose from the meat pathway.	19.91	5	0	1	5	11	3
Fish consumption (kg/yr)	Affects the radiation dose from the aquatic food pathway.	0.46	5	0	1	7	13	3
Other seafood consumption (kg/yr)	Affects the radiation dose for the soil ingestion pathway. Because there is no dilution involved in the radionuclide concentrations, for some radionuclides, the radiation dose from soil ingestion is comparable to or even greater than doses from other ingestion pathways (plant, meat, and milk), although the soil ingestion rate is small.	0.68	5	0	1	7	13	3
Soil ingestion rate (g/yr)		61.42	5	0	1	4	10	2
Drinking water intake (L/yr)	Affects the radiation dose for the drinking water pathway. Because of the large ingestion rate, it is usually the dominant ingestion pathway once radionuclides reach the groundwater table. Usually set to either 0 or 1.	260.92	5	0	1	3	9	2
Drinking water contaminated fraction	Usually set to either 0 or 1.		1	9			> 10	3
Household water contaminated fraction	Usually set to either 0 or 1.		1	9			> 10	3
Livestock water contaminated fraction	Usually set to either 0 or 1.		1	9			> 10	3
Irrigation water contaminated fraction	Usually set to either 0 or 1.		1	9			> 10	3
Aquatic food contaminated fraction	Affects doses from the aquatic food pathway.	0.4	1	0	1	7	9	2
Plant food contaminated fraction	Can be calculated with information on the source area.		1	9			> 10	3
Meat contaminated fraction	Can be calculated with information on the source area.		1	9			> 10	3
Milk contaminated fraction	Can be calculated with information on the source area.		1	9			> 10	3
Ingestion Pathway, Non-Dietary Data	Parameters affect ingestion doses.							
Livestock fodder intake for meat (kg/d)	Indirectly impacts the radiation dose from the meat pathway.	11.17	9	0	3	5	17	3
Livestock fodder intake for milk (kg/d)	Indirectly impacts the radiation dose from the milk pathway.	23.42	9	0	3	5	17	3
Livestock water intake for meat (L/d)	Indirectly impacts the radiation dose from the meat pathway.	0.35	9	0	3	7	19	3
Livestock water intake for milk (L/d)	Indirectly impacts the radiation dose from the milk pathway.	2.42	9	0	3	7	19	3
Livestock intake of soil (kg/d)	Indirectly impacts the radiation doses from the meat and milk pathways.	9.15	9	0	3	6	18	3

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Mass loading for foliar deposition (g/m ³)	Affects the radionuclide concentrations in plants, including plant food for human and livestock.	1.45	1	0	3	7	11	3
Depth of soil mixing layer (m)	Used to account for redistribution of radionuclides in the surface soil. Affects the radionuclide concentrations in air from suspension, which then impact the plant concentration through dust deposition. When there is no cover material and thickness of the contaminated zone is greater than the mixing depth, no impact on radiation dose is observed.	20.01	1	0	3	5	9	2
Groundwater fractional usage for household water	Usually set to either 0 or 1.		1	9			> 10	3
Groundwater fractional usage for livestock water	Usually set to either 0 or 1.		1	9			> 10	3
Groundwater fractional usage for irrigation water	Usually set to either 0 or 1.		1	9			> 10	3
Groundwater fractional usage for drinking water	Usually set to either 0 or 1.		1	9			> 10	3
Depth of roots (m)	Affects the amount of radionuclides uptake by plant roots. Among the four mechanisms (root uptake, foliar deposition, overhead irrigation, and ditch irrigation) that cause plant contamination, root uptake is the most important one. Impacts doses from the plant, meat, and milk pathways.	253.37	1	0	1	3	5	1
Wet-weight crop yields for non-leafy vegetables (kg/m ²)	Affect radionuclide concentrations in plants. The larger the yield, the smaller the concentrations, and the smaller the ingestion doses.	12.58	1	0	3	5	9	2
Wet-weight crop yields for leafy vegetables (kg/m ²)		0.28	1	0	3	7	11	3
Wet-weight crop yields for fodder (kg/m ²)		1.04	1	0	3	7	11	3
Length of growing season for non-leafy vegetables (yr)	Used to account for decay of radionuclide concentrations in plants due to weathering during the growing season.	0.34	1	0	3	7	11	3
Length of growing season for leafy vegetables (yr)		0.81	1	0	3	7	11	3
Length of growing season for fodder (yr)		0.75	1	0	3	7	11	3
Translocation factor for non-leafy vegetables	Used to calculate radionuclide concentrations in plants through foliar deposition.	2.71	1	0	3	7	11	3
Translocation factor for leafy vegetables		1.32	1	0	3	7	11	3
Translocation factor for fodder		0.75	1	0	3	7	11	3
Weathering removal constant (1/yr)	Used to account for decay of radionuclide concentrations in plants due to weathering during the growing season.	6.11	1	0	3	6	10	2

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵					
Wet foliar interception fraction for non-leafy vegetables	Affect radionuclide concentrations in plants through the irrigation mechanism.	2.58	1	0	3	7	11	3
Wet foliar interception fraction for leafy vegetables		3.75	1	0	3	6	10	2
Wet foliar interception fraction for fodder		2.19	1	0	3	7	11	3
Dry foliar interception fraction for non-leafy vegetables	Affect radionuclide concentrations in plants through the foliar deposition mechanism.	0.42	1	0	3	7	11	3
Dry foliar interception fraction for leafy vegetables		0.66	1	0	3	7	11	3
Dry foliar interception fraction for fodder		0.06	1	0	3	7	11	3
Radon Parameters	Parameters affect the radon dose.							
Cover total porosity	Affect the flux of radon to the building and open atmosphere.		1	9			> 10	3
Cover volumetric water content			1	9			> 10	3
Cover radon diffusion coefficient (m ² /s)			1	9			> 10	3
Building foundation thickness (m)	Affect the flux of radon to the building and open atmosphere.		1	9			> 10	3
Building foundation density (g/cm ³)			1	9			> 10	3
Building foundation total porosity			1	9			> 10	3
Building foundation volumetric water content			1	9			> 10	3
Building foundation radon diffusion coefficient (m ² /s)			1	9			> 10	3
Contamination radon diffusion coefficient (m ² /s)	Affects the flux of radon to the building; however, its value can be calculated by using foundation depth and area of contaminated zone.		1	9			> 10	3
Building indoor area factor			1	9			> 10	3
Radon vertical dimension of mixing (m)			1	9			> 10	3
Building air exchange rate (1/h)	Determines the surface area available for radon diffusion to the indoor air.		1	9			> 10	3
Building height (m)			1	9			> 10	3
Foundation depth below ground surface (m)			1	9			> 10	3
Radon-222 emanation coefficient	Determines the amount of radon that escapes the soil particles and gets to the air.		1	9			> 10	3
Radon-220 emanation coefficient			1	9			> 10	3

Table 4.1 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
Storage Times for Fruits, Non-Leafy Vegetables, and Grain	Parameters affect the ingestion doses.		Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Storage times for fruits, non-leafy vegetables, and grain (d)	Used to account for radioactive decay during the food storage period. Affect the radiation doses for short-lived radionuclides.	0.26	5	0	3	7	15	3
Storage times for leafy vegetables (d)		0	5	0	3	7	15	3
Storage times for milk (d)		0	5	0	3	7	15	3
Storage times for meat (d)		0.02	5	0	3	7	15	3
Storage times for fish (d)		0	5	0	3	7	15	3
Storage times for crustacea and mollusks (d)		0	5	0	3	7	15	3
Storage times for well water (d)		0	5	0	3	7	15	3
Storage times for surface water (d)		0	5	0	3	7	15	3
Storage times for livestock fodder (d)		0	5	0	3	7	15	3
C-12 concentration in local water (g/cm ³)	Used to calculate C-14 flux to the air.	0.02	1	0	5	7	13	3
C-12 concentration in contamination soil (g/g)		1.37	1	0	3	7	11	3
Fraction of vegetation carbon absorbed from soil	Used to calculate C-14 concentration in plant food.	1.15	1	0	7	7	13	3
Fraction of vegetation carbon adsorbed from air		0.69	1	0	5	7	13	3
C-14 evasion layer thickness in soil (m)	Used to determine the extent of C-14 in the soil that evades to the air.	136.57	1	0	5	3	9	2
C-14 evasion flux rate from soil (l/s)	Used to calculate C-14 flux to the air.	5.16	1	0	5	6	12	3
C-12 evasion flux rate from soil (l/s)	Used to calculate C-14 flux to the air.	0	1	0	3	7	11	3
Grain fraction in livestock feed for beef cattle	Used to calculate C-14 concentration in fodder.	2.72	5	0	3	7	15	3
Grain fraction in livestock feed for milk cow		1.15	5	0	3	7	15	3

Table 4.1 (Continued)

Parameters Dose or Risk Conversion Factors	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵	Sum of Ranking Scores ⁶	Final Ranking ⁷
Inhalation dose conversion factors (mrem/pCi)	A fixed value should be used at the present time.		9	9			> 18	3
Ingestion dose conversion factors (mrem/pCi)			9	9			> 18	3
Slope factor - external [(risk/yr)/(pCi/g)]			9	9			> 18	3
Slope factor - inhalation (risk/pCi)			9	9			> 18	3
Slope factor - ingestion (risk/pCi)			9	9			> 18	3
Transfer Factors								
Transfer factors for plants	Impacts radiation doses for the plant, meat, and milk pathways.	480.55	1	0	3	2	6	1
Transfer factors for meat [(pCi/kg)/(pCi/d)]	Impacts radiation dose for the meat pathway.	101.22	1	0	3	3	7	2
Transfer factors for milk [(pCi/L)/(pCi/d)]	Impacts radiation dose for the milk pathway.	179.8	1	0	3	3	7	2
Bioaccumulation Factors								
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	Impacts radiation dose for the aquatic food pathway.	3.51	1	0	3	6	10	2
Bioaccumulation factors for crustacea and mollusks [(pCi/kg)/(pCi/L)]		0.49	1	0	3	7	11	3

¹ Values from prior dose variability analysis results; they correspond to the values for the "Max. NDD" in Table 3.1.

² 1 = Physical, 5 = Behavioral, 9 = Metabolic.

³ 0 = relevant, 9 = irrelevant

⁴ On a scale of 1 (known data availability) to 5 (little or no information).

⁵ On a scale of 1 (extremely sensitive) to 7 (insensitive), 1 for max. NDD > 1,000, 2 for max. NDD ≤ 1,000 and > 300, 3 for max. NDD ≤ 300 and > 100, 4 for max. NDD ≤ 100 and > 50, 5 for max. NDD ≤ 50 and > 10, 6 for max. NDD ≤ 10 and > 3, and 7 for max. NDD ≤ 3.

⁶ Type + Relevance + Data Availability + Dose Variability.

⁷ 1 = Sum is between 3-6, 2 = Sum is between 7-10, 3 = Sum is >10.

Table 4.2 Summary of the Overall Ranking Results for RESRAD

Priority 1	Priority 2	Priority 3
Distribution coefficient	Nuclide concentration	Number of unsaturated zone
Density of cover material	Area of contaminated zone	Time since placement of material
Density of contaminated zone	Thickness of contaminated zone	Groundwater concentration
Density of saturated zone	Length parallel to aquifer flow	Leach rate
Saturated zone total porosity	Cover depth	Solubility limit
Saturated zone effective porosity	Cover erosion rate	Use plant/soil ratio
Saturated zone hydraulic conductivity	Contaminated zone total porosity	Basic radiation dose limit
Unsaturated zone thickness	Contaminated zone erosion rate	Time for calculations
Depth of roots	Contaminated zone hydraulic conductivity	Contaminated zone field capacity
Transfer factors for plant	Contaminated zone b parameter	Humidity in air
	Evapotranspiration coefficient	Irrigation mode
	Wind speed	Irrigation rate
	Precipitation rate	Watershed area for nearby stream or pond
	Runoff coefficient	Accuracy for water soil computation
	Saturated zone hydraulic gradient	Saturated zone field capacity
	Saturated zone b parameter	Water table drop rate
	Well pump intake depth	Model: nondispersion or mass-balance
	Well pumping rate	Unsaturated zone field capacity
	Unsaturated zone density	Inhalation rate
	Unsaturated zone total porosity	Exposure duration
	Unsaturated effective porosity	Indoor time fraction
	Unsaturated zone soil-b parameter	Outdoor time fraction
	Unsaturated zone hydraulic conductivity	Shape of the contaminated zone (shape factor flag)
	Mass loading for inhalation	Leafy vegetable consumption
	Indoor dust filtration factor	Meat and poultry consumption
	External gamma shielding factor	Fish consumption
	Fruit, vegetables, and grain consumption	Other seafood consumption
	Milk consumption	Drinking water contaminated fraction
	Soil ingestion rate	Household water contaminated fraction
	Drinking water ingestion rate	Livestock water contaminated fraction
	Aquatic food contaminated fraction	Irrigation water contaminated fraction
	Depth of soil mixing layer	Plant food contaminated fraction
	Wet-weight crop yields for non-leafy vegetables	Meat contaminated fraction
	Weathering removal constant	Milk contaminated fraction
	Wet foliar interception fraction for leafy vegetables	Livestock water intake for meat
	C-14 evasion layer thickness in soil	Livestock fodder intake for meat
	Transfer factors for meat	Livestock fodder intake for milk
	Transfer factors for milk	Livestock water intake for milk
	Bioaccumulation factors for fish	Livestock intake of soil
		Mass loading for foliar deposition
		Groundwater fractional usage for household water
		Groundwater fractional usage for livestock water
		Groundwater fractional usage for irrigation water
		Groundwater fractional usage for drinking water
		Wet-weight crop yields for leafy vegetables
		Wet-weight crop yields for fodder
		Length of growing season for non-leafy vegetables
		Length of growing season for leafy vegetables
		Length of growing season for fodder
		Translocation factor for non-leafy vegetables
		Translocation factor for leafy vegetables
		Translocation factor for fodder
		Wet foliar interception fraction for non-leafy vegetables
		Wet foliar interception fraction for fodder
		Dry foliar interception fraction for non-leafy vegetables
		Dry foliar interception fraction for leafy vegetables
		Dry foliar interception fraction for fodder
		Cover total porosity
		Cover volumetric water content
		Cover radon diffusion coefficient
		Building foundation thickness
		Building foundation density
		Building foundation total porosity
		Building foundation volumetric water content
		Building foundation radon diffusion coefficient
		Contamination radon diffusion coefficient
		Building indoor area factor
		Radon vertical dimension of mixing
		Building air exchange rate

Table 4.2 (Continued)

Priority 1	Priority 2	Priority 3
		Building height Foundation depth below ground surface Radon-222 emanation coefficient Radon-220 emanation coefficient Storage times for fruits, non-leafy vegetables, and grain Storage times for leafy vegetables Storage times for milk Storage times for meat Storage times for fish Storage times for crustacea and mollusks Storage times for well water Storage times for surface water Storage times for livestock fodder C-12 concentration in local water C-12 concentration in contamination soil Fraction of vegetation carbon absorbed from soil Fraction of vegetation carbon adsorbed from air C-14 evasion flux rate from soil C-12 evasion flux rate from soil Grain fraction in livestock feed for beef cattle Grain fraction in livestock feed for milk cow Inhalation dose conversion factors Ingestion dose conversion factors Slope factor - inhalation Slope factor - ingestion Slope factors - external Bioaccumulation factors for crustacea and mollusks

Table 4.3 Overall Ranking Results for the RESRAD-BUILD Parameters

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
External dose conversion factor [(mrem/yr)/(pCi/g)]	A fixed value should be used.		9	9			> 18	3
Inhalation dose conversion factor (mrem/pCi)	A fixed value should be used.		9	9			> 18	3
Ingestion dose conversion factor (mrem/pCi)	A fixed value should be used.		9	9			> 18	3
Air submersion, dose conversion factor [(mrem/yr)/(pCi/m ³)]	A fixed value should be used.		9	9			> 18	3
Exposure duration (d)	For annual dose estimate, a value of 365, i.e., 1 year, should be used. The total time spent in the building can be varied by using the indoor time fraction parameter.		5	9			> 14	3
Number of evaluation times	Not used directly in dose calculations.		1	9			> 10	3
Time (yr)	Can be specified as any time less than 1,000 yr, the limit for D&D dose calculations.		1	9			> 10	3
Number of rooms	Not used directly in dose calculations. For sensitivity analyses, one-room model was considered.		1	9			> 10	3
Indoor fraction	Affects radiation doses for all pathways.	67.25	5	0	1	4	10	2
Deposition velocity (m/s)	Results in depletion of radionuclides from the air and increases the radionuclides deposited on the ground. Therefore, the larger the deposition velocity is, the smaller the inhalation and air immersion doses are and the larger the deposition and secondary ingestion doses are.	206.19	1	0	3	3	7	2
Resuspension rate (1/s)	Resuspension contributes to the air concentration and reduces the concentration on the ground. Increases inhalation dose and decreases secondary ingestion dose.	11969.23	1	0	1	1	3	1
Room height (m)	Used to determine the volume of the room, which is related to the dilution of airborne radionuclides. Indirectly affects the amount of radionuclides deposited on the floor.	83.09	1	0	5	4	10	2
Room area (m ²)	Used to determine the volume of the room, which is related to the dilution of airborne radionuclides. Affects the radionuclide concentrations on the floor and thereby affects the resuspension amount of radionuclides.	990	1	0	5	2	8	2
Air exchange rate for building and room (1/h)	Affects the air concentrations of radionuclides through the dilution factor.	390.57	5	0	1	2	8	2
Net flow (m ³ /h)	Not used in dose calculations for one-room model.		5	9			> 14	3
Outdoor inflow (m ³ /h)	Not used in dose calculations for one-room model.		1	9			> 10	3
Number of receptors	Assigning distribution is not appropriate.		1	9			> 10	3
Receptor room	Should be set to 1 for one-room model. Not appropriate to have a distribution.		1	9			> 10	3
Receptor time fraction	Usually set at 1.		1	9			> 10	3
Number of sources	Not appropriate to have a distribution.		1	9			> 10	3

Table 4.3 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Source type	Should use site-specific data. Not appropriate to have a distribution.		1	9			> 10	3
Source room or primary room	Should use site-specific data. Not appropriate to have a distribution.		1	9			> 10	3
Source direction	Should use site-specific data. Not appropriate to have a distribution.		1	9			> 10	3
Source location	Should use site-specific data. Not appropriate to have a distribution.		1	9			> 10	3
Receptor inhalation rate (m ³ /d)	Affects the inhalation dose directly.	99.19	5	0	1	4	10	2
Receptor location (m)	The relative location between the radiation source and the receptor determines the exposure distance and affects the external dose.	94.83	5	0	5	4	14	3
Receptor indirect ingestion rate (m ² /h)	Affects the ingestion dose through secondary ingestion.	3740	5	0	1	1	7	2
Source length or area (m or m ²)	Used to determine the amount of radionuclides in the source. Affects all the exposure pathways.	990	1	0	5	2	8	2
Air release fraction	Affects the airborne emission rate of radionuclides and the amount of radionuclides left in the source.	990	5	0	3	2	10	2
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	Affects the ingestion dose.	1143.09	5	0	3	1	9	2
Removable fraction	Affects the amount of radionuclides that is released to the air and the amount of radionuclides left in the source.	490.55	1	0	3	2	6	1
Time for source removal or source lifetime (d)	Affects the release rate of radionuclides to the air and the amount of radionuclides left in the source.	99	1	0	5	4	10	2
Radon release fraction	Affects radon doses.		1	9			> 10	3
Radionuclide concentration (pCi/g, pCi/m ³ , pCi/m, pCi)	Affects all the pathways. Site-specific data should be used.	990	1	0	5	2	8	2
Number of regions in volume source	Not appropriate to have a distribution.		1	9			> 10	3
Contaminated region - volume source	Not appropriate to have a distribution.		1	9			> 10	3
Source thickness, volume source (cm)	Used to estimate the amount of radionuclides in the source and set the upper limit for source erosion.	94.46	1	0	5	4	10	2
Source density, volume source (g/cm ³)	Used in determining the total amount of radionuclides in the source volume. Affects the external dose.	81.22	1	0	1	4	6	1
Source erosion rate, volume source (cm/d)	Determines the radionuclides emission rate, which affects the air concentrations and the source thickness over time.	9719.96	1	0	5	1	7	2
Shielding material	Affects the external radiation dose.		1	9	5		>15	3
Shielding thickness (cm)	Affects the external radiation dose.	97.93	1	0	5	4	10	2
Shielding density (g/cm ³)	Affects the external radiation dose.	187.47	1	0	1	3	5	1
Dry zone thickness (cm)	Increases the diffusion distance for tritiated water (HTO) vapor. Affects the inhalation dose.	41.89	1	0	5	5	11	3

Table 4.3 (Continued)

Parameters	Comments / Effects on Radiation Dose	Maximum of NDD ¹	Ranking Criteria				Sum of Ranking Scores ⁶	Final Ranking ⁷
			Type ²	Relevance ³	Data Availability ⁴	Dose Variability ⁵		
Wet + dry zone thickness (cm)	Used to consider the extent of tritium contamination over time. Affects mainly the inhalation dose.	102.7	1	0	5	3	9	2
Volumetric water content	Used in the H-3 model to estimate the air-filled porosity and the water-filled porosity in the contaminated material. The air-filled porosity affects the diffusivity of HTO, which then affects the tritium exposure. Affects the inhalation dose.	0.54	1	0	1	7	9	2
Water fraction available for evaporation	Affects the amount of HTO available for diffusion. Affects the inhalation dose.	100	1	0	5	4	10	2
Humidity (g/m3)	Affects the emission rate of moisture from the contaminated material, which then affects the emission rate of HTO. Affects the inhalation dose.	40.27	1	0	3	5	9	2
Source porosity	Affects the diffusivity of HTO, which then affects the airborne emission rate of HTO. Affects the inhalation dose.	4.05	1	0	1	6	8	2
Radon release fraction	Affect the radon dose.		1	9			>10	3
Radon effective diffusion coefficient (m ² /s)			1	9			>10	3
Radon emanation coefficient			1	9			>10	3

¹ Values from dose variability analysis results; they correspond to the values for the "Max. of NDD" in Table 3.3.

² 1 = Physical, 5 = Behavioral, 9 = Metabolic.

³ 0 = relevant, 9 = irrelevant.

⁴ On a scale of 1 (known data availability) to 5 (little or no information).

⁵ On a scale of 1 (extremely sensitive) to 7 (insensitive). 1 for max. NDD > 1,000, 2 for max. NDD ≤ 1,000 and > 300, 3 for max. NDD ≤ 300 and > 100, 4 for max. NDD ≤ 100 and > 50, 5 for max. NDD ≤ 50 and > 10, 6 for max. NDD ≤ 10 and > 3, and 7 for max. NDD ≤ 3.

⁶ Type + Relevance + Data Availability + Dose Variability.

⁷ 1 = Sum is between 3-6, 2 = Sum is between 7-10, 3 = Sum is >10.

Table 4.4 Summary of the Overall Ranking Results for RESRAD-BUILD

Priority 1	Priority 2	Priority 3
Resuspension rate	Indoor fraction	External dose conversion factor
Removable fraction	Deposition velocity	Inhalation dose conversion factor
Source density	Room height	Ingestion dose conversion factor
Shielding density	Room area	Air submersion dose conversion factor
	Air exchange rate for building and room	Exposure duration
	Receptor inhalation rate	Number of evaluation times
	Receptor indirect ingestion rate	Time
	Source length or area	Number of rooms
	Air release fraction	Net flow
	Direct ingestion rate	Outdoor inflow
	Time for source removal or source lifetime	Number of receptors
	Radionuclide concentration	Receptor room
	Source thickness	Receptor time fraction
	Source erosion rate	Number of sources
	Shielding thickness	Source type
	Wet + dry zone thickness	Source room or primary room
	Volumetric water content	Source direction
	Water fraction available for evaporation	Source location
	Humidity	Receptor location
	Source porosity	Number of regions in volume source
		Contaminated region - volume source
		Shielding material
		Dry zone thickness
		Radon release fraction
		Radon effective diffusion coefficient
		Radon emanation coefficient

Table A.1 Peak Radiation Doses for the Base Case¹ in the RESRAD Code

Radionuclide	Peak Dose Time (yr)	Doses for Water-Independent Pathways (mrem/yr) ²							Doses for Water-Dependent Pathways (mrem/yr) ²							Total Dose (mrem/yr)
		Ground	Inhalation	Radon	Plant	Meat	Milk	Soil	Water	Fish	Radon	Plant	Meat	Milk		
H-3	1.403	0.00E+00	1.24E-11	0.00E+00	4.37E-10	2.07E-10	9.69E-10	5.98E-14	2.42E-03	3.14E-07	0.00E+00	1.52E-04	1.46E-04	6.28E-04	3.35E-03	
C-14	123.900	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.50E-03	4.08E-02	0.00E+00	1.53E-03	2.53E-03	1.92E-03	5.33E-02	
Ca-45	0.000	1.51E-05	5.21E-08	0.00E+00	1.78E-02	4.56E-04	6.45E-03	2.25E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.47E-02	
Co-60	0.000	5.71E+00	3.18E-06	0.00E+00	4.46E-02	2.81E-02	1.57E-02	3.53E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.80E+00	
Sr-90	0.000	1.06E-02	1.97E-05	0.00E+00	9.87E-01	1.43E-01	2.54E-01	2.08E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.40E+00	
Cs-137	0.000	1.28E+00	4.63E-07	0.00E+00	4.16E-02	6.24E-02	8.07E-02	6.56E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E+00	
Ra-226	0.000	4.30E+00	1.39E-04	3.03E+01	1.21E+00	6.21E-02	2.90E-01	2.02E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.62E+01	
Ra-228	1.817	3.56E+00	2.59E-03	8.30E-02	9.67E-01	4.92E-02	2.31E-01	2.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.91E+00	
Th-230	70.800	7.00E-02	1.35E-03	4.31E-01	2.87E-02	2.67E-03	5.62E-03	3.01E-03	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.42E-01	
U-238	65.400	6.58E-12	1.58E-13	0.00E+00	2.76E-12	2.57E-13	5.29E-13	3.26E-13	1.60E+00	2.51E-03	0.00E+00	7.50E-02	5.37E-03	5.29E-02	1.74E+00	
Pu-239	138.000	7.41E-10	8.14E-09	0.00E+00	9.79E-08	1.43E-08	5.15E-10	6.06E-08	3.09E+00	1.32E-02	0.00E+00	1.45E-01	3.05E-03	1.70E-04	3.25E+00	
Am-241	0.000	1.95E-02	6.88E-03	0.00E+00	8.18E-02	5.96E-03	8.64E-04	5.09E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.66E-01	
Cf-252	0.000	6.86E-05	2.13E-03	0.00E+00	2.13E-02	1.86E-03	8.43E-05	1.33E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	3.87E-02	

¹ The base case considers a contaminated site with an area of 2,400 m², a contamination depth of 0.15 m, and a radionuclide concentration of 1pCi/g for each radionuclide.

² Values listed are radiation doses for the individual pathways and radionuclides observed at the time the peak total doses for the individual radionuclides occur.

³ Values listed are the peak total doses for each individual radionuclides.

Table A.2 Maximum Radiation Doses for the Base Case of Volume Contamination¹ in the RESRAD-BUILD Code

Radionuclide	Radiation Doses (mrem) for Individual Pathways						Total Dose (mrem)
	External	Deposition	Immersion	Inhalation	Radon	Ingestion	
H-3	0.00E+00	0.00E+00	0.00E+00	3.70E-03	0.00E+00	0.00E+00	3.70E-03
Co-60	2.49E+00	8.39E-07	2.92E-09	5.33E-07	0.00E+00	3.52E-07	2.49E+00
Sr-90	4.09E-03	9.52E-09	6.69E-12	4.64E-06	0.00E+00	2.99E-06	4.10E-03
Cs-137	5.81E-01	2.96E-07	9.26E-10	1.13E-07	0.00E+00	9.79E-07	5.81E-01
Ra-226	1.86E+00	9.86E-07	3.33E-09	3.50E-05	1.21E+00	3.10E-05	3.07E+00
Th-230	5.76E-04	1.04E-09	1.38E-12	1.28E-03	2.62E-04	1.19E-05	2.13E-03
U-238	2.22E-02	1.74E-08	5.13E-11	4.64E-04	1.60E-16	5.85E-06	2.26E-02
Pu-239	5.12E-05	7.93E-10	1.59E-13	1.69E-03	0.00E+00	7.70E-05	1.81E-03
Am-241	5.76E-03	2.37E-08	3.05E-11	1.73E-03	0.00E+00	7.85E-05	7.57E-03

¹ The base case considers a volume contamination source with an area of 36 m², a depth of 15 cm, and a radionuclide concentration of 1 pCi/g for each radionuclide.

Table A.3 Maximum Radiation Doses for the Base Case of Surface Contamination¹ in the RESRAD-BUILD Code

Radionuclide	Radiation Doses (mrem) of Individual Pathways						Total Dose (mrem)
	External	Deposition	Immersion	Inhalation	Radon	Ingestion	
Co-60	1.42E-05	3.99E-07	1.39E-09	2.53E-07	0.00E+00	1.67E-07	1.51E-05
Sr-90	1.14E-07	4.53E-09	3.18E-12	2.21E-06	0.00E+00	1.42E-06	3.75E-06
Cs-137	3.55E-06	1.41E-07	4.40E-10	5.40E-08	0.00E+00	4.66E-07	4.21E-06
Ra-226	1.08E-05	4.69E-07	1.58E-09	1.66E-05	1.51E-06	1.47E-05	4.42E-05
Th-230	1.13E-08	4.95E-10	6.54E-13	6.09E-04	6.55E-10	5.67E-06	6.15E-04
U-238	1.90E-07	8.27E-09	2.44E-11	2.21E-04	2.71E-21	2.78E-06	2.24E-04
Pu-239	8.72E-09	3.77E-10	7.57E-14	8.02E-04	0.00E+00	3.66E-05	8.38E-04
Am-241	2.59E-07	1.13E-08	1.45E-11	8.24E-04	0.00E+00	3.74E-05	8.61E-04

¹ The base case considers an area contamination source with an area of 36 m² and a radionuclide concentration of 1 pCi/m² for each radionuclide.

ATTACHMENT C

PARAMETER DISTRIBUTIONS FOR USE IN RESRAD AND RESRAD-BUILD COMPUTER CODES

Prepared by

B.M. Biwer, S. Kamboj, J.-J. Cheng, E. Gnanapragasam, C. Yu, J. Arnish,
D. LePoire, Y.-Y. Wang,* J.P. Butler, H. Hartmann, and S.Y. Chen
Environmental Assessment Division
Argonne National Laboratory

* Wang is affiliated with Information Technology, Sears, Roebuck and Co., Hoffman Estates, Illinois.

CONTENTS

ABBREVIATIONS AND ACRONYMS	xiii
1 INTRODUCTION	1-1
2 METHODOLOGY FOR PARAMETER DISTRIBUTION ASSIGNMENT	2-1
2.1 Selection of Parameters To Be Assigned Distributions	2-1
2.2 Parameters Not Assigned Distributions	2-2
2.3 Data Collection	2-2
2.4 Assignment of Parameter Distributions	2-2
2.4.1 Parameters with Well-Characterized Distributions	2-5
2.4.2 Parameters with Sufficient Data	2-5
2.4.3 Parameters with Some Data	2-5
2.4.4 Parameters with Insufficient Data	2-5
2.4.5 Multiple Distributions	2-6
2.4.6 Parameter Correlations	2-6
2.5 Presentation of Results	2-6
3 HYDROGEOLOGICAL PARAMETER DISTRIBUTIONS	3-1
3.1 Density of Soil	3-1
3.2 Total Porosity	3-5
3.3 Effective Porosity	3-8
3.4 Hydraulic Conductivity	3-11
3.5 Soil b Parameter	3-15
3.6 Hydraulic Gradient	3-18
3.7 Unsaturated Zone Thickness	3-21
3.8 Cover and Contaminated Zone Erosion Rate	3-25
3.9 Distribution Coefficients	3-29
3.10 Well Pumping Rate	3-38
3.11 Well Pump Intake Depth	3-40
3.12 Depth of Soil Mixing Layer	3-42
3.13 Cover Depth	3-44
4 METEOROLOGICAL PARAMETER DISTRIBUTIONS	4-1
4.1 Precipitation Rate	4-1
4.2 Runoff Coefficient	4-4
4.3 Evapotranspiration Coefficient	4-8
4.4 Humidity	4-10

CONTENTS (Cont.)

4.5	Wind Speed	4-13
4.6	Mass Loading for Inhalation	4-15
5	HUMAN INTAKE PARAMETER DISTRIBUTIONS	5-1
5.1	Inhalation Rate	5-1
5.2	Drinking Water Intake	5-6
5.3	Milk Consumption Rate	5-10
5.4	Fruit, Vegetable, and Grain Consumption Rate	5-13
5.5	Aquatic Food Contaminated Fraction	5-17
5.6	Soil Ingestion Rate	5-19
5.7	Direct Ingestion Rate	5-26
5.8	Indirect Ingestion Rate	5-27
6	CROPS AND LIVESTOCK PARAMETER DISTRIBUTIONS	6-1
6.1	Depth of Roots	6-1
6.2	Transfer Factors for Plants	6-4
6.3	Transfer Factors for Meat	6-7
6.4	Transfer Factors for Milk	6-10
6.5	Wet Weight Crop Yields for Nonleafy Vegetables	6-13
6.6	Weathering Removal Constant	6-15
6.7	Wet Foliar Interception Fraction for Leafy Vegetables	6-17
6.8	Bioaccumulation Factors for Fish	6-19
7	BUILDING CHARACTERISTICS PARAMETER DISTRIBUTIONS	7-1
7.1	Indoor Dust Filtration Factor	7-1
7.2	Resuspension Rate	7-5
7.3	Shielding Density	7-8
7.4	Air Exchange Rate for Building and Room	7-11
7.5	Deposition Velocity	7-18
7.6	Indoor Fraction	7-23
7.7	Room Area	7-29
7.8	Room Height	7-31
7.9	Shielding Thickness	7-33
7.10	External Gamma Shielding Factor	7-35

CONTENTS (Cont.)

8	SOURCE CHARACTERISTICS PARAMETER DISTRIBUTIONS	8-1
8.1	Source Density, Volume Source	8-1
8.2	Source Erosion Rate, Volume Source	8-4
8.3	Removable Fraction	8-6
8.4	Source Porosity	8-10
8.5	Volumetric Water Content	8-13
8.6	Air Release Fraction	8-14
8.7	Wet + Dry Zone Thickness	8-17
8.8	Time for Source Removal or Source Lifetime	8-20
8.9	Source Thickness, Volume Source	8-22
8.10	Water Fraction Available for Evaporation	8-24
8.11	C-14 Evasion Layer Thickness in Soil	8-27
9	REFERENCES	9-1
	APPENDIX A: Parametric Distribution Types	A-1

LIST OF FIGURES

3.1-1	Soil Density Probability Density Function for the Generic Soil Type	3-4
3.2-1	Total Porosity Probability Density Function for the Generic Soil Type	3-7
3.3-1	Effective Porosity Probability Density Function for the Generic Soil Type	3-10
3.4-1	Hydraulic Conductivity Probability Density Function for the Generic Soil Type	3-14
3.5-1	Soil-b Parameter Probability Density Function for the Generic Soil Type	3-17
3.6-1	Hydraulic Gradient Probability Density Function	3-20
3.7-1	Probability Density Function for Unsaturated Zone Thickness	3-24

LIST OF FIGURES (Cont.)

3.7-2	Cumulative Distribution Function for Unsaturated Zone Thickness	3-24
3.8-1	Cumulative Distribution for Input to RESRAD for Erosion Rate	3-28
3.11-1	Well Pump Intake Depth Probability Density Function	3-41
3.12-1	Depth of Soil Mixing Layer Probability Density Function	3-43
4.2-1	Runoff Coefficient Probability Density Function	4-7
4.3-1	Evapotranspiration Coefficient Probability Density Function	4-9
4.4-1	Absolute Humidity Probability Density Function for RESRAD-BUILD	4-12
4.4-2	Absolute Humidity Probability Density Function for RESRAD	4-12
4.5-1	Wind Speed Histogram and the Fitted Probability Density Function	4-14
4.6-1	Mass Loading Histogram and Cumulative Distribution Function	4-16
5.1-1	Inhalation Rate Probability Density Function for RESRAD	5-5
5.2-1	Drinking Water Intake Probability Density Function	5-9
5.3-1	Milk Consumption Rate Probability Density Function	5-12
5.4-1	Fruit, Vegetable, and Grain Consumption Rate Probability Density Function	5-16
5.5-1	Aquatic Food Contaminated Fraction Probability Density Function	5-18
5.6-1	Soil Ingestion Rate Probability Density Function	5-25
5.8-1	Indirect Ingestion Rate Probability Density Function	5-29
6.1-1	Depth of Roots Probability Density Function	6-3

LIST OF FIGURES (Cont.)

6.5-1	Wet Weight Crop Yields for Nonleafy Vegetables Probability Density Function	6-14
6.6-1	Weathering Removal Constant Probability Density Function	6-16
6.7-1	Wet Foliar Interception Fraction Probability Density Function	6-18
7.1-1	Indoor Dust Filtration Factor Probability Density Function	7-4
7.2-1	Indoor Resuspension Rate Probability Density Function	7-7
7.3-1	Concrete Shielding Density Probability Density Function	7-10
7.4-1	Building and Room Air Exchange Rate Probability Density Function	7-17
7.5-1	Idealized Representation of Indoor Particle Deposition Velocity	7-20
7.5-2	Trimodal Nature of Aerosol Particle Size Distribution	7-20
7.5-3	Indoor Deposition Velocity Probability Distribution	7-22
7.6-1	Indoor Fraction Cumulative Distribution Function for RESRAD-BUILD	7-26
7.6-2	Indoor Fraction Cumulative Distribution Function for RESRAD	7-28
7.7-1	Probability Density Function for Room Area	7-30
7.8-1	Room Height Probability Density Function	7-32
7.9-1	Shielding Thickness Probability Density Function	7-34
7.10-1	External Gamma Shielding Factor Probability Density Function	7-37
8.1-1	Concrete Source Density Probability Distribution Function	8-3
8.2-1	Source Erosion Rate Probability Density Function	8-5
8.3-1	Removable Fraction Probability Distribution	8-7

LIST OF FIGURES (Cont.)

8.4-1	Concrete Source Porosity Probability Density Function	8-12
8.6-1	Air Release Fraction Probability Density Function	8-16
8.7-1	Wet + Dry Zone Thickness Probability Density Function	8-19
8.8-1	Time for Source Removal or Source Lifetime Probability Density Function	8-21
8.9-1	Source Thickness Probability Density Function	8-23
8.10-1	Water Fraction Available for Evaporation	8-26
8.11-1	C-14 Evasion Layer Thickness in Soil Probability Density Function	8-28

LIST OF TABLES

2.1-1	Parameters Selected for Assignment of Probability Density Functions	2-3
2.4-1	Potential Correlations among RESRAD and RESRAD-BUILD Parameters Assigned Distributions	2-7
2.5-1	Comparison of Parameter Distribution Data Sources for RESRAD and RESRAD-BUILD with DandD	2-8
3.1-1	Normal Distribution Values for Dry Bulk Density by Soil Type	3-3
3.1-2	CONUS-SOIL Texture Summary	3-3
3.2-1	Normal Distribution Values for Total Porosity by Soil Type	3-6
3.3-1	Distribution Type and Parameters for Effective Porosity by Soil Type	3-9
3.4-1	Distribution Type and Parameter Values for Hydraulic Conductivity by Soil Type	3-13

LIST OF TABLES (Cont.)

3.5-1	Distribution Type and Parameter Values for Soil-b Parameter by Soil Type	3-16
3.6-1	Hydraulic Gradient for 12 Hydrogeologic Environments	3-19
3.7-1	Estimated Depth to Water at Gridded Sampling Locations	3-23
3.8-1	Cover and Contaminated Zone Erosion Rate Cumulative Distribution . . .	3-25
3.8-2	Annual Soil Loss from Land with Various Crops in Different Regions	3-27
3.8-3	Soil Erosion at a Site in Northeastern Oregon for Three Treatments	3-28
3.9-1	Lognormal Distribution Values for the K_d Parameter for Different Elements	3-30
3.9-2	Comparison of the Mean K_d Values from Table 3.9-1 with Those from Other Sources	3-34
3.9-3	Comparison of the Mean K_d Values from Table 3.9-1 with the Ranges of K_d Values from Other Sources	3-36
3.10-1	Example Calculations for Estimating the Well Pumping Rate	3-39
4.1-1	Precipitation Data for 273 U.S. Weather Recording Stations	4-2
4.2-1	Runoff Coefficient Values	4-5
4.2-2	SCS Runoff Curve Numbers for Average Antecedent Moisture Condition	4-6
4.6-1	Cumulative Distribution Function for Mass Loading for Inhalation	4-16
5.1-1	Inhalation Rate Distributions	5-2
5.1-2	Summary of EPA's Recommended Values for Inhalation	5-4
5.1-3	Recommended Default Inhalation Rates for the Residential Scenario	5-4

LIST OF TABLES (Cont.)

5.2-1	Drinking Water Intake Rate Distributions	5-7
5.2-2	Summary of Recommended Drinking Water Intake Rates	5-8
5.3-1	Mean per Capita Intake of Fresh Cow's Milk	5-11
5.3-2	Annual per Capita Consumption of Beverage Milk	5-11
5.4-1	Median per Capita Intake of Total Fruits, Vegetables, and Grains	5-15
5.4-2	Per Capita Consumption Values for Fresh Fruits, Fresh Vegetables, and Grains	5-15
5.6-1	Soil and Dust Ingestion Rate Distributions	5-20
5.6-2	Soil Ingestion Model Parameters for Various Lifestyle Scenarios	5-24
5.8-1	Indirect Ingestion Rates	5-28
6.1-1	Normal Root-Zone Depths of Mature, Irrigated Crops Grown in a Deep, Permeable, Well-Drained Soil	6-2
6.1-2	Range of Active Plant Rooting Depths	6-3
6.2-1	Lognormal Distribution Parameter Values for Plant/Soil Transfer Factors	6-5
6.3-1	Lognormal Distribution Parameter Values for the Transfer Factors for Meat	6-8
6.4-1	Lognormal Distribution Parameter Values for the Transfer Factors for Milk	6-11
6.8-1	Lognormal Distribution Parameter Values for Bioaccumulation Factors for Fish	6-21
7.1-1	Indoor/Outdoor Air Concentration Ratios	7-2
7.1-2	Fraction of Outdoor Particles Found Indoors at Equilibrium	7-3

LIST OF TABLES (Cont.)

7.2-1	Indoor Resuspension Rates	7-6
7.3-1	Density of Shielding Materials Allowed in RESRAD-BUILD	7-9
7.3-2	Concrete Density from Various Sources	7-9
7.4-1	Residential Air Exchange Rates Distribution Characteristics	7-12
7.4-2	Outside Air Exchange Rates for Commercial Buildings	7-15
7.5-1	Estimated Indoor Deposition Velocities by Particle Size	7-21
7.5-2	Estimated Deposition Velocities by Particle Size in Residences with and without Furniture	7-22
7.5-3	Estimated Indoor Deposition Velocities for Various Radionuclides	7-22
7.6-1	Cumulative Distribution Functions for the Indoor Fraction	7-23
7.6-2	Relative Frequency of Hours Worked by Persons Working 35 Hours or More per Week	7-24
7.6-3	Statistics for Fraction of Time Spent Indoors at Work	7-25
7.6-4	Statistics for Fraction of Time Spent Indoors in a Residence	7-27
7.8-1	Room Height in New Conventional and Manufactured Homes, 1996	7-32
7.10-1	External Shielding Factors	7-36
8.1-1	Density of Shielding Materials Allowed in RESRAD-BUILD	8-2
8.1-2	Concrete Density from Various Sources	8-2
8.3-1	Influence of Surface and Contaminant Types on Smear Tests	8-8
8.3-2	Percent Removal of Contamination for Different Sampling Methods	8-9

LIST OF TABLES (Cont.)

8.4-1	Bulk Density and Porosity of Rocks Commonly Used as Building Materials	8-11
A.1	Continuous Probability Density Distribution Functions	A-4

ABBREVIATIONS AND ACRONYMS

AIHC	American Industrial Health Council
AIRS	Aerometric Information Retrieval System
ANS	American Nuclear Society
ANSI	American National Standards Institute
ARF	airborne release fraction
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
BLS	Bureau of Labor Statistics
BNL	Brookhaven National Laboratory
BTM	best tracer method
CDF	cumulative distribution function
CFR	<i>Code of Federal Regulations</i>
CN	runoff curve number
CR	root uptake transfer factor
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
GIS	geographical information system
HT	tritium gas
HTO	tritiated water
HVAC	heating, ventilation, and air conditioning
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISO	International Organization for Standardization
K_d	distribution coefficient
LHS	Latin Hypercube Sampling
NAHB	National Association of Home Builders
NCDC	National Climatic Data Center
NCRP	National Council on Radiation Protection and Measurements
NFCS	National Food Consumption Survey
NRC	U.S. Nuclear Regulatory Commission
PFT	perfluorocarbon tracer
PM-10	particulates of less than or equal to 10 micrometers in diameter
PM-2.5	particulates of less than or equal to 2.5 micrometers in diameter
PTEAM	Particle Team (U.S. Environmental Protection Agency)
RF	respirable fraction
RH	relative humidity
SCS	Soil Conservation Service
TEDE	total effective dose equivalent
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project

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 standards (Subpart E to Title 10, *Code of Federal Regulations*, Part 20 [10 CFR Part 20]) and that risks to the exposed “critical group” of the public will be within prescribed limits (10 CFR 20.1402 and 20.1403) (NRC, 1998a,b).

The NRC has developed a generic modeling approach (presented in NUREG/CR-5512 [Kennedy and Strenge, 1992] and computerized in the DandD code [Wernig et al., undated]) to translate residual contamination levels into potential radiation doses to the public. In that approach, a multilevel screening process is used to assess potential radiation exposure to the public. Level 1 modeling uses generic screening factors. Level 2 modeling involves substitution of site-specific parameter values for some of the default values and elimination of irrelevant pathways to more closely approximate the exposure conditions at a specific site. Level 3 modeling involves using an even more site-specific approach that is not provided by the generic screening methods. The RESRAD (Yu et al., 1993a) and RESRAD-BUILD (Yu et al., 1994) computer codes are currently designed to address Level 2 and Level 3 objectives entailing site-specific analysis and can also be used for Level 1 screening calculations if a default data set is developed. These two codes have been developed by Argonne National Laboratory and approved by the U.S. Department of Energy (DOE) for use in evaluating radioactively contaminated sites and buildings, respectively, and are widely used in the United States and abroad. The RESRAD codes complement NRC's licensing efforts in developing methods for demonstrating compliance with decontamination and decommissioning rules.

Argonne was contracted by the NRC to evaluate the input parameters used in the RESRAD and RESRAD-BUILD dose calculations. The objective is to collect information and develop generic values for characterizing distributions of the input parameters so that distributions of the potential end doses can be better understood. The project was divided into several subtasks, with a deliverable to be produced under each subtask. The subtasks are (1) listing parameters and parameter types, (2) selecting parameters for detailed distribution analysis, (3) analyzing the selected parameters and developing distribution data, (4) analyzing distribution of the end doses by using distribution data developed for the parameters, (5) developing an interface module for the RESRAD and RESRAD-BUILD computer codes to perform uncertainty analysis on input parameters, (6) testing the two computer codes for the added capability, and (7) documenting project results.

In a previous letter report to the NRC on Subtask 1.1 (Kamboj et al., 1999)¹, all the input parameters used in the RESRAD and RESRAD-BUILD codes were listed, categorized, and defined. In Subtask 1.2 (Cheng et al., 1999)², a strategy was developed to rank the input parameters and identify parameters for detailed distribution analysis. This report documents the development of distribution data for the top-ranked (i.e., high- and medium-priority) parameters identified in Subtask 1.2. It is the third in a series of letter reports for the first four subtasks discussed above.

Development of distributions entailed data gathering and analysis. Relevant data were obtained from NRC-sponsored work and an extensive literature search using library and Internet resources. However, it is recognized that many of the parameters in question have not been well studied or can vary significantly from site to site or even within a site. Therefore, the focus of this initial work was to analyze the available data and to make the most plausible distribution assignments for each selected parameter for use in an initial round of dose calculations.

The effect of these parameter distributions on the distribution of estimated doses will be assessed in Subtask 1.4³. Parallel development of the probabilistic interface for the RESRAD and RESRAD-BUILD codes (Subtask 1.6)⁴ is underway, taking into account parameter correlations as they are identified. As experience is gained in the use of the parameter distributions and application of the codes to decontamination and decommissioning efforts, more information will become available for the future refinement of the parameter distributions. These refinements can be achieved, through an iterative process, by investigation of sensitivity and uncertainty when the codes are fully developed.

¹ This report is included as Attachment A of the main document.

² This report is included as Attachment B of the main document.

³ Refer to Kamboj et al., 2000 (NUREG/CR-6676, ANL/EAD/TM-89)

⁴ Refer to LePoire et al., 2000 (NUREG/CR-6692, ANL/EAD/TM-91)

2 METHODOLOGY FOR PARAMETER DISTRIBUTION ASSIGNMENT

The Subtask 1.2 letter report (Cheng et al., 1999) ranked the input parameters in the RESRAD and RESRAD-BUILD codes and set the priorities on the collection of parameter distribution data for Subtask 1.3 (the task reported here). Subtask 1.3 has assigned distributions to those parameters found to be most relevant to the NRC objective of showing compliance with the radiological criteria for decommissioning and license termination.

The generic screening approach is one method used for showing compliance (NUREG-1549). In that approach, the total effective dose equivalent (TEDE) to an average member of the critical group from exposure to residual radioactivity is estimated. The critical group refers to the group of persons most likely to receive the greatest exposure for a given scenario. For decommissioning and license termination, one of two scenarios is evaluated, depending on the nature of the contamination. One scenario involves surface contamination or thin layers of contamination within a structure (building scenario), and the other scenario involves residual radioactive contamination assumed to be in a surface layer in the soil (resident farmer scenario).

In the building occupancy scenario, an average member of the critical group is represented by a person who works in a commercial building following license termination. The average member of the critical group in the resident farmer scenario is represented by a person who lives on the site after license termination. That person grows some portion of his/her diet on the site and obtains some drinking water from an on-site well. Thus, input parameters to RESRAD-BUILD (building scenario) and RESRAD (resident farmer scenario) should be reflective of the appropriate scenario and critical group.

The parameter distributions assigned in this letter report were selected to be representative of adult male workers or farmers in generic site conditions that might be found on average throughout the United States. The detailed plan for selection of parameters, parameters not assigned distributions, data collection, and assignment of default distributions is discussed below.

2.1 Selection of Parameters To Be Assigned Distributions

In Subtask 1.2, parameters were ranked and placed in one of three priority categories — Priorities 1 through 3. Priority 1 was assigned to the most relevant (high priority) parameters and Priority 3 to the least relevant (low priority). Argonne and the NRC Dose Modeling Working Group agreed that Priority 3 parameters would be excluded from distribution analysis at the present time because parameters of this category had already

been determined to be of low priority and had insignificant impact on the overall results. This letter report for Subtask 1.3 includes the assignment of distributions to all Priority 1 and Priority 2 (i.e., medium priority) parameters. However, a few directly measurable, site-input parameters, such as nuclide concentration, area of contamination, and thickness of contaminated zone, will not be assigned distributions in the supplement. Table 2.1-1 lists the parameters considered.

2.2 Parameters Not Assigned Distributions

For those parameters not assigned distributions (i.e., Priority 3 parameters), the currently documented RESRAD and RESRAD-BUILD default, minimum, and maximum values were maintained except for applicable values that differed from the DandD code (Wernig et al., undated). For Subtask 1.4 probabilistic dose analysis, DandD input values were assigned to RESRAD and RESRAD-BUILD deterministic parameters where there was overlap between the RESRAD, RESRAD-BUILD, and DandD input parameters (Kamboj et al., 1999).

2.3 Data Collection

The most recent data were gathered for the selected input parameters. The starting point for this step was NUREG/CR-5512 and its supporting documents. Additional data on the selected parameters were collected through a search of available electronic databases (library and Internet resources). Only data provided directly from the NRC or obtained from readily available, citable, published sources were used. The assignment of parameter distributions was dependent on the quantity and quality of relevant data available in each case. The following section discusses the approach that was taken.

2.4 Assignment of Parameter Distributions

Assignment of an appropriate distribution to an input parameter was primarily determined by the quantity of relevant data available. The distribution assigned each parameter was as specific as the data warranted. Documented distributions were used where available. However, data are often lacking for environmental exposure pathways. Some parameters have adequate data that follow a general trend, thus allowing assignment of a distribution. For some other parameters, data are too sparse to define a distribution. As fewer data become available, secondary types of information must be used in conjunction with the existing sample data. For each assignment in this task, supporting evidence and reasoning are presented in conjunction with any limitations so that the user

Table 2.1-1 Parameters Selected (Priority 1 and 2) for Assignment of Probability Density Functions

Parameter	Priority ^a	Type ^b	Assigned Distribution Type	Report Section ^c
RESRAD-BUILD				
Removable fraction	1	P,B	Uniform	8.3
Resuspension rate (1/s)	1	P,B	Loguniform	7.2
Shielding density (g/cm ³)	1	P	Uniform	7.3
Source density, volume source (g/cm ³)	1	P	Uniform	8.1
Air exchange rate for building and room (1/h)	2	B	Lognormal	7.4
Air release fraction ^c	2	B	Triangular	8.6
Deposition velocity (m/s)	2	P	Loguniform	7.5
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	2	B	None recommended	5.7
Humidity (g/m ³)	2	P,B	Uniform	4.4
Indoor fraction	2	B	Empirical	7.6
Receptor indirect ingestion rate (m ² /h)	2	B	Loguniform	5.8
Receptor inhalation rate (m ³ /d)	2	M,B	Triangular	5.1
Room area (m ²)	2	P	Triangular	7.7
Room height (m)	2	P	Triangular	7.8
Shielding thickness (cm)	2	P,B	Triangular	7.9
Source erosion rate, volume source (cm/d)	2	P,B	Triangular	8.2
Source porosity	2	P	Uniform	8.4
Source thickness, volume source (cm)	2	P	Triangular	8.9
Time for source removal or source lifetime (d)	2	P,B	Triangular	8.8
Volumetric water content	2	P	Uniform	8.5
Water fraction available for evaporation	2	P	Triangular	8.10
Wet + dry zone thickness (cm)	2	P	Uniform	8.7
RESRAD				
Density of contaminated zone (g/cm ³)	1	P	Normal	3.1
Density of cover material (g/cm ³)	1	P	Normal	3.1
Density of saturated zone (g/m ³)	1	P	Normal	3.1
Depth of roots (m)	1	P	Uniform	6.1
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone)(cm ³ /g)	1	P	Lognormal	3.9
Saturated zone effective porosity	1	P	Normal	3.3
Saturated zone hydraulic conductivity (m/yr)	1	P	Lognormal	3.4
Saturated zone total porosity	1	P	Normal	3.2
Transfer factors for plants	1	P	Lognormal	6.2
Unsaturated zone thickness (m)	1	P	Lognormal	3.7
Aquatic food contaminated fraction	2	B,P	Triangular	5.5
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	2	P	Lognormal	6.8
C-14 evasion layer thickness in soil (m)	2	P	Triangular	8.11
Contaminated zone b parameter	2	P	Lognormal	3.5
Contaminated zone erosion rate (m/yr)	2	P,B	Empirical	3.8
Contaminated zone hydraulic conductivity (m/yr)	2	P	Lognormal	3.4
Contaminated zone total porosity	2	P	Normal	3.2
Cover depth (m)	2	P	None recommended	3.13
Cover erosion rate (m/yr)	2	P,B	Empirical	3.8
Depth of soil mixing layer (m)	2	P	Triangular	3.12

Table 2.1-1 (Cont.)

Parameter	Priority ^a	Type ^b	Assigned Distribution Type	Report Section ^c
Drinking water intake (L/yr)	2	M,B	Lognormal	5.2
Evapotranspiration coefficient	2	P	Uniform	4.3
External gamma shielding factor	2	P	Lognormal	7.10
Fruit, vegetables, and grain consumption (kg/yr)	2	M,B	Triangular	5.4
Indoor dust filtration factor	2	P,B	Uniform	7.1
Mass loading for inhalation ($\mu\text{g}/\text{m}^3$)	2	P,B	Empirical	4.6
Milk consumption (L/yr)	2	M,B	Triangular	5.3
Precipitation rate (m/yr)	2	P	None recommended	4.1
Runoff coefficient	2	P	Uniform	4.2
Saturated zone b parameter	2	P	Lognormal	3.5
Saturated zone hydraulic gradient	2	P	Lognormal	3.6
Soil ingestion rate (g/yr)	2	M,B	Triangular	5.6
Transfer factors for meat [(pCi/kg)/(pCi/d)]	2	P	Lognormal	6.3
Transfer factors for milk [(pCi/L)/(pCi/d)]	2	P	Lognormal	6.4
Unsaturated zone density (g/cm^3)	2	P	Normal	3.1
Unsaturated zone effective porosity	2	P	Normal	3.3
Unsaturated zone hydraulic conductivity (m/yr)	2	P	Lognormal	3.4
Unsaturated zone, soil-b parameter	2	P	Lognormal	3.5
Unsaturated zone total porosity	2	P	Normal	3.2
Weathering removal constant (1/yr)	2	P	Triangular	6.6
Well pumping rate (m^3/yr)	2	B,P	None recommended	3.10
Well pump intake depth (below water table) (m)	2	P	Triangular	3.11
Wet foliar interception fraction for leafy vegetables	2	P	Triangular	6.7
Wet-weight crop yields for nonleafy vegetables (kg/m^2)	2	P	Lognormal	6.5
Wind speed (m/s)	2	P	Lognormal	4.5
Humidity in air (g/m^3) ^d	3	P	Lognormal	4.4
Indoor fraction ^d	3	B	Empirical	7.6
Inhalation rate (m^3/yr) ^d	3	M,P	Triangular	5.1

^a Priority as determined in Cheng et al. (1999). For RESRAD, Priority 2 parameters exclude nuclide concentration, area of contamination, length parallel to aquifer flow, and thickness of contaminated zone. These parameters are directly measurable as input from a site, and no meaningful distributions can be developed. 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.

^d Priority 3 parameters with corresponding Priority 2 parameters in RESRAD-BUILD.

can understand the relevance of the assigned distribution. A number of distributions are necessarily broad because of the generic nature of the building occupancy and residential farmer scenarios. The following subsections describe the methodology used as the amount of available data becomes more limited.

2.4.1 Parameters with Well-Characterized Distributions

Empirical distributions were available for some parameters within the context of the critical group or national average. For those parameters for which additional sampling was not expected to significantly change the distribution's shape (i.e., the variability of the parameter is well represented), direct use of the statistical data was made. A user-specified continuous distribution was used as input to the Latin Hypercube Sampling (LHS) program.

2.4.2 Parameters with Sufficient Data

Sufficient relevant statistical data (data sets/matching function and parameter characteristics) were available for some parameters to clearly show a distribution type. If the use of an empirical distribution was not appropriate, the data were fit to the identified distribution. Goodness-of-fit may have been determined through the use of probability plots or other graphical representations.

2.4.3 Parameters with Some Data

Some parameters had some data available, but those data were not sufficient to define a distribution type. These parameters may have been assigned a distribution based on supporting information. If there was a mechanistic basis for assigning a given distribution to the data, such a distribution may have been used in the case of a sparse data set. In another case, surrogate data may have been used. If a distribution was well known for a parameter on a regional basis, the same distribution may have been used on a national basis. In either case, care must be taken to ensure that the existing data for the target scenario are complemented.

2.4.4 Parameters with Insufficient Data

In the case of a parameter for which a sufficient body of data was not available, an attempt was made to assign a distribution that fit a similar class of parameters or similar body of data. If an appropriate distribution was not found, a maximum entropy approach was used. In such a case, the distribution was restricted only by what was known.

Examples included the use of a uniform distribution if only potential lower and upper bounds were available, or the use of a triangular distribution if a most likely value was known in addition to potential lower and upper bounds.

2.4.5 Multiple Distributions

Some parameters can have more than one distribution assigned (e.g., hydraulic conductivity and total porosity can exhibit different distributions for different soil types).

2.4.6 Parameter Correlations

A few input parameters are clearly related, such as effective porosity and total porosity. Care was taken to ensure that consistent minimum and maximum distribution values were assigned in such cases. Such relationships were identified for later consideration when performing calculations and designing the LHS code interface in Subtasks 1.4 and 1.6, respectively. Table 2.4-1 lists the potential correlations among the RESRAD and RESRAD-BUILD parameters assigned distributions.

2.5 Presentation of Results

For presentation, the parameters for both RESRAD and RESRAD-BUILD were grouped into six categories according to their use in the exposure calculations. The assigned parameter distributions are presented in the following sections according to the following categories: hydrogeological (Section 3), meteorological (Section 4), human intake (Section 5), crops and livestock (Section 6), building characteristics (Section 7), and source characteristics (Section 8). The presentation of each parameter distribution identifies the code in which it is used and gives a brief description of the parameter, its units, its assigned distribution, and input data. Also presented is a discussion on the available data and the reasoning behind the distribution assignment made. The inputs for the assigned distributions are given following the requirements of the LHS code interface as shown in Table A.1 in Appendix A.

Previously, parameter distributions had been assigned for use in the probabilistic version of the DandD code currently under development for screening analysis (Beyeler et al., 1998a-b). Because a number of those parameters are also applicable to RESRAD and RESRAD-BUILD, those overlapping parameters assigned distributions in this report were generally assigned the same distributions as selected for use in DandD. Table 2.5-1 summarizes the data sources used for each parameter assigned a distribution in this report

Table 2.4-1 Potential Correlations among RESRAD and RESRAD-BUILD Parameters Assigned Distributions

Parameter	Correlated with	Positive/Negative Correlation
RESRAD		
Depth of roots	Precipitation rate	Negative
Distribution coefficients	Soil/plant transfer factors	Negative
Drinking water intake	Well pumping rate, milk consumption	Positive, negative
Effective porosity	Total porosity	Strong positive
Erosion rate	Wind speed, runoff coefficient, precipitation rate	Positive for all three
Evapotranspiration coefficient	Irrigation rate	Positive
Irrigation rate	Precipitation rate, well pumping rate, evapotranspiration coefficient	Strong negative, positive, positive
Precipitation rate	Irrigation rate, erosion rate, runoff coefficient, wet foliar interception fraction for leafy vegetables, depth of roots, soil ingestion rate	Strong negative, positive, positive, negative, negative, negative
Runoff coefficient	Erosion rate, precipitation rate	Positive for both
Soil density	Total porosity	Negative
Soil ingestion rate	Precipitation rate	Negative
Soil/plant transfer factors	Distribution coefficients	Negative
Total porosity	Soil density, effective porosity	Negative, strong positive
Well pumping rate	Drinking water intake, irrigation rate	Positive for both
Wind speed	Erosion rate	Positive
RESRAD-BUILD		
Air release fraction	Direct ingestion rate	Negative
Deposition velocity	Indirect ingestion rate, resuspension rate	Positive, positive
Direct ingestion rate	Source lifetime, indoor fraction, source erosion rate, air release fraction	Negative, positive, positive, negative
Indirect ingestion rate	Deposition velocity	Positive
Indoor fraction	Direct ingestion rate, source lifetime	Positive, negative
Resuspension rate	Deposition velocity	Positive
Source erosion rate	Direct ingestion rate	Positive
Source lifetime	Indoor fraction, direct ingestion rate	Negative, negative

Table 2.5-1 Comparison of Parameter Distribution Data Sources for RESRAD and RESRAD-BUILD with DandD^a

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Density of soil	3.1	Derived from porosities in Carsel and Parrish (1988) (total porosities listed below from NUREG/CR-6565)	Derived from porosity	Soil densities for the 12 USDA soil types used in RESRAD/RESRAD-BUILD and DandD are the same.	
Total porosity	3.2	Same as DandD for the 12 USDA soil classifications	NUREG/CR-6565		
Effective porosity	3.3	NUREG/CR-6565	Not applicable ^c		
Hydraulic conductivity	3.4	NUREG/CR-6565 (same as used in DandD to derive the infiltration rate for each of the 12 USDA soil types)	Not applicable, but used hydraulic conductivity from NUREG/CR-6565 to derive the infiltration rate		
Soil b parameter	3.5	NUREG/CR-6565 (same as used in DandD to derive the saturation ratio for each of the 12 USDA soil types)	Not applicable, but used the soil b parameter values from NUREG/CR-6565 to derive the saturation ratio		
Hydraulic gradient	3.6	Newell et al. (1989)	Not applicable		
Unsaturated zone thickness	3.7	Based on same data as DandD, lognormal fit to data in Beyeler et al. (1998b)	Empirical distribution based on data in Beyeler et al. (1998b)	A lognormal distribution gave a reasonable fit to the data. Further sampling would alter the empirical distribution and would be expected to fill in the gaps in the rather limited data set used.	
Cover and contaminated zone erosion rate	3.8	Pimental et al. (1976)	Not applicable		

Table 2.5-1 (Cont.)

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Distribution coefficients	3.9	Various references	Various references		Distributions obtained from fitting experimental data in Beyeler et al. (1998b) were given first consideration. Assignments by radionuclide were made by giving highest priority to field and laboratory measurements and then to correlations with root uptake factors.
Well pumping rate	3.10	No distribution recommended	Not applicable		
Well pump intake depth	3.11	Newell et al. (1989); Driscoll (1986); EPA (1975)	Not applicable		
Depth of soil mixing layer	3.12	Various references	Not applicable		
Cover depth	3.13	No distribution recommended, site-specific	Not applicable		
Precipitation rate	4.1	No distribution recommended	Empirical U.S. distribution (area weighted) used to develop irrigation rates		The analyst should use local data. There can be a wide disparity in rates within regional U.S. or state levels.
Runoff coefficient	4.2	Gilbert et al. (1989); NUREG/CR-6565	Not applicable		
Evapotranspiration coefficient	4.3	Palmer (1993)	Not applicable		
Humidity	4.4	RESRAD - NCDC (1999); Dean (1999) RESRAD-BUILD - Sterling et al. (1985)	Not applicable		
Wind speed	4.5	NCDC (1999)	Not applicable		
Mass loading for Inhalation	4.6	Used annual average PM-10 air concentrations from over 1,700 air monitoring stations (EPA, 1999b)	Various sources		The PM-10 air information used for RESRAD is the most recent and comprehensive data set directly applicable to the input parameter.

Table 2.5-1 (Cont.)

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Inhalation rate	5.1	RESRAD - Most likely value same as recommended for DandD RESRAD-BUILD - Most likely value same as recommended for DandD	Beyeler et al. (1998b) for the residential scenario; Beyeler et al. (1998a) for the building occupancy scenario		
Drinking water intake	5.2	Same as DandD	Lognormal distribution for adults in Roseberry and Burmaster (1992)		
Milk consumption rate	5.3	EPA (1997), most likely value of 102 L/yr	NUREG/CR-5512 Draft Vol.2 cites 233 kg/yr (Table D.5) and references Vol.1 (Table 6.23) which lists 100 L/yr		The milk consumption information used for RESRAD is the most recent and comprehensive data set directly applicable to the input parameter.
Fruit, vegetable, and grain consumption rate	5.4	EPA (1997); Putnam (1999)	Not directly applicable, has separate categories for food ingestion		
Aquatic food contaminated fraction	5.5	EPA (1997), assumes most likely value of 0.39	Assumes a value of 1		The RESRAD value was chosen in an effort to remove the conservatism associated with the arbitrary assumption of 1 for the value.
Soil ingestion rate	5.6	Same as DandD	Beyeler et al. (1998b)		
Direct ingestion rate	5.7	None recommended	Not applicable		
Indirect ingestion rate	5.8	Same as DandD, uses the lower estimate in Beyeler et al. (1998a)	Beyeler et al. (1998a)		
Depth of roots	6.1	Various sources	Not applicable		
Transfer factors for plants	6.2	Primarily NCRP (1999); Yu et al. (1993a)	Not applicable, has separate groupings for plants		

Table 2.5-1 (Cont.)

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Transfer factors for meat	6.3	Primarily NCRP (1999); Hoffman et al. (1982)	NUREG/CR-5512 (Kennedy and Streng, 1992)		The transfer factor information used for RESRAD is the most recent and widely accepted data set.
Transfer factors for milk	6.4	Primarily NCRP (1999); Hoffman et al. (1982)	NUREG/CR-5512 (Kennedy and Streng, 1992)		The transfer factor information used for RESRAD is the most recent and widely accepted data set.
Wet weight crop yields for nonleafy vegetables	6.5	USDA (1999)	NUREG/CR-5512 (Kennedy and Streng, 1992)		The crop yields information used for RESRAD is the most recent and comprehensive data set directly applicable to the input parameter.
Weathering removal constant	6.6	NUREG/CR-6523 (Brown et al., 1997)	Not applicable		
Wet foliar interception fraction for leafy vegetables	6.7	NUREG/CR-6523 (Brown et al., 1997)	NUREG/CR-5512 (Kennedy and Streng, 1992)		The wet foliar interception fraction for leafy vegetables in RESRAD uses values based on recent expert opinions (Brown et al., 1997).
Bioaccumulation factors for fish	6.8	Wang et al. (1993); NCRP (1996)	NUREG/CR-5512 (Kennedy and Streng, 1992)		The fish bioaccumulation factor information used for RESRAD is a more recent data set.
Indoor dust filtration factor	7.1	Wallace (1996)	Not applicable		
Resuspension rate (indoor)	7.2	Data cited in Healy (1971) and Thatcher and Layton (1995); most rates in Healy (1971) were derived from resuspension factors (most of which were used in Beyeler et al. [1998a])	Not applicable, uses resuspension factors		
Shielding density	7.3	Various sources for concrete	Not applicable		
Air exchange rate for building and room	7.4	Turk et al. (1987)	Not applicable		
Deposition velocity (indoor)	7.5	Various sources	Not applicable		

Table 2.5-1 (Cont.)

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Indoor fraction	7.6	RESRAD - EPA (1997), same as DandD RESRAD-BUILD - EPA (1997)	Beyeler et al. (1998b) for the residential farmer scenario (used same source of data as used in EPA [1997]); Beyeler et al. (1998a) for the building occupancy scenario;		A large, consistent set of data for adults at both residences and at work was used for RESRAD and RESRAD-BUILD.
Room area	7.7	Professional judgment	Not applicable		
Room height	7.8	EPA (1997); NAHB (1998)	Not applicable		
Shielding thickness	7.9	Ayers et al. (1999)	Not applicable		
External gamma shielding factor	7.10	Derived using statistics on current construction practices (Dept. of Housing and Urban Development, 1996,1999)	Beyeler et al. (1998b), derived shielding factors for three different floor types (non-continuous distribution)		In light of the range in floor and wall materials and thicknesses, a continuous distribution attempting to represent this variability was considered the best approach for RESRAD.
Source density, volume source	8.1	Various sources for concrete	Not applicable		
Source erosion rate, volume source	8.2	Based on conservative assumptions	Not applicable		
Removable fraction	8.3	DOE (1994a); NRC (1974)	Assumed value of 10%		Most likely value for RESRAD-BUILD (20%) based on maximum allowed removable concentration limits.
Source porosity	8.4	Various sources for concrete	Not applicable		
Volumetric water content	8.5	Various sources for concrete	Not applicable		
Air release fraction	8.6	DOE (1994b)	Not applicable		
Wet + dry zone thickness	8.7	Based on various sources with data for concrete	Not applicable		

Table 2.5-1 (Cont.)

Parameter	Section ^b	Data Source			Comment
		RESRAD / RESRAD-BUILD	DandD		
Time for source removal or source lifetime	8.8	Derived from data in ANS (1998)	Not applicable		
Source thickness, volume source	8.9	Ayers et al. (1999)	Not applicable		
Water fraction available for evaporation	8.10	Various sources	Not applicable		
C-14 evasion layer thickness in soil	8.11	Sheppard et al. (1991); Amiro et al. (1991)	Not applicable		

^a For parameters selected for distributional analysis.

^b Reference to section in this report in which the specific parameter is discussed.

^c Not applicable; a direct correlation between model parameters in DandD and RESRAD or RESRAD-BUILD does not exist.

and the corresponding data source, if applicable, used for DandD input. If a parameter common to RESRAD/RESRAD-BUILD and DandD was assigned a distribution in this report different from that assigned for DandD, the reason for the difference is listed in the "Comment" column of Table 2.5-1.

3 HYDROGEOLOGICAL PARAMETER DISTRIBUTIONS

3.1 Density of Soil

Applicable Code: RESRAD

Description: RESRAD uses the dry bulk density values for five distinct materials (cover layer, contaminated zone, unsaturated and saturated zones, and building foundation material). The soil bulk, or dry, density is the ratio of the mass of soil in the solid phase (i.e., dried soil) to its total volume, including solid and pore volumes together.

Units: grams per cubic centimeter (g/cm³)

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

Mean value:	1.52	Lower quantile value:	0.001
Standard deviation:	0.230	Upper quantile value:	0.999

Discussion: Characteristics of the contaminated, unsaturated, and saturated zone are represented by several parameters, such as dry bulk density, total porosity, effective porosity, hydraulic conductivity, and others. These properties depend on the particle size distribution of the soil. Because the U.S. Department of Agriculture (USDA) soil texture classification is also based on the relative proportions of the different particle size classes, probability distributions for each of the parameters can be developed for each of the soil classes. These class-specific probability distributions of parameters for soil texture are more compact and relevant for each class of soil than an overall distribution encompassing all types of soils.

The dry bulk density, ρ_b , is related to the soil particle density, ρ_s , by the total soil porosity, p_t , according to the following equation:

$$\rho_b = (1 - p_t) \rho_s \quad (3.1-1)$$

From the above definition, it is obvious that the value of the dry bulk density is always smaller than the value of the soil particle density. The soil particle density represents the density of the soil particles collectively and is expressed as the ratio of the solid phase mass to the volume of the solid phase of the soil. In most mineral soils, the soil

particle density has a narrow range of 2.6 to 2.7 g/cm³ (Hillel, 1980). This density is close to that of quartz, which is usually the predominant constituent of sandy soils. Aluminosilicate clay minerals have particle density variations in the same range. The presence of iron oxides and other heavy minerals increases the value of the soil particle density. The presence of solid organic materials in the soil decreases the density. A typical value of 2.65 g/cm³ has been suggested to characterize the soil particle density of a general mineral soil (Freeze and Cherry, 1979; Beyeler et al., 1998b). With that, the bulk density becomes:

$$\rho_b = (1 - p_t) * 2.65 \quad . \quad (3.1-2)$$

The density of cover material affects the degree of attenuation to the external radiation dose contributed by the cover material. The density of the contaminated zone determines the total mass of soil within a specified source volume. Because the radionuclide concentrations are specified in units of picocuries per gram (pCi/g), the density also determines the total amount of radionuclides within the volume. It is used to calculate the leach rate of radionuclides. Thus, the density has the potential of affecting all pathways. The dry bulk density of the unsaturated zone, along with other parameters, is used to calculate the breakthrough time for a radionuclide. (The “breakthrough time” is the time required for a material to reach the saturated zone.) The dry bulk density of the saturated zone, along with other parameters, is used to calculate the time required for contaminants to travel from the upgradient edge to the downgradient edge of the saturated zone.

Using data on bulk density, sand, and clay contents from a database compiled from soil survey information for 42 states, Carsel and Parrish (1988) inferred the saturated water content and reported the descriptive statistics for each of the 12 USDA soil classes. Meyer et al. (1997) report that the saturated water contents are normally distributed. The distributions suggested here (Table 3.1-1) were computed by first assuming that the total porosity is equal to the saturated water content and then applying Equation 3.1-2.

The distribution to be used for cases in a generic setting was obtained as the weighted average of the distributions for the individual soil classes. In examining the CONUS-SOIL database, Beyeler et al. (1998b) found that approximately 85% of the area covered by materials with USDA classified soil textures is a consistent texture for the three uppermost layers (down to a depth of 20 cm). Volume-weighted percentages of each of the 12 USDA soil textures were derived on the basis of areal distributions of the textures of the three uppermost CONUS-SOIL database layers. These percentages, as shown in Table 3.1-2, were used to derive a soil density distribution for the generic soil type in RESRAD. Note that the resulting distribution should be replaced by site-specific data when available. The likelihood of occurrence to be used is only valid to the depth (0.2 m) examined by Beyeler et al. (1998b). The actual contaminated soil depths considered under

Table 3.1-1 Normal Distribution Values for Dry Bulk Density by Soil Type

Soil Type	Density (g/cm ³)			
	Mean	Standard Deviation	Lower Limit	Upper Limit
Sand	1.5105	0.159	1.019	2.002
Loamy sand	1.5635	0.2385	0.827	2.3
Sandy loam	1.5635	0.2385	0.827	2.3
Sandy clay loam	1.6165	0.1855	1.043	2.19
Loam	1.5105	0.265	0.692	2.329
Silt loam	1.4575	0.212	0.802	2.113
Silt	1.431	0.2915	0.53	2.332
Clay loam	1.5635	0.2385	0.827	2.3
Silty clay loam	1.5105	0.1855	0.937	2.084
Sandy clay	1.643	0.1325	1.234	2.052
Silty clay	1.696	0.1855	1.123	2.269
Clay	1.643	0.2385	0.906	2.38
Generic soil type ^a	1.52	0.230	0.8136	2.234

^a Parameters for the generic soil type are derived from the distribution enveloping all soil types. The lower and upper limits correspond to the 0.001 and 0.999 quantile values, respectively.

Source: Derived from porosity values listed in Carsel and Parrish (1988).

Table 3.1-2 CONUS-SOIL Texture Summary

USDA Soil Texture	Layer 1 [0-5 cm] (% of area)	Layer 2 [5-10 cm] (% of area)	Layer 3 [10-20 cm] (% of area)	Volume Weighed % of 0-20 cm
Silt	0.005	0.005	0.015	0.01
Sandy clay	0.000	0.065	0.216	0.124
Sandy clay loam	0.398	0.650	1.323	0.923
Silty clay	1.569	1.623	1.316	1.456
Loamy sand	3.822	3.719	3.540	3.655
Clay	3.525	3.845	5.766	4.726
Clay loam	4.385	4.706	6.003	5.274
Silty clay loam	4.578	4.734	5.407	5.032
Sand	7.267	7.188	7.385	7.306
Sandy loam	23.541	22.673	21.792	22.450
Silt loam	25.339	25.336	24.424	24.881
Loam	25.571	25.456	22.813	24.163

Source: Beyeler et al. (1998b).

remedial actions can easily reach depths greater than 10 m. The CONUS-SOIL database itself only contains data for depths of 2.5 m or less. The probability density function of the weighted average was plotted, and the parameters of the normal distribution were chosen to represent the weighted average curve over the range of interest.

To be the most representative of sites across the United States, the default distribution in RESRAD is that for the generic soil type. Its probability density function is shown in Figure 3.1-1. When a site-specific analysis is being conducted, the distribution for the soil type present at the site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: effective porosity, total porosity, hydraulic conductivity, and the soil b parameter.

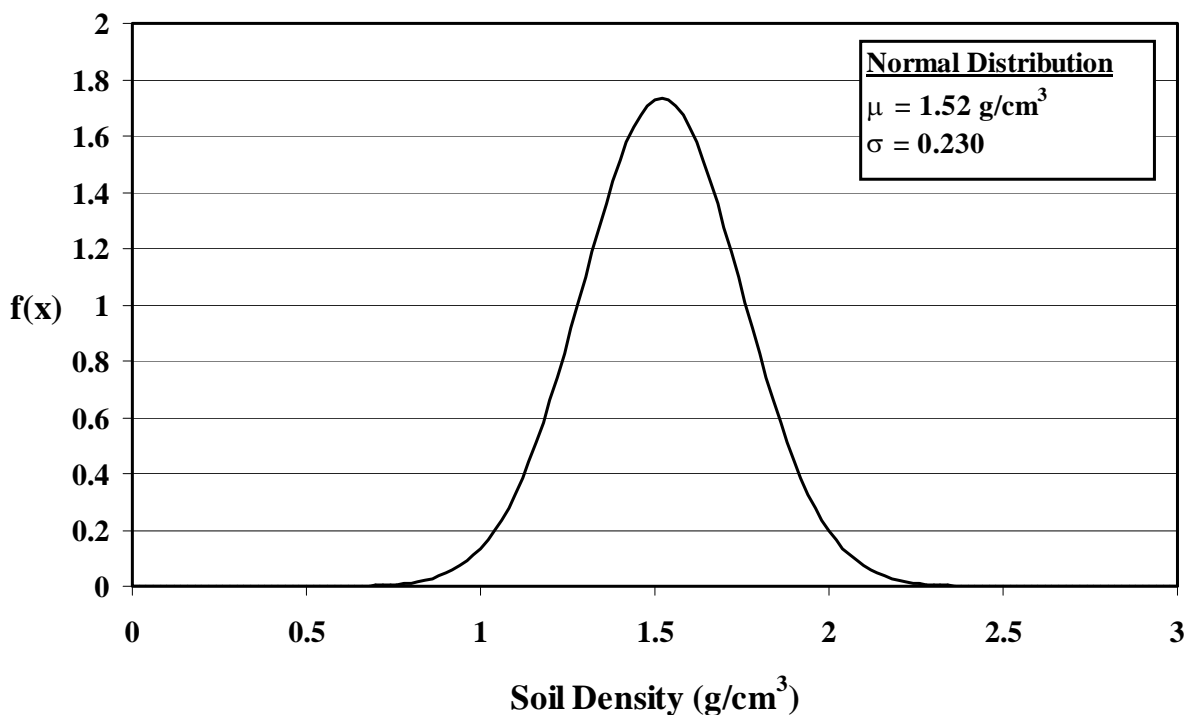


Figure 3.1-1 Soil Density Probability Density Function for the Generic Soil Type

3.2 Total Porosity

Applicable Code: RESRAD

Description: The total porosity of a porous medium is the ratio of the pore volume to the total volume for a representative sample of the medium. Separate input values are required for the contaminated, saturated, and unsaturated zones.

Units: unitless

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

Mean value:	0.425	Lower quantile value:	0.001
Standard deviation:	0.0867	Upper quantile value:	0.999

Discussion: Total porosity is one of the many parameters characterizing the contaminated, unsaturated, and saturated zones (see Section 3.1). This parameter can be calculated in the following manner. Assuming that the soil system is composed of three phases – solid, liquid (water), and gas (air) – where V_s is the volume of the solid phase, V_l is the volume of the liquid phase, V_g is the volume of the gaseous phase, $V_p = V_l + V_g$ is the volume of the pores, and $V_t = V_s + V_l + V_g$ is the total volume of the sample, then the total porosity of the soil sample, p_t , is defined as:

$$p_t = \frac{V_p}{V_t} = \frac{V_l + V_g}{V_s + V_l + V_g} \quad (3.2-1)$$

The total porosity value is used along with the saturation ratio in determining the moisture content in soil, which in turn is used to determine the retardation factor and the transport speed of water in the contaminated zone. In the unsaturated zone, the total porosity value is used to calculate the breakthrough time. In the saturated zone, it is used to calculate the time required for radionuclides to move with groundwater from the upgradient edge to the downgradient edge of the contaminated zone.

Table 3.2-1 lists the distribution of porosities (assumed to be equivalent to saturated water content) for different USDA soil classifications. The values in the table are taken from Carsel and Parish (1988) and are the same values suggested by Beyeler et al. (1998b). Carsel and Parish (1988) inferred the saturated water content from the data on bulk density and reported the descriptive statistics for each of the 12 USDA soil

Table 3.2-1 Normal Distribution Values for Total Porosity by Soil Type

Soil Type	Mean	Standard Deviation	Lower Limit	Upper Limit	Number of Sampling Locations
Sand	0.43	0.06	0.2446	0.6154	246
Loamy sand	0.41	0.09	0.1319	0.6881	315
Sandy loam	0.41	0.0899	0.1322	0.6878	1183
Sandy clay loam	0.39	0.07	0.1737	0.6063	214
Loam	0.43	0.0998	0.1216	0.7398	735
Silt loam	0.45	0.08	0.2028	0.6972	1093
Silt	0.46	0.11	0.1161	0.7959	82
Clay loam	0.41	0.09	0.1319	0.6881	364
Silty clay loam	0.43	0.0699	0.214	0.646	641
Sandy clay	0.38	0.05	0.2255	0.5345	46
Silty clay	0.36	0.07	0.144	0.576	374
Clay	0.38	0.09	0.1019	0.6581	400
Generic soil type ^a	0.425	0.0867	0.157	0.693	5693

^a Values for the generic soil type were derived from the distribution enveloping all soil types. The lower and upper limits correspond to the 0.001 and 0.999 quantile values, respectively.

Source: Beyeler et al. (1998); Carsel and Parrish (1988).

classes. Meyer et al. (1997) report that the saturated water contents are normally distributed and that the distributions are applicable to total porosity.

The Penn State University's Web site (http://www.essc.psu.edu/soil_info) maintains porosity data for each standard layer of each map unit for the conterminous United States. The map units have been gridded at a cell size of 1 km. The porosity data are available in several formats to accommodate users with a variety of geographical information system (GIS) software.

The distribution to be used when the type of soil is not known (the selected default for RESRAD) was calculated as the weighted average of the distributions for the individual soil classes. The same weighting factor scheme as discussed for the generic soil type in Section 3.1 was used. The probability density function of the weight average was plotted, and the parameters of the normal distribution were chosen to represent the weighted average curve over the range of interest. Figure 3.2-1 displays the probability density function for total porosity for this generic soil type. When a site-specific analysis is conducted, the distribution for the soil type present at the site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: soil density, effective porosity, hydraulic conductivity, and the soil b parameter.

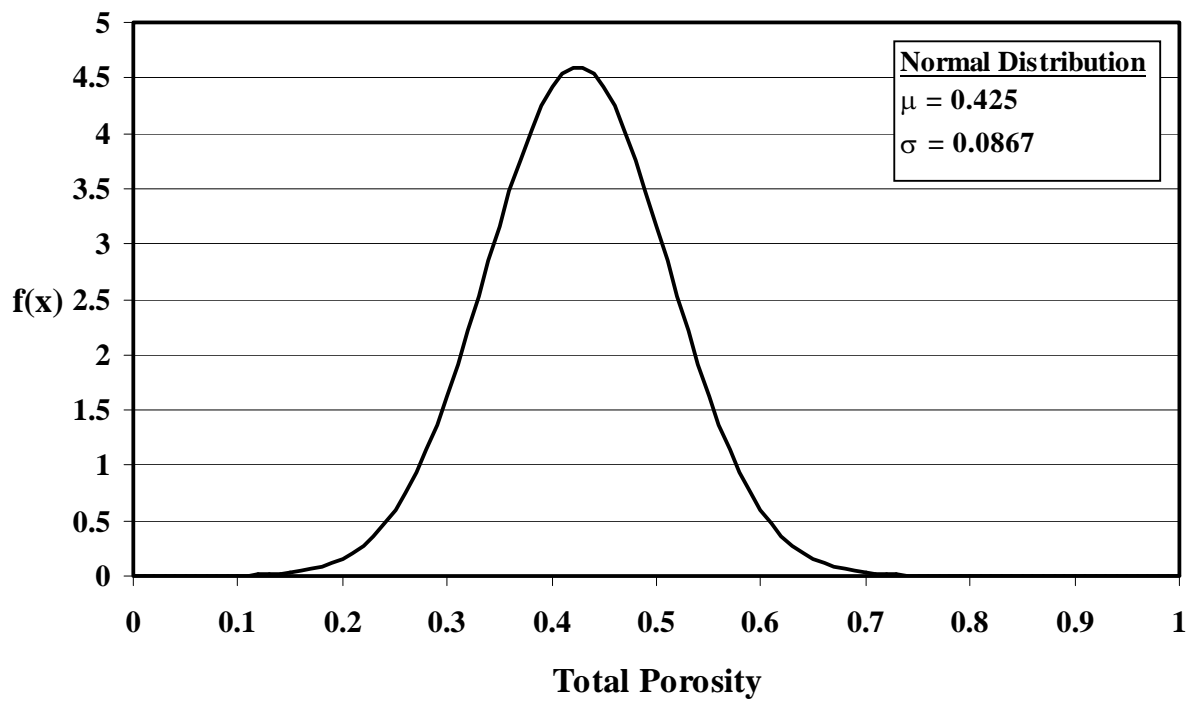


Figure 3.2-1 Total Porosity Probability Density Function for the Generic Soil Type

3.3 Effective Porosity

Applicable Code: RESRAD

Description: The effective porosity (also called the kinematic porosity) of a porous medium is defined as the ratio of the part of the pore volume where the water can circulate to the total volume of the representative sample of the medium. Separate effective porosity input values for the unsaturated and saturated zones are required in RESRAD.

Units: unitless

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

Mean value:	0.355	Lower quantile value:	0.001
Standard deviation:	0.0906	Upper quantile value:	0.999

Discussion: Effective porosity is one of the several soil parameters used to calculate the breakthrough time in the unsaturated zone. In the saturated zone, it is used to calculate the rise time (i.e., the time required to transport groundwater from the upgradient edge to the downgradient edge of the saturated zone). Several aspects of the soil system influence the value of its effective porosity: (1) the adhesion of water on minerals, (2) the absorption of water in the clay-mineral lattice, (3) the existence of unconnected pores, and (4) the existence of dead-end pores (Yu et al., 1993b).

The effective soil porosity, p_e , is related to the specific retention, θ_r , irreducible volumetric water content, or residual water content, and the total porosity, p_t , according to the following expression (Meyer et al., 1997):

$$p_e = p_t - \theta_r. \quad (3.3-1)$$

Carsel and Parrish (1988) used data on bulk density to infer the saturated water content. They then applied the data on sand and clay contents and the inferred saturated water content to the multiple regression model developed by Rawls and Brakensiek (1985) to generate estimates of residual water content for the 12 USDA soil textural classifications. The estimates were fitted by either a normal distribution or a transformed normal distribution by using methods in Johnson (1987) and Johnson and Kotz (1970). Meyer et al. (1997) then used the data generated by Carsel and Parrish (1988) for saturated

water content and residual water content to develop distributions for effective porosity by subtraction. Table 3.3-1 gives the distributions and the defining parameters for effective porosity for the 12 soil textural classes and for the generic soil type.

The distribution to be used for cases when the type of soil is not known (the RESRAD default distribution) was obtained as the weighted average of the distributions for the individual soil classes. The same weighting factor scheme as discussed for the generic soil type in Section 3.1 was used. The probability density function of the weight average was plotted, and the parameters of the normal distribution were chosen to represent the weighted average curve over the range of interest. The probability density function for the effective porosity for this generic soil type is shown in Figure 3.3-1. When a site-specific analysis is being conducted, the distribution for the soil type present at the site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: soil density, total porosity, hydraulic conductivity, and the soil b parameter.

Table 3.3-1 Distribution Type and Parameters for Effective Porosity by Soil Type

Soil Type	Distribution	Mean	Standard Deviation	Lower Limit	Upper Limit
Sand	Normal	0.383	0.0610	0.195	0.572
Loamy sand	Normal	0.353	0.0913	0.0711	0.635
Sandy loam	Normal	0.346	0.0915	0.0629	0.628
Sandy clay loam	Normal	0.289	0.0703	0.0723	0.507
Loam	Normal	0.352	0.101	0.0414	0.663
Silt loam	Normal	0.383	0.0813	0.132	0.634
Silt	Normal	0.425	0.110	0.0839	0.766
Clay loam	Normal	0.315	0.0905	0.0349	0.594
Silty clay loam	Normal	0.342	0.0705	0.124	0.560
Sandy clay	Normal	0.281	0.0513	0.122	0.439
Silty clay	Normal	0.289	0.0735	0.0623	0.517
Clay	Normal	0.311	0.0963	0.0138	0.609
Generic soil type ^a	Normal	0.355	0.0906	0.075	0.635

^a Parameters for the generic soil type were derived from the distribution enveloping all soil types. The lower and upper limits correspond to the 0.001 and 0.999 quantile values, respectively.

Sources: Carsel and Parrish (1988); Meyer et al. (1997).

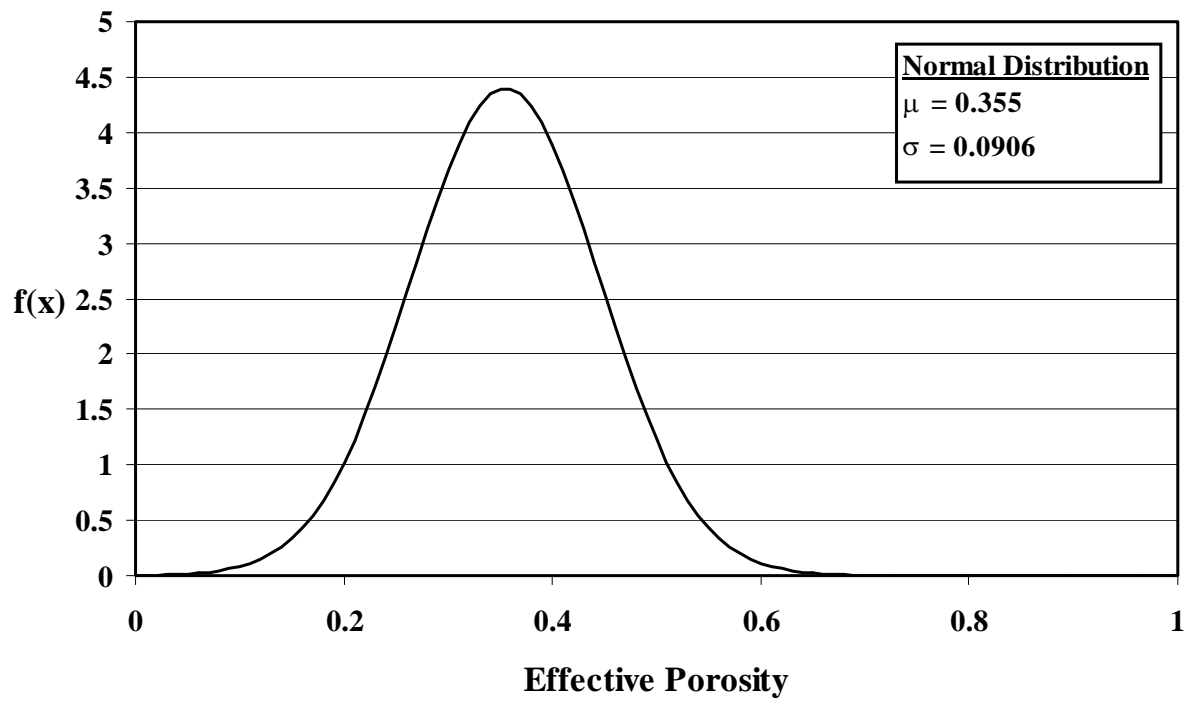


Figure 3.3-1 Effective Porosity Probability Density Function for the Generic Soil Type

3.4 Hydraulic Conductivity

Applicable Code: RESRAD

Description: The hydraulic conductivity of a soil is the measure of the ability of that soil to transmit water when subjected to a hydraulic gradient. RESRAD uses separate hydraulic conductivity values for three soil materials: contaminated, unsaturated, and saturated zones.

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	2.3	Lower limit:	0.004
Underlying standard deviation:	2.11	Upper limit:	9250

Discussion: The hydraulic conductivity (sometimes referred to as “coefficient of permeability”) is defined by Darcy’s law, which, for one-dimensional vertical flow, can be written as:

$$U = -K \frac{dh}{dz} , \quad (3.4-1)$$

where U is Darcy’s velocity (or the average velocity of the soil fluid through a geometric cross-sectional area within the soil), h is the hydraulic head, z is the distance along the direction of groundwater flow in the soil, and K is the hydraulic conductivity.

The hydraulic conductivity of a soil governs the rate of groundwater flow within that soil. The rate of groundwater flow increases with increasing hydraulic conductivity. The hydraulic conductivity of a particular soil is affected by the size, abundance, and geometry of the open pores within the soil. Fine-grained soils, such as clay and silt, have very small pores and have much lower hydraulic conductivity than coarse-grained soils, such as sand and gravel.

The hydraulic conductivity in the contaminated zone is used along with the water infiltration rate and soil b parameter to determine the water saturation ratio in soil, which is then used to determine the leach rate of the contaminants (radionuclides). Leaching of radionuclides affects the doses for both the water-dependent and -independent pathways.

In the unsaturated zone, the hydraulic conductivity is used in determining the moisture content of soil, which affects the retardation factor and the pore water velocity and, thus, the travel time in the unsaturated zone. In the saturated zone, hydraulic conductivity is used to determine the groundwater flow rate, which affects the travel time in the aquifer to the water point of use as well as the dilution factor for radionuclides in well water. The saturated hydraulic conductivity values related to the contaminated and unsaturated zones of the soil should represent the vertical component of hydraulic conductivity. For isotropic soil materials, the vertical and horizontal component of the hydraulic conductivity are the same; for anisotropic soils, the vertical component is typically one or two orders of magnitude lower than the horizontal component (Yu et al., 1993b).

Distribution of saturated hydraulic conductivity is given in Carsel and Parrish (1988) for the 12 USDA soil textural classifications. Carsel and Parrish (1988) inferred the saturated water content from data on bulk density. They then applied data on sand and clay contents and the inferred saturated water contents to the multiple regression model developed by Rawls and Brakensiek (1985) to estimate saturated hydraulic conductivity for the 12 USDA soil textural classifications. The data were fitted by either a normal distribution or a transformed normal distribution using methods in Johnson (1987) and Johnson and Kotz (1970). Meyer et al. (1997) fitted the estimated data generated by Carsel and Parrish (1988) to the distribution forms that are more commonly used and more easily constructed. Meyer et al. (1997) used the following procedure:

- Generate realizations of the parameters using Latin Hypercube Sampling and the distributions from Carsel and Parrish (1988).
- Calculate the Kolmogorov D-statistic for a fit of each simulated parameter distribution to normal, lognormal, and beta distributions.
- Select the recommended distribution based on the D-statistic values.

In most cases, the distribution type with the smallest D-statistic value was selected as the recommended distribution. Table 3.4-1 provides the distribution recommended by Meyer et al. (1997) on the basis of the soil type. The distribution to be used for cases when the type of soil is not known (the generic soil type) was obtained as the weighted average of the distributions for the individual soil classes. The same weighting factor scheme as discussed for the generic soil type in Section 3.1 was used. The probability density function of the weighted average was plotted, and the parameters of the lognormal distribution were chosen to represent the weighted average curve over the range of interest. This generic soil type is the default distribution chosen for RESRAD to be the most representative soil type found at sites across the United States. However, when evaluating a given site, the distribution most appropriate to local conditions should be used. The probability density function for hydraulic conductivity for this generic soil type is shown in Figure 3.4-1. When a site-specific analysis is being conducted, the distribution for the soil type present at the

site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: soil density, total porosity, effective porosity, and the soil b parameter.

**Table 3.4-1 Distribution Type and Parameter Values (m/yr)
for Hydraulic Conductivity by Soil Type**

Soil Type	Distribution ^a	Lower Limit ^b	Upper Limit ^b
Sand	Beta (1.398, 1.842, 110, 5870)	110	5,870
Loamy sand	Beta(0.7992, 1.910, 12.3, 4230)	12.3	4,230
Sandy loam	LN(5.022, 1.33)	2.49	9,250
Sandy clay loam	LN(3.36, 1.75)	0.129	6,440
Loam	LN(3.40, 1.66)	0.178	5,070
Silt loam	LN(2.26, 1.49)	0.096	960
Silt	LN(2.66, 0.475)	3.302	62.2
Clay loam	LN(1.36, 2.17)	0.00478	3,190
Silty clay loam	LN(0.362, 1.59)	0.0106	195
Sandy clay	LN(0.462, 2.02)	0.00309	816
Silty clay	LN(-1.238, 1.31)	0.00506	16.6
Clay	LN(0.302, 2.269)	0.00122	1,500
Generic soil type	Bounded Lognormal-N (2.3, 2.11, 0.004, 9250)	0.004 ^c	9,250 ^c

^a LN(.) = lognormal distribution with two defining parameters,
Beta(.) = beta distribution and bounded lognormal-N with four defining parameters.

^b Lower and upper limits are 0.001 and 0.999 quantiles for lognormal distribution.

^c Correspond to lower and upper observed values.

Sources: Beyeler (1998b); Meyer et al. (1997); Meyer and Gee (1999).

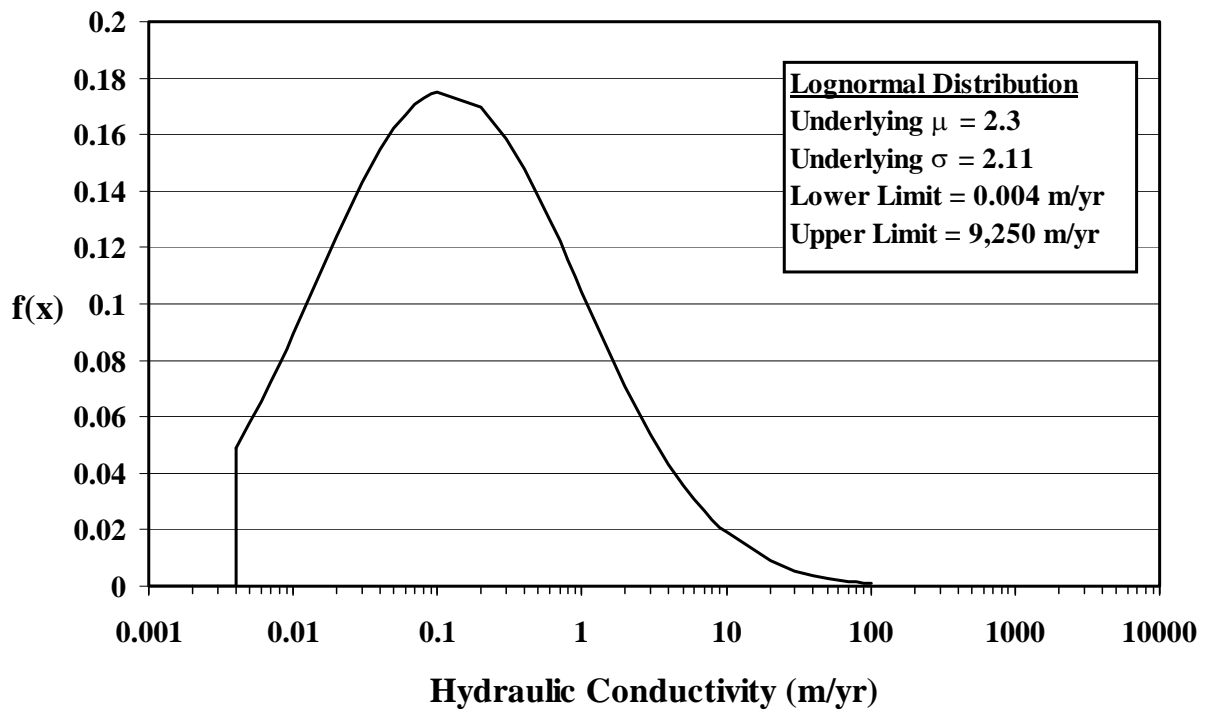


Figure 3.4-1 Hydraulic Conductivity Probability Density Function for the Generic Soil Type

3.5 Soil b Parameter

Applicable Code: RESRAD

Description: The soil-specific b parameter is an empirical parameter used to evaluate the saturation ratio of the soil. Three separate inputs are used in RESRAD, one each for the contaminated, unsaturated, and saturated zones.

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	1.06	Lower limit: 0.5
Underlying standard deviation:	0.66	Upper limit: 30

Discussion: The following equation is used in the RESRAD code to evaluate the saturation ratio, R_s , in all unsaturated regions of the soil system (Yu et al., 1993b):

$$R_s = \left[\frac{I_r}{K_{sat}} \right]^{\left(\frac{1}{2b+3} \right)}, \quad (3.5-1)$$

where I_r is the infiltration rate and K_{sat} is the saturated hydraulic conductivity. When the medium is fully saturated, infiltration rate and hydraulic conductivity are equal, and saturation ratio equals unity.

The soil-specific exponential b parameter is one of several hydrological parameters used to calculate the radionuclide leaching rate in the contaminated zone and the moisture content in the unsaturated zone. In the code, the user is requested to input b parameter values for the contaminated zone, the unsaturated zone, and the saturated zone. (Input for the saturated zone b parameter will only be required if the water table drop rate is greater than 0.)

Meyer et al. (1997) derived a relationship for b by using the soil water retention parameters considered in Carsel and Parrish (1988). Using the derived relationship, Meyer et al. (1997) then constructed distributions for the soil-b parameter for the 12 USDA soil textural classifications. The distribution type and the parameters for the 12 soil types and

for the generic soil type are provided in Table 3.5-1. The distribution to be used for cases where the type of soil is not known (generic soil type) was obtained as the weighted average of the distributions for the individual soil classes. The distribution for the generic soil type is the RESRAD default. The probability density function for the soil-b parameter for this generic soil type is shown in Figure 3.5-1. When a site-specific analysis is being conducted, the distribution for the soil type present at the site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: soil density, total porosity, effective porosity, and hydraulic conductivity.

Table 3.5-1 Distribution Type and Parameter Values for Soil-b Parameter by Soil Type

Soil Type	Distribution ^a	Lower Limit ^b	Upper Limit ^b
Sand	LN(-0.0253,0.216)	0.501	1.90
Loamy sand	LN(0.305,0.258)	0.610	3.01
Sandy loam	LN(0.632,0.282)	0.786	4.50
Sandy clay loam	LN(1.41,0.275)	1.75	9.57
Loam	LN(1.08,0.271)	1.28	6.82
Silt loam	LN(1.28,0.334)	1.28	10.1
Silt	LN(1.16,0.140)	2.06	4.89
Clay loam	LN(1.73,0.323)	2.08	15.3
Silty clay loam	LN(1.96,0.265)	3.02	15.5
Sandy clay	LN(1.89,0.260)	2.97	14.8
Silty clay	LN(2.29,0.259)	4.43	22.0
Clay	Beta(1.751,11.61)	4.93	75.0
Generic soil type	Bounded lognormal-N (1.06,0.66,0.5,30)	0.5 ^c	30 ^c

^a LN(.) = lognormal distribution with two defining parameters, Beta(.) = beta distribution and bounded lognormal-N with four defining parameters.

^b Lower and upper limits are 0.001 and 0.999 quantiles for lognormal distribution.

^c Correspond to lower and upper observed values.

Sources: Beyeler et al. (1998b); Meyer et al. (1997); Meyer and Gee (1999).

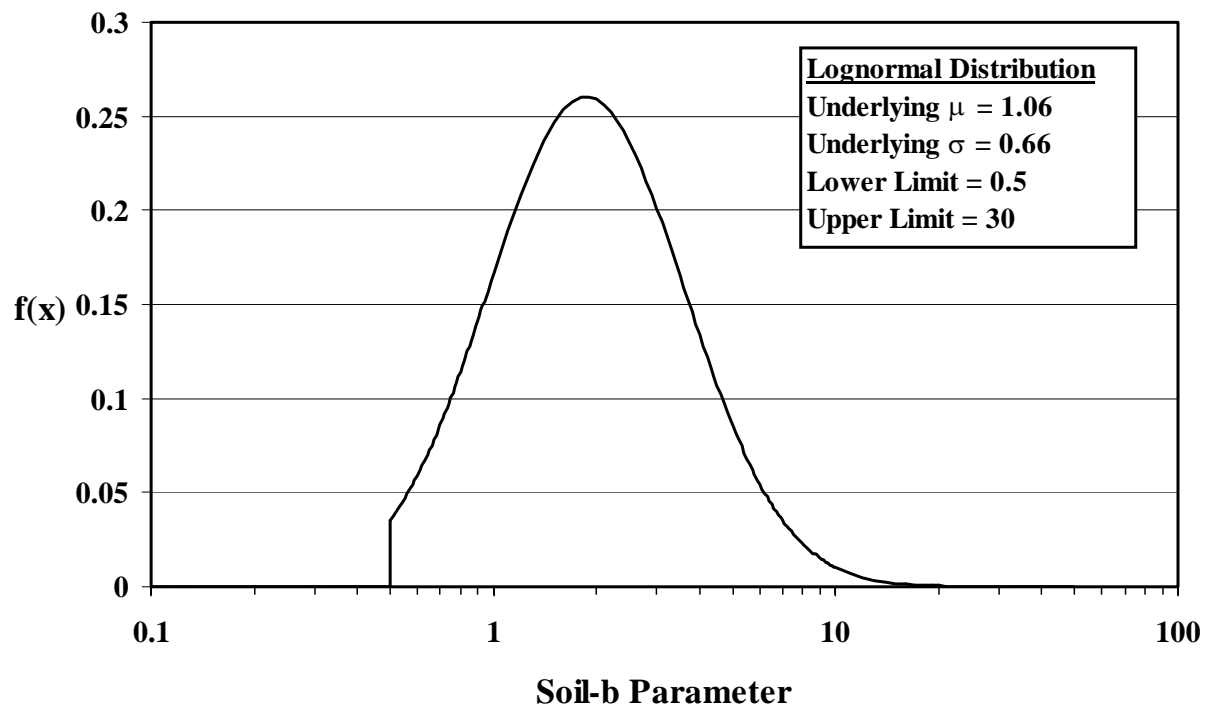


Figure 3.5-1 Soil-b Parameter Probability Density Function for the Generic Soil Type

3.6 Hydraulic Gradient

Applicable Code: RESRAD

Description: The hydraulic gradient is the change in hydraulic head per unit of distance of the groundwater flow in a given direction.

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	-5.11	Lower limit: 7×10^{-5}
Underlying standard deviation:	1.77	Upper limit: 0.5

Discussion: The saturated zone hydraulic gradient is used in the RESRAD code to determine the groundwater flow rate, which affects the rise time as well as the dilution factor of radionuclides in well water. The hydraulic gradient, J_x , in the flow direction x , is expressed as follows:

$$J_x = \frac{h_1 - h_2}{\nabla x} , \quad (3.6-1)$$

where h_1 and h_2 represent the hydraulic head at points 1 and 2, respectively, and x is the distance between these two points. In the code, the user is requested to input a value for the hydraulic gradient in the dominant groundwater flow direction in the underlying aquifer at the site.

In an unconfined (water table) aquifer, the horizontal hydraulic gradient of groundwater flow is approximately the slope of the water table. In a confined aquifer, it represents the difference in potentiometric surfaces over a unit distance. The potentiometric surface is the elevation to which water rises in a well that taps a confined aquifer. It is an imaginary surface analogous to a water table. In general, the hydraulic gradient of groundwater flow in a highly permeable geological material, such as sand or gravel, is far less than that in a geological material with a low permeability, such as silt and clay (Yu et al., 1993b). Groundwater moves through an aquifer in a direction generally parallel to the hydraulic gradient. The movement generally is perpendicular to the lines of equal altitude of the potentiometric surface. The altitude of the potentiometric surface of

different aquifer systems can be obtained from the *Ground Water Atlas of the United States* at <http://wwwcapp.er.usgs.gov/publicdocs/gwa/>.

The American Petroleum Institute, the National Water Well Association, and Rice University conducted a technical survey to collect hydrogeologic information from groundwater professionals. Data gathered for 401 locations representing 48 U.S. states (Newell et al., 1989) were analyzed for 12 hydrogeologic environments on the basis of groupings of similar geologic settings. The data were collected for six hydrogeological parameters: hydraulic conductivity, seepage velocity, vertical penetration depth into saturated zone, hydraulic gradient, saturated thickness of aquifer, and depth to top of aquifer.

Newell et al. (1989) found that the hydraulic gradient was best described by a lognormal (base 10) distribution. The raw data were used to calculate the mean, median, geometric mean, and standard deviations for each hydrogeologic environment. Table 3.6-1 provides values for these four parameters for 12 hydrogeologic environments. The default lognormal distribution listed above was obtained by conversion of the lognormal (base 10) distribution obtained for the national average in Newell et al. (1989). The probability density function for the hydraulic gradient is shown in Figure 3.6-1.

Table 3.6-1 Hydraulic Gradient (ft/ft) for 12 Hydrogeologic Environments

Hydrogeologic Environment	Number of Cases	Mean	Median	Standard Deviation	Geometric Mean
National Average	346	0.021	0.006	0.046	0.006
Metamorphic/Igneous	23	0.037	0.019	0.043	0.017
Bedded Sedimentary Rocks	52	0.023	0.009	0.027	0.011
Till Over Sedimentary Rocks	17	0.016	0.010	0.016	0.007
Sand and Gravel	223	0.027	0.005	0.068	0.005
River Valleys with Overbank	25	0.005	0.004	0.005	0.003
River Valleys Without Overbank	30	0.017	0.005	0.045	0.005
Alluvial Basins, Valleys and Fans	38	0.026	0.005	0.048	0.010
Outwash	26	0.005	0.002	0.077	0.003
Till and Till over Outwash	25	0.066	0.010	0.121	0.020
Unconsolidated and Semiconsolidated	25	0.013	0.005	0.022	0.0033
Coastal Beaches	25	0.018	0.004	0.036	0.0037
Solution Limestone	17	0.016	0.006	0.029	0.0045

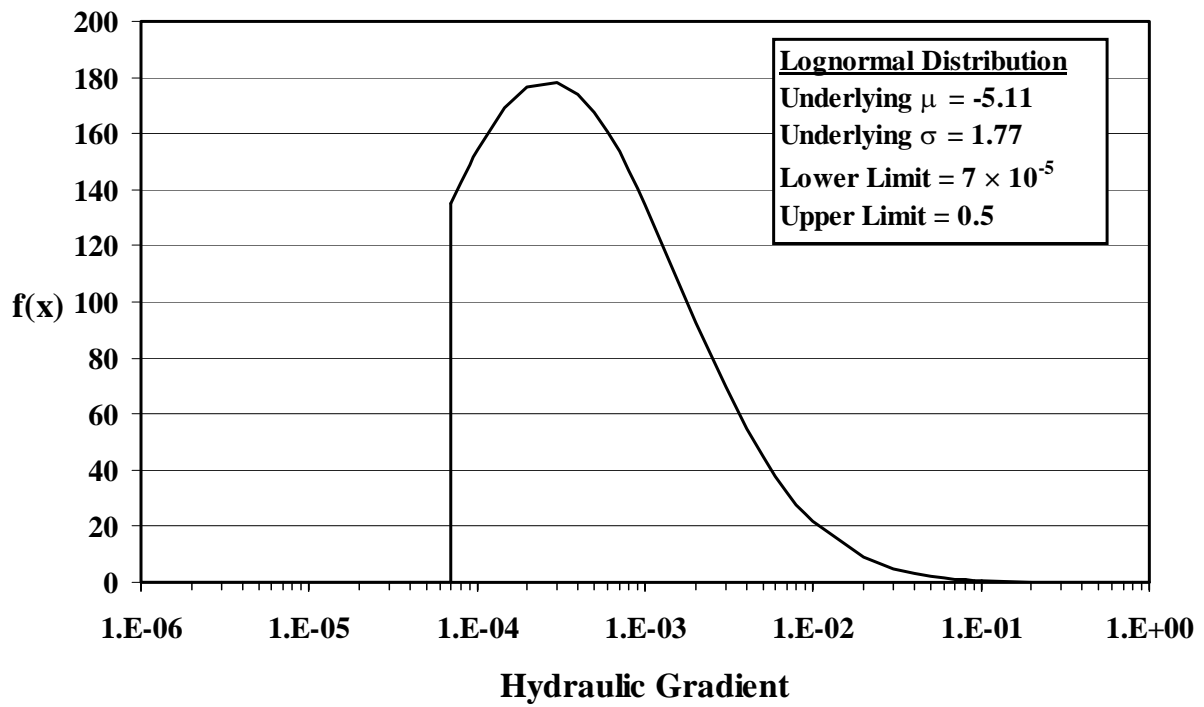


Figure 3.6-1 Hydraulic Gradient Probability Density Function

3.7 Unsaturated Zone Thickness

Applicable Code: RESRAD

Description: The uncontaminated unsaturated zone is the portion of the uncontaminated zone that lies below the bottom of the contaminated zone and above the water table. The RESRAD code has provisions for up to five different horizontal strata (unsaturated zones). Each stratum is characterized by six radionuclide independent parameters: (1) thickness of the layer, (2) soil density, (3) total porosity, (4) effective porosity, (5) soil-specific b parameter, and (6) hydraulic conductivity.

Units: meters (m)

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	2.296	Lower limit: 0.18 ¹
Underlying standard deviation:	1.276	Upper limit: 320

Discussion: Unsaturated zone thickness is the distance for the radionuclides must travel from the contaminated zone to reach the groundwater table. The greater the thickness, the longer the travel time (breakthrough time). The breakthrough time affects the ingrowth and decay of radionuclides, factors that affect the amounts of radionuclides reaching the groundwater table.

In the code, the user is required to input a value for each stratum used in the calculation. Entering a nonzero thickness for a stratum activates that stratum, and, similarly, changing the thickness to zero deletes the stratum from calculations. By default, only one stratum is active in the code.

The American Petroleum Institute, the National Water Well Association, and Rice University collected hydrogeologic information through a technical survey from groundwater professionals. Data from 401 locations representing 48 U.S. states were gathered (Newell et al., 1989). The data were analyzed for 12 hydrogeologic environments on the basis of groupings of similar geologic settings. The data were collected for six hydrogeological parameters: hydraulic conductivity, seepage velocity, vertical penetration depth into

¹ Corresponds to the cumulative probability of 0.1%.

saturated zone, hydraulic gradient, saturated thickness of aquifer, and depth to top of aquifer.

Newell et al. (1989) found that depth to the water table was best described by a lognormal (base 10) distribution. The raw data were used to calculate the mean, median, geometric mean, and standard deviations for each hydrogeologic environment. Newell et al. (1989) found that the coastal beaches, till, and the unconsolidated and semiconsolidated shallow aquifers had the least depth to water, with coastal beaches having a very low median value of 6 ft (1.8 m). Alluvial basins had the highest median value at 25 ft (7.6 m).

The RESRAD probability distribution function for the unsaturated zone thickness was derived from data from Beyeler et al. (1998a), who used water table depths from U.S. Geological Survey (USGS) data sources on a 1.5-degree grid overlain onto a continental U.S. map. This grid was chosen to approximate the density of grid points per groundwater region to the areal density of the groundwater region. The average water level from the closest well to the grid point was used to assign a value of the water table depth for the grid. Values for all grid points were not found, but the data did include representative values from all regions. Table 3.7-1 lists the empirical data. Bayesian estimation was used to fit the data in Table 3.7-1 to a lognormal distribution. Figures 3.7-1 and 3.7-2 show the probability density and cumulative density, respectively, for the unsaturated zone thickness.

Table 3.7-1 Estimated Depth (m) to Water at Gridded Sampling Locations

Observation	Depth	Observation	Depth	Observation	Depth	Observation	Depth
1	0.30	54	3.88	107	8.99	160	27.22
2	0.67	55	4.17	108	9.00	161	27.30
3	0.81	56	4.25	109	9.13	162	27.57
4	0.92	57	4.44	110	9.14	163	27.73
5	0.99	58	4.44	111	9.20	164	27.78
6	1.03	59	4.63	112	9.31	165	27.99
7	1.07	60	4.87	113	9.55	166	28.60
8	1.14	61	5.13	114	9.59	167	29.44
9	1.21	62	5.18	115	9.63	168	30.06
10	1.30	63	5.54	116	9.86	169	30.34
11	1.31	64	5.83	117	10.47	170	30.34
12	1.32	65	5.85	118	10.71	171	30.55
13	1.56	66	5.86	119	11.31	172	30.75
14	1.58	67	5.90	120	11.54	173	31.12
15	1.61	68	6.06	121	11.67	174	31.69
16	1.69	69	6.13	122	11.97	175	31.70
17	1.69	70	6.17	123	12.57	176	31.74
18	1.69	71	6.22	124	12.63	177	32.23
19	1.78	72	6.31	125	12.79	178	33.87
20	1.80	73	6.36	126	13.15	179	34.82
21	1.81	74	6.40	127	13.24	180	35.44
22	1.84	75	6.46	128	13.35	181	36.04
23	1.87	76	6.51	129	13.37	182	36.77
24	1.92	77	6.55	130	13.62	183	40.30
25	2.04	78	6.60	131	13.68	184	40.72
26	2.10	79	6.86	132	13.75	185	42.37
27	2.11	80	6.92	133	14.09	186	42.88
28	2.32	81	6.92	134	14.49	187	44.18
29	2.36	82	6.95	135	15.05	188	47.17
30	2.37	83	6.97	136	15.23	189	49.66
31	2.39	84	7.09	137	16.08	190	51.15
32	2.44	85	7.18	138	16.22	191	61.31
33	2.44	86	7.35	139	16.49	192	61.90
34	2.45	87	7.36	140	16.56	193	62.28
35	2.59	88	7.40	141	16.85	194	63.15
36	2.63	89	7.43	142	17.38	195	65.87
37	2.69	90	7.46	143	18.17	196	67.33
38	2.79	91	7.59	144	18.42	197	74.67
39	2.81	92	7.60	145	18.43	198	79.24
40	2.90	93	7.64	146	18.66	199	81.17
41	2.95	94	7.87	147	19.45	200	82.81
42	3.07	95	8.10	148	20.05	201	84.72
43	3.18	96	8.28	149	20.68	202	89.58
44	3.22	97	8.35	150	20.76	203	94.68
45	3.29	98	8.70	151	21.69	204	107.60
46	3.34	99	8.71	152	22.37	205	113.13
47	3.37	100	8.73	153	22.73	206	114.78
48	3.44	101	8.79	154	22.86	207	141.71
49	3.58	102	8.80	155	22.94	208	176.91
50	3.61	103	8.82	156	24.01	209	177.99
51	3.66	104	8.85	157	24.66	210	180.25
52	3.74	105	8.89	158	25.96	211	315.85
53	3.86	106	8.90	159	26.47		

Source: Beyeler et al. (1998a).

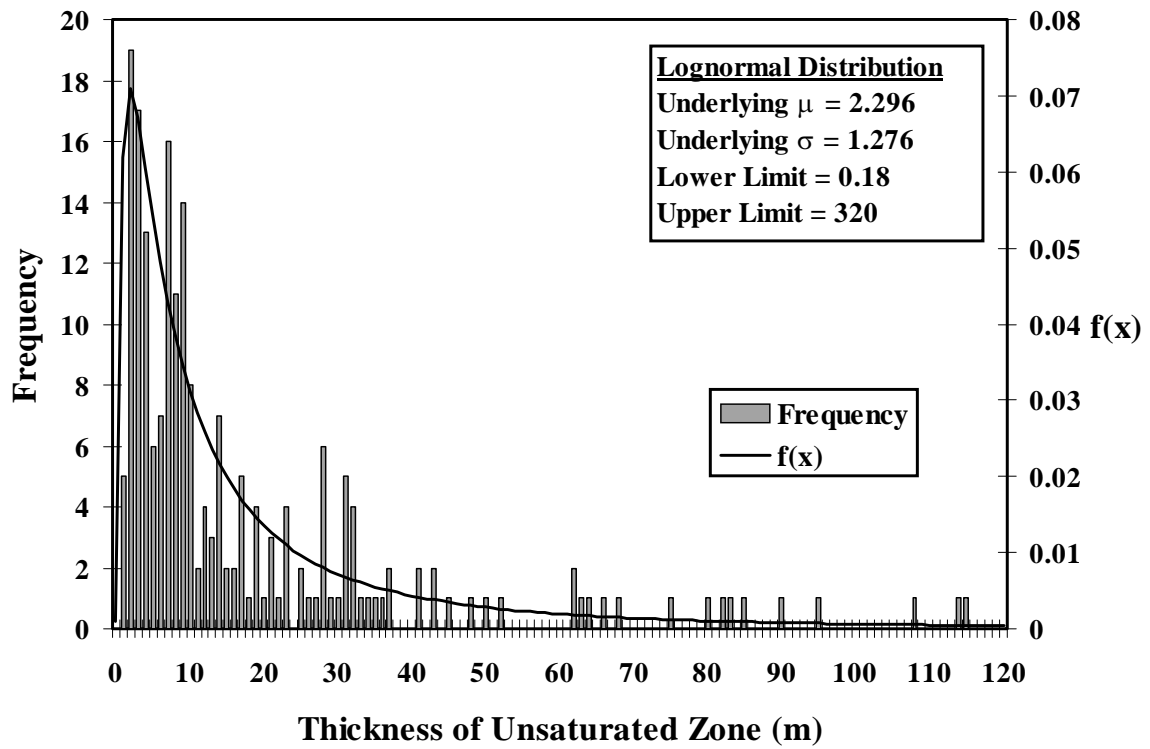


Figure 3.7-1 Probability Density Function for Unsaturated Zone Thickness

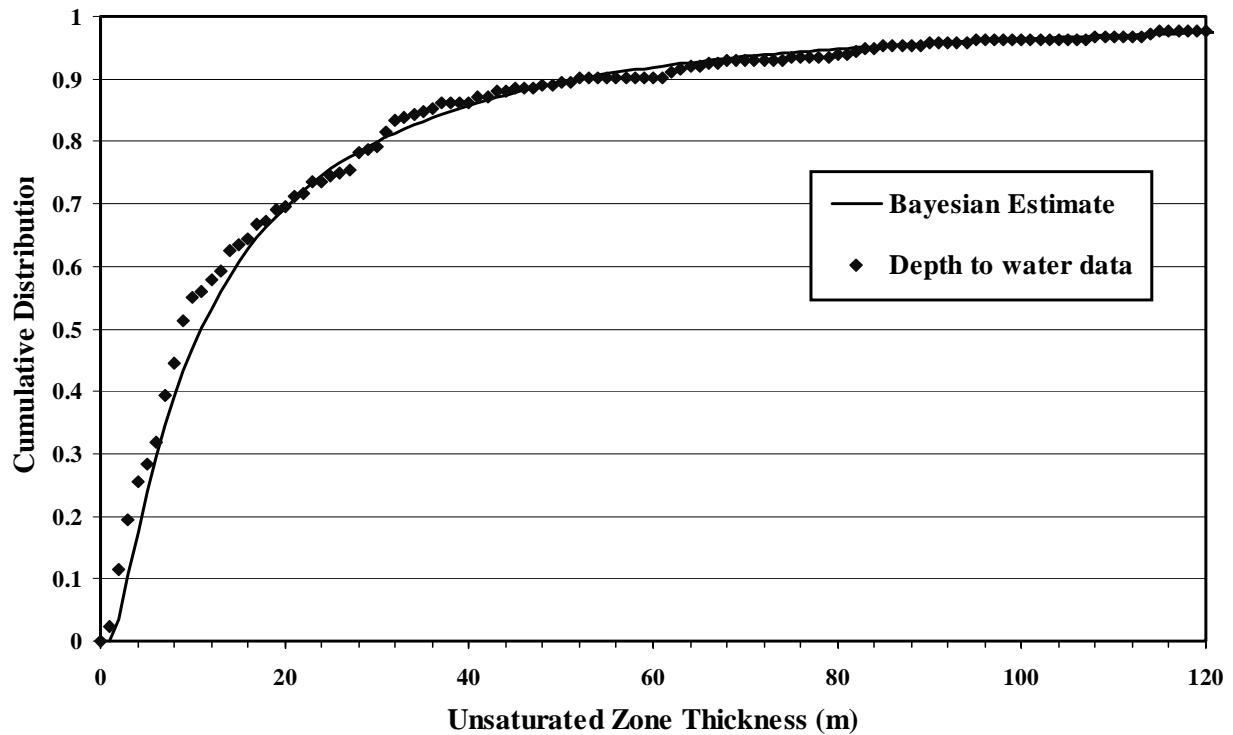


Figure 3.7-2 Cumulative Distribution Function for Unsaturated Zone Thickness

3.8 Cover and Contaminated Zone Erosion Rate

Applicable Code: RESRAD

Description: The erosion rate is a measure of the amount of soil material that is removed from one place to another by running water, waves and currents, wind, or moving ice per unit of ground surface area and per unit of time. In RESRAD, the erosion rate is represented by the average depth of soil that is removed from the ground surface at the site per unit of time.

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: User defined with continuous logarithmic interpolation

Defining Values for Distribution: See Table 3.8-1 for the cumulative distribution.

Discussion: The erosion rate is used in the RESRAD code to calculate the time dependence of the cover depth and the time dependence of the contaminated zone thickness. The contaminated zone erosion rate is only significant if and when the cover depth becomes 0.

Erosion rates for both the cover and the contaminated zone can be estimated by means of the Universal Soil Loss Equation (USLE), an empirical model that has been developed for predicting the rate of soil loss by sheet and rill erosion. If sufficient site-specific data are available, a site-specific erosion rate can be calculated. Details are discussed by Wischmeier and Smith (1978) and Foster (1979). Estimates based on the range of erosion rates for typical sites in humid areas east of the Mississippi River (based on model site calculations for locations in New York, New Jersey, Ohio, and Missouri) may also be used (Knight, 1983). For a site with a 2% slope, these model calculations predict an erosion rate range of 8×10^{-7} to 3×10^{-6} m/yr for natural succession vegetation, 1×10^{-5} to 6×10^{-5} m/yr for permanent pasture, and 9×10^{-5} to 6×10^{-4} m/yr for row-crop agriculture. The rate increases by a factor of about 3 for a 5% slope, 7 for a 10% slope, and 15 for a 15% slope. If these generic values are used for a farm-garden scenario in which the dose contribution from food ingestion

Table 3.8-1 Cover and Contaminated Zone Erosion Rate Cumulative Distribution

Erosion Rate (m/yr)	Cumulative Probability
5.0×10^{-8}	0
7.0×10^{-4}	0.22
5.0×10^{-3}	0.95
2.0×10^{-1}	1.0

pathways is expected to be significant, an erosion rate of 6×10^{-4} m/yr should be assumed for a site with a 2% slope. This rate would result in erosion of 0.6 m of soil in 1,000 years. A proportionately higher erosion rate must be used if the slope exceeds 2%. An erosion rate of 6×10^{-5} m/yr, leading to erosion of 0.06 m of soil in 1,000 years, may be used for a site with a 2% slope if it can be reasonably shown that the farm-garden scenario is unreasonable; for example, because the site is, and will likely continue to be, unsuitable for agriculture use.

The erosion rates are more difficult to estimate for arid sites in the West than for humid sites in the East. Although water erosion is generally more important than wind erosion, the latter can also be significant. Water erosion in the West is more difficult to estimate because it is likely to be due to infrequent heavy rainfalls for which the empirical constants used in the USLE may not be applicable. Long-term erosion rates are generally lower for sites in arid locations than for sites in humid locations. Pimentel (1976) has estimated that in the United States, soil erosion on agriculture land occurs at a rate of about 30 tons per hectare per year. (If the average soil density was assumed to be 1.5 g/cm^3 [mean for generic soil type] the average erosion rate would be 1.9×10^{-3} m/yr.) Table 3.8-2 gives the annual soil loss from various crops in different regions. Figure 3.8-1 shows the fitted cumulative distribution function selected for input into RESRAD, along with the observed erosion.

Zuzel et al. (1993), in a study at a site in northeastern Oregon, reported on soil erosion for 12 years (1979-1989) from three treatments (continuous fallow, fall-seeded winter wheat, and fall-plowed wheat stubble). The authors observed that relatively rare events were the major contributors to the long-term soil losses. Table 3.8-3 presents the soil erosion data for the three treatments. The site had a 16% north-facing slope, and the soil type was silt loam.

Baffault et al. (1998) analyzed frequency distributions of measured daily soil loss values and determined if the Water Erosion Prediction Project (WEPP) model accurately reproduced statistical distributions of the measured daily erosion rate. They fitted a log Pearson type III distribution to measured and WEPP-predicted soil loss values from six sites for periods ranging from 6 to 10 years. Cumulative soil loss results indicated that large storms contributed a major portion of the erosion under conditions where cover was high, but not necessarily under conditions of low cover. They found the maximum erosion rates of between 3 and 30 kg/m² for a given day for the six sites studied.

Table 3.8-2 Annual Soil Loss from Land with Various Crops in Different Regions

Crop	Location	Slope (%)	Soil Loss (tons/acre)	Estimated Annual Erosion Rate ^a (m/yr)
Corn (continuous)	Missouri (Columbia)	3.68	19.7	3.19×10^{-3}
Corn (continuous)	Wisconsin (LaCrosse)	16	89	1.44×10^{-2}
Corn	Mississippi (northern)	NA ^b	21.8	3.54×10^{-3}
Corn	Iowa (Clarinda)	9	28.3	4.60×10^{-3}
Corn (plow-disk-harrow)	Indiana (Russell, Wea)	NA	20.9	3.39×10^{-3}
Corn (plow-disk-harrow)	Ohio (Canfield)	NA	12.2	1.98×10^{-3}
Corn (conventional)	Ohio (Coshocton)	NA	2.8	4.52×10^{-4}
Corn (conventional)	South Dakota (eastern)	5.8	2.7	4.36×10^{-4}
Corn (continuous chem.)	Missouri (Kingdom City)	3	21	3.41×10^{-3}
Corn (contour)	Iowa (southwestern)	2 to 13	21.4	3.48×10^{-3}
Corn (contour)	Iowa (western)	NA	24	3.90×10^{-3}
Corn (contour)	Missouri (northwestern)	NA	24	3.90×10^{-3}
Cotton	Georgia (Watkinsville)	2 to 10	19.1	3.10×10^{-3}
Cotton	Georgia (Watkinsville)	2 to 10	20.4	3.31×10^{-3}
Wheat	Missouri (Columbia)	3.68	10.1	1.64×10^{-3}
Wheat (black fallow)	Nebraska (Alliance)	4	6.3	1.02×10^{-3}
Wheat	Pacific Northwest (Pullman)	NA	5 to 10	8.10×10^{-4} to 1.62×10^{-3}
Wheat-pea rotation	Pacific Northwest (Pullman)	NA	5.6	9.12×10^{-4}
Wheat (following fallow)	Washington (Pullman)	NA	6.9 to 9.9	1.12×10^{-3} to 1.61×10^{-3}
Bermuda grass	Texas (Temple)	4	0.03	4.91×10^{-6}
Native grass	Kansas (Hays)	5	0.03	4.91×10^{-6}
Forest	North Carolina (Statesville)	10	0.002	3.27×10^{-7}
Forest	New Hampshire (central)	20	0.01	1.64×10^{-6}

^a Estimated soil erosion assuming average soil density of 1.54 g/cm³.

^b NA = data not available.

Source: Pimentel et al. (1976).

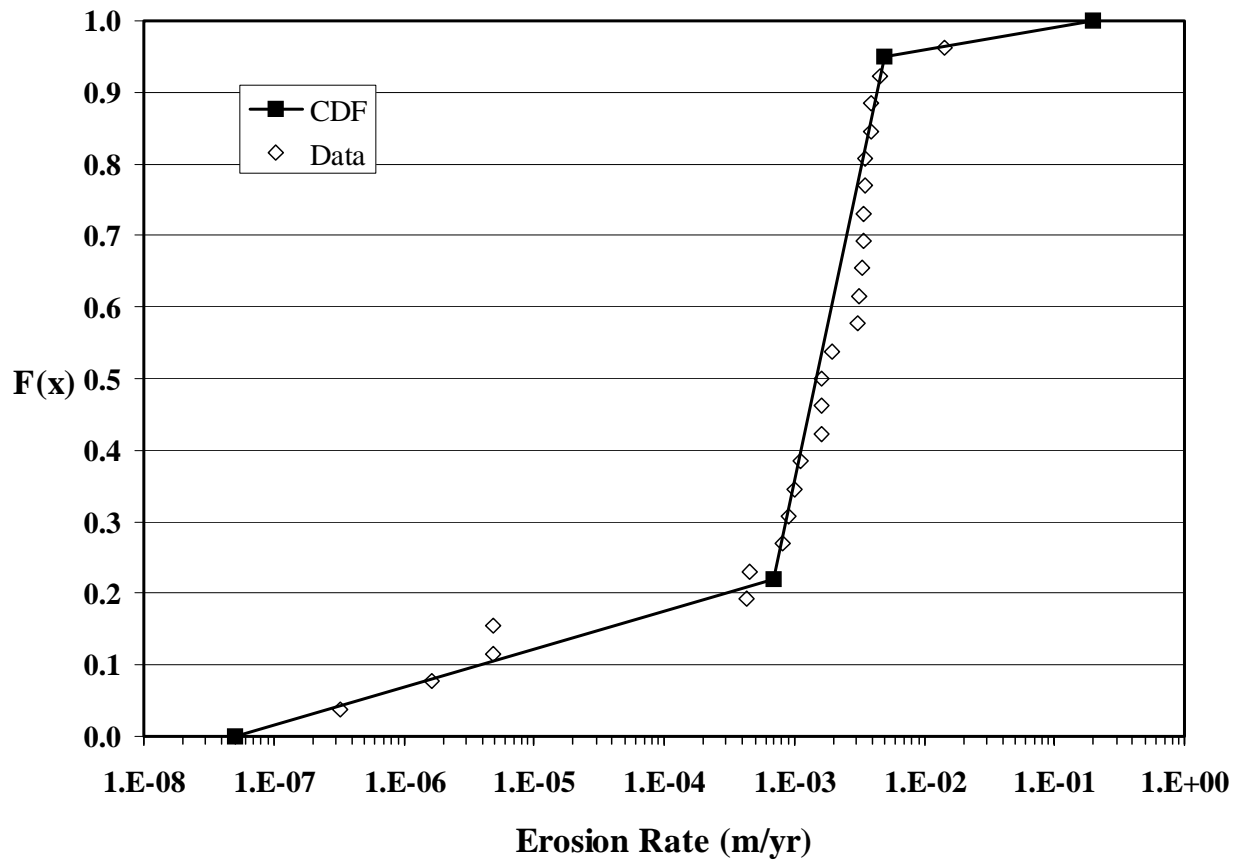


Figure 3.8-1 Cumulative Distribution for Input to RESRAD for Erosion Rate

Table 3.8-3 Soil Erosion at a Site in Northeastern Oregon for Three Treatments (1978-1989)

Treatment	Bulk Density (g/cm ³)	Erosion (t/ha)			Number of Events	Estimated Average Erosion Rate (m/yr)
		Total	Mean	Maximum		
Fall-seeded winter wheat	1.14	41.2	1.3	6.5	31	3×10^{-4}
Fall-plowed wheat stubble	-	22.6	1.4	9.6	16	2×10^{-4a}
Continuous fallow	1.23	461.9	5.4	53.3	86	3.1×10^{-3}

^a For estimating average erosion, bulk density is assumed to be ~1 g/cm³.

Source: Zuzel et al. (1993).

3.9 Distribution Coefficients

Applicable Code: RESRAD

Description: The distribution coefficient (soil/water partition coefficient, K_d) is an empirical parameter that estimates the distribution of radionuclides between the solid and liquid phases in soil.

Units: cubic centimeters per gram (cm^3/g) or liters per kilogram (L/kg)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned for each element as listed in Table 3.9-1. The lower and upper quantile values for all elements are 0.001 and 0.999, respectively.

Discussion: In the K_d model, it is assumed that the liquid and solid phases in soil are at equilibrium and that there is a linear relationship between solute concentration in the solid (C_s) and liquid (C_l) phases (Sheppard, 1985; Sheppard and Evenden, 1988), as expressed by the equation: $C_s = K_d C_l$. Although several mechanisms may affect the retention of radionuclides in soil, the K_d model lumps all of them into one value (Ames and Rai, 1978).

In the RESRAD code, the K_d values are used to estimate the retardation factors, which are the ratios of relative transport speeds of radionuclides to that of water in soil. The retardation factor of a radionuclide can be calculated as:

$$R_d = 1 + \rho_b K_d / \theta, \quad (3.9-1)$$

where ρ_b is the soil bulk density, and θ is the volumetric water content in soil. The larger the value of K_d is for a radionuclide, the greater the soil retention is for that radionuclide, and the more slowly the radionuclide will move through the soil column.

Experimental data of the K_d values for different elements are scattered in the literature. They were compiled and analyzed by different researchers to develop generic values for use in risk assessments. In addition to data compilation and analysis, studies were also conducted to investigate correlation between the K_d values and the root uptake transfer factors (CRs). The proposed distribution values listed in Table 3.9-1 were obtained by reviewing and comparing the published compilations and analyses, analyzing the compiled data, and using the K_d -CR correlation.

Table 3.9-1 Lognormal Distribution Values for the K_d Parameter for Different Elements

Element	Source ^a	Number of Samples	μ^b	σ^c	$\exp(\mu)^d$
Ac	2	NA ^e	6.72	3.22	825
Al	2	NA	6.45	3.22	634
Ag	3	26	5.38	2.10	216
Am	1	219	7.28	3.15	1445
Au	2	NA	4.65	3.22	105
Ba	2	NA	6.33	3.22	560
Bi	2	NA	4.65	3.22	105
C	2	NA	2.40	3.22	11
Ca	4	10	1.40	0.78	4.1
Cd	1	87	3.52	2.99	34
Ce	3	22	7.60	2.08	1998
Cf	2	NA	7.23	3.22	1378
Cl	2	NA	1.68	3.22	5.4
Cm	1	23	8.82	1.82	6761
Co	3	110	5.46	2.53	235
Cr	1	22	4.63	2.76	103
Cs	1	564	6.10	2.33	446
Eu	2	NA	6.72	3.22	825
Fe	3	44	5.34	2.67	209
Gd	2	NA	6.72	3.22	825
Ge	2	NA	3.87	3.22	48
H	5	NA	-2.81	0.5	0.06
I	1	109	1.52	2.19	4.6
Ir	2	NA	5.32	3.22	205
K	4	10	1.7	0.49	5.5
Mn	3	118	5.06	2.29	158
Mo	1	24	3.27	1.73	26
Na	2	NA	5.04	3.22	154
Nb	2	NA	5.94	3.22	380
Ni	3	44	6.05	1.46	424
Np	3	77	2.84	2.25	17
Pa	2	NA	5.94	3.22	380
Pb	1	18	7.78	2.76	2392
Pm	2	NA	6.72	3.22	825
Po	1	50	5.20	1.68	181
Pu	1	205	6.86	1.89	953
Ra	1	53	8.17	1.70	3533
Ru	1	47	7.37	3.13	1588
S	2	NA	3.65	3.22	38
Sb	2	NA	5.94	3.22	380
Sc	2	NA	6.84	3.22	935
Se	1	22	4.73	0.57	113
Sm	2	NA	6.72	3.22	825
Sn	2	NA	6.72	3.22	825
Sr	1	539	3.45	2.12	32
Ta	2	NA	5.55	3.22	257
Tc	3	59	-0.67	3.16	0.51

Table 3.9-1 (Cont.)

Element	Source ^a	Number of Samples	μ^b	σ^c	$\exp(\mu)^d$
Te	2	NA	3.64	3.22	38
Th	1	26	8.68	3.62	5884
Tl	2	NA	4.26	3.22	71
U	1	60	4.84	3.13	126
Zn	1	98	6.98	4.44	1075
Zr	2	NA	7.23	3.22	1378

^a The source of the distribution values is indicated by 1, 2, 3, 4, or 5:

- 1 - Developed by Beyeler et al. (1998b) by fitting available literature data.
- 2 - Developed by using the RESRAD default root uptake transfer factor and the correlation between K_d and CR for loamy soil as suggested by Baes et al. (1984).
- 3 - Developed by using the experimental data compiled by Thibault et al. (1990).
- 4 - Developed by Baes and Sharp (1983) by fitting experimental data.
- 5 - Developed on the basis of consideration that tritiated water (HTO) travels with the same speed as water. The mean value for K_d should be very small, and the range of distribution should be narrow.

^b The mean of the underlying normal distribution after taking natural logarithm of the K_d values.

^c The standard deviation of the underlying normal distribution after taking natural logarithm of the K_d values. Standard deviation for data obtained from source 2 was set to 3.22 to consider a potential wide range of distribution.

^d Exponential of the mean value.

^e NA = not available.

Baes and Sharp (1983) compiled and analyzed K_d values for agriculture soils that have a pH value normally distributed with a mean of 6.7 and ranges between 4.7 and 8.7. Lognormal distribution was assumed on the basis of data for cesium (Cs) and strontium (Sr). The agriculture soils are typified by loamy and clayey types.

Thibault et al. (1990) compiled data for all important elements present in Canada's nuclear fuel waste vault inventory, with the exception of noble gases and hydrogen (H). The mineral soils were categorized by texture into sand, clay, and loam soils. Soils that had organic content of greater than 30% and that were either classic peat or muck soils were categorized as organic soils. The compiled data were fitted into a lognormal distribution, and distribution values were developed for each element for the four different soil categories. For those elements for which no experimental K_d values could be found, the K_d -CR correlations and the CR values from Baes et al. (1984) were used to develop the distribution values. Correlation between K_d and CR was expressed as:

$$\ln(K_d) = 4.62 + \text{stex} - 0.56 [\ln(\text{CR})] , \quad (3.9-2)$$

where $\text{stex} = -2.52$ for sand soil, -1.26 for loam soil, -0.84 for clay soil, and 0 for organic soil, and the value for CR is wet-weight based.

The compilation of K_d values by Thibault et al. (1990) was quite comprehensive and covered many important elements. The results were used by Kennedy and Streng (1992) for conducting screening assessments in NUREG/CR-5512 and were also incorporated into the International Atomic Energy Agency's *Handbook of Parameter Values for Prediction of Radionuclides Transfer in Temperate Environments* (IAEA, 1994).

Beyeler et al. (1998b) analyzed the experimental data compiled by Thibault et al. (1990) and found no direct correlation between the soil texture and the K_d values. They combined the experimental data in Thibault et al. (1990) with those from the Nuclear Energy Agency (NEA, 1989) sorption database to develop distribution values for different elements. After taking logarithms of the K_d values, 21 of the 34 elements analyzed fit a normal distribution; 7 did not have enough data to develop distribution fit to the data; 3 fit a lognormal distribution; and 3 demonstrated best fit with the Gumbel distribution. The developed mean values for the distributions were compared with the range of K_d values collected for large-scale repository performance assessments (McKinley and Scholtis, 1991). Three of the 21 elements that were analyzed as demonstrating normal distribution with their logarithmic values have a developed mean value outside the range reported by McKinley and Scholtis (1991).

The U.S. Environmental Protection Agency (EPA) in cooperation with the DOE recently published two reports (EPA 1999a,b) discussing in detail the measurement methods for the K_d values and different factors and mechanisms affecting the K_d values.

Lookup tables suggesting ranges of K_d values for soils of different pH and different clay content were provided for 10 elements. However, distribution values were not developed.

Because of the finding by Beyeler et al. (1998b) that no obvious correlation was found between the soil texture and the K_d values, only one set of distribution values was selected or developed for generic soil for each element considered in the RESRAD code. For some elements, although it was found by Beyeler et al. (1998b) that Gumbel or lognormal distributions demonstrated better fit for the logarithms of the experimental data, similar findings were not reported by other researchers. Therefore, a lognormal distribution was used to characterize the K_d values for all the elements.

To determine values for the distribution parameters, literature data developed on the basis of laboratory or field measurements were given first consideration. When no measurement data were available, correlation with the root transfer factor was then used. For the second approach, the root transfer factors were obtained from a previous report by ANL (Wang et al., 1993). The suggestions in that report were made after extensive review and comparison of various literature data and are in good agreement with the mean values developed in Section 6.2 of this report. For the first approach, three data sources were considered: (1) Beyeler et al. (1998b), (2) Thibault et al. (1990), and (3) Baes et al. (1984). The first source contains measurement data compiled in the second source and incorporates additional data from NEA (1989). The second source contains measurement data used in the third source and incorporates other scattering data. Therefore, data sources 1, 2, and 3 were given a priority of 1, 2 and 3, respectively when developing the distribution values.

Distribution data for 17 of the elements listed in Table 3.9-1 were obtained from Beyeler et al. (1998b). For cerium, nickel, and technetium, the developed mean values by Beyeler et al. (1998) differ substantially from those by Baes and Sharp (1983) and Sheppard and Thibault (1990), so the lognormal distribution values from Beyeler et al. (1998) were discarded.

Distribution data for eight of the elements listed in Table 3.9-1 were obtained by analyzing the experimental data compiled by Thibault et al. (1990). The experimental data were fitted into a lognormal distribution to obtain the means and standard deviations. Distribution data for Ca and K were obtained from Baes and Sharp (1983).

For the rest of the elements, except for H, the mean values were developed by using the correlation with root transfer factors. Because the mean values were not developed from experimental data, statistical standard deviation could not be determined. In this case, a large value of 3.22, as used by Beyeler et al. (1998) for elements without experimental data, was assigned. The use of a large standard deviation allows the

sampling of K_d values from a wider range of distribution that extends farther in both directions from the mean value.

One thing to note is the K_d value for H. The K_d value estimated with the K_d -CR correlation is 12. However, a K_d of 0 or of a small value has been used for risk assessments because tritiated water (HTO) is thought to travel in the soil column with the same speed as water. Therefore, the derived value of 12 was discarded and a mean value of 0.06 was selected. The value of 0.06 was determined by taking the geometric mean of 0.04 and 0.1, which are the lower and upper range of K_d values for sandy soil reported by Sheppard and Thibault (1990). The standard deviation for H was set to 0.5, which was arbitrarily selected to represent a narrow distribution.

The selected or developed distribution values are listed in Table 3.9-1. Tables 3.9-2 and 3.9-3 compare the selected or developed mean values for all the elements with the reported mean values and ranges, respectively, from other sources. The mean values selected or developed for all the elements fall into the ranges reported by other sources, except for Pm, Sc, Se, Sn, and Te, for which the mean values were outside the range reported by McKinley and Scholtis (1991). However, the sampling sizes that McKinley and Scholtis used to obtain the reported ranges are unknown.

Table 3.9-2 Comparison of the Mean K_d Values (cm^3/g or L/kg) from Table 3.9-1 with Those from Other Sources

Element	Table 3.9-1 Value	Baes and Sharp (1983)	Sheppard and Thibault (1990)				Kennedy and Strenge (1992)	Beyeler et al. (1998b)
			Sand	Loam	Clay	Organic		
Ac	825	NA ^a	450	1,500	2,400	5400	420	1,738
Al	634	NA	NA	NA	NA	NA	NA	NA
Ag	216	110	90	120	180	15,000	90	110
Am	1,445	810	1,900	9,600	8,400	112,000	1,900	1,445
Au	105	NA	NA	NA	NA	NA	30	158
Ba	560	NA	NA	NA	NA	NA	NA	45
Bi	105	NA	100	450	600	1,500	120	447
C	11	NA	5	20	1	70	NA	21
Ca	4.1	4.1	5	30	50	90	8.9	1,479
Cd	34	6.7	80	40	560	800	40	34
Ce	1,998	1,100	500	8,100	20,000	3,300	500	85
Cf	1,378	NA	NA	NA	NA	NA	510	158
Cl	5.4	NA	NA	NA	NA	NA	1.7	5.0
Cm	6761	3,300	4,000	18,000	6,000	6,000	4,000	6,761
Co	235	55	60	1,300	550	1,000	60	1,000
Cr	103	NA	70	30	1,500	270	30	103
Cr(II)	NA	2,200	NA	NA	NA	NA	NA	NA
Cr(VI)	NA	37	NA	NA	NA	NA	NA	NA
Cs	446	1,110	280	4,600	1,900	270	NA	446
Eu	825	NA	NA	NA	NA	NA	240	955

Table 3.9-2 (Cont.)

Element	Table 3.9-1 Value	Baes and Sharp (1983)	Sheppard and Thibault (1990)				Kennedy and Strenge (1992)	Beyeler et al. (1998b)
			Sand	Loam	Clay	Organic		
Fe	209	55	220	800	165	600	160	891
Gd	825	NA ^a	NA	NA	NA	NA	240	5.0
Ge	48	NA	NA	NA	NA	NA	NA	NA
H	0.06	NA	NA	NA	NA	NA	NA	NA
I	4.6	NA	1	5	1	25	NA	4.6
Ir	205	NA	NA	NA	NA	NA	91	158
K	5.5	5.5	15	55	75	200	18	5.0
Mn	158	150	50	750	180	150	50	14
Mo	26	20	10	125	90	25	10	26
Na	154	NA	NA	NA	NA	NA	NA	5.0
Nb	380	NA	160	550	900	2,000	160	631
Ni	424	NA	400	300	650	1,100	400	37
Np	17	11	5	25	55	1,200	5	7.1
Pa	380	NA	550	1,800	2,700	6,600	510	2,042
Pb	2,392	99	270	16,000	550	22,000	270	2,392
Pm	825	NA	NA	NA	NA	NA	240	5,012
Po	181	540	150	400	3,000	7,300	150	181
Pu	953	1,800	550	1,200	5,100	1,900	550	953
Ra	3,533	NA	500	36,000	9,100	2,400	500	3,533
Ru	1,588	220	55	1,000	800	66,000	55	1,588
S	38	NA	NA	NA	NA	NA	NA	100
Sb	380	NA	45	150	250	550	NA	174
Sc	935	NA	NA	NA	NA	NA	310	158
Se	113	NA	150	500	740	1,800	140	113
Se(IV)	NA	2.7	NA	NA	NA	NA	NA	NA
Sm	825	NA	245	800	1,300	3,000	240	933
Sn	825	NA	130	450	670	1,600	130	501
Sr	32	27	15	20	110	150	15	32
Ta	257	NA	220	900	1,200	3,300	NA	NA
Tc	0.51	0.033	0.1	0.1	1	1	0.1	7.4
Te	38	NA	125	500	720	1,900	NA	550
Th	5,884	60,000	3,200	3,300	5,800	89,000	3,200	5,884
Tl	71	NA	NA	NA	NA	NA	390	158
U	126	45	35	15	1,600	410	15	126
Zn	1,075	16	200	1,300	2,400	1,600	200	1,075
Zr	1,378	NA	600	2,200	3,300	7,300	580	2,398

^a NA = not applicable.

Table 3.9-3 Comparison of the Mean K_d Values (cm^3/g or L/kg) from Table 3.9-1 with the Ranges of K_d Values from Other Sources

Element	Table 3.9-1 Value	Baes and Sharp (1983)	Sheppard and Thibault (1990)				McKinley and Scholtis (1991)	EPA (1999b)
			Sand	Loam	Clay	Organic		
Ac	825	NA ^a	NA	NA	NA	NA	10 to 5,011	NA
Al	634	NA	NA	NA	NA	NA	NA	NA
Ag	216	10 to 1,000	2.7 to 1,000	28 to 333	100 to 300	4,400 to 33,000	NA	NA
Am	1,445	1.0 to 47,230	8.2 to 300,000	400 to 48,309	25 to 400,000	6,398 to 450,000	316 to 100,000	NA
Au	105	NA	NA	NA	NA	NA	NA	NA
Ba	560	NA	NA	NA	NA	NA	NA	NA
Bi	105	NA	NA	NA	NA	NA	15.8 to 158	NA
C	11	NA	1.7 to 7.1	NA	NA	NA	0 to 100.0	NA
Ca	4.1	1.2 to 9.8	NA	NA	NA	NA	NA	NA
Cd	34	1.26 to 26.8	2.7 to 625	7.0 to 962	112 to 2,450	23 to 17,000	NA	1 to 12,600
Ce	1,998	58 to 6,000	40 to 3,968	1,200 to 56,000	12,000 to 31,623	NA	NA	NA
Cf	1,378	NA	NA	NA	NA	NA	NA	NA
Cl	5.4	NA	NA	NA	NA	NA	0 to 100	NA
Cm	6,761	93.9 to 51,900	780 to 22,970	7,666 to 44,260	NA	NA	NA	NA
Co	235	0.2 to 3,800	0.07 to 9,000	100 to 9,700	20 to 14,000	120 to 4,500	NA	NA
Cr	103	NA	1.7 to 1,729	2.2 to 1,000	NA	6.0 to 2,517	NA	NA
Cr(II)	NA	470 to 150,000	NA	NA	NA	NA	NA	NA
Cr(VI)	NA	1.2 to 1,800	1.7 to 1,729	2.2 to 1,000	NA	6.0 to 2,517	NA	0 to 1,770
Cs	446	10 to 52,000	0.2 to 10,000	560 to 61,287	37 to 31,500	0.4 to 145,000	100 to 10,000	10 to 66,700
Eu	825	NA	NA	NA	NA	NA	NA	NA
Fe	209	1.4 to 1,000	5 to 6,000	290 to 2,240	15 to 2,121	NA	NA	NA
Gd	825	NA	NA	NA	NA	NA	0.03 to 1,000	NA
Ge	48	NA	NA	NA	NA	NA	NA	NA
H	0.06	NA	0.04 to 0.1	NA	NA	NA	NA	NA
I	4.6	NA	0.04 to 81	0.1 to 43	0.2 to 29	1.4 to 368	0 to 100	NA
Ir	205	NA	NA	NA	NA	NA	NA	NA
K	5.5	2.0 to 9.0	NA	NA	NA	NA	NA	NA
Mn	158	0.2 to 10,000	6.4 to 5,000	40 to 77,079	23.6 to 48,945	NA	NA	NA
Mo	26	0.37 to 400	1.0 to 52	NA	13 to 400	18 to 50	NA	NA
Na	154	NA	NA	NA	NA	NA	NA	NA
Nb	380	NA	NA	NA	NA	NA	1 to 5011	NA
Ni	424	NA	60 to 3,600	NA	305 to 2,467	360 to 4,700	10 to 1,000	NA
Np	17	0.16 to 929	0.5 to 390	1.3 to 79	0.4 to 2,575	857 to 1,900	10 to 1,000	NA
Pa	380	NA	NA	NA	NA	NA	NA	NA
Pb	2,392	4.5 to 7,640	19 to 1,405	3,500 to 59,000	NA	9,000 to 31,590	NA	150 to 44,580
Pm	825	NA	NA	NA	NA	NA	1,000 to 100,000	NA
Po	181	196 to 1,063	9 to 7,020	24 to 1,830	NA	NA	NA	NA
Pu	953	11 to 300,000	27 to 36,000	100 to 5,933	316 to 190,000	60 to 62,000	12 to 100,000	5 to 2,550

Table 3.9-3 (Cont.)

Element	Table 3.9-1 Value	Sheppard and Thibault (1990)				McKinley and Scholtis (1991)	EPA (1999b)
		Baes and Sharp (1983)	Sand	Loam	Clay	Organic	
Ra	3,533	NA	57 to 21,000	1,262 to 530,000	696 to 56,000	NA	NA
Ru	1,588	48 to 1,000	5 to 490	NA	NA	39,000 to 87,000	NA
S	38	NA	NA	NA	NA	NA	NA
Sb	380	NA	NA	NA	NA	NA	NA
Sc	935	NA	NA	NA	NA	NA	NA
Se	113	NA	NA	NA	NA	NA	NA
Se(IV)	NA	1.2 to 8.6	NA	NA	NA	NA	NA
Sm	825	NA	NA	NA	NA	NA	NA
Sn	825	NA	NA	NA	NA	NA	NA
Sr	32	0.15 to 3,300	0.05 to 190	0.01 to 300	3.6 to 32,000	8 to 4,800	1 to 1,700
Ta	257	NA	0.01 to 16	NA	NA	NA	NA
Tc	0.51	0.0029 to 0.28	0.01 to 16	0.01 to 0.4	1.16 to 1.32	0.02 to 340	NA
Te	38	NA	NA	NA	NA	NA	NA
Th	5,884	2,000 to 510,000	207 to 150,000	NA	244 to 160,000	1,579 to 13,000,000	20 to 30,000
Tl	71	NA	NA	NA	NA	NA	NA
U	126	2,000 to 510,000	0.03 to 2,200	0.2 to 4,500	46 to 395,100	33 to 7,350	0.4 to 1,000,000
Zn	1,075	0.1 to 8,000	0.1 to 8,000	3.6 to 11,000	200 to 100,000	70 to 13,000	NA
Zr	1,378	NA	NA	NA	NA	NA	NA

^a NA = not applicable.

3.10 Well Pumping Rate

Applicable Code: RESRAD

Description: This parameter represents the total volume of water withdrawn from the well for all purposes per unit time. It is used to estimate the dilution that occurs in the well. For a subsistence farmer (resident farmer) scenario, this volume would include that water extracted from the well to fill the water demand for the household, livestock, and crop irrigation.

Units: cubic meters per year (m^3/yr)

Probabilistic Input:

Distribution: none recommended

Discussion: The distribution being sought here is not that of the pumping rates of wells serving communities (large and small) but the water extraction rate of a well serving a single family farm. This family well would have to satisfy the dietary needs (drinking water, water used in cooking food, water used to clean foods) and the personal hygiene needs of the members of the farm household; the livestock water requirements (ingestion and cleaning); and any water needed for other agricultural activities (such as irrigating crops).

No general distribution is recommended for this parameter because of its large variability due to a number of site-specific considerations. A site-specific input distribution for well pumping rate can be determined as the sum of individual water needs. The water use components considered should include household water use, including human drinking water intake; livestock intake; crop irrigation; and pasture irrigation. Summaries of household water use per occupant are given in EPA (1997); human drinking water intake is discussed in Section 5.2; livestock intake will vary with the number and type of animals; and crop and pasture irrigation use will vary with the land area farmed. An even wider distribution will be obtained when uncertainties related to the fraction of contaminated water used are considered.

For perspective, Table 3.10-1 presents three cases for which total water use is estimated. Each case assumes the same number of livestock and four occupants. Land area varies from 100 to 10,000 m^2 , and the fraction of contaminated water used is varied for irrigation. All values used are taken from the RESRAD manual (Yu et al., 1993a), except the irrigation rate, which is from Cheng et al. (1999).

Table 3.10-1 Example Calculations for Estimating the Well Pumping Rate

Water Use Component	General Case	Water Use as a Function of Land Area		
		100 m ²	2,400 m ²	10,000 m ²
Household	$225 \times 4 \text{ L/d}$ $\equiv 328.7 \text{ m}^3 \text{ yr}^{-1}$	$328.7 \text{ m}^3 \text{ yr}^{-1}$	$328.7 \text{ m}^3 \text{ yr}^{-1}$	$328.7 \text{ m}^3 \text{ yr}^{-1}$
Livestock	$50+160 \text{ L/d}$ $\equiv 76.7 \text{ m}^3 \text{ yr}^{-1}$	$76.7 \text{ m}^3 \text{ yr}^{-1}$	$76.7 \text{ m}^3 \text{ yr}^{-1}$	$76.7 \text{ m}^3 \text{ yr}^{-1}$
Irrigation of vegetable plot				
Contaminated fraction	$f_p = \min(\text{Area}/2000, 0.5)$	0	0.5	0.5
Irrigation rate	$I_r \text{ (m yr}^{-1}\text{)}$	0	0.1125 m yr^{-1}	0.1125 m yr^{-1}
Irrigation water	$f_p \times I_r \times 2000$	0	$112.5 \text{ m}^3 \text{ yr}^{-1}$	$112.5 \text{ m}^3 \text{ yr}^{-1}$
Irrigation of pasture				
Contaminated fraction	$f_m = \text{Area}/20,000 \leq 1$	0	0.065	0.445
Irrigation rate	$I_r \text{ (m yr}^{-1}\text{)}$	0	0.1125 m yr^{-1}	0.1125 m yr^{-1}
Irrigation water	$f_m \times I_r \times 20,000$	0	$146.3 \text{ m}^3 \text{ yr}^{-1}$	$1001 \text{ m}^3 \text{ yr}^{-1}$
Drinking water	$409.5 \times 4 \text{ L/yr}$ $\equiv 1.64 \text{ m}^3 \text{ yr}^{-1}$ (Section 5.2)	$1.64 \text{ m}^3 \text{ yr}^{-1}$	$1.64 \text{ m}^3 \text{ yr}^{-1}$	$1.64 \text{ m}^3 \text{ yr}^{-1}$
Total (m ³ yr ⁻¹)		407	666	1519

3.11 Well Pump Intake Depth

Applicable Code: RESRAD

Description: The well pump intake depth is the depth below the water table where the well pump intake is located.

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 6 Maximum: 30 Most likely: 10

Discussion: For most domestic well systems, the pump intake depth can be taken to be the difference between the top of the water table and the bottom of the well screen. If the depth to the bottom of the screen is not known, the completion depth of the well can serve as a surrogate. Most states maintain records of domestic and municipal well systems, but some of these databases do not contain information on the screen depth or water level in a given well. The water well information that is available can usually be obtained for free or a nominal fee by contacting the state agency responsible for natural resources.

At any given location, the well pump intake depth will vary according to temporal variations in the level of the water table. Pump intake depth must be sufficiently below the level of the water table to account for drawdown during pump operation and low water levels during periods of drought. Some states have minimum requirements. It is generally recommended that the well screen be positioned in the lower one-half or one-third of the aquifer (EPA, 1975). Positioning the well screen at the bottom of the aquifer allows for a larger screen length (therefore larger intake), more drawdown is available (permitting larger well yield), and, as mentioned above, well yield can better be maintained during periods of severe drought or overpumping (Driscoll, 1986). However, positioning the screen at or near the bottom of the aquifer may not be desirable or necessary in the case of extremely thick aquifers (it is not economical to drill the entire depth), where there is poorer water quality near the bottom (poor water quality can occur in any portion of the aquifer), or when it is most efficient to place the screen at the center of the aquifer (which is often the most uniform part of the aquifer) (Driscoll, 1986).

In the absence of a nationwide database, a rough approximation of the well pump intake depth distribution can be made by using aquifer thickness data and the assumption

that the wells are normally completed to the bottom of the aquifer. Data on thicknesses of 350 aquifers located across the continental United States were collected for a hydrogeological database (Newell et al., 1989). The reported median and geometric mean were 9.14 m (30.0 ft) and 11.2 m (36.9 ft), respectively, for the saturated thickness. The mean and standard deviation were reported as 27.3 m (89.6 ft) and 68.3 m (224.0 ft), respectively. For RESRAD input, a most likely value of 10 m was selected as the most likely value of a triangular distribution because it lies between the values of the median and the geometric mean. To hedge against variations in the level of the water table and pump drawdown, a minimum value of 6 m (20 ft) was chosen. In addition, a screen length of 3 m (10 ft) or longer is recommended for supporting domestic farming operations (Driscoll, 1986). Thus, any depth less than 6 m below the water table would result in a risk of dewatering the screen. Because of the costs involved, it is unlikely that a domestic well would be completed 30 m (100 ft) below the water table; therefore, a maximum value of 30 m was selected for the distribution.

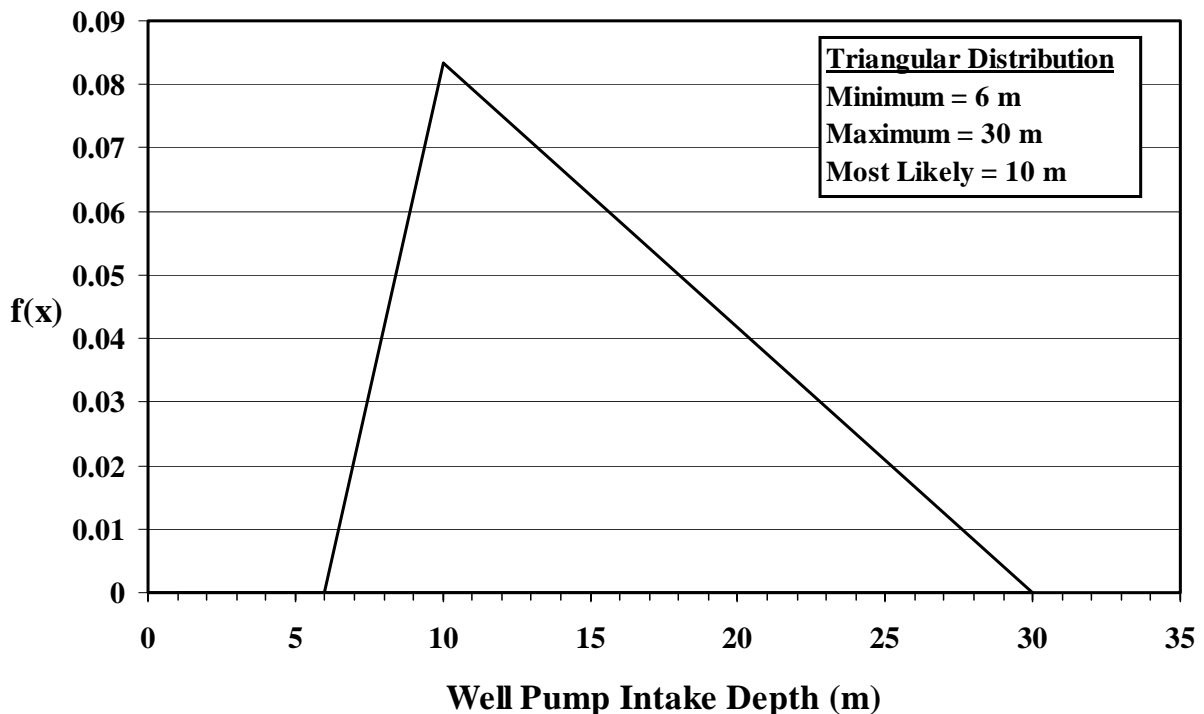


Figure 3.11-1 Well Pump Intake Depth Probability Density Function

3.12 Depth of Soil Mixing Layer

Applicable Code: RESRAD

Description: The depth of soil mixing layer parameter is used in calculating the depth factor for the dust inhalation and soil ingestion pathways and for foliar deposition for the ingestion pathway.

Units: meters (m)

Probabilistic Input

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.0 Maximum: 0.6 Most likely: 0.15

Discussion: The depth factor is the fraction of resuspendable soil particles at the ground surface that are contaminated. It is calculated by assuming that mixing of the soil with contamination will occur within the uppermost soil layer. The thickness of this layer is equal to the depth of the soil mixing layer.

Mixing of the upper soil layer can occur through atmospheric (wind or precipitation/runoff) and mechanical disturbances. For a residential farmer scenario, the greatest affected depths, on a routine basis, result from mechanical disturbances. Such disturbances include use of farm equipment (e.g., plowing) and foot and vehicle traffic. On relatively undisturbed portions of the land, a mixing layer depth close to 0 is expected. On the other hand, mixing of the soil to as deep as about 0.6 m (23 in.) is expected on the crop-producing portion of the land subjected to periodic plowing and other agricultural activities.

Tillage of the soil for crop production should be as shallow as possible and still meet the objectives of aerating the soil, removing stubble, controlling weeds, incorporating fertilizer, controlling erosion, and providing a suitable seedbed and rootbed (Buckingham, 1984). Typical plow depths are on the order of 0.15 to 0.20 m (6 to 8 in.). However, a plow sole, or hardpan (compacted soil layer), can form when a field is plowed to the same depth each year (Buckingham, 1984). This compacted layer should be broken up periodically by plowing to a deeper depth so as not to restrict air and water movement. Deeper tillage of this type, down to approximately 0.6 m (23 in.), can be routinely achieved with commercially available equipment. Thus, the soil mixing layer depth is expected to range from 0 to 0.6 m for the residential farmer scenario. A triangular distribution for the soil

mixing layer between these two values, with 0.15 m (6 in.) as a most likely value, was selected for use in RESRAD as an approximation, because knowledge of the percentage of land used for crops and the crop types affect the amount of land and depth of plowing required, respectively. The probability density function for the soil mixing layer depth is shown in Figure 3.12-1.

Tillage deeper than 0.6 m is possible, but it is considered to be a nonstandard practice (Dunker et al., 1995; Allen et al., 1995). Commercial equipment capable of tillage down to depths of 1.2 m are available (Dunker et al., 1995). One of the countermeasures attempted, with mixed results, to reduce contamination of foodstuffs following the Chernobyl accident was deep plowing (Konoplev et al., 1993; Vovk et al., 1993). Deep plowing had been considered to be a practical method for restoring large agricultural areas contaminated by radionuclides in the former USSR, with plow depths of approximately 0.6 to 0.75 m reported for different cases (Vovk et al., 1993).

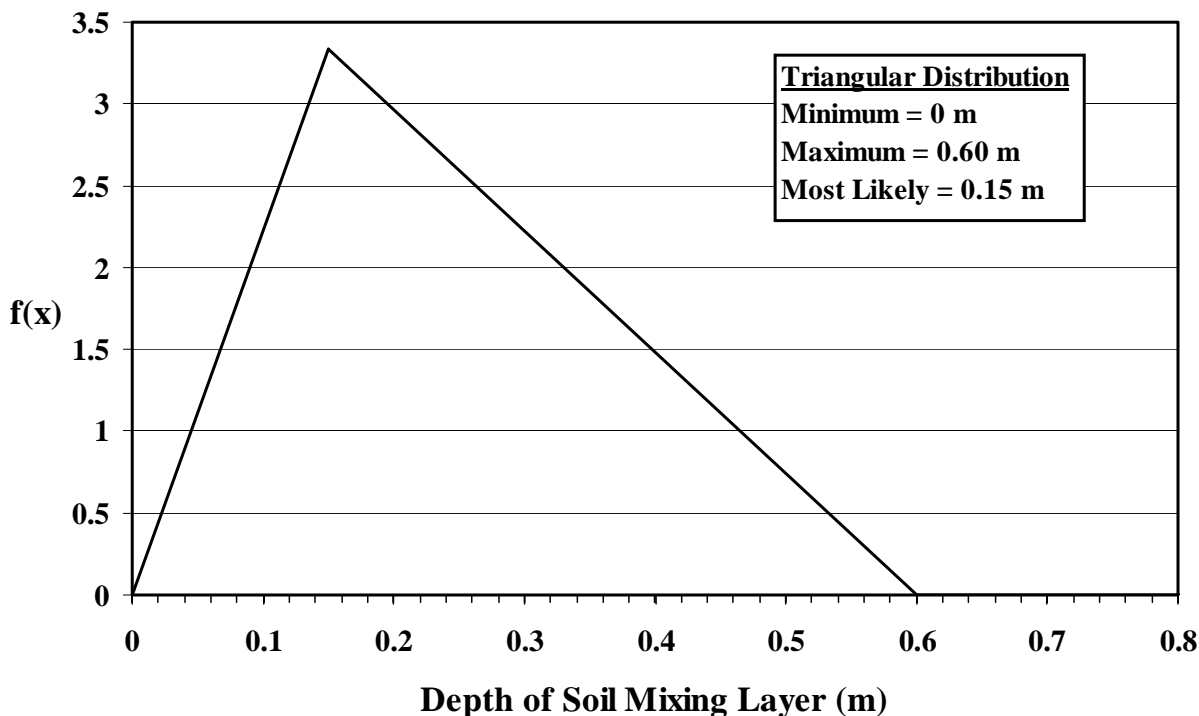


Figure 3.12-1 Depth of Soil Mixing Layer Probability Density Function

3.13 Cover Depth

Applicable Code: RESRAD

Description: The cover depth is the distance, in meters (m), from the ground surface to the location of the uppermost soil sample with radionuclide concentrations that are clearly above background.

Units: meters (m)

Probabilistic Input:

Distribution: none recommended

Discussion: The RESRAD default for cover depth is 0, and that value is recommended for deriving soil guideline values. However, RESRAD allows input of a cover depth greater than 0 when computing doses for a specific site where cover is present. The density of the cover material and the cover erosion rate are input only if a cover depth greater than 0 is used. Cover depth is very site specific; therefore, no distribution is provided.

4 METEOROLOGICAL PARAMETER DISTRIBUTIONS

4.1 Precipitation Rate

Applicable Code: RESRAD

Description: The precipitation rate is defined as the average volume of water in the form of rain, snow, hail, or sleet that falls per unit of area and per unit of time at the site.

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: none recommended.

Discussion: The precipitation rate, P_r , is used in the RESRAD code along with other input parameters, such as runoff coefficient, irrigation rate, and evapotranspiration coefficient, to determine the deep water percolation rate according to mass balance. The deep water percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

For a given site, the precipitation rate varies with time because the annual precipitation changes from year to year. Spatial variation within a site will be insignificant unless the area of the site is very large. Table 4.1-1 gives the annual average precipitation (in inches) for the major observing stations in all 50 states, Puerto Rico, and Pacific Islands (<http://www4.ncdc.noaa.gov>). The annual average precipitation is the sum of the arithmetic means for each month over the 30-year period and includes the liquid water equivalent of snowfall. The average annual precipitation for the major cities in the 48 conterminous U.S. states listed in Table 4.1-1 is 34.12 in./yr (0.867 m/yr).

A national average precipitation rate distribution is not recommended because of the large variations in precipitation that occur across the United States. Even state precipitation rate distributions may not properly represent all relevant locations because of differences in climate caused by local topography. A deterministic value for a nearby location from Table 4.1-1 may be used as a starting point for risk analysis, but the precipitation rate is a site-specific parameter that should be characterized at a contaminated site before the appropriate remedial action(s) can be selected.

Table 4.1-1 Precipitation Data for 273 U.S. Weather Recording Stations (average inches per year for the period 1961-1990)

Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)
Birmingham AP, AL	54.58	Jacksonville, FL	51.32	Muskegon, MI	32.56
Huntsville, AL	57.18	Key West, FL	39.59	Sault Ste. Marie, MI	34.23
Mobile, AL	63.96	Miami, FL	55.91	Duluth, MN	30
Montgomery, AL	53.43	Orlando, FL	48.11	International Falls, MN	24.36
Anchorage, AK	15.91	Pensacola, FL	62.25	Minneapolis-St. Paul, MN	28.32
Annette, AK	103.28	Tallahassee, FL	65.71	Rochester, MN	29.66
Barrow, AK	4.49	Tampa, FL	43.92	Saint Cloud, MN	27.43
Bethel, AK	14.99	Vero Beach, FL	51.16	Jackson, MS	55.37
Bettles, AK	13.74	West Palm Beach, FL	60.75	Meridian, MS	56.71
Big Delta, AK	11.96	Athens, GA	49.74	Tupelo, MS	55.87
Cold Bay, AK	36	Atlanta, GA	50.77	Columbia, MO	39.05
Fairbanks, AK	10.87	Augusta, GA	44.66	Kansas City, MO	37.62
Gulkana, AK	10.87	Columbus, GA	51	St. Louis, MO	37.51
Homer, AK	25.39	Macon, GA	44.63	Springfield, MO	43.04
Juneau, AK	54.31	Savannah, GA	49.22	Billings, MT	15.08
King Salmon, AK	19.82	Hilo, HI	129.19	Glasgow, MT	10.96
Kodiak, AK	67.58	Honolulu, HI	22.02	Great Falls, MT	15.21
Kotzebue, AK	8.98	Kahului, HI	20.92	Helena, MT	11.6
Mcgrath, AK	15.96	Lihue, HI	43	Kalispell, MT	16.51
Nome, AK	14.88	Boise, ID	12.11	Missoula, MT	13.46
St. Paul Island, AK	23.32	Lewiston, ID	12.43	Grand Island, NE	24.9
Talkeetna, AK	29.21	Pocatello, ID	12.14	Lincoln, NE	28.26
Unalakleet, AK	15.59	Chicago, IL	35.82	Norfolk, NE	25.15
Valdez, AK	64.04	Moline, IL	39.08	North Platte, NE	19.3
Yakutat, AK	151.25	Peoria, IL	36.25	Omaha Eppley AP, NE	29.86
Flagstaff, AZ	22.8	Rockford, IL	36.28	Omaha (North), NE	29.39
Phoenix, AZ	7.66	Springfield, IL	35.25	Scottsbluff, NE	15.27
Tucson, AZ	12	Evansville, IN	43.14	Valentine, NE	18.23
Winslow, AZ	8.04	Fort Wayne, IN	34.75	Elko, NV	9.93
Yuma, AZ	3.17	Indianapolis, IN	39.94	Ely, NV	10.13
Fort Smith, AR	40.9	South Bend, IN	39.14	Las Vegas, NV	4.13
Little Rock, AR	50.86	Des Moines, IA	33.12	Reno, NV	7.53
North Little Rock, AR	49.25	Dubuque, IA	38.36	Winnemucca, NV	8.23
Bakersfield, CA	5.72	Sioux City, IA	25.86	Concord, NH	36.37
Bishop, CA	5.37	Waterloo, IA	33.7	Mt. Washington, NH	98.96
Eureka, CA	37.53	Concordia, KS	28.78	Atlantic City AP, NJ	40.29
Fresno, CA	10.6	Dodge City, KS	21.49	Atlantic City C.O., NJ	37.1
Long Beach, CA	11.8	Goodland, KS	18.2	Newark, NJ	43.97
Los Angeles AP, CA	12.01	Topeka, KS	35.23	Albuquerque, NM	8.88
Los Angeles C.O., CA	14.77	Wichita, KS	29.33	Clayton, NM	15.09
Redding, CA	33.3	Greater Cincinnati AP	41.33	Roswell, NM	12.58
Sacramento, CA	17.52	Jackson, KY	49.67	Albany, NY	36.17
San Diego, CA	9.9	Lexington, KY	44.55	Binghamton, NY	36.99
San Francisco AP, CA	19.7	Louisville, KY	44.39	Buffalo, NY	38.58
San Francisco C.O., CA	19.71	Paducah KY	49.31	Islip, NY	46.07
Santa Barbara, CA	16.25	Baton Rouge, LA	60.89	New York C.park, NY	47.25
Santa Maria, CA	12.36	Lake Charles, LA	54.84	New York (JFK AP), NY	41.59
Stockton, CA	13.95	New Orleans, LA	61.88	New York (Laguardia AP), NY	42.12
Alamosa, CO	7.57	Shreveport, LA	46.11	Rochester, NY	31.96
Colorado Springs, CO	16.24	Caribou, ME	36.6	Syracuse, NY	38.93
Denver, CO	15.4	Portland, ME	44.34	Asheville, NC	47.59
Grand Junction, CO	8.64	Baltimore, MD	40.76	Cape Hatteras, NC	56.09
Pueblo, CO	11.19	Blue Hill, MA	48.95	Charlotte, NC	43.09
Bridgeport, CT	41.66	Boston, MA	41.51	Greensboro-Wnstr-Salm-Hghpt, NC	42.62
Hartford, CT	44.14	Worcester, MA	47.75	Raleigh, NC	41.43
Wilmington, DE	40.84	Alpena, MI	28.83	Wilmington, NC	54.27
Washington Dulles AP, D.C.	40.24	Detroit, MI	32.62	Bismarck, ND	15.47
Washington Natl AP, D.C.	38.63	Flint, MI	30.28	Fargo, ND	19.45
Apalachicola, FL	54.95	Grand Rapids, MI	36.04	Williston, ND	13.67
Daytona Beach, FL	47.89	Houghton Lake, MI	28.25	Akron, OH	36.82
Fort Myers, FL	53.37	Lansing, MI	30.62	Cleveland, OH	36.63
Gainesville, FL	51.81	Marquette, MI	35.3	Columbus, OH	38.09
Dayton, OH	36.64	Providence, RI	45.53	Victoria, TX	37.41
Mansfield, OH	39.66	Charleston AP, SC	51.53	Waco, TX	31.96
Toledo, OH	32.97	Charleston C.O., SC	48.52	Wichita Falls, TX	28.9
Youngstown, OH	37.32	Columbia, SC	49.91	Salt Lake City, UT	16.18
Oklahoma City, OK	33.36	Greenville-Spartanburg AP, SC	51.27	Burlington, VT	34.47
Tulsa, OK	40.59	Aberdeen, SD	18.55	Lynchburg, VA	40.88

Table 4.1-2 (Cont.)

Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)	Station	Annual Average Precipitation (Inches)
Astoria, OR	66.4	Huron, SD	20.08	Norfolk, VA	44.64
Burns, OR	9.96	Rapid City, SD	16.64	Richmond, VA	43.16
Eugene, OR	49.37	Sioux Falls, SD	23.86	Roanoke, VA	41.13
Medford, OR	18.86	Bristol-Jhnsn Cty-Kngsprt, TN	40.72	Wallops Island, VA	39.93
Pendleton, OR	12.02	Chattanooga, TN	53.46	Olympia, WA	50.59
Portland, OR	36.3	Knoxville, TN	47.14	Quillayute, WA	105.18
Salem, OR	39.16	Memphis, TN	52.1	Seattle C.o., WA	38
Guam, PC	103.04	Nashville, TN	47.3	Seattle Sea-Tac AP, WA	37.19
Koror, PC	147.97	Oak Ridge, TN	53.77	Spokane, WA	16.49
Kwajalein, Marshall IS.	102.09	Abilene, TX	24.4	Yakima, WA	7.97
Majuro, Marshall IS, PC	131.34	Amarillo, TX	19.56	San Juan, PR	52.34
Pago Pago, Amer Samoa, PC	121.8	Austin, TX	31.88	Beckley, WV	41.03
Pohnpei, Caroline Is., PC	187.76	Brownsville, TX	26.61	Charleston, WV	42.53
Chuuk, E. Caroline Is., P	138.78	Corpus Christi, TX	30.13	Elkins, WV	44.84
Wake Island, PC	35.68	Dallas-Fort Worth, TX	33.7	Huntington, WV	41.49
Yap, W Caroline Is., PC	120.06	Del Rio, TX	18.24	Green Bay, WI	28.83
Allentown, PA	43.52	El Paso, TX	8.81	La Crosse, WI	30.55
Erie, PA	41.53	Houston, TX	46.07	Madison, WI	30.88
Middletown/Harrisburg Int	40.5	Lubbock, TX	18.65	Milwaukee, WI	32.93
Philadelphia, PA	41.41	Midland-Odessa, TX	14.96	Casper, WY	12.52
Pittsburgh, PA	36.85	Port Arthur, TX	57.18	Cheyenne, WY	14.4
Avoca, PA	36.18	San Angelo, TX	20.45	Lander, WY	13.01
Williamsport, PA	40.72	San Antonio, TX	30.98	Sheridan, WY	14.48

a To convert from inches to meters, multiply by 0.0254.

Source: Wood (1995); National Oceanic and Atmospheric Administration (1999).

4.2 Runoff Coefficient

Applicable Code: RESRAD

Description: The average annual runoff coefficient is the fraction of the average annual precipitation that does not infiltrate into the soil and is not transferred back to the atmosphere through evapotranspiration. The runoff coefficient represents the fraction of the precipitation, in excess of the deep percolation and evapotranspiration, that becomes surface flow and ends up in either perennial or intermittent surface water bodies.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for Distribution:

Minimum: 0.1 Maximum: 0.8

Discussion: The runoff coefficient (C_r) is one of the input parameters used in the RESRAD code to determine the deep water percolation rate according to mass balance. The water deep percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

The runoff rate at any specific location is influenced by the morphology of the region, the degree of the slopes, the type of soil material, and the type of soil utilization. The runoff coefficient varies with the frequency, the duration, and the magnitude of precipitation events. If the precipitation rate exceeds the hydraulic conductivity of the cover or contaminated zone, the excess will be removed by runoff, and the runoff coefficient will be increased. Thus, in addition to the factors considered in Table 4.2-1, the average annual precipitation rate, the land coverage of urban environment, and the hydraulic conductivity of the unsaturated stratum exert an influence on the runoff coefficient.

Runoff curve numbers (CNs) can be used to estimate the runoff coefficient for a particular site. The Soil Conservation Service (SCS) runoff curve number indicates runoff potential for a particular area on the basis of land use and hydrologic soil groups. In the past, SCS runoff curve numbers were produced by manually relating land uses and hydrologic soil types within particular areas and performing calculations. Now, by using the ARC/INFO UNION command, engineers can compute the SCS runoff curve number for

Table 4.2-1 Runoff Coefficient Values

Type of Area	Coefficient	Value
Agricultural environment ^a		
Flat land with average slopes of 0.3-0.9 m/mi	c_1	0.3
Rolling land with average slopes of 4.6-6.1 m/mi	c_1	0.2
Hilly land with average slopes of 46-76 m/mi	c_1	0.1
Open sandy loam	c_2	0.4
Intermediate combinations of clay and loam	c_2	0.2
Tight, impervious clay	c_2	0.1
Woodlands	c_3	0.2
Cultivated lands	c_3	0.1
Urban environment		
Flat, residential area C about 30% impervious	C_r	0.4
Moderately steep, residential area C about 50% impervious	C_r	0.65
Moderately steep, built-up area C about 70% impervious	C_r	0.8

^a The runoff coefficient for an agricultural environment is given by $C_r = 1 - c_1 - c_2 - c_3$.

Source: Gilbert et al. (1989).

the entire subbasin based on the land use and hydrologic soil type (Robbins and Phipps, 1996).

The following equation gives the SCS relationship for estimating Q (depth of runoff) from P (rainfall) and S (Maidment, 1992).

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S}, \quad (4.2-1)$$

where:

$$S = (1000/CN) - 10 \text{ and}$$

CN = runoff curve number.

The value of CN depends on the soil, cover, and hydrologic condition of the land surface. These conditions are described by Maidment (1992). The value of CN also depends on the antecedent moisture condition, which represents the degree of saturation of the soil prior to a rainfall event. Table 4.2-2 provides the SCS runoff curve numbers for average antecedent moisture conditions. These values need to be modified for very dry

Table 4.2-2 SCS Runoff Curve Numbers for Average Antecedent Moisture Condition

Land Use or Cover	Hydrologic Condition ^a	Runoff Curve No. by Hydrologic Soil Group			
		A	B	C	D
Fallow		77	86	91	94
Pasture or range	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Contoured pasture or range	Poor	47	67	81	88
	Fair	25	59	75	83
	Good	6	35	70	79
Meadow		30	58	71	78
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	25	55	70	77
Brush-brushwood grass mixture with brush the major element	Poor	48	67	77	88
	Fair	35	56	70	77
	Good	30	48	65	73
Woods-grass combination (orchard or tree farm)	Poor	57	70	82	86
	Fair	48	65	76	82
	Good	32	58	72	79
Roads (dirt)		72	82	87	89
Roads (hard surface)		74	84	90	92

^a Poor = less than 50% ground cover, fair = 50-75% ground cover, good = greater than 75% ground cover.

Source: Meyer et al. (1997).

and very wet conditions (Meyer et al., 1997). Standard values of CN for various land uses and soil types are given by Maidment (1992).

According to the SCS, if the soil has been disturbed but no significant compaction has occurred, the hydrologic soil group can be assigned based on soil texture as follows:

- Group A: Sand, loamy sand, or sandy loam,
- Group B: Silt loam or loam,

- Group C: Silt, Sandy clay loam, and
- Group D: Clay loam, silty clay loam, sandy clay, silty clay, or clay.

A uniform distribution has been assigned as input to RESRAD for the runoff coefficient with minimum and maximum values of 0.1 and 0.8, respectively, as suggested by the data in Table 4.2-1. These input data should be changed to reflect local site conditions when performing site-specific analyses. Figure 4.2-1 displays the probability density function for the runoff coefficient.

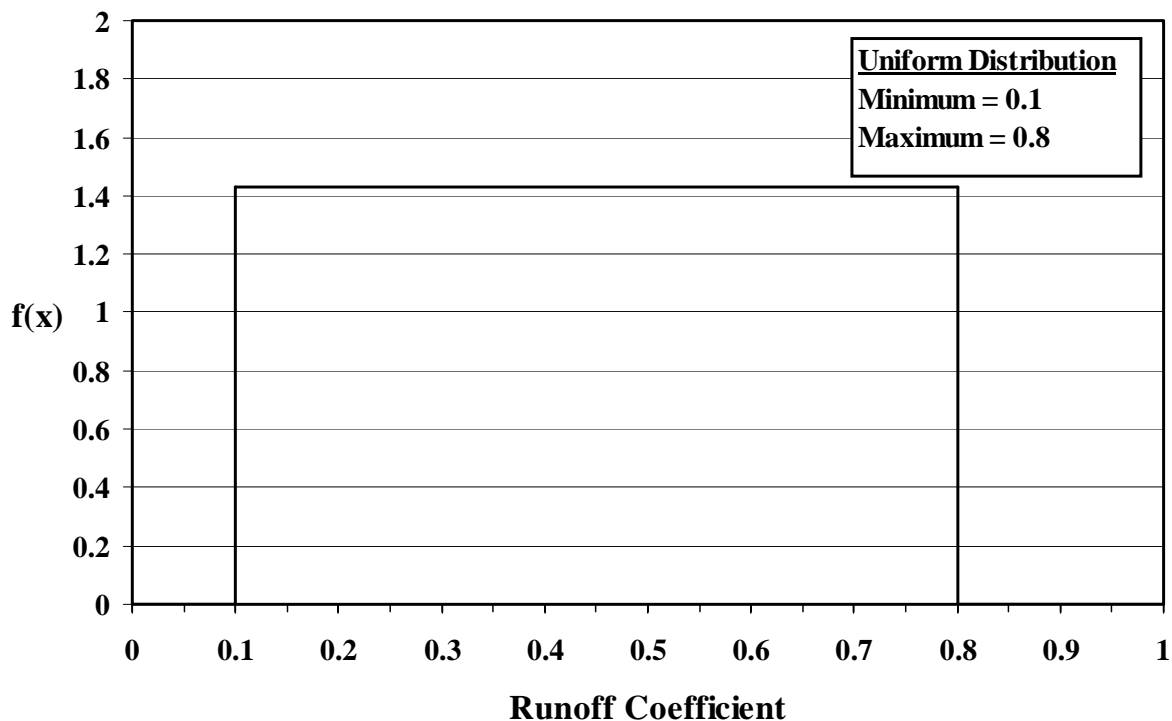


Figure 4.2-1 Runoff Coefficient Probability Density Function

4.3 Evapotranspiration Coefficient

Applicable Code: RESRAD

Description: The evapotranspiration coefficient is the ratio of the total volume of water vapor that is transferred to the atmosphere through evapotranspiration to the total volume of water available within the root zone of the soil.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for the Distribution:

Minimum: 0.5 Maximum: 0.75

Discussion: The evapotranspiration coefficient, C_e , can be expressed as:

$$C_e = \frac{ET_r}{(1 - C_r)Pr + IR_r}, \quad (4.3-1)$$

where

ET_r = the evapotranspiration rate (m/yr),

P_r = the precipitation rate (m/yr),

IR_r = the irrigation rate (m/yr), and

C_r = the runoff coefficient.

This parameter and certain other input parameters, such as precipitation, irrigation rate, and the runoff coefficient, are used in RESRAD to determine the water deep percolation rate according to mass balance. The deep water percolation rate is ultimately used to calculate the radionuclide leaching rate of the contaminated zone and the subsequent contamination of the underlying groundwater system.

Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation. Evaporation is defined as the process by which water is changed into vapors from liquid or solid state through heat energy and carried into the

atmosphere. The rate of evaporation depends on solar radiation, temperature, vapor pressure, humidity of air, and wind. Because of variation in climatic conditions, evaporation rates vary from one location to another. The basins in arid parts of Nevada and southeastern California have virtually zero runoff because most precipitation that falls is evaporated almost immediately.

Water used for transpiration enters the roots of plants from the surrounding soil water and moves upward through the plant tissues and into the surrounding air. The evapotranspiration coefficient depends on the method, frequency, and rate of irrigation; the texture and condition of the soil; the plant species; the age of the plant; and the climate of the region. Palmer (1993) gives a range of 0.6 to 0.75 for irrigation efficiency. The farm-irrigation efficiency is the percentage of water delivered that is utilized in crop evapotranspiration, which is equivalent to evapotranspiration for an irrigated site. The efficiency is influenced by the size of the farm because of the effect of conveyance losses between the point of delivery to the farm and the several fields. A range of 0.5 to 0.75 is suggested because a small family farm may not be well managed. Under certain conditions, a value of 0.5 is more likely if water-dependent pathways dominate. That value is consistent with a poorly managed irrigation system and leads to a higher leaching rate and a higher concentration of contaminants in the well water as a result of a lower dilution. A value of 0.75 is more likely if water-independent pathways dominate. Figure 4.3-1 displays the probability function used in RESRAD for the evapotranspiration coefficient.

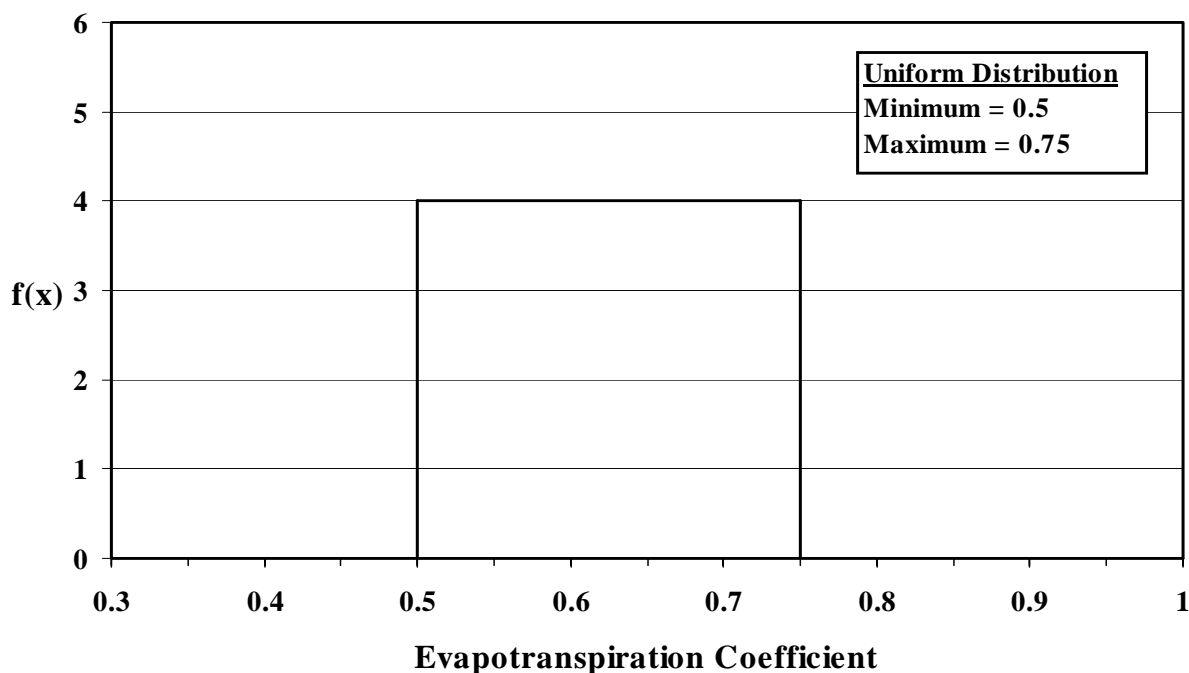


Figure 4.3-1 Evapotranspiration Coefficient Probability Density Function

4.4 Humidity

Applicable Code: RESRAD, RESRAD-BUILD

Description: In RESRAD, this parameter represents the average absolute humidity outdoors. The absolute humidity is an input used only for the computation of tritium concentration in air if tritium is present in the soil. 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.

Units: grams per cubic meter (g/m^3)

Probabilistic Input:

RESRAD

Distribution: truncated lognormal-n

Defining values for distribution:

Underlying mean value: 1.98	Lower quantile value: 0.001
Underlying standard deviation: 0.334	Upper quantile value: 0.999

RESRAD-BUILD

Distribution: uniform

Defining values for distribution:

Minimum: 6.5 Maximum: 13.1

Discussion: RESRAD and RESRAD-BUILD require input for the absolute humidity, the actual concentration of water vapor in air. The relevant data available are given in terms of the relative humidity. The relative humidity 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 relative humidity (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% relative humidity corresponds to an absolute humidity range of 6.5 to 13.1 g of water per cubic meter at 1 atmosphere pressure and 24°C (75°F). The probability density function is shown in Figure 4.4-1. 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.

For RESRAD, data from 231 weather stations across the conterminous 48 U.S. states, most with data for more than 30 years of record, 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 4.4-2. This distribution is only indicative of what might be expected, because the sampling is not representative of a uniform grid across the United States, although it is indicative of the larger population centers. Site-specific data should be used when available.

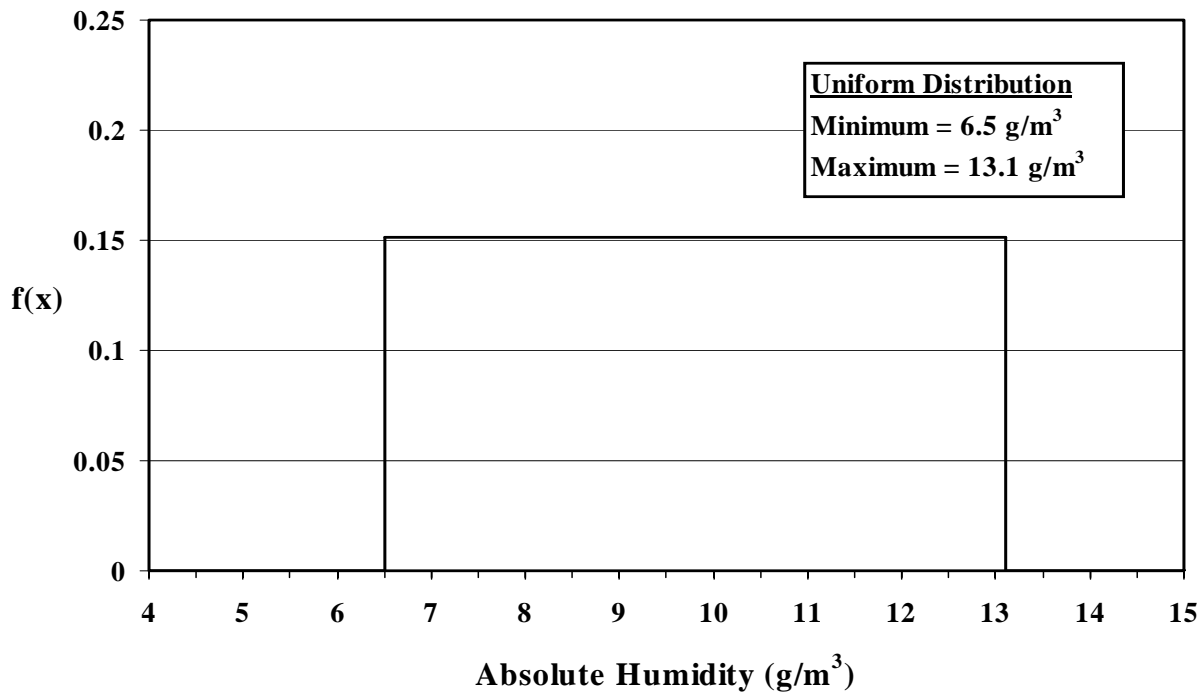


Figure 4.4-1 Absolute Humidity Probability Density Function for RESRAD-BUILD

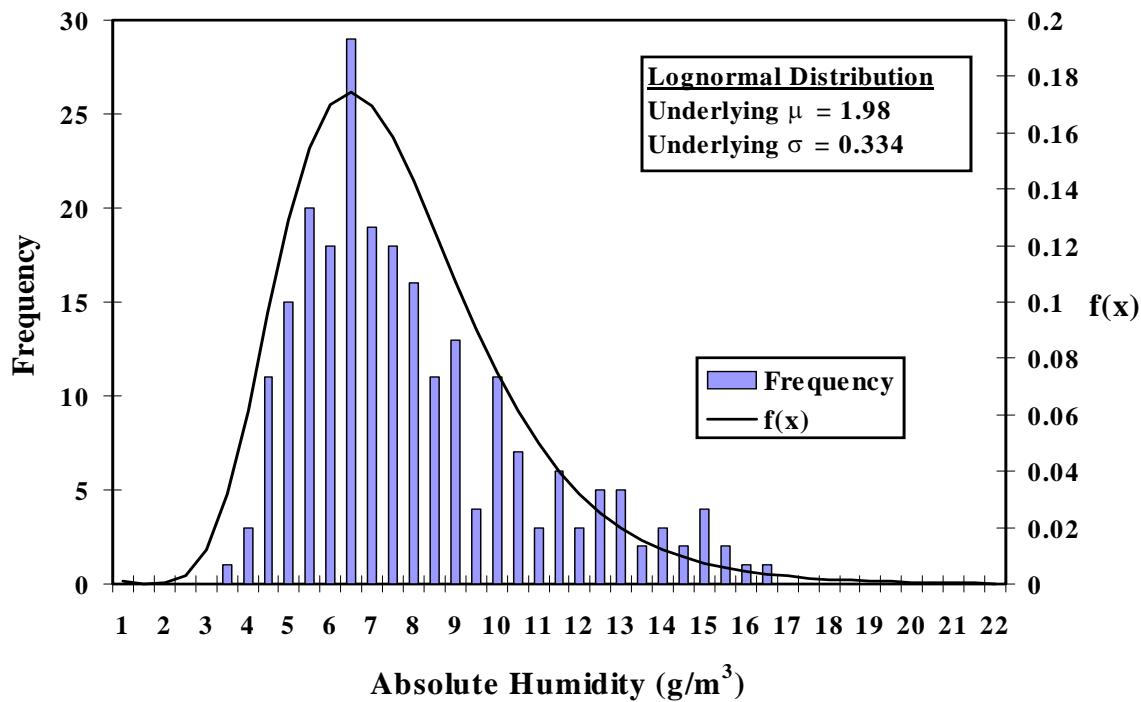


Figure 4.4-2 Absolute Humidity Probability Density Function for RESRAD

4.5 Wind Speed

Applicable Code: RESRAD

Description: The wind speed represents the annual average wind speed at a site.

Units: meters per second (m/s)

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value :	1.445	Lower limit:	1.4
Underlying standard deviation:	0.2419	Upper limit:	13

Discussion: The wind speed at a given location varies by time of day and by season. Wind speed distribution at a given site has been characterized by both lognormal (Luna and Church, 1974; Justus et al., 1976) and Weibull distributions (Justus et al., 1976). Annual average wind speed varies by location across the United States. To obtain a reasonable estimate for a nationwide distribution for the United States, annual average wind speed data from 271 U.S. weather stations were analyzed (NCDC, 1999). The average number of years of recorded data available for each station was 43 years.

The nationwide distribution was shown to be fit well by a lognormal distribution. Bayesian estimation was used to fit the probability density function shown in Figure 4.5-1 to a lognormal distribution. The maximum likelihood mean and standard deviation for the wind speed distribution were estimated to be 1.445 and 0.2419, respectively. Thus, the median (50th percentile) of the distribution corresponds to 4.2 m/s ($e^{1.445}$), near the national average wind speed of 4.1 m/s as determined by taking the arithmetic average of the 271 station annual averages. Lower and upper limits of 1.4 and 13 m/s imposed on the distribution correspond to the 0.000001 and 0.999999 quantiles, respectively.

This distribution is only indicative of what might be expected, because the sampling is only of limited size (271 data points) and is not representative of a uniform grid across the United States. Also, monitor sites are not always representative of all nearby areas because of differences in terrain over relatively short distances.

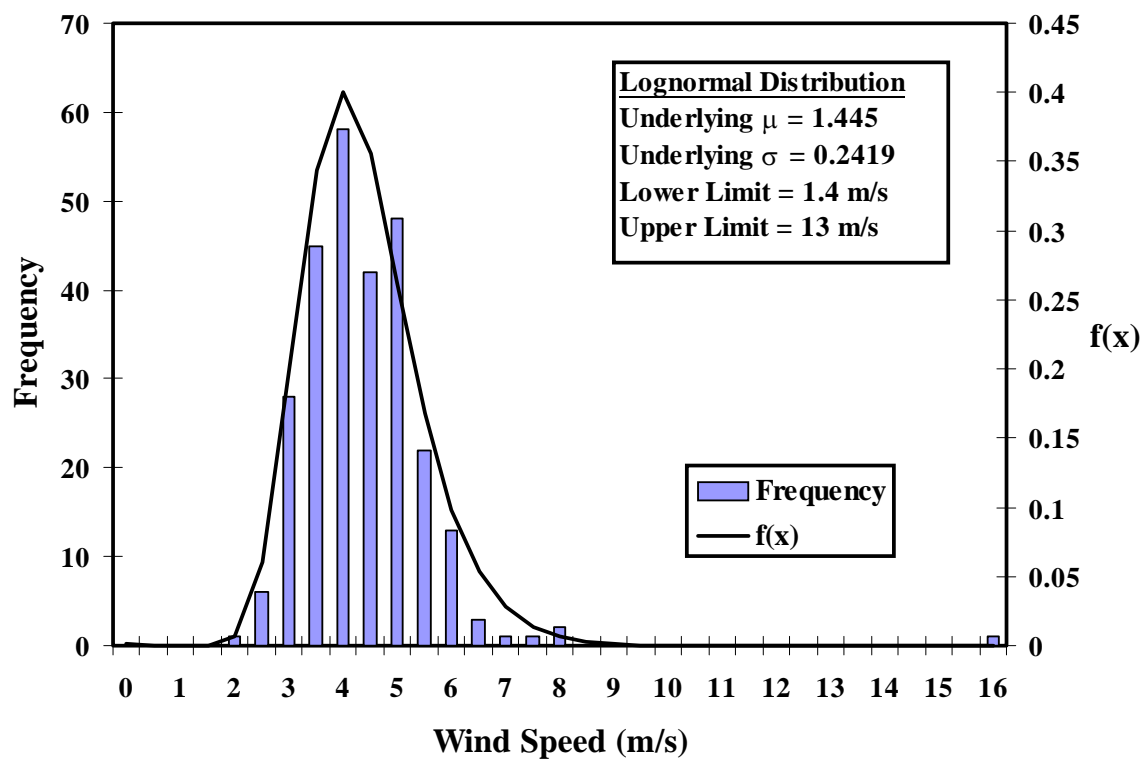


Figure 4.5-1 Wind Speed Histogram and the Fitted Probability Density Function

4.6 Mass Loading for Inhalation

Applicable Code: RESRAD

Description: This parameter represents the concentration of contaminated airborne particulate matter (e.g., soil) that is respirable.

Units: micrograms per cubic meter ($\mu\text{g}/\text{m}^3$)

Probabilistic Input:

Distribution: user-defined continuous with linear interpolation

Defining Values for Distribution: See Table 4.6-1 for the input values.

Discussion: Resuspended contaminated soil and dust pose a radiological inhalation risk. The mass loading input to RESRAD provides the time-averaged respirable concentration of contaminated soil and dust. The respirable portion of resuspended material can be represented by the PM-10 fraction of airborne particulate matter (particulates $\leq 10 \mu\text{m}$ in diameter). The PM-10 fraction represents particles that are capable of being deposited in thoracic (tracheobronchial and alveolar) portions of the lower respiratory tract (EPA, 1999c). Ambient PM-10 air concentrations were obtained from the EPA's Aerometric Information Retrieval System (AIRS) (EPA, 1999d).

Five years (1994-1998) of annual average ambient PM-10 air concentration measurements and the average for 1999 through November 27 for approximately 1,790 air monitoring stations across the United States and its territories were analyzed. The data are only indicative of what might be expected because the set of monitoring stations included is not representative of a uniform grid across the United States. Furthermore, the monitor sites are not always representative of all nearby areas because of differences in local weather patterns. Figure 4.6-1 presents a histogram of the data in conjunction with the cumulative distribution function (CDF) for the PM-10 data. Table 4.6-1 lists the values used for the CDF.

The RESRAD code uses the mass loading factor to estimate the annual inhalation dose. Therefore, use of a high, short-term loading will result in an overestimate of the annual dose. A time average mass loading factor should be used in RESRAD for a more realistic dose estimate.

Table 4.6-1 Cumulative Distribution Function for Mass Loading for Inhalation

Mass Loading ($\mu\text{g}/\text{m}^3$)	Cumulative Probability	Mass Loading ($\mu\text{g}/\text{m}^3$)	Cumulative Probability	Mass Loading ($\mu\text{g}/\text{m}^3$)	Cumulative Probability
0	0	36	0.9151	72	0.9974
2	0.0001	38	0.9349	74	0.9977
4	0.0015	40	0.9495	76	0.9983
6	0.0040	42	0.9592	78	0.9984
8	0.0151	44	0.9675	80	0.9984
10	0.0315	46	0.9736	82	0.9985
12	0.0558	48	0.9799	84	0.9986
14	0.0904	50	0.9844	86	0.9986
16	0.1365	52	0.9882	88	0.9988
18	0.2061	54	0.9905	90	0.9988
20	0.3020	56	0.9919	92	0.9990
22	0.4213	58	0.9928	94	0.9990
24	0.5433	60	0.9937	96	0.9990
26	0.6542	62	0.9948	98	0.9991
28	0.7448	64	0.9957	100	0.9992
30	0.8119	66	0.9962	>100	1.0000
32	0.8579	68	0.9965		
34	0.8897	70	0.9970		

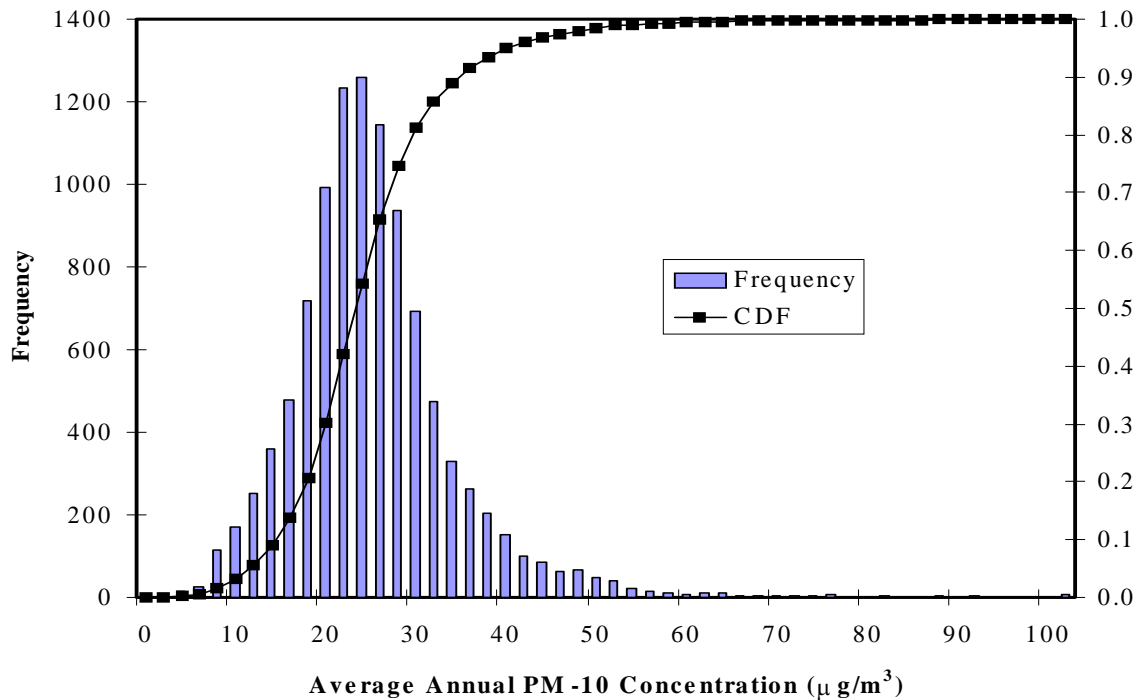


Figure 4.6-1 Mass Loading Histogram and Cumulative Distribution Function

5 HUMAN INTAKE PARAMETER DISTRIBUTIONS

5.1 Inhalation Rate

Applicable Code: RESRAD, RESRAD-BUILD

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

Units: cubic meters per year (m^3/yr) (RESRAD)
cubic meters per day (m^3/d) (RESRAD-BUILD)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

RESRAD

Minimum: 4,380 Maximum: 13,100 Most likely: 8,400

RESRAD-BUILD

Minimum: 12 Maximum: 46 Most likely: 33.6

Discussion: The range of estimates of inhalation rate (Table 5.1-1) 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, 1989a, 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 for the population under study. In the RESRAD code, the yearly inhalation rate is used, which represents the average values for different activity levels both indoors and outdoors for the

Table 5.1-1 Inhalation Rate Distributions

Basis	Distribution Type	Inhalation Rate (m ³ /d)				References
		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, 1989a, 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, 1989a, 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%.

residential scenario. The hourly average inhalation rate in RESRAD-BUILD is meant to represent workers in an occupational setting. For assessments involving other specific activities, inhalation rates can be selected that are thought to be representative of these particular activities. Similarly, if receptors of a certain age group are being evaluated, breathing rate values should be selected specifically for that age group.

Layton (1993) proposed three alternative approaches for deriving inhalation rates that are based on oxygen uptake associated with energy expenditures: (1) average daily intakes of food energy from dietary surveys, (2) average daily energy expenditure calculated from ratios of total daily expenditure to basal metabolism, and (3) daily energy expenditures determined from a time-activity survey. These approaches consistently yield inhalation rate estimates that are lower than 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 5.1-2 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 m³/d for women and 15.2 m³/d for men.

The residential scenario defines three exposure situations or contexts for resident farmers: indoors, outdoors, and gardening. The inhalation rate parameters represent the annual average breathing rate of the average member of the screening group for these three contexts; Table 5.1-3 summarizes the recommended default values for each. Because of the wide variation in inhalation rates possible for the residential scenario, a triangular distribution was selected to represent the rate of the average member of the critical group. The most likely value was taken to be 8,400 m³/yr (23 m³/d) as recommended by Beyeler et al. (1998b) for the on-site residential scenario. A minimum value of 4,380 m³/yr (0.5 m³/h) was selected on the basis of recommendations for sedentary adult activities, and the maximum value of 13,100 m³/yr (1.5 m³/h) selected corresponds to moderate outdoor activities (see Table 5.1-2). Figure 5.1-1 displays the probability distribution function for inhalation selected for the residential scenario.

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 m³/d (1.4 m³/h) as recommended in Beyeler et al. (1998a). The minimum value of 12 m³/d (0.5 m³/h) was selected on the basis of recommendations for sedentary adult activities, and

a maximum value of 46 m³/d (1.9 m³/h) was selected because it represented the highest average value reported in Beyeler et al. (1998a) for workers in light industry and falls within the range of moderate to heavy activities for both adults and outdoor workers (Table 5.1-2).

Table 5.1-2 Summary of EPA's Recommended Values for Inhalation

Population	Mean	Population	Mean
Long-Term Exposures		Short-Term Exposures	
Infants (<1 year)	4.5 m ³ /d	Adults	
Children		Rest	0.4 m ³ /h
1-2 years	6.8 m ³ /d	Sedentary Activities	0.5 m ³ /h
3-5 years	8.3 m ³ /d	Light Activities	1.0 m ³ /h
6-8 years	10 m ³ /d	Moderate Activities	1.6 m ³ /h
9-11 years		Heavy Activities	3.2 m ³ /h
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	Outdoor Workers	
Females	12 m ³ /d	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 m³/h.

Source: EPA (1997).

Table 5.1-3 Recommended Default Inhalation Rates for the Residential Scenario

Exposure Context/Parameter	Inhalation Rate (m ³ /h)	Time Spent (days/year)
Indoors	0.9	240
Outdoors	1.4	40.2
Gardening	1.7	2.92
Average on-site rate	23 m ³ /d	

Source: Beyeler (1998b).

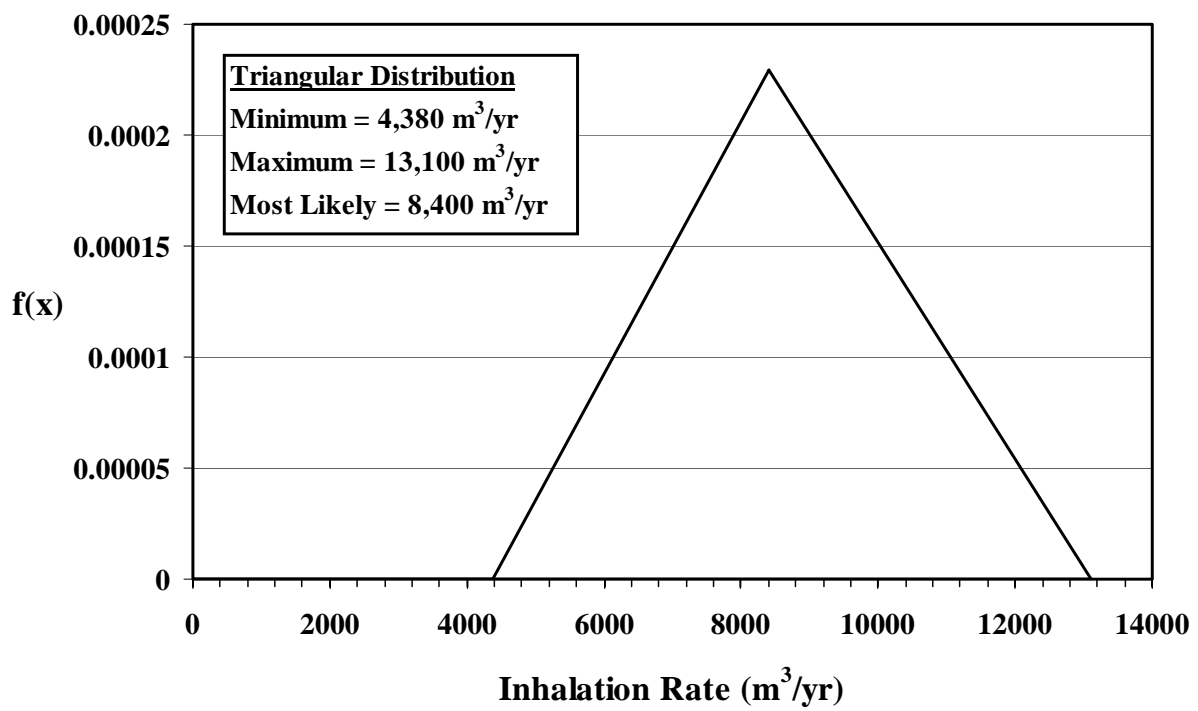


Figure 5.1-1 Inhalation Rate Probability Density Function for RESRAD

5.2 Drinking Water Intake

Applicable Code: RESRAD

Description: The drinking water intake rate is defined as the average amount of water consumed by an adult per unit of time. It includes juices and beverages containing tap water (e.g., coffee).

Units: liters per year (L/yr)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value:	6.015	Lower quantile value:	0.001
Underlying standard deviation:	0.489	Upper quantile value:	0.999

Discussion: The distribution of the drinking water intake rate generally varies from 0.10 to 3 L/d, depending on the age, body weight, and activity level of the receptor. A rigorous statistical treatment of water intake data for a large data set ($n = 26,081$; Ershow and Cantor, 1989) is provided by Roseberry and Burmaster (1992). Estimates are provided for (1) tap water intake (the sum of water drunk directly as a beverage and water added to foods and beverages during preparation); and (2) total water intake, which includes tap water intake and intrinsic water intake (i.e., the water intrinsic in foods as purchased). The values associated with tap water intake are more likely to apply for risk assessment purposes.

The mean and standard deviations for the underlying normal distribution for five age categories are provided by Roseberry and Burmaster (1992). Alternatively, the mean and standard deviation for the entire population may be used when intake over a lifetime is being evaluated. Finley et al. (1994) used the same data set to generate age-specific cumulative distributions for drinking water intake. The results of Roseberry and Burmaster (1992) are reported here (see Table 5.2-1) because of ease of use in Monte Carlo analyses. The mean total tap water intake rates for the two adult populations (age 20 to 65 years, and 65+ years) were estimated to be 1.27 and 1.34 L/d, respectively.

Other parameters that correlate with drinking water intake are the body weight and activity level of the receptor evaluated. Temperature and humidity levels also influence drinking water intake rates.

Table 5.2-1 Drinking Water Intake Rate^a Distributions

Distribution Type	Age Range	Mean	Standard Deviation	Comments
Lognormal				
Total water	<1	6.98	0.29	μ and SD of underlying normal distribution shown. Transforms to mL/d. Based on $n = 26,081$ (1.5% <1; 21.4% 1-<11; 22.2% 11-<20; 45% 20-<65; 9.7% >65).
	1 - <11	7.18	0.34	
	11 - <20	7.49	0.35	
	20 - <65	7.56	0.40	
	>65	7.58	0.36	
	Total	7.49	0.41	
Tap water				
Tap water	<1	5.59	0.62	
	1 - <11	6.43	0.50	
	11 - <20	6.67	0.54	
	20 - <65	7.02	0.49	
	>65	7.09	0.48	
	Total	6.86	0.58	

^a 97.5 percentile intake rate = $\exp [\mu + (1.96\sigma)]$,

75 percentile intake rate = $\exp [\mu + (0.6745\sigma)]$,

50 percentile intake rate = $\exp [\mu]$,

mean intake rate = $\exp [\mu + 0.5\sigma^2]$.

Source: Roseberry and Burmaster (1992) (based on 1977-1978 Nationwide Food Consumption Survey, USDA).

The American Industrial Health Council's (AIHC's) *Exposure Factors Sourcebook* (AIHC, 1994) presents drinking water intake recommendations for adults. The recommended mean drinking water intake is 1.4 L/d, and the reasonable "worst-case" value is 2.0 L/d.

In its *Exposure Factors Handbook*, the EPA (1997) has compiled the available studies on drinking water consumption rate. The EPA has classified the studies as either key studies or relevant studies on the basis of the applicability of their survey designs to exposure assessment of the entire U.S. population. On the basis of the results of the key studies, the recommended drinking water intake rates for different age groups/populations are shown in Table 5.2-2. The table also presents the mean, 50th, 90th, and 95th percentile values.

The age-specific rates for adults recommended by the EPA (1997) are based on data from the 1977-1978 USDA Nationwide Food Consumption Survey (EPA, 1984). The same data were used by Roseberry and Burmaster (1992) and by Ershow and Cantor (1989) to develop intake distributions. In addition, the lognormal distributions derived in

Table 5.2-2 Summary of Recommended Drinking Water Intake Rates^a

Age Group/ Population	Mean	Percentiles		
		50th	90th	95th
<1 year	0.30 L/day 44 mL/kg-day	0.24 L/day 35 mL/kg-day	0.65 L/day 102 mL/kg-day	0.76 L/day 127 mL/kg-day
<3 years	0.61 L/day	-	1.5 L/day	-
3-5 years	0.87 L/day	-	1.5 L/day	-
1-10 years	0.74 L/day 35 mL/kg-day	0.66 L/day 31 mL/kg-day	1.3 L/day 64 mL/kg-day	1.5 L/day 79.4 mL/kg-day
11-19 years	0.97 L/day 18 mL/kg-day	0.87 L/day 16 mL/kg-day	1.7 L/day 32 mL/kg-day	2.0 L/day 40 mL/kg-day
Adults	1.4 L/day 21 mL/kg-day	1.3 L/day 19 mL/kg-day	2.3 L/day 34 mL/kg-day	
Pregnant women	1.2 L/day 18.3 mL/kg-day	1.1 L/day 16 mL/kg-day	2.2 L/day 35 mL/kg-day	2.4 L/day 40 mL/kg-day
Lactating women	1.3 L/day 21.4 mL/kg-day	1.3 L/day 21 mL/kg-day	1.9 L/day 35 mL/kg-day	2.2 L/day 37 mL/kg-day
Adults in high activity/ hot climate conditions	0.21 to 0.65 L/hour, depending on ambient temperature and activity level			
Active adults	6 L/day (temperate climate) to 11 L/day (hot climate)			

^a Source: EPA (1997).

Roseberry and Burmaster (1992) were recommended as a good mathematical description of drinking water intake by the EPA (1997). Therefore, the suggested parameter distribution for drinking water intake in RESRAD is taken to be the lognormal distribution for adults in Roseberry and Burmaster (1992). Adjusted for drinking rate input units of liters per year (409.5 L/yr), the adjusted underlying mean and standard deviation are 6.015 and 0.489, respectively. The probability density function is shown in Figure 5.2-1.

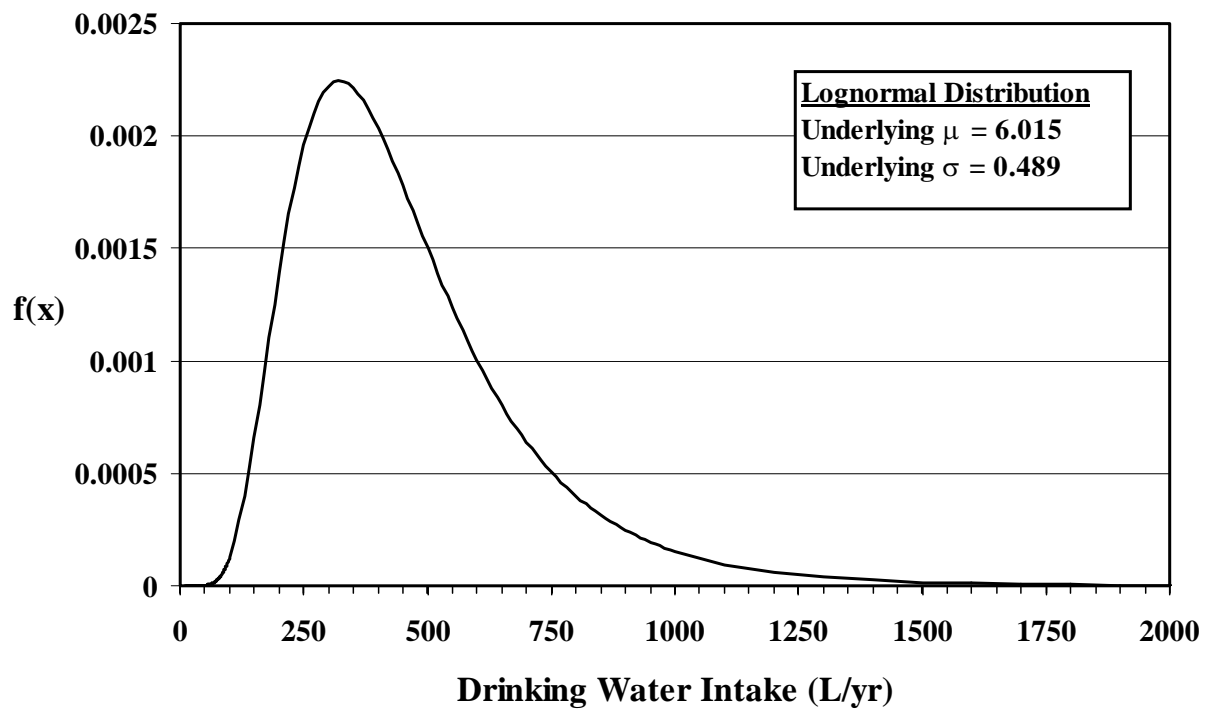


Figure 5.2-1 Drinking Water Intake Probability Density Function

5.3 Milk Consumption Rate

Applicable Code: RESRAD

Description: The milk consumption rate is the amount of fluid milk (beverage) consumed per year.

Units: liters per year (L/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 60 Maximum: 200 Most likely: 102

Discussion: The milk consumption rate can vary for different population groups, ages, and geographic locations. In RESRAD, the consumption rate of milk is for fluid milk only. This rate is required by the RESRAD computer code when the milk ingestion pathway is active (Yu et al., 1993a).

The EPA's *Exposure Factor Handbook* (EPA, 1997) provides milk consumption rates that were obtained from the USDA's *National Food Consumption Survey* (NFCS) (USDA, 1980, 1992), *Continuing Survey of Food Intakes by Individuals* (USDA, 1996a,b), and *Food Consumption, Prices and Expenditures 1970-1992* (USDA, 1993).

An indication of consumption rates for a variety of foodstuffs is provided in the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The estimates of food for human consumption are derived by subtracting other measurable uses, such as exports, industrial uses, farm inputs, and end-of year stocks, from total supply (the sum of domestic production, imports and beginning stocks) (Putman et al., 1999). Hence, the data provided in this report would be an upper bound on human consumption assuming no spoilage or wastes. The food consumption rates are grouped by food categories, with several subcategories under the major categories (e.g., major category — dairy products, subcategory — beverage milk). Further information, such as the individual consumption rates for each food type, is provided in the report for each year reported (Putnam et al., 1999).

An average fresh milk consumption rate of 294 g/d was estimated by the NFCS for 1977-1978 (EPA, 1997). This average daily consumption value corresponds to an annual consumption rate of 104 L/yr averaged over all age brackets. The largest milk

consumption rate was in the 10- to 14-year-old age range. This group consumed approximately 456 g/d (162 L/yr), which is over 2.5 times higher than the consumption rate of the age bracket (40-59) that consumed the least amount of milk. The age-bracketed milk consumption rates are provided in Table 5.3-1.

The USDA *Food Consumption, Prices and Expenditures Report* (Putnam, 1999) provides year-bracketed consumption rates for beverage milk for the years 1972-1997. The average beverage milk consumption rate was estimated to be approximately 101 L/yr, which agrees well with the NFCS data. Table 5.3-2 provides the yearly milk consumption rate averaged in four-year intervals. The largest milk consumption rate in a 4-year interval occurred between 1972-1976, when the per capita beverage milk consumption averaged 113 L/yr. After that time, per capita milk consumption declined to the 1997 value of 90 L/yr.

A triangular probability distribution was chosen for the milk consumption rate. The minimum value was taken to be 60 L/yr, which corresponded to the consumption rate of 40-59 age bracket of the NFCS study. The maximum milk consumption rate was set at 200 L/yr, which is equal to the fluid milk consumption rate stipulated in NRC Regulatory Guide 1.109 for a child (NRC, 1977). A value of 102 L/yr was chosen as the most likely value because it is the average of the NFCS and USDA values. Figure 5.3-1 shows the resulting probability density function for the milk consumption rate.

Table 5.3-1 Mean per Capita Intake of Fresh Cow's Milk

Age Group (years)	Fluid Milk (g/d)
<1	272
1-4	337
5-9	446
10-14	456
15-19	405
20-24	264
25-39	218
30-39	183
40-59	169
60+	192
Average	294

Source: EPA (1997).

Table 5.3-2 Annual per Capita Consumption of Beverage Milk

Year	Consumption (L/yr)
1972-1976	112
1977-1981	105
1982-1986	99
1987-1999	97
1992-1996	92
1997	93
Average (1972-1997)	101

Source: Derived from Putnam et al. (1999).

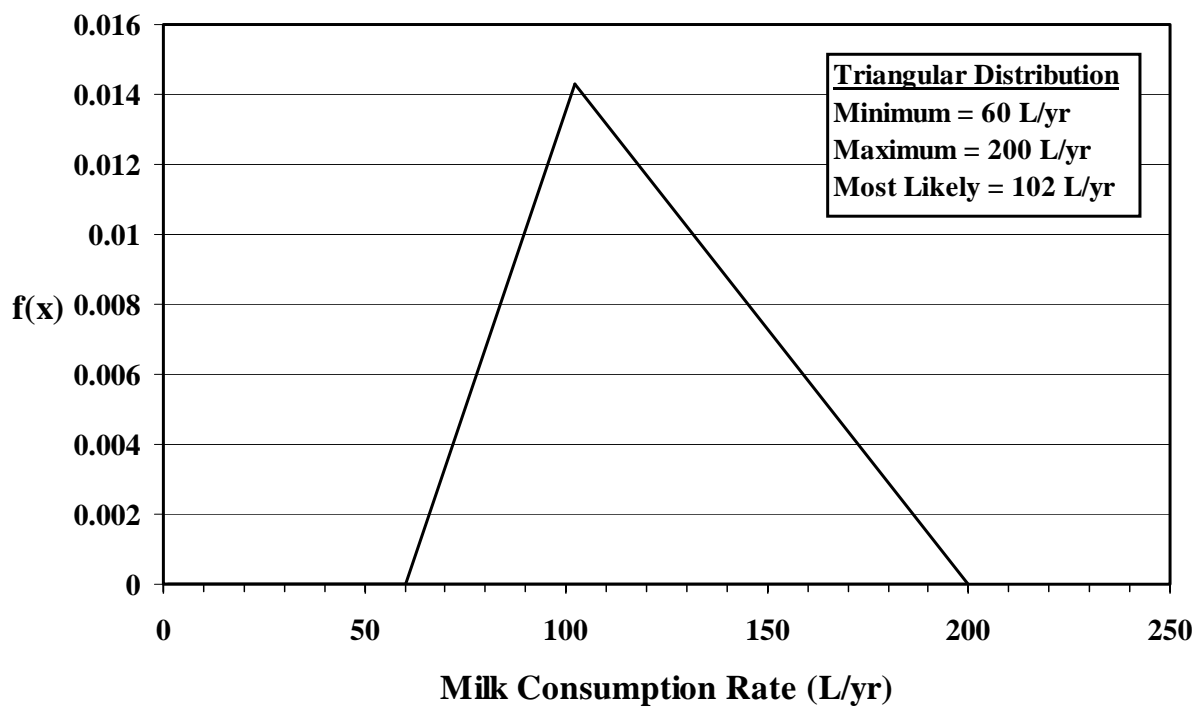


Figure 5.3-1 Milk Consumption Rate Probability Density Function

5.4 Fruit, Vegetable, and Grain Consumption Rate

Applicable Code: RESRAD

Description: The fruit, vegetable, and grain consumption rate is the total quantity of these food items (contaminated and noncontaminated) consumed per year.

Units: kilograms per year (kg/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 135 Maximum: 318 Most likely: 178

Discussion: The fruit, vegetable, and grain consumption rate can vary for different population groups, ages, and geographic locations. In RESRAD, the consumption rate for fruits, vegetables, and grain is a composite value obtained by summing the individual consumption rates for fresh fruits, fresh vegetables (nonleafy), and grain.

The vegetable portion of this parameter does not include leafy vegetables consumed. Leafy vegetable consumption is a separate parameter in the RESRAD computer code (Yu et. al., 1993a). In addition, the fruit, vegetable, and grain consumption rate should only apply to fresh fruits and vegetables. This parameter is used when the plant ingestion exposure pathway is active.

The EPA published the *Exposure Factors Handbook* (EPA, 1997) to summarize data on human behaviors and to recommend values to use in modeling those activities. The consumption rates for fruits, vegetables, and grain provided in the handbook were obtained from the USDA's *National Food Consumption Survey* (USDA, 1980, 1992), *Continuing Survey of Food Intakes by Individuals* (USDA, 1996a,b), and *Food Consumption, Prices and Expenditures 1970-1992* (USDA, 1993).

The *Exposure Factors Handbook* (EPA, 1997) provides intake rates in units of grams of food consumed per kilogram of body weight per day. The data are grouped by age, season, urbanization (central city, nonmetropolitan, and suburban), race, and region (Midwest, Northeast, South, and West). Converting the intake rates into units of kg/yr by multiplying by a single average body weight is inappropriate because intake rates were indexed to the reported body weights of the survey respondents. An average adult body weight of approximately 72 kg was estimated by averaging the combined male-female body weights contained in Table 7-2 of the *Exposure Factors Handbook* (EPA, 1997). Since the

results are grouped by age, the average consumption rate was derived for each food class on the basis of the dietary habits of adults (ages 20-70+). The average consumption rates on a per-kilogram-body-weight basis are provided in Table 5.4-1 for each age group.

An indication of food consumption for a variety of foodstuffs is provided in the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The estimates of food for human consumption are derived by subtracting measurable uses such as exports, industrial uses, farm inputs, and end-of year stocks from total supply (the sum of domestic production, imports, and beginning stocks) (Putnam et al., 1999). Hence, the data provided in this report would be an upper bound on human consumption assuming no spoilage or wastes. The foods are grouped by totals, fresh fruits/vegetables, and major subcategories (citrus, noncitrus, etc.). Further information, such as the individual consumption rates for each food type, is provided in the report for each year reported (Putnam et al., 1999).

Fresh fruits and vegetables accounted for approximately 42% and 44%, respectively, of the total fruits and vegetables consumed during the 25-year period from 1972 through 1997 (Putnam et al., 1999). The fresh vegetable percentage remained relatively constant throughout the 25-year period, while the fresh fruit consumption rose from 40% from 1972-1976 to 45% in 1997. The fraction of nonleafy fresh vegetables¹ consumed from 1972-1997 was estimated at 0.67 of the total fresh vegetable consumption rate. Table 5.4-2 provides consumption values for fresh fruits, fresh vegetables, and grain for the years 1972-1997 (Putnam et al., 1999).

A probability distribution (triangular, see Figure 5.4-1) for the fruit, vegetable, and grain consumption rate was derived from the information provided in the EPA *Exposure Factor Handbook* (EPA, 1997) and the USDA report *Food Consumption, Prices, and Expenditures 1970-1997* (Putnam et al., 1999). The lower bound of the distribution was obtained by averaging the median per capita consumption rate for ages 20-70+ provided in Table 5.4-1 and multiplying by the average weight of an adult. Correction factors of 0.42 and 0.44 were applied to the fruit and vegetable consumption rate to account for the consumption of fresh fruits and vegetables only. A further correction factor of 0.67 was applied to the vegetable consumption rate to account for the intake of nonleafy vegetables only. These values were summed to yield a single consumption rate for fruit, vegetables, and grains. The upper bound of the distribution was estimated in the same manner, except the 95th percentile was used for the per-capita consumption rate instead of the median value. The average value of the total given in Table 5.4-2 was used for the most likely value of the triangular distribution.

¹ Nonleafy vegetables are all vegetables except cabbage, cauliflower, broccoli, celery, lettuce, and spinach (EPA, 1997).

**Table 5.4-1 Median per Capita Intake
of Total Fruits, Vegetables, and Grains
(g/kg-d as consumed)**

Age Group (years)	Total Fruits	Total Vegetables	Total Grains
<1	14.9	6.8	7.0
1-2	11.8	7.9	10.6
3-5	8.4	7.1	9.5
6-11	5.0	5.5	6.4
12-19	2.2	3.8	3.8
20-39	1.9	3.5	3.1
40-69	2.1	3.7	2.8
70+	3	4.1	3.3

Source: EPA (1997).

**Table 5.4-2 Per Capita Consumption Values for
Fresh Fruits, Fresh Vegetables, and Grains
(kg/yr)**

Year	Fresh Fruits	Fresh Vegetables (nonleafy)	Grains	Total
1972-1976	45	45	63	152
1977-1981	47	43	65	154
1982-1986	51	46	69	166
1987-1999	54	50	81	185
1992-1996	57	55	88	200
1997	61	58	91	210
Average (1972-1997)	52	50	76	178

Source: Derived from Putnam et al. (1999).

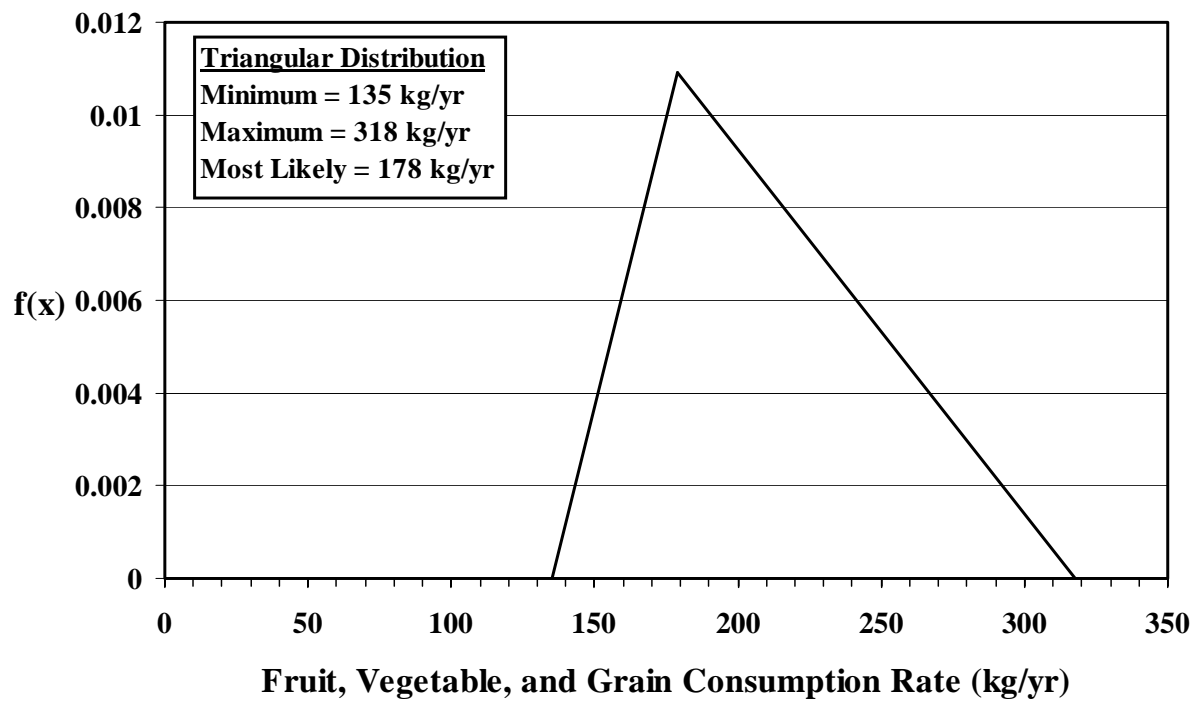


Figure 5.4-1 Fruit, Vegetable, and Grain Consumption Rate Probability Density Function

5.5 Aquatic Food Contaminated Fraction

Applicable Code: RESRAD

Description: The aquatic food contaminated fraction is the fraction of aquatic foods that are consumed from the site that are contaminated.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0 Maximum: 1 Most likely: 0.39

Discussion: The aquatic foods contaminated fraction can range from 0 (none of the seafood products consumed are contaminated) to 1 (all seafood products consumed are contaminated). The balance of the aquatic foods (1 - aquatic food contamination fraction) is assumed to come from uncontaminated sources. The parameter is dependent on whether there is an on-site pond capable of producing seafood products, as well as dietary and other habits of the individual being modeled. The aquatic food contamination fraction is required by the RESRAD computer code when the seafood ingestion pathway is active (Yu et al., 1993a).

One measure of this parameter is the percentage of the annual seafood consumption rate from home-caught fish and shellfish. The EPA published the *Exposure Factor Handbook* (EPA, 1997) in part to summarize data on human behaviors and recommend values to use to model those activities. The consumption rates for home-consumed seafood products provided in the handbook were obtained from the USDA's *National Food Consumption Survey* (NFCS) (USDA, 1980, 1992). Data from the 1987-1988 NFCS study were used to generate the homegrown intake rates. These intake rates vary by age, season, and geographic location. Among members of fishing households, home-caught fish accounted for 38% of the total fish consumption for the year (EPA, 1997).

A triangular distribution, as displayed in Figure 5.5-1, is recommended for the aquatic food contamination fraction. Since the limits of the parameter can range from 0 (no aquatic foods consumed are contaminated) to 1 (all aquatic foods consumed are contaminated), these values were chosen for the upper and lower bounds of the distribution. A most likely value of 0.39 was chosen on the basis of the recreational fishing habits and consumption rates provided in the *Exposure Factor Handbook* (EPA, 1997).

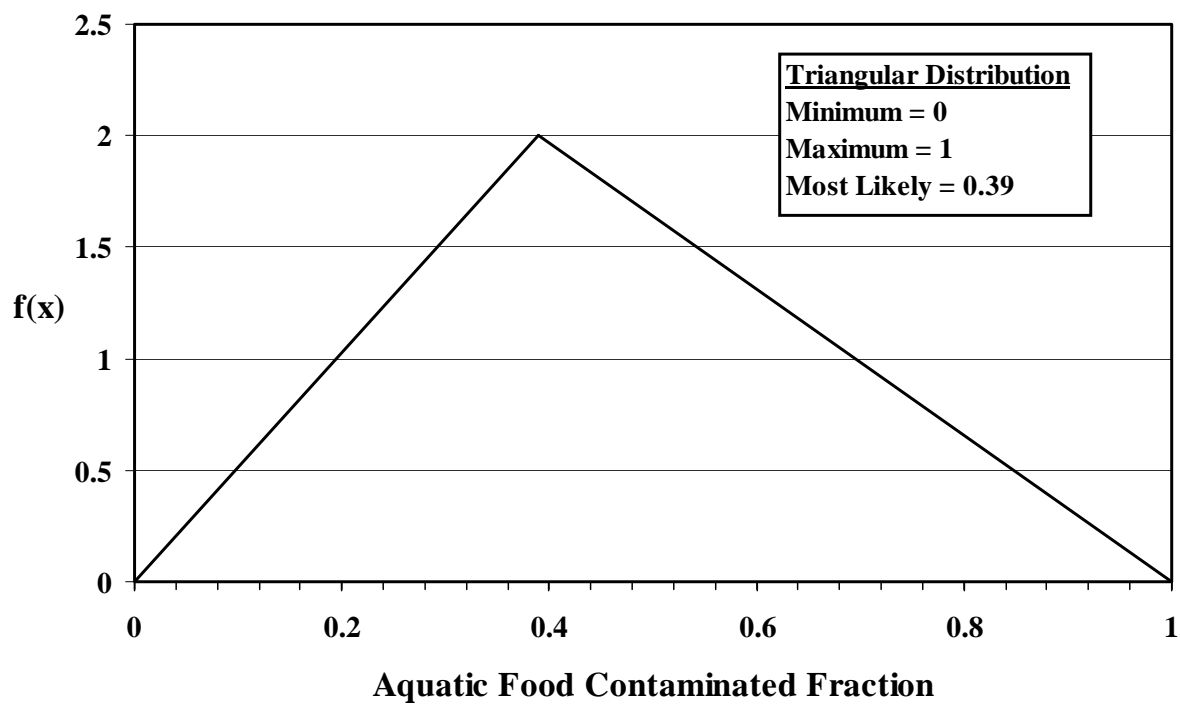


Figure 5.5-1 Aquatic Food Contaminated Fraction Probability Density Function

5.6 Soil Ingestion Rate

Applicable Code: RESRAD

Description: Ingestion rate of soil from outdoor activities.

Units: grams per year (g/yr)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0 Maximum: 36.5 Most likely: 18.3

Discussion: The soil and dust ingestion rate varies over a wide range, depending on the age, activities, and possible dietary anomalies (e.g., pica, the desire to eat substances not normally eaten) of the receptor, and weather at the time of exposure. To date, most study has been focused on soil and dust ingestion rates for children aged 1 through 6 because of concern over elevated exposures from intensive mouthing behavior in children of this age group. Table 5.6-1 summarizes selected work.

The best data are considered to come from studies that use a mass-balance approach to estimate ingestion rates. That approach measures nonabsorbed tracer elements in soil, dust, and feces and accounts for other dietary sources of the tracers. Estimates of soil and dust ingestion rates for individuals vary from 0 mg/d (Calabrese et al., 1989) to 10 g/d (Kimbrough et al., 1984) for a child exhibiting pica. Information on the amount of soil ingested by children with abnormal soil ingestion behavior is limited. The Calabrese et al. (1991) study included one pica child among the 64 children who participated. In that study, a 3.5-year-old female exhibited extremely high soil ingestion behavior during one of the two weeks of observation. Intake ranged from 74 mg/d to 2.2 g/d during the first week and 10.1 to 13.6 g/d during the second week. These results were based on mass-balance analyses for seven tracer elements. Calabrese and Stanek (1992) concluded that the origin of the soil ingestion for the pica child was from outdoor soil, not from indoor dust. Median soil and dust ingestion rates for children in this age group are generally about 50 mg/d (Binder and Sokal, 1986; Calabrese et al., 1989; Davis and Waller, 1990; Thompson and Burmaster, 1991).

A strong inverse correlation of soil ingestion rate with precipitation has been documented (Van Wijnen et al., 1990), presumably related to the fact that precipitation decreases the opportunity for soil contact. However, no widely accepted method is

Table 5.6-1 Soil and Dust Ingestion Rate Distributions

Distribution Type	μ	SD	Comments	References
Lognormal	91 mg/d	126 mg/d	Age 1-3. Mean and SD of underlying lognormal distribution shown. $n = 65$. Based on the combined data for Al and Si tracers.	Thompson and Burmaster, 1991; based on data from Binder and Sokal, 1986
Lognormal	153 mg/d	852 mg/d	Age 1-4. Median = 29 mg/d. Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 64$. Based on data for Al tracer.	Calabrese et al., 1989
Normal	5.0 - Daycare 5.2 - Campers	0.81 - Daycare 0.55 - Campers	Age 1-4. Mean and SD of underlying normal distribution shown. $n = 292$ (daycare group); $n = 78$ (campers). Based on combined data for Al, Ti, and acid-insoluble residue tracers.	Van Wijnen et al., 1990
Lognormal	Al-39 mg/d Si-82 mg/d	Al-145 mg/d Si-123 mg/d	Age 2-7 (42% ≤ 4 years old). Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 101$. Based on data for Al and Si tracers.	Davis and Waller, 1990
Normal	195 mg/d	53 mg/d	Age applicable to 2 year olds. Although underlying distributions were not normal, the reported values are the mean and SD of mean rates obtained with different tracers, so this distribution approaches the normal (Central Limit Theorem). Based on data for Al, Si, Ti, V and Y tracers.	Sedman and Mahmood, 1994; based on data from Calabrese et al., 1989 and Binder and Sokal, 1986
Lognormal	Al-77 mg/d Si-5 mg/d	Al-65 mg/d Si-55 mg/d	Age 25-41. Mean and SD of lognormal distribution shown (underlying normal mean and SD not given). $n = 6$. Based on data for Al and Si tracers.	Calabrese et al., 1990
Lognormal	10 mg/d	94 mg/d	Age - Adults. $n = 10$. Mass balance studies on 10 adults over a period of 28 days.	Stanek et al., 1997

currently available for determining the relative contribution of outdoor soil versus indoor dust to the daily total ingestion rate, and the effect of climatic variation has yet to be determined (EPA, 1991).

Calabrese et al. (1990) also estimated soil ingestion rates for adults by using a mass-balance approach. Although the number of subjects studied (six) was too small to be certain of the distribution type, the medians were considerably lower than the mean values, suggesting that the distributions are also lognormal, as has been noted for children. The EPA (1991) recommended that the median soil ingestion rate from this study that is based on aluminum as the tracer (i.e., 50 mg/d) be used as the point estimate for adult soil ingestion in occupational settings (except for construction work). A point value of 100 mg/d for adults in residential settings was recommended (EPA, 1989b); presumably, this increased value was intended to account for certain activities that would involve greater soil ingestion than was found in the Calabrese et al. (1990) study.

Calabrese et al. (1989) studied soil ingestion among 64 children between the ages of 1 and 4 years by using eight tracer elements. That study was conducted over eight days during a two-week period and used mass-balance methodology. On the basis of the three most reliable tracer elements, the mean soil intake rate for children was estimated to be 153 mg/d based on aluminum tracer, 154 mg/d based on silicon tracer, and 85 mg/d based on yttrium tracer. Median intake rates were somewhat lower (29 mg/d for aluminum, 40 mg/d for silicon, and 9 mg/d for yttrium), 95th percentile values were 223 mg/d for aluminum, 276 mg/d for silicon, and 106 mg/d for yttrium.

Van Wijnen et al. (1990) studied soil ingestion among Dutch children aged 1 to 5 years old by using a tracer element methodology. A total of 292 children attending daycare centers were sampled during the first of two sampling periods, and 187 children were sampled in the second sampling period; 162 children were sampled during both periods. A total of 78 children were sampled at campgrounds, and 15 hospitalized children were sampled. The mean value for these groups were 162 mg/d for children in daycare centers, 213 mg/d for campers, and 93 mg/d for hospitalized children. The soil intake rates were found to be skewed, and the log transformed data were approximately normally distributed. Geometric means were 111, 174, and 74 mg/d, respectively, for daycare, camping, and hospitalized children. Van Wijnen et al. (1990) suggest that the mean value for hospitalized infants represents background intake of tracers and should be used to correct the soil intake rates for other sampling groups. Using mean values, corrected soil intake rates were 69 mg/d for daycare children and 120 mg/d for campers.

Davis and Waller (1990) used a mass-balance/tracer technique to estimate soil ingestion among children. In that study, 104 children between the ages of 2 and 7 were randomly selected from a three-city area in southeastern Washington State. Soil ingestion rates were highly variable, especially those based on titanium. This study also evaluated

the extent to which differences in tracer concentrations in house dust and yard soil affected soil ingestion rate estimates. The adjusted mean soil/dust intake rates were 64.5 mg/d for aluminum, 160 mg/d for silicon, and 268.4 mg/d for titanium. Adjusted median soil/dust intake rates were: 51.8 mg/d for aluminum, 112.4 mg/d for silicon, and 116.6 mg/d for titanium. This study was conducted over a one-week period.

Thompson and Burmaster (1991) developed parameterized distributions of soil ingestion rates for children based on a reanalysis of the data collected by Binder and Sokal (1986). The mean intake rates were 97 mg/day for aluminum, 85 mg/day for silicon, and 1,004 mg/day for titanium. On the basis of the arithmetic average of aluminum and silicon for each child, mean soil intake was estimated to be 91 mg/day. Statistical testing of the data indicated that only silicon and the average of the silicon and aluminum tracers were lognormally distributed — median: 59 mg/d, standard deviation: 126, arithmetic mean: 91 mg/d.

Sedman and Mahmood (1994) used the results of two children's tracer studies (Calabrese et al., 1989; Davis and Waller, 1990) to estimate average daily soil ingestion in young children and for a lifetime. The average ages of children were 2.4 and 4.7 years, respectively, in these two studies. The mean of the adjusted levels of soil ingestion for a two-year-old child was 220 mg/d for the Calabrese et al. (1989) study and 170 mg/d for the Davis and Waller (1990) study. From the adjusted soil ingestion estimates, based on a normal distribution of means, the mean estimate for a 2-year-old child was 195 mg/d, and the standard deviation of mean was 53 mg/d.

Stanek and Calabrese (1995) recalculated ingestion rates that were estimated in three mass-balance studies (Calabrese et al., 1989; Davis and Waller, 1990 for children's soil ingestion; and Calabrese et al., 1990 for adult soil ingestion) using the best tracer method (BTM). This method allows for the selection of the most recoverable tracer for a particular subject or group of subjects. For adults, Stanek and Calabrese (1995) used data for eight tracers from the Calabrese et al. (1990) study to estimate soil ingestion by the BTM. On the basis of the median of the soil ingestion rates for the best four tracer elements, the average adult soil ingestion rate was estimated to be 64 mg/d, with a median of 87 mg/d. The 90th percentile soil ingestion was 142 mg/d (18 subject weeks for six adults). For children, Stanek and Calabrese (1995) used data on eight tracers from Calabrese et al. (1989) and data on three tracers from Davis and Waller (1990) to estimate soil ingestion rates. On the basis of the median of soil ingestion estimates from the best four tracers in the Calabrese et al. (1989) study, the mean soil ingestion rate was 132 mg/d, and the median was 33 mg/d. The 95th percentile value was 154 mg/d (128 subject weeks, 64 children).

For the 101 children in the Davis and Waller (1990) study, the mean soil ingestion rate was 69 mg/d and the median was 44 mg/d. The 95th percentile estimate was

246 mg/d. When the Calabrese et al. (1989) and Davis and Waller (1990) studies were combined, the soil ingestion was estimated to be 113 mg/d (mean); 37 mg/d (median); and 217 mg/d (95th percentile), using BTM.

Sheppard (1995) summarized the available literature on soil ingestion to estimate the amount of soil ingestion in humans for the purposes for risk assessment. He categorized the available soil ingestion studies into two general approaches: (1) those that measured the soil intake rate with the use of tracers in the soil, and (2) those that estimated soil ingestion based on activity (e.g., hand-to-mouth) and exposure duration. Sheppard assumed that the data from the previous studies were lognormally distributed because of the broad range, the concept that soil ingestion is never zero, and the possibility of very high values. The geometric mean for soil ingestion rate for children under six was estimated to be 100 mg/d. For children above 6 and adults it was estimated to be 20 mg/d.

Stanek et al. (1997) studied soil ingestion in 10 adults (5 males, 5 females) in the age range of 22-45 years during the months of September through November by using the mass-balance approach. Soil ingestion estimates indicated that the average adult ingested 10 mg/d of soil, the upper 95th percentile value was 331 mg/d.

Simon (1998) reviewed much of the available literature on soil ingestion and lists a set of soil ingestion parameters for nine different lifestyle scenarios for adults and children. Values are listed for inadvertent soil ingestion and also for geophagia¹ (intentional soil ingestion). Table 5.6-2 gives the soil ingestion parameters for various lifestyle scenarios from the Simon (1998) study. These parameter values are presented either as triangular distributions, specified as Tri(minimum, mode, maximum) or lognormal distributions, specified as LN(geometric mean, geometric standard deviation). Lifestyle scenarios 1-7 may apply to localized populations within the United States or elsewhere, depending on the knowledge or judgment of the risk assessor. Lifestyle scenarios 8 and 9 would have greater applicability for scenarios outside of the United States. Simon (1998) assigned lognormal distributions to represent inadvertent ingestion for children and adults and triangular distributions for geophagia among adults and children. For the U.S. population, suggested inadvertent ingestion geometric mean values vary from 0.05 g/d to 0.2 g/d for adults and 0.1 g/d to 0.2 g/d for children. The geometric standard deviation of 3.2 was assigned for adults and 4.2 for children.

The EPA has recommended a mean soil ingestion rate of 50 mg/d for adults, but does not have a recommended upper percentile value because of the lack of data (EPA,

¹ Geophagia is defined to be a condition in which the patient eats inedible substances, as chalk, clay or earth. It is agreed by many that geophagia or earth eating is a special case of pica.

Table 5.6-2 Soil Ingestion Model Parameters for Various Lifestyle Scenarios

Lifestyle Scenarios	Adult		Child (ages 1 through 6 yr)	
	Inadvertent Ingestion (g/d)	Geophagia (g/d)	Inadvertent Ingestion (g/d)	Geophagia (g/d)
Occupations on tilled agriculture land (no homes) – bare part of year, vegetated part of year (Scenario 1)	LN(0.1, 3.2)	0	0	0
Occupations on pasture land (no homes) – heavily vegetated (Scenario 2)	LN(0.05, 3.2)	0	0	0
Occupations on pasture land (no homes) – sparsely vegetated, range land for grazing (Scenario 3)	LN(0.1, 3.2)	0	0	0
Occupations at construction sites (no homes) – distributed by earth-moving, traffic, bulldozing, etc. (Scenario 4)	LN(0.1, 3.2)	0	0	0
Rural lifestyles (w/homes) – heavily vegetated, forests and fields (Scenario 5)	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.1, 4.2)	Tri(1.0, 3.0, 5.0)
Rural lifestyles (w/homes) – sparsely vegetated (Scenario 6)	LN(0.2, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.2, 4.2)	Tri(1.0, 3.0, 5.0)
Suburban lifestyles (w/homes) – including lawns, parks, recreational areas, some gardens (Scenario 7)	LN(0.1, 3.2)	Tri(1.0, 3.0, 5.0)	LN(0.2, 4.2)	Tri(1.0, 3.0, 5.0)
Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies) – wet climates/regions of thick ground vegetation (Scenario 8)	LN(1.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)
Lifestyles of indigenous peoples (mainly hunters/food gathering/nomadic societies) – dry climates/regions of sparse ground vegetation (Scenario 9)	LN(2.0, 3.0)	Tri(1.0, 3.0, 10.0)	LN(3.0, 4.0)	Tri(2.0, 5.0, 10.0)

Source: Simon (1998).

1997). Beyeler et al. (1998b), upon review of the adult studies, proposed a triangular distribution with a most likely value of 50 mg/d for the residential farmer scenario and with minimum and maximum values of 0 and 100 mg/d, respectively. As noted in these reports, these estimates are highly uncertain because of the limited data available. The same triangular distribution proposed in Beyeler et al. (1998b) is suggested for use in RESRAD for the residential farmer scenario. The probability density function is shown in Figure 5.6-1. The average of 50 mg/d (18.3 g/yr) is above the 10 mg/d found in the most comprehensive adult study to date (Stanek et al., 1997), but needs to account for the outdoor lifestyle of a residential farming scenario.

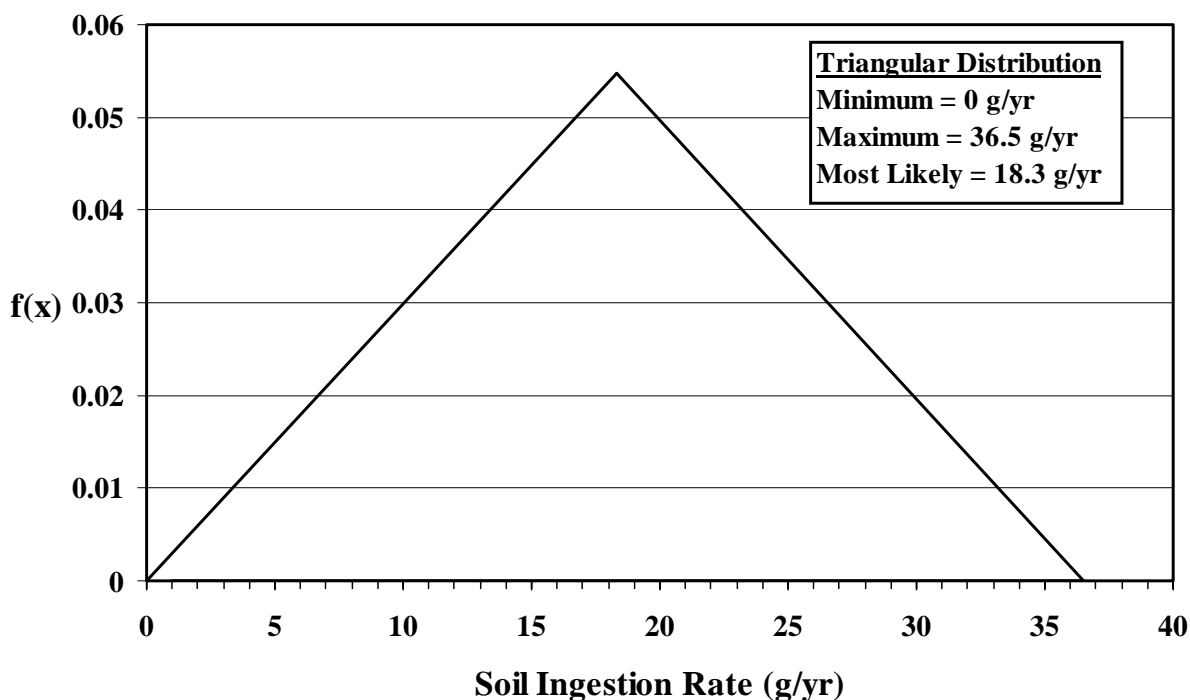


Figure 5.6-1 Soil Ingestion Rate Probability Density Function

5.7 Direct Ingestion Rate

Applicable Code: RESRAD-BUILD

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 for unlikely events when a receptor could directly ingest source material. Such a receptor could be conducting a maintenance or renovation activity that involved physical contact with the source. The direct ingestion rate is normally set to 0 for most calculations.

The magnitude of the direct ingestion rate is highly correlated with other input parameters. For volume sources, the total amount of material ingested may range from 0 to a maximum specified by the mass of the source (area \times thickness [Section 8.9] \times density [Section 8.1]). In addition, the direct ingestion rate cannot exceed the amount removed per unit time as determined by the source erosion rate (Section 8.2). The soil ingestion rate for RESRAD (Section 5.6) could be used as a guide for this parameter. Indirect ingestion (Section 5.8) 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 8.2).

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 8.3) and the source lifetime (Section 8.3) input parameters. If the direct ingestion rate is large enough to match the removal rate, then the air release fraction (Section 8.6) input must be set to 0 to maintain mass balance.

5.8 Indirect Ingestion Rate

Applicable Code: RESRAD-BUILD

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.

Units: square meters per hour (m²/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. (1998a), only eight data references are available (Dunster, 1962; Gibson and Wrixon, 1979; Healy, 1971; Kennedy et al., 1981; Sayre et al., 1974; Lepow et al., 1975; Walter et al., 1980; Gallacher et al., 1984). However, half of these studies concerned intake by children, not adults in an occupational setting. A larger, secondary set of data from soil ingestion studies is available (see Section 5.6), 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., 1998a). 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., 1998a). For this reason, Beyeler et al. (1998a) 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/m², taken to be the lower limit in a residential setting, to 5,000 mg/m², taken to correspond to heavily soiled hands.

The resulting loguniform distributions (Table 5.8-1) for the indirect ingestion rate parameter ranged from 4.4×10^{-4} to 4.6×10^{-3} m²/d, with a mean of 1.8×10^{-3} m²/d; and from 5.1×10^{-2} to 4.3×10^{-1} m²/d, with a mean of 1.8×10^{-1} m²/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 Table 5.8-1. As discussed in Beyeler et al. (1998a), an ingestion rate corresponding to 1×10^{-2} m²/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 5.8-1 presents the probability density function.

Table 5.8-1 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. (1998a).

^b Assumes a 16-hour day using the results from Beyeler et al. (1998a).

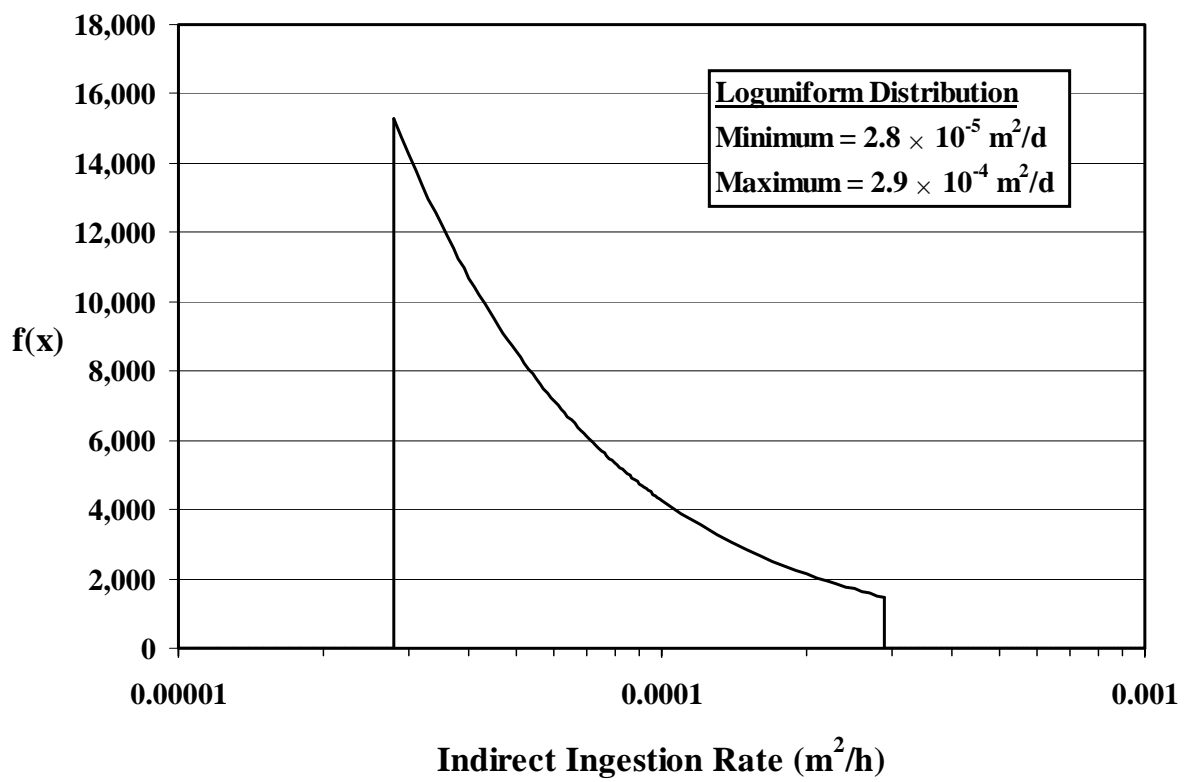


Figure 5.8-1 Indirect Ingestion Rate Probability Density Function

6 CROPS AND LIVESTOCK PARAMETER DISTRIBUTIONS

6.1 Depth of Roots

Applicable Code: RESRAD

Description: This parameter represents the average root depth of various plants grown in the contaminated zone.

Units: meters (m)

Probabilistic Input:

Distribution: Uniform

Defining Values for Distribution:

Minimum: 0.3 Maximum: 4.0

Discussion: Root depth varies for different plants. For some plants, such as beets, carrots, lettuce, and others, root depth does not extend below about 0.3 m. For other plants, such as fruit trees, the roots may extend 2 or 3 m below the surface; tap roots for some crops (e.g., alfalfa) can extend to 5 m. Most of the plant roots from which nutrients are obtained, however, usually extend less than 1 m below the surface.

This parameter is used to calculate the cover and depth factor for the plant, meat, and milk exposure pathways because edible plants become contaminated through root uptake of radionuclides. Uptake of radionuclides from plant roots is assumed possible only when the roots extend to the contaminated zone and is limited to the fraction of roots that have direct contact with contaminated soil.

Each crop has characteristic rooting habits that it will tend to follow if the soil is deep, uniform, and equally moist throughout. The depth of rooting increases during the growing period. Crops that mature in 2 months usually penetrate only 0.6 to 0.9 m, and crops requiring 6 months to mature may penetrate 1.8 to 3.0 m or more.

When the upper portion of the soil is kept moist, plants will obtain most of their moisture supply from near the surface. As the moisture content of the upper layers decreases, the plants draw more water from the lower layers, which will encourage more root development in the lower levels. Fewer roots exist in the lower portion of the root zone because of the inability of the root system to extract enough moisture from the lower levels.

Generally, the average root-zone depths are reached by the time the foliage of the plant has reached its maximum size. Root-zone depths are limited to the soil depth above the water table.

Tables 6.1-1 and 6.1-2 list rooting depths for a variety of crops. Because growing conditions (e.g., amount of rainfall or temperature) and plant types vary widely across the United States, a uniform distribution spanning the range of potential crops is suggested for use in RESRAD, with a minimum of 0.3 m and a maximum of 4.0 m, as shown in Figure 6.1-1. If specific conditions are known, values from Tables 6.1-1 and 6.1-2 may be used.

Table 6.1-1 Normal Root-Zone Depths of Mature, Irrigated Crops Grown in a Deep, Permeable, Well-Drained Soil

Crop	Depth (m)	Crop	Depth (m)
Alfalfa	1.5-3.0	Grapes	1.2-1.8
Artichokes	1.2	Grass pasture	0.9-1.2
Asparagus	1.8-3.0	Hops	1.5-2.4
Beans	0.9-1.2	Ladino clover	0.6
Beets (sugar)	1.2-1.8	Lettuce	0.3-0.5
Beets (table)	0.6-0.9	Mint	0.9-1.2
Broccoli	0.6	Onions	0.3
Cabbage	0.6	Parsnips	0.9
Cantaloupes	1.2-1.8	Peas	0.9-1.2
Cane berries	0.9-1.2	Potatoes (Irish)	0.9-1.2
Carrots	0.6-0.9	Potatoes (sweet)	1.2-1.8
Cauliflower	0.6	Pumpkins	1.8
Celery	0.9	Radishes	0.3
Citrus	1.2-1.8	Spinach	0.6
Corn (sweet)	0.9	Squash	0.9
Corn (field)	0.9-1.5	Strawberries	0.9-1.2
Cotton	1.2-1.8	Tomatoes	1.8-3.0
Cranberries	0.3-0.6	Turnips	0.9
Deciduous orchards	1.8-2.4	Walnuts	3.7
Grain	1.2	Watermelons	1.8

Sources: Modified from Calvin and Knutson (1983); Peirce (1987); Zipparro et al. (1993).

Table 6.1-2 Range of Active Plant Rooting Depths

Crop	Depth (m)	Crop	Depth (m)
Corn	0.6-1.2	Potatoes	0.15-0.45
Soybeans	0.3-0.6	Peanuts	0.3-0.6
Cotton	0.3-0.9	Tobacco	0.3-0.6
Wheat	0.15-0.3	Grain sorghum	0.15-0.3

Source: EPA (1993).

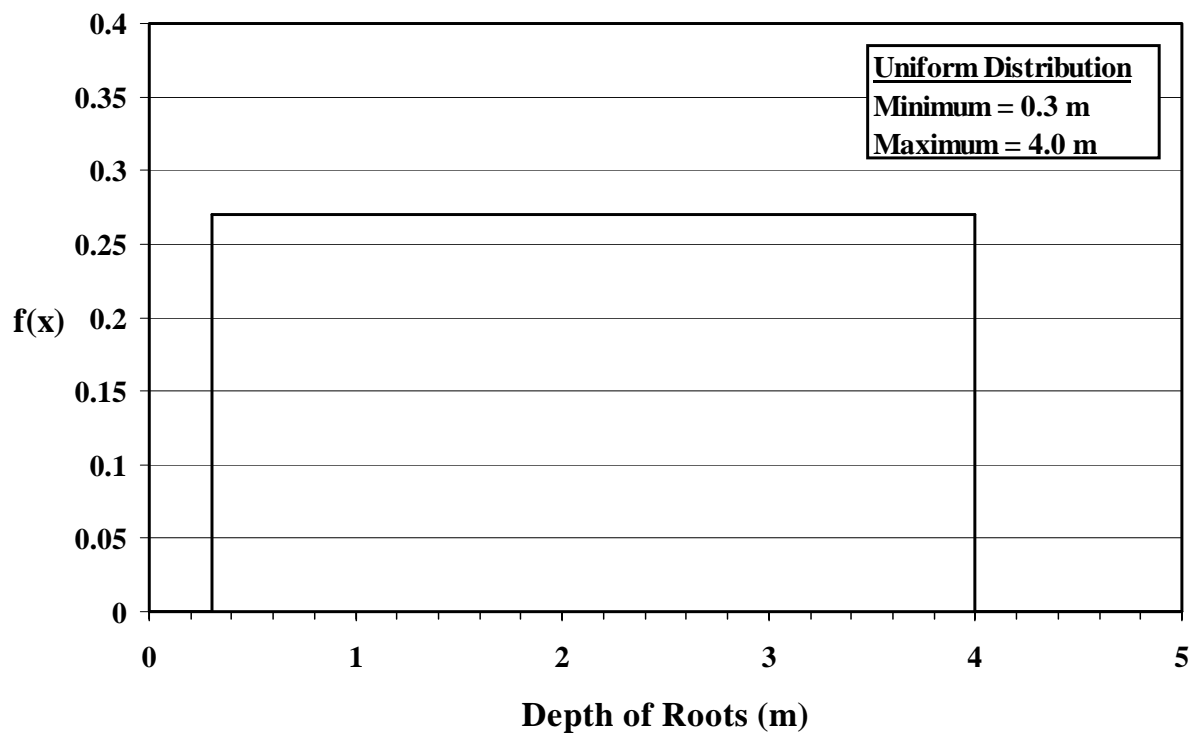


Figure 6.1-1 Depth of Roots Probability Density Function

6.2 Transfer Factors for Plants

Applicable Code: RESRAD

Description: The plant/soil concentration ratios for root uptake are given by the vegetable/soil transfer factors. In the RESRAD code, the plant/soil transfer factor is expressed as the ratio: picocuries per gram (pCi/g) plant (wet)/pCi/g soil (dry) (Yu et al., 1993a).

Units: pCi/g plant (wet) per pCi/g soil (dry)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope, as given in Table 6.2-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The plant/soil transfer factor, B_v , is defined as the ratio of radionuclide concentration in vegetation to that of the soil. The plant/soil transfer factor of a radionuclide varies in a complex manner with soil properties and the geochemical properties of the radionuclide in the soil. The transfer factor for a given plant type can vary from site to site and season to season. In addition, management practices such as plowing, liming, fertilizing, and irrigating greatly affect the plant/soil transfer ratio (International Atomic Energy Agency [IAEA], 1994). After entering the transpiration stream, radionuclides may not be uniformly distributed within a plant, but instead they tend to concentrate in certain plant organs (Grogan, 1985). Sparse data exist for most radionuclides, and the data that do exist are restricted to only limited vegetation types (National Council on Radiation Protection and Measurements [NCRP], 1999). Even for the most studied radionuclides, the values of the plant/soil transfer factors can vary over several orders of magnitude (IAEA, 1994).

In the RESRAD code, the plant/soil transfer factor is a composite value of multiple vegetation types and is expressed as the ratio: pCi per gram plant (wet) / pCi per gram soil (dry). An example of calculating the composite plant/soil transfer factor is provided in Appendix B of Gnanapragasam and Yu (1997). In other published radiological assessment reports, as discussed below for NUREG/CR-5512, the plant/soil transfer factors are provided for different vegetation types and are given as the ratio of pCi per gram plant (dry)/pCi per gram soil (dry). To convert from the vegetation-specific dry plant/soil transfer

Table 6.2-1 Lognormal Distribution Parameter Values for Plant/Soil Transfer Factors

Element	μ	σ	Element	μ	σ
H	1.57	1.1	Ta	-6.21	1.1
Be	-5.52	1.1	Cu	-3.00	1.0
C ^a	-0.36	0.9	Zn	-0.92	0.9
N ^a	3.40	0.9	Ge	-0.92	1.1
F	-3.91	1.1	As	-2.53	1.1
Na	-3.00	1.0	Se	-2.30	1.1
Mg	-3.5	1.1	Br	-0.92	1.1
Si	-3.9	1.1	Rb	-1.61	1.0
Al	-5.52	1.1	Sr	-1.20	1.0
P	0.00	1.1	Y	-6.21	1.1
S	-0.51	1.1	Zr	-6.91	1.1
Cl	3.00	1.1	Nb	-4.61	1.1
K	-1.20	1.1	Mo	-2.30	1.1
Ca	-0.69	1.1	Tc	1.61	0.9
Sc	-6.21	1.1	Ru	-3.51	0.9
Cr	-4.61	1.0	Rh	-3.51	1.0
Mn	-1.20	0.9	Pd	-2.30	1.1
Fe	-6.91	0.9	Ag	-5.52	0.9
Co	-2.53	0.9	Cd	-0.69	1.1
Ni	-3.00	0.9	W	-0.22	1.0
In	-5.81	1.1	Ir	-3.51	1.1
Sn	-1.20	1.1	Au	-2.30	1.1
Sb	-4.61	1.0	Hg	-1.20	1.1
Te	-2.30	1.0	Tl	-1.61	1.1
I	-3.91	0.9	Pb	-5.52	0.9
Cs	-3.22	1.0	Bi	-2.30	1.1
Ba	-4.61	1.1	Po	-6.9	0.9
La	-6.21	0.9	Ra	-3.22	0.9
Ce	-6.21	1.0	Ac	-6.91	1.1
Pr	-6.21	1.0	Th	-6.91	0.9
Nd	-6.21	1.0	Pa	-4.61	1.1
Pm	-6.21	1.1	U	-6.21	0.9
Sm	-6.21	1.1	Np	-3.91	0.9
Eu	-6.21	1.1	Pu	-6.91	0.9
Gd	-6.21	1.1	Am	-6.91	0.9
Tb	-6.21	1.1	Cm	-6.91	0.9
Ho	-6.21	1.1	Cf	-6.91	1.1

^a Derived from Yu et al. (1993a).

Source: NCRP (1999) except as noted.

factor to a composite wet plant/soil transfer factor, a dry to wet conversion factor must be determined for each vegetation type. In addition, the vegetation-specific transfer factors must be weighted by relative importance (measured in kilograms) of each vegetable category (Wang et al., 1993). Although the transfer factors may range over a couple of orders of magnitude for different radionuclides, the range among vegetation types for a given radionuclide is not as great (NCRP, 1999).

A lognormal distribution is consistently proposed as most appropriate for the plant/soil transfer factor (Beyeler et al., 1998b). The plant/soil transfer factors were obtained from Appendix D of the National Council on Radiation Protection and Measurements Report 129 (NCRP, 1999), except as noted. The report provides median and geometric standard deviations for composite wet plant/soil transfer factors for each element listed in Table 6.2-1. These values were compared with the values currently used in the RESRAD computer code and were found to be consistent. The parameters describing the lognormal probability distribution of the plant/soil transfer factors for each element were estimated by setting the natural logarithm of the geometric standard deviation equal to σ and setting μ equal to the natural logarithm of the median value given in Appendix D of NCRP Report 129 (NCRP, 1999).

The current version of the RESRAD computer code requires the plant transfer factors to be expressed as the ratio of pCi per gram plant (wet)/pCi per gram soil (dry). Other studies, such as NUREG/CR-5512 (Kennedy and Streng, 1992), express the transfer factor for the four plant types as the ratio of pCi per gram plant type (dry)/pCi per gram soil (dry). A dry-to-wet weight conversion factor must therefore be applied to make proper comparisons between the transfer factors. An overall average conversion factor of 0.428 has been estimated by Baes et al. (1984). This average factor is based on several factors, including (1) calculation of the dry-to-wet weight conversion factors for exposed produce, protected produce, and grains on the basis of relative importance of various nonleafy vegetables in the United States; and (2) calculation of the average dry-to-wet conversion factor by weighting these calculated values by the relative importance (based on production, in kilograms) of each vegetable category grown in the United States. When an overall average dry-to-wet conversion factor of 0.428 is applied to the plant transfer factors given in Table 6.2-1, the values are in good agreement with the values presented in NUREG/CR-5512 (Kennedy and Streng, 1992), especially when the transfer factors can vary by a factor of 10 or more for the same vegetation type.

6.3 Transfer Factors for Meat

Applicable Code: RESRAD

Description: The radionuclide transfer factor for meat is the ratio of the concentration of a radionuclide in meat (pCi/kg) to the rate of intake of that radionuclide (pCi/d) by the animal (Yu et al., 1993a). This parameter is used when the meat ingestion pathway is active. In the RESRAD code, the default transfer factors are for beef.

Units: picocuries per kilogram per picocuries per day (pCi/kg per pCi/d)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope as given in Table 6.3-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The migration of a radioisotope from feed to a meat product is commonly modeled by using a transfer coefficient. This transfer coefficient is defined as the amount of an animal's daily intake of a radionuclide that is transferred to one kilogram of the animal meat product at equilibrium (IAEA, 1994).

For many elements and radionuclides, the transfer factor is derived from sources such as stable element concentrations in feed and animal tissues, extrapolations from single-dose tracer experiments, and comparison of elemental concentrations in associated or unassociated meat, or milk and feed (Ng et. al., 1982).

Many difficulties are associated with the development of transfer factors to meat products:

- *The need for equilibrium* — With a few exceptions, the time required for a radionuclide to reach equilibrium in many animal products (e.g., beef) is so long that few experiments can be conducted sufficiently long to establish equilibrium (IAEA, 1994).
- *Metabolic homeostasis* — Some elements, and therefore their radioisotopes, are subject to homeostatic control; hence an increase in feed concentrations will not necessarily be reflected in tissues.

Table 6.3-1 Lognormal Distribution Parameter Values for the Transfer Factors for Meat (Beef)

Element	μ	σ	Element	μ	σ
H ^a	-4.42	1.0	Cu	-4.61	0.4
Be	-5.30	1.0	Zn	-2.30	0.3
C ^a	-3.47	1.0	Ge	-1.61	1.0
Na	-2.53	0.2	As	-3.91	1.0
Mg	-5.8	0.2	Se	-2.30	0.9
Si	-8.1	1.0	Br	-3.00	1.0
Al	-7.60	1.0	Rb	-3.51	0.7
P	-3.00	0.2	Sr	-4.61	0.4
S	-1.61	1.0	Y	-6.21	0.9
Cl	-3.22	0.7	Zr	-13.82	0.9
K	-3.91	0.2	Nb	-13.82	0.9
Ca	-6.21	0.2	Mo	-13.82	0.9
Sc	-6.21	1.0	Tc	-9.21	0.7
Cr	-3.51	0.4	Ru	-6.21	0.9
Mn	-6.91	0.7	Rh	-6.21	1.0
Fe	-3.51	0.4	Pd	-8.52	1.0
Co	-3.51	1.0	Ag	-6.21	0.7
Ni	-5.30	0.9	Cd	-6.91	0.9
In	-5.52	1.0	W	-3.22	0.9
Sn	-4.61	1.0	Ir	-6.21	1.0
Sb	-6.91	0.9	Au	-5.30	1.0
Te	-4.96	0.9	Hg	-4.61	1.0
I	-3.22	0.4	Tl	-3.91	1.0
Cs	-3.00	0.4	Pb	-7.13	0.7
Ba	-8.52	0.9	Bi	-6.21	1.0
La	-6.21	1.0	Po	-5.30	0.7
Ce	-10.82	0.9	Ra	-6.91	0.7
Pr	-6.21	1.0	Ac	-10.82	1.0
Nd	-6.21	1.0	Th	-9.21	1.0
Pm	-6.21	1.0	Pa	-12.21	1.0
Sm	-6.21	1.0	U	-7.13	0.7
Eu	-6.21	1.0	Np	-6.91	0.7
Gd	-6.21	1.0	Pu	-9.21	0.2
Tb	-6.21	1.0	Am	-9.90	0.2
Ho	-6.21	1.0	Cm	-10.82	1.0
Ta	-12.21	1.0	Cf	-9.72	1.0

^a Derived from Hoffman et al. (1982).

Source: NCRP (1999) except as noted.

- *Effects of chemical and physical form of radionuclide and diet composition* — the availability of a radionuclide for gut uptake differs markedly, depending on the chemical and physical forms of the radionuclide and on the constituents of the diet (Beresford et al., 1989; Howard et al., 1989; Johnson et al., 1968).
- *Influence of age* — The intake of radionuclides by an animal is dependent on the animal's species, mass, age, and growth rate, as well as the digestibility of the feed (Wang et al., 1993). Although the transfer factors are higher for some young animals, this artifact is balanced by the lower feed intake rates of young animals (NCRP, 1999).

The variability in the transfer factors is assumed to follow a lognormal probability distribution (NCRP, 1999). The values for the parameters associated with the lognormal distribution for the meat transfer factors are given for each element and in Table 6.3-1.

The meat transfer factors provided in RESRAD are for beef, since beef is generally consumed in larger quantities in the United States than other meat products (NCRP, 1999). Although the values provided in Table 6.3-1 are for beef, the uncertainty estimates of the meat transfer factors were made to accommodate other meat types (pork, lamb, veal, poultry) (IAEA, 1994; NCRP, 1999).

6.4 Transfer Factors for Milk

Applicable Code: RESRAD

Description: The radionuclide transfer factor for milk is the ratio of the concentration of a radionuclide in milk (pCi/L) to the rate of intake of the same radionuclide by the animal (pCi/d) (Yu et al., 1993a). This parameter is used when the milk ingestion pathway is active. In the RESRAD computer code, the default transfer factors are for cow's milk.

Units: picocuries per liter per picocurie per day (pCi/L per pCi/d)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution: Values are assigned according to the element of the radioactive isotope as given in Table 6.4-1. Lower and upper quantile input values are 0.001 and 0.999 for all elements.

Discussion: The migration of a radioisotope from feed to milk of a dairy animal is commonly modeled by using a transfer coefficient. This transfer coefficient is defined as the amount of an animal's daily intake of a radionuclide that is transferred to one liter of milk at equilibrium (IAEA, 1994).

For many elements and radionuclides, the transfer factor is derived from sources such as stable element concentrations in feed and animal tissues, extrapolations from single-dose tracer experiments, and comparison of elemental concentrations in associated or unassociated meat, or milk and feed (Ng et. al., 1982).

Many difficulties are associated with the development of transfer factors to milk:

- *The need for equilibrium* — With a few exceptions, the time required for a radionuclide to reach equilibrium in many animal products (e.g., milk) is so long that few experiments can be conducted sufficiently long to establish equilibrium (IAEA, 1994).
- *Metabolic homeostasis* — Some elements, and therefore their radioisotopes, are subject to homeostatic control; hence an increase in feed concentrations will not necessarily be reflected in tissues and milk.

Table 6.4-1 Lognormal Distribution Parameter Values for the Transfer Factors for Milk (Cow)

Element	μ	σ	Element	μ	σ
H ^a	-4.6	0.9	Zn	-4.61	0.9
Be	-13.12	0.9	Ge	-4.61	0.9
C ^a	-4.4	0.9	As	-9.21	0.9
Na	-3.22	0.5	Se	-4.61	0.9
Al	-8.52	0.9	Br	-3.91	0.9
P	-3.91	0.7	Rb	-4.61	0.7
S	-3.91	0.7	Sr	-6.21	0.5
Cl	-3.91	0.5	Y	-9.72	0.9
K	-4.96	0.5	Zr	-14.33	0.7
Ca	-5.81	0.5	Nb	-13.12	0.7
Sc	-5.12	0.9	Mo	-6.21	0.7
Cr	-6.21	0.7	Tc	-6.91	0.7
Mn	-8.11	0.7	Ru	-10.82	0.6
Fe	-8.11	0.7	Rh	-7.60	0.9
Co	-6.21	0.7	Pd	-9.21	0.9
Ni	-3.91	0.7	Ag	-5.12	0.7
In	-8.52	0.9	Cd	-6.21	0.9
Sn	-6.91	0.9	W	-8.11	0.9
Sb	-9.72	0.9	Ir	-13.12	0.9
Te	-7.60	0.6	Au	-11.51	0.9
I	-4.61	0.5	Hg	-7.60	0.7
Cs	-4.61	0.5	Tl	-5.81	0.9
Ba	-7.60	0.7	Pb	-8.11	0.9
La	-9.72	0.9	Bi	-6.91	0.9
Ce	-10.41	0.7	Po	-7.82	0.7
Pr	-9.72	0.9	Ra	-6.91	0.5
Nd	-9.72	0.9	Ac	-13.12	0.9
Pm	-9.72	0.9	Th	-12.21	0.9
Sm	-9.72	0.9	Pa	-12.21	0.9
Eu	-9.72	0.9	U	-7.82	0.6
Gd	-9.72	0.9	Np	-11.51	0.7
Tb	-9.72	0.9	Pu	-13.82	0.5
Ho	-9.72	0.9	Am	-13.12	0.7
Ta	-12.21	0.9	Cm	-13.12	0.9
Cu	-6.21	0.9	Cf	-13.12	0.9

^a Derived from Hoffman et al. (1982).

Source: NCRP (1999) except as noted.

- *Effects of chemical and physical form of radionuclide and diet composition* — the availability of a radionuclide for gut uptake differs markedly depending on the chemical and physical forms of the radionuclide and on the constituents of the diet (Beresford et al., 1989; Howard et al., 1989; Johnson et al., 1968).
- *Influence of age* — The intake of radionuclides by an animal is dependent on the animal's species mass, age, and growth rate, as well as the digestibility of the feed (Wang et al., 1993). Although the transfer factors are higher for some young animals, this artifact is balanced by the lower feed intake rates of young animals (NCRP, 1999).

The variability in the transfer factors are assumed to follow a lognormal probability distribution. The values for the parameters associated with the lognormal distribution for the milk transfer factors are given for each element in Table 6.4-1.

The milk transfer factors provided in RESRAD are for cow's milk, since cow's milk is generally consumed in larger quantities in the United States than other milk types (NCRP, 1999). To model the doses associated with consuming milk products other than cow's milk, the transfer factors should be adjusted for the appropriate ingestion product (e.g., goat's milk).

6.5 Wet Weight Crop Yields for Nonleafy Vegetables

Applicable Code: RESRAD

Description: The wet weight crop yield is the quantity of nonleafy vegetables that can be produced over an area of land. This parameter is used in calculating the plant-food/soil concentration ratio for foliar deposition and the plant-food/water concentration ratio for overhead irrigation.

Units: kilograms per square meter (kg/m²)

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value :	0.56	Lower quantile value:	0.001
Underlying standard deviation:	0.48	Upper quantile value:	0.999

Discussion: Crop yields vary from state to state. The USDA publishes an annual statistical bulletin listing production rates and estimated crop values for all food commodities. Data from the statistical bulletin *Vegetables: Final Estimates by States, 1992-1997* (USDA, 1999) were used to estimate the crop yields for nonleafy vegetables.¹ The crop yields were found to remain relatively constant over the 6-year interval covered by the report. The data varied the greatest from state to state, with Oklahoma having the smallest nonleafy crop yield (0.6 kg/m²) and Idaho having the largest (6.8 kg/m²). The probability distribution function reflects the variance in crop production over the 50 states.

The nonleafy crop yield for a particular state was estimated by subtracting the production rates for leafy vegetables from the total vegetable production rate. States with the largest leafy vegetable production included California, Arizona, and Florida (USDA, 1999). Since the annual crop yields did not vary much over the 6-year period, data from 1992 were used to estimate the nonleafy vegetable crop yields for each state. The nonleafy vegetable crop yield was assumed to be distributed lognormally, and the parameters of the lognormal distribution were estimated from 1992 data for all 50 states. The crop yields were weighted on the basis of the size of the agricultural area of the state. Bayesian techniques were used to estimate the posterior probability densities for the parameters μ and σ . The posterior means for both parameters were then estimated, and

¹ Nonleafy vegetables include all vegetables except cabbage, cauliflower, broccoli, celery, lettuce, and spinach.

these values were used as the defining values for the probability distribution for the wet weight crop yield. Figure 6.5-1 presents the probability density function.

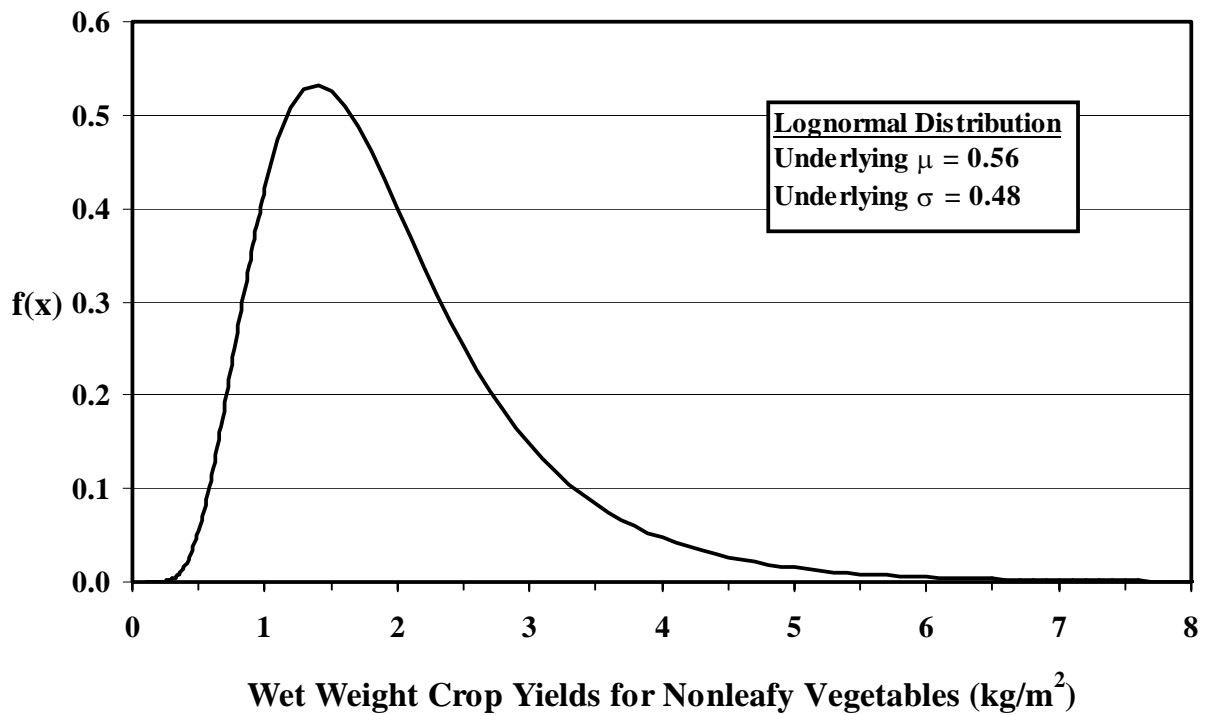


Figure 6.5-1 Wet Weight Crop Yields for Nonleafy Vegetables Probability Density Function

6.6 Weathering Removal Constant

Applicable Code: RESRAD

Description: Some of the airborne contaminants that are intercepted and initially retained by the foliage of plants are removed from the plant by a number processes. This removal is modeled by an exponential function of time, and the rate of removal is represented in RESRAD by the weathering removal constant.

Units: year⁻¹

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 5.1 Maximum: 84 Most likely: 18

Discussion: The concentration of contaminants initially intercepted and retained by the foliage of plants decreases over time because of a number of removal processes, including radioactive decay, wash off, wind action, dilution by new growth, and volatilization (IAEA, 1994). This reduction is modeled in RESRAD by a first order removal rate termed the “weathering removal rate,” λ_w . Two related parameters are the retention half life, $T_{1/2}$, and the residence time or time constant, τ . These parameters are related by:

$$\lambda_w = \frac{1}{\tau} = \frac{\ln 2}{T_{1/2}} \quad (6.6-1)$$

Brown et al. (1997) report values for the retention half-life submitted by a number experts. These values were converted to removal constants and were used to estimate the values for the triangular distribution suggested here. Retention half-life values ranged from 2 to 15 days for 5th percentile estimates, 7 to 30 days for 50th percentile estimates, and 15 to 50 days for 95th percentile estimates (Brown et al., 1997). Estimates varied in part because of effects specific to plant type and radionuclide species. Maximum, minimum, and most likely retention half-lives of 50, 3, and 14 days were selected. These values correspond to minimum, maximum, and most likely values of 5.1, 84, and 18 yr⁻¹, respectively, for the weathering removal constant. The probability density function is shown in Figure 6.6-1.

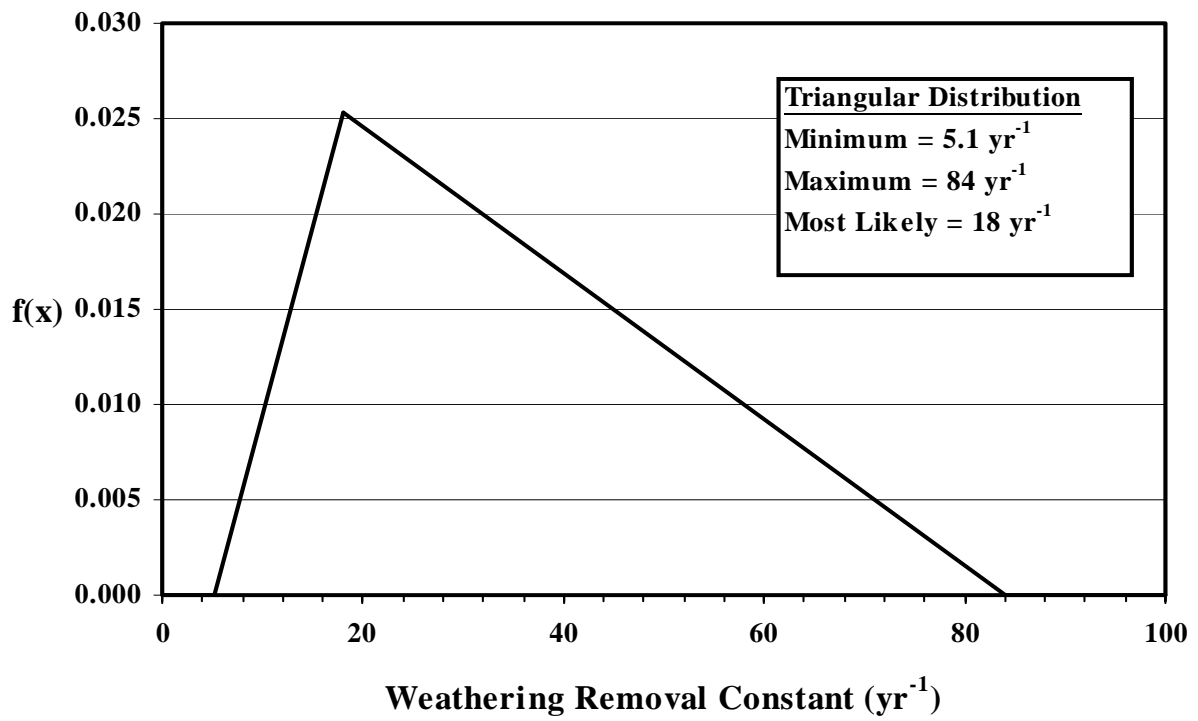


Figure 6.6-1 Weathering Removal Constant Probability Density Function

6.7 Wet Foliar Interception Fraction for Leafy Vegetables

Applicable Code: RESRAD

Description: This parameter represents the fraction of airborne contamination wet deposited on an agricultural or pasture area that is intercepted and initially retained by the foliage of leafy vegetables.

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 0.06 Maximum: 0.95 Most likely: 0.67

Discussion: Retention of wet-deposited contaminants on vegetation is strongly influenced by both the ionic nature of the contaminant species and the amount of rainfall at the time of deposition. Anions are retained much less than insoluble particulates or cations because plant surfaces tend to have a negative charge (Hoffman et al., 1995; Prohl et al., 1995). Thus, chemical species with a higher positive charge tend to be retained the most. The amount of rainfall in a discrete rain event also plays an important part in the amount of deposited contamination that is initially retained (Prohl et al., 1995). The larger the amount of rainfall in the overall event, the less intercepted contamination is retained.

Only an approximation of the probability density function for the wet foliar interception fraction can be made because of the broad application of the distribution in RESRAD to all event types (i.e., different species and rainfall amounts) and because limited data are available for only a few chemical species and associated rainfall amounts. Brown et al. (1997) report values for the wet foliar interception fraction solicited from a number of experts. Wet foliar interception factors for green vegetables ranged from 0.03 to 0.6 for 5th percentile estimates, 0.05 to 0.8 for 50th percentile estimates, and 0.8 to 1.0 for 95th percentile estimates (Brown et al., 1997). Minimum, maximum, and most likely interception fractions of 0.06, 0.95, and 0.67 were selected for use in a triangular distribution. The probability density function is shown in Figure 6.7-1.

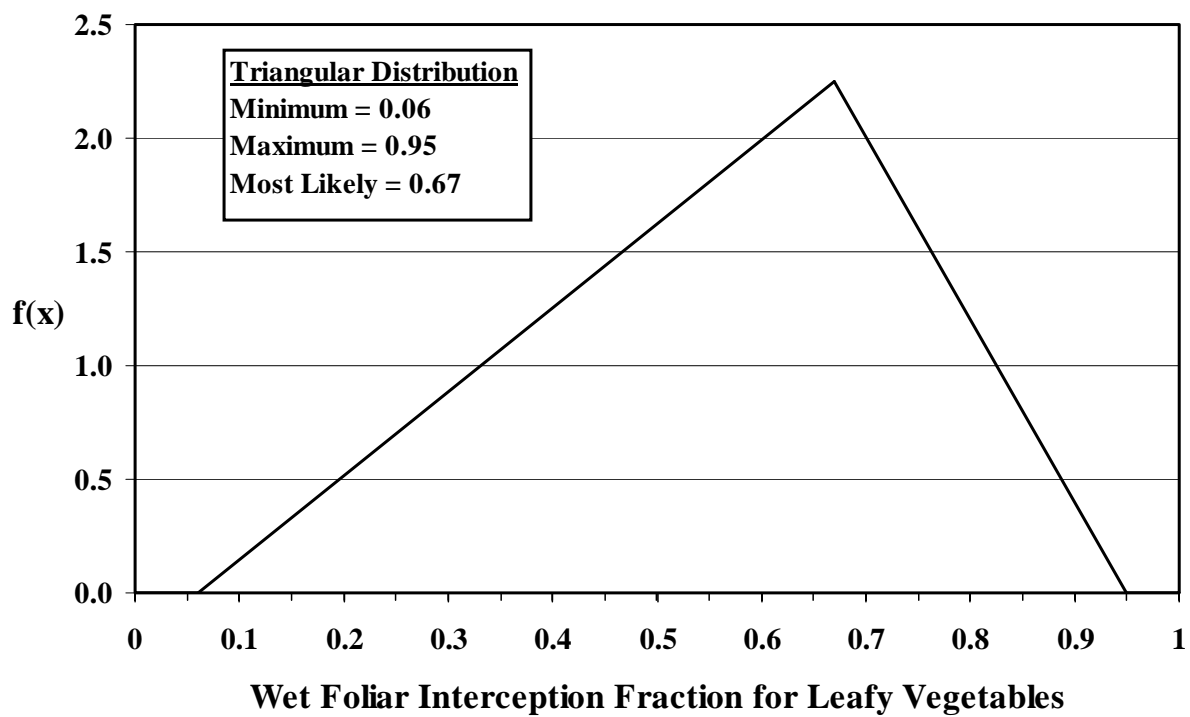


Figure 6.7-1 Wet Foliar Interception Fraction Probability Density Function

6.8 Bioaccumulation Factors for Fish

Applicable Code: RESRAD

Description: The bioaccumulation factor for fish is used to calculate the transfer of a radionuclide from contaminated water through various trophic levels of aquatic foodstuffs consumed by humans. This factor is normally expressed as the ratio of radioactivity in animal tissue to that in water at equilibrium conditions.

Units: picocuries per kilogram (of tissue) per picocurie per liter (of water) (pCi/kg per pCi/L)

Probabilistic Input:

Distribution: lognormal-n

Defining Values for Distribution: Values are assigned specific to each radioactive isotope, as provided in Table 6.8-1.

Discussion: The bioaccumulation factor for an aquatic organism or tissue is the ratio of radionuclide concentration in the whole organism or tissue to the concentration of that same radionuclide in water. The incorporation of a radionuclide into fish is a complex process. Factors such as the age of the fish, feeding habits, freshwater versus marine environments, seasonal variations, and the chemical composition of the water dramatically affect the bioaccumulation factor (Wang et al., 1993; NCRP, 1984). In addition, the method used to estimate the bioaccumulation factor can itself influence the results of the measurements (NCRP, 1984).

Young, rapidly growing fish may accumulate higher levels of biologically active radionuclides than fish in a stationary growth period. The differences in osmoregulatory problems faced by freshwater fish compared with marine fish also produce differences in route of radionuclide uptake (Poston and Klopfer, 1986). In seawater, the salt concentration is high, and marine fish drink large amounts of water and expend considerable energy to excrete salt against the concentration gradient (Wang et al., 1993). In freshwater, fish retain salt and excrete a large amount of water. Therefore, radionuclides in the water column, present either as dissolved species or sorbed onto particulate matter, are more prone to gastrointestinal absorption by marine species than by freshwater species (Poston and Klopfer, 1986). The chemical composition of water can also influence the bioaccumulation of radionuclides by freshwater biota. Recommendations have been made to use different bioaccumulation factors depending on the mineral content of the water (NCRP, 1984).

In the literature, bioaccumulation factors are derived by a number of methods, and the reported values vary widely (Wang et al., 1993). Historically, radioactivity in animal tissue is estimated on the basis of ash weight, dry weight, wet weight, and whole body burdens, or muscle tissue. These different measurement methods can dramatically affect the computed bioaccumulation factor of the fish. As an example, estimating the bioaccumulation factor on the basis of the whole-body burden of a fish for bone-seeking radionuclides (radium, strontium) would lead to an overestimate of the concentration in the muscle tissue (NCRP, 1984). This overestimation would ultimately lead to an overestimate of the dose to a receptor from the ingestion of fish. Radioactivity in water is measured on the basis of filtered or unfiltered water. Since a significant fraction of some elements in water may be in the suspended phase, bioaccumulation factors based on filtered samples may be much greater than the bioaccumulation factors on unfiltered samples (NCRP, 1984).

The bioaccumulation factors presented in this section were obtained from Wang et al. (1993). On the basis of the research of Hoffman and Baes (1979) and Vanderploeg et al. (1975), it was assumed that the bioaccumulation factors were distributed lognormally. Values for the parameter μ (the underlying mean) for the lognormal distributions were obtained by taking the natural logarithm of the suggested value in Table 12 of Wang et al. (1993). Since bioaccumulation factors can range over orders of magnitude, the geometric standard deviation was set to 3 for most elements, and the parameter σ (standard deviation) for the lognormal distribution was estimated by taking the natural logarithm of the geometric standard deviation.

Table 6.8-1 Lognormal Distribution Parameter Values for Bioaccumulation Factors for Fish

Element	μ	σ	Element	μ	σ
H	0	0.1	Sn	8.0	1.1
Be	4.6	1.1	In ^a	9.2	1.1
C	10.8	1.1	Sb	4.6	1.1
N	12	1.1	Te	6.0	1.1
F	2.3	1.1	I	3.7	1.1
Na	3	1.1	Cs	7.6	0.7
Al ^a	6.2	1.1	Ba	1.4	1.1
P	10.8	1.1	La	3.4	1.1
S	6.9	1.1	Ta ^a	4.6	1.1
Cl	6.9	1.1	Ce	3.4	1.1
K	6.9	1.1	Pr	4.6	1.1
Ca	6.9	1.1	Nd	4.6	1.1
Sc	4.6	1.1	Pm	3.4	1.1
Cr	5.3	1.1	Sm	3.2	1.1
Mn	6	1.1	Eu	3.9	1.1
Fe	5.3	1.1	Gd	3.2	1.1
Co	5.7	1.1	Tb	3.2	1.1
Ni	4.6	1.1	Ho	3.2	1.1
Cu	5.3	1.1	W	3.2	1.1
Zn	6.9	1.1	Ir	2.3	1.1
Ge ^a	8.3	1.1	Au ^a	3.5	1.1
As	5.7	1.1	Hg	6.9	1.1
Se	5.1	1.1	Tl ^a	9.2	1.1
Br	6.0	1.1	Pb	5.7	1.1
Rb	7.6	1.1	Bi	2.7	1.1
Sr	4.1	1.1	Po	4.6	1.1
Y	3.4	1.1	Ra	3.9	1.1
Zr	5.7	1.1	Ac	2.7	1.1
Nb	5.7	1.1	Th	4.6	1.1
Mo	2.3	1.1	Pa	2.3	1.1
Tc	3.0	1.1	U	2.3	1.1
Ru	3.0	1.1	Np	3.4	1.1
Rh	3.0	1.1	Pu	3.4	1.1
Pd	3.0	1.1	Am	3.4	1.1
Ag	1.6	1.1	Cm	3.4	1.1
Cd	5.3	1.1	Cf	3.2	1.1

^a NCRP (1996).

Source: Based on Wang et. al. (1993) except as noted.

7 BUILDING CHARACTERISTICS PARAMETER DISTRIBUTIONS

7.1 Indoor Dust Filtration Factor

Applicable Code: RESRAD

Description: The indoor dust filtration factor represents the fraction of outdoor contaminated dust that is available indoors.

Units: unitless

Probabilistic Input:

Distribution: uniform

Defining Values for Distribution:

Minimum: 0.15 Maximum: 0.95

Discussion: The indoor dust filtration factor, the ratio of the long-term indoor-to-outdoor air concentrations of particulates, provides a measure of a building's effectiveness at removing particulate contaminants from the outdoor air that enters the building. This parameter is sometimes referred to as an inhalation shielding factor or a dose reduction factor when applied to inhalation exposures. The contribution of outdoor air to indoor particulate levels is primarily a function of a building's ventilation rate (including infiltration) and the indoor deposition velocity of the particulates.

As further discussed in Section 7.4, the ventilation rate of buildings depends on the climate and season. For example, aside from mechanical ventilation, infiltration of outdoor air depends on temperature, wind speed, and quality of building construction. Earlier investigations found indoor/outdoor air concentration ratios for different building types ranging from close to 0 up to 1 (see Table 7.1-1). Even for office or industrial building types, with the mechanical ventilation systems turned off, air exchange can still be significant, and estimates of the indoor/outdoor air concentrations ratios could range above 0.1 when all outdoor entrances are closed (Engelmann, 1992).

It is believed that particulates of less than 10 μm in aerodynamic diameter are able to enter buildings with the same efficiency as nonreactive gases (Wallace, 1996). However, larger contaminant particles will deposit faster than smaller particulates, posing less of a radiological inhalation risk (Fogh et al., 1997).

Table 7.1-1 Indoor/Outdoor Air Concentration Ratios

Pollutant	Structure	Measured Indoor/Outdoor Ratio	Reference
Total suspended particulates	Homes and public buildings	0.16 to 0.51	Yocum et al., 1971
0.1–20 µm dust particulates	Old/new homes/university buildings	< 0.1 to 0.42	Alzona et al., 1979
Ca, Fe, Zn, Pb, Br	Homes and public and commercial buildings	0.043 to 0.85 (excluding Zn)	Cohen and Cohen, 1979
Particulates, iodine, noble gases	Wood or concrete construction	Calculated DRFs of 0.072 to 1	Kocher, 1980
Be-7	Danish and Finnish homes	0.23 to 0.86	Christensen and Mustonen, 1987
Various radioisotopes	Danish home	0.1 to 0.5	Roed and Cannell, 1987
Noble gases, methyl iodide, elemental iodine, aerosols 0.1 to 2 µm	Homes, large buildings, manufacturing facilities	Calculated DRFs of 0.004 to 1	Brenk and De Witt, 1987

A comprehensive review by Wallace (1996) indicates that numerous studies show indoor particulate concentrations can exceed outdoor concentrations because of indoor sources. When only considering outdoor sources, mean values are expected to be close to 0.5. Table 7.1-2 lists estimates of the indoor/outdoor ratio made by Wallace (1996) based on the results of the EPA's Particle Team (PTEAM) study of residential housing. An average value of approximately 0.57 was found for PM₁₀, which is between the values estimated for the fine particle fraction (PM_{2.5}) and the coarse particle fraction (difference of PM₁₀ and PM_{2.5}), 0.67 and 0.48, respectively. These values were derived with the assumption of decay rates of 0.39, 0.65, and 1.01 h⁻¹ for fine particles, PM₁₀, and the coarse particles, respectively, with the decay rate given by:

$$k = \frac{k_d S}{V}, \quad (7.1-1)$$

where

k_d = the deposition velocity,

Table 7.1-2 Fraction of Outdoor Particles Found Indoors at Equilibrium (results from the PTEAM Study)

Statistic	Daytime (sample size = 174)			Overnight (sample size = 175)		
	Fine	PM ₁₀	Coarse	Fine	PM ₁₀	Coarse
Mean	0.68	0.58	0.49	0.66	0.55	0.46
Standard deviation	0.17	0.19	0.20	0.15	0.17	0.17
Standard error	0.013	0.015	0.015	0.012	0.013	0.013
Geometric mean	0.66	0.55	0.45	0.64	0.53	0.42
Minimum	0.28	0.19	0.13	0.28	0.19	0.13
25th percentile	0.55	0.42	0.32	0.55	0.43	0.34
Median	0.70	0.58	0.47	0.66	0.54	0.43
75th percentile	0.83	0.75	0.65	0.79	0.69	0.59
Maximum	0.95	0.93	0.89	0.94	0.90	0.85

Source: Wallace (1996).

S = interior surface area, and

V = interior volume.

The indoor/outdoor ratios were estimated using these decay rates and average air exchange rates from the PTEAM study using the relationship:

$$\frac{C_{in}}{C_{out}} = \frac{Pa}{a + k}, \quad (7.1-2)$$

where

C_{in} = indoor particulate concentrations,

C_{out} = outdoor particulate concentrations,

P = the penetration factor (set equal to 1), and

a = the building air exchange rate (h^{-1}).

If the average air exchange rate found in Murray and Burmaster (1995) for residential housing (0.76 h^{-1}), is used in the above relationship, the estimated

indoor/outdoor ratio for PM_{10} would be 0.54, in good agreement with the values of 0.58 and 0.55 for daytime and overnight conditions, respectively, as presented in Table 7.1-2.

Limited measurement data are available for occupational settings. Table 7.1-1 shows that a fairly wide range is possible. As discussed further in Section 7.4, a wide range of air exchange rates, and therefore a wide range in indoor/outdoor concentration ratios, is expected for commercial buildings. Except for isolated instances (e.g., electronic manufacturing “clean” rooms) or shipping/receiving intensive enterprises, indoor/outdoor concentration ratios for residential settings are not expected to differ greatly, on average, from light industrial environments because the ratios depend on air exchange rates, and human comfort depends (in part) on air exchange rates. Because the air exchange rates can vary considerably with climate and season, as well as the difference attributable to particle size and occupational setting, it is not reasonable to assign a most likely value to the indoor dust filtration factor (indoor/outdoor air dust concentration ratio). Thus, a uniform distribution is selected for a generic setting, with minimum and maximum values of 0.15 and 0.95 as suggested by the results in Table 7.1-2. The probability density function is shown in Figure 7.1-1.

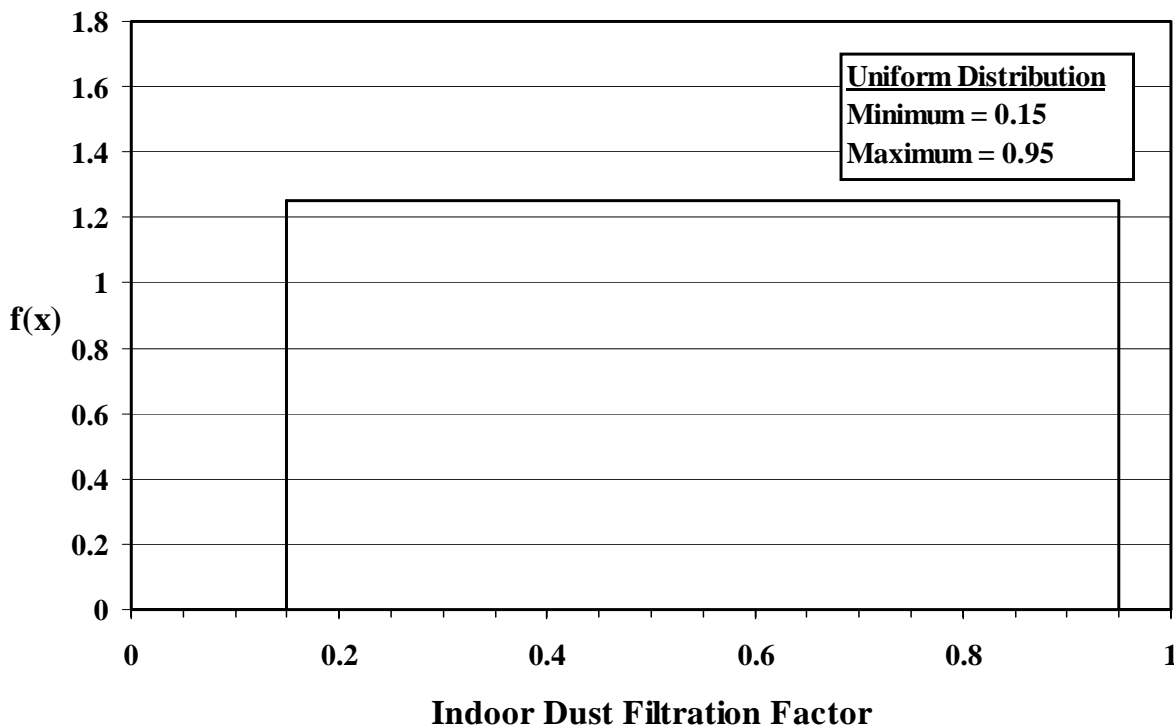


Figure 7.1-1 Indoor Dust Filtration Factor Probability Density Function

7.2 Resuspension Rate (Indoor)

Applicable Code: RESRAD-BUILD

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.

Units: 1/s

Probabilistic Input:

Distribution: loguniform

Defining Values for Distribution:

Minimum: 2.8×10^{-10} Maximum: 1.4×10^{-5}

Discussion: Indoor resuspension of contamination can lead to internal exposure via inhalation. The resuspension rate is the fraction of deposited particles resuspended per unit time. Factors that can affect resuspension include the type of disturbance (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 done in measuring or estimating indoor resuspension rates. The most recent work by Thatcher and Layton (1995) monitored an SF₆ tracer in a residential setting under varying conditions. Results based on particle size are given in Table 7.2-1. These results demonstrate that the larger particle sizes are more susceptible to resuspension. Earlier studies of indoor resuspension of radioactive contamination (Brunskill, 1967; Fish et al., 1967; Glauberman et al., 1967; Jones and Pond, 1967; Mitchell and Eutsler, 1967; Spangler and Willis, 1967) reported the extent of resuspension in terms of a resuspension factor, the ratio of airborne contamination to the amount deposited on surfaces.

Healy (1971) reviewed some of the earlier work on resuspension factors and estimated resuspension rates using the following approximation:

$$\lambda_r = R_f \frac{V}{A} \lambda_v, \quad (7.2-1)$$

Table 7.2-1 Indoor Resuspension Rates

Resuspension Rate (1/s)	Resuspension Factor (m ⁻¹) ^a	Conditions	Reference	Comments
2.8 × 10 ⁻¹⁰ 1.2 × 10 ⁻¹⁰ 5.0 × 10 ⁻⁹ 2.3 × 10 ⁻⁸ 1.1 × 10 ⁻⁷ 9.4 × 10 ⁻⁹		0.3-0.5 µm particles 0.5-1 µm particles 1-5 µm particles 5-10 µm particles 10-25 µm particles > 25 µm particles	Thatcher and Layton, 1995	Estimated for residence with four residents performing "normal" activities. Assumed air exchange rate of 0.3 h ⁻¹ .
2.8 × 10 ⁻⁸		"Characteristic value" for a uranium diffusion plant	Healy, 1971	Quoted from study by Spangler and Willis (1967).
1.7 × 10 ⁻⁶ 5.6 × 10 ⁻⁷ 2.8 × 10 ⁻⁷ 1.9 × 10 ⁻⁶	1.9 × 10 ⁻⁴ 3.9 × 10 ⁻⁵ 9.4 × 10 ⁻⁶ 7.1 × 10 ⁻⁴	Vigorous work including sweeping (ZnS) Vigorous walking (ZnS) Collecting contaminated samples (ZnS) Light sweeping with fans on for circulation (CuO)	Healy, 1971	Estimated from data in Fish et al. (1967) on measurements of ZnS and CuO tracers.
8.3 × 10 ⁻⁷ 5.6 × 10 ⁻⁶ to 1.4 × 10 ^{-5b}	1.2 × 10 ⁻⁴ 3.8 × 10 ⁻³	Walking in socks, two separate experiments	Healy, 1971	Estimated from Brunskill (1967).
0 to 3 × 10 ⁻⁶	0 to 1.77 × 10 ⁻⁴	No movement up to about 100 steps per minute, minimum value observed where movement was involved (14 steps per minute) was 6 × 10 ⁻⁹ s ⁻¹ (3 × 10 ⁻⁷ m ⁻¹)	Healy, 1971	Estimated from Jones and Pond (1967) for activity on different floor types contaminated with plutonium oxide or plutonium nitrate.

^a Where applicable, the resuspension factor used by Healy (1971) to derive an estimated resuspension rate is given.

^b Assumed number of air changes per hour ranged between 2 and 5.

where

λ_r = the resuspension rate,

R_f = the resuspension factor,

V = the room volume,

A = the contaminated surface area, and

λ_v = the ventilation rate.

Healy's estimates are given in Table 7.2-1. Beyeler et al. (1998a) have also reviewed the earlier work in the context of resuspension factors rather than rates.

A loguniform distribution is suggested to represent the resuspension rate because of the limited data available and the wide range of estimated values. All values in

Table 7.2-1 contain inherent assumptions with respect to ventilation rates and contaminant floor loadings. However, 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 7.2-1 was chosen, $2.8 \times 10^{-10} \text{ s}^{-1}$. Similarly, the largest value in Table 7.2-1, $1.4 \times 10^{-5} \text{ s}^{-1}$, was chosen as the maximum value for the distribution. The probability density function selected for the indoor resuspension rate is shown in Figure 7.2-1.

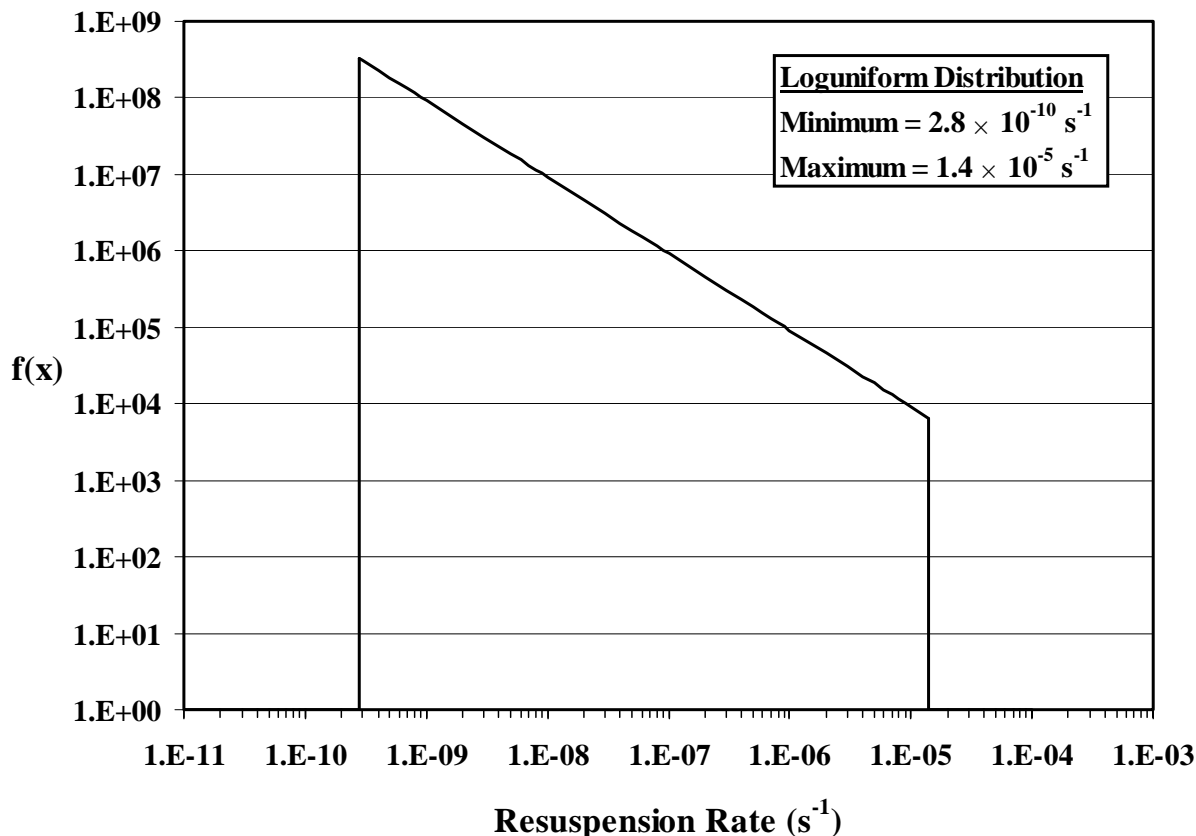


Figure 7.2-1 Indoor Resuspension Rate Probability Density Function

7.3 Shielding Density

Applicable Code: RESRAD-BUILD

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

Units: 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 shielding characteristics). RESRAD-BUILD accommodates eight types of shielding materials: concrete, water, aluminum, iron, lead, copper, tungsten, and uranium. Table 7.3-1 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 7.3-2 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. The probability density function for concrete shielding density is displayed in Figure 7.3-1.

**Table 7.3-1 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).

Table 7.3-2 Concrete Density from Various Sources

Aggregate	Concrete Density (g/cm ³)		
	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) or normal weight	2.2-2.4	2.2-2.6	2.3
Heavy weight	— ^a	—	2.4-6.15
Limonite (goethite, hyd. Fe ₂ O ₃)	2.6-3.7	—	—
Ilmenite (nat. FeTiO ₃)	2.9-3.9	—	—
Magnetite (nat. Fe ₃ O ₄)	2.9-4.0	—	—
Limonite and magnetite	—	—	3.35-3.59
Iron (shot, punchings, etc.) or steel	4.0-6.0	—	4.0- 4.61
Barite	3.0-3.8	—	3.72
Lightweight	—	0.3-1.85	0.55-1.85
Pumice	—	0.8-1.8	1.45-1.6
Scoria	—	1.0-1.85	1.45-1.75
Expanded clay and shale	—	1.4-1.8	—
Vermiculite	—	0.3-0.8	0.55-1.2
Perlite	—	0.4-1.0	0.8-1.3
Clinker	—	1.1-1.4	—
Cinders without sand	—	—	1.36
Cinders with sand	—	—	1.75-1.85
Shale or clay	—	—	1.45-1.75
Cellular	—	0.36-1.5.	—
No-fines	—	1.6-2.0	1.68-1.8
No-fines with light weight aggregate	—	0.64-higher	—
Nailing	—	0.65-1.6	—
Foam	—	—	0.3-1.75

^a — = data not available.

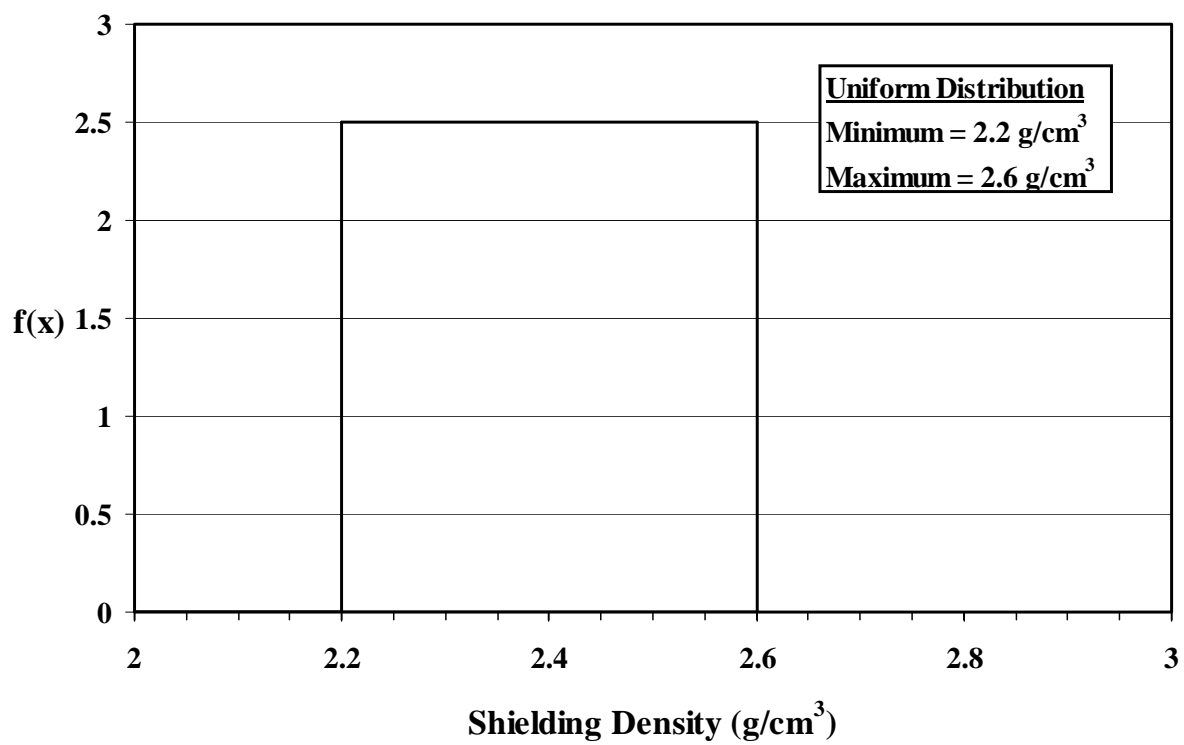


Figure 7.3-1 Concrete Shielding Density Probability Density Function

7.4 Air Exchange Rate for Building and Room

Applicable Code: RESRAD-BUILD

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.

Units: 1/h

Probabilistic Input:

Distribution: truncated lognormal-n

Defining Values for Distribution:

Underlying mean value:	0.4187	Lower quantile value:	0.001
Standard deviation:	0.88	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 – air flow 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.

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 7.4-1 presents summary statistics from that study on air exchange rates in the United States and regionally. Pandian et al. (1993) also analyzed the data by season and by the number of levels with the homes. They concluded that exchange rates are higher in Southwest than in the Northeast and Northwest; summer ventilation rates are much higher than winter and fall rates; and multilevel residences have higher air exchange rates than single-level

Table 7.4-1 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					Pre-retrofit in one house:	Berk et al., 1981
	0.36	0.71	0.62	0.25	$n = 17$ measurements with fan on	
	0.18	0.56	0.33	0.14	$n = 11$ measurements with fan off	
					Post-retrofit in one house:	
	0.22	0.69	0.49	0.11	$n = 16$ measurements with fan on	
	0.10	0.33	0.20	0.08	$n = 11$ measurements with fan off	
Normal	0.08	0.27	0.17	0.06	$n = 12$ energy-efficient houses	Lipschutz et al., 1981
Lognormal	0.1	3.1	0.5 median		$n = 312$ houses in North America	Grimsrud et al., 1983, as cited in Godish, 1989
	0.1	3.6	0.9 median		Subsample of low-income housing	
Lognormal	0.17	1.33	0.33 median		$n = 8$ mobile home measurements	Godish and Rouch, 1988
	0.18	1.45	0.36 median		$n = 10$ UFF-insulated home measurements	
Normal					$n = 9$ houses in upstate New York	Offermann et al., 1982
	0.22	0.50	0.35	0.08	With mechanical ventilation off	
	0.47	0.78	0.63	0.10	With mechanical ventilation on	
Normal					$n = 10$ houses in Washington state	Lamb et al., 1985
	0.40	0.98	0.27		Pre-weatherization retrofit	
	0.23	1.00	0.30		Post-weatherization retrofit	

Table 7.4-1 (Cont.)

Distribution Type	Min	Max	Mean	SD	Comments	References
Lognormal	0.89			3.44	All regions ($n = 1,836$) geometric mean, SD	Pandian et al., 1993
	0.34			1.88	Northwest ($n = 423$)	
	0.40			2.07	Northeast ($n = 423$)	
	1.86			3.02	Southwest ($n = 990$)	
	1.99			3.28	All regions ($n = 1,836$) arithmetic mean, SD	Murray and Burrmaster, 1995
	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 ($n = 2844$)	
	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	

residences. The authors present both arithmetic and geometric means and standard deviations, as well as percentile distributions.

Murray and Burmaster (1995) also used the data compiled by BNL using the PFT technique to estimate univariate parametric probability distributions for air exchange rates for residential structures in the United States. The analysis was characterized by four key points: the use of data for 2,844 households; a four-region breakdown based on heating degree days; estimation of lognormal distributions as well as provision of empirical (frequency) distributions; and provision of these distributions for all of the data. The authors summarized distributions for subsets of the data defined by climate region and season. The coldest region (region 1) was defined as having 7,000 or more heating degree days, the colder region (region 2) as 5,500-6,999 degree days, the warmer region (region 3) as 2,500-5,499 degree days, and the warmest region (region 4) as fewer than 2,500 degree days. The months of December, January, and February were defined as season 1; March, April, and May as season 2; June, July, and August as season 3; and September, October, and November as season 4. The authors concluded that the air exchange rate was well fit by lognormal distributions for small samples sizes except in a few cases. The mean and standard deviations are listed in Table 7.4-1. The authors recommended that the empirical or lognormal distribution may be used in indoor air models or as input variables for probabilistic health risk assessments.

In a study sponsored by the EPA (Koontz and Rector [1995]), a similar data set as analyzed by Murray and Burmaster (1995) was used, but 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 7.4-1, 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 7.4-1. 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}), reflecting the extremely "tight" building construction and ventilation systems installed in the houses.

Doyle et al. (1984) measured air exchange rates in 58 weatherized houses during a 4- to 5-month period during both winter and summer sampling periods. The houses were located in Fargo, North Dakota; Colorado Springs, Colorado; Portland, Maine; and Charleston, North Carolina. The investigators determined the geometric means and

geometric standard deviations for air exchange rates for each city and for the entire sample. Because of the relatively small number of measurements in each city, conclusions about the geographic distribution of air exchange rates are limited. However, combining the data for the cities provides an overall lognormal distribution of $0.8 \pm 1.8 \text{ h}^{-1}$ (ranging from 0.2 to 2.3 h^{-1}), which appears to encompass most air exchange rates determined in other studies.

Studies on the air exchange rates of large commercial buildings have been much more limited. Table 7.4-2 lists results from some studies on commercial buildings. It can be seen that these values are relatively close to those for residential construction. Although the primary outside air source for large buildings is the mechanical ventilation system, infiltration is the primary outside air source for residential homes (American Society of Heating, Refrigeration, and Air-Conditioning Engineers [ASHRAE], 1997). In either case, a continuous supply of outside air is required to dilute and eventually remove indoor contaminants. Thus, the air exchange requirements are expected to be similar for both residential and commercial construction. However, differences in local airflow and temperature, as well as air exchange, may be required to maintain workers' comfort according to their activity level.

Table 7.4-2 Outside Air Exchange Rates for Commercial Buildings

Building Air Exchange Rate (h^{-1})	Building Description	Reference
0.33 – 1.04	Large office buildings	Persily and Grot, 1985
0.9	The National Archive Building	Silberstein and Grot, 1985
	38 commercial buildings studied in the Pacific Northwest during all seasons of the year. Two buildings were sampled twice at different times of the year.	Turk et al., 1987
	Number of buildings:	
0.0 – 0.5	3	
0.5 – 1.0	10	
1.0 – 1.5	9	
1.5 – 2.0	8	
2.0 – 2.5	6	
2.5 – 3.0	2	
3.0 – 3.5	0	
3.5 – 4.0	1	
4.0 – 4.5	1	
0.6, 4.0, and 8.2	Three buildings in an office/laboratory complex	Weschler et al., 1989

Turk et al. (1987) examined the outdoor exchange rates of 38 buildings in the Pacific Northwest. The buildings included schools, libraries, and office buildings in mild and harsh climates measured during different seasons of the year. Results are shown in Table 7.4-2. The arithmetic mean and standard deviation are 1.52 h^{-1} and 0.873 , respectively. Although this set of data is limited, the mean falls between the arithmetic means determined Pandian et al. (1993) and Murray and Burmaster (1995), 1.99 and 0.76 h^{-1} , respectively, for residential air exchange rates. The air exchange data from Persily and Grot (1985) and Silberstein and Grot (1985), as shown in Table 7.4-2, fall within the range observed by Turk et al. (1987). The study of a laboratory/office complex by Weschler et al. (1989) has two values outside this range, 4.0 and 8.2 h^{-1} . However, maximum values of 11.77 and 45.6 h^{-1} were used by Murray and Burmaster (1995) and Pandian et al. (1993), respectively.

While the data on commercial building air exchange rates are limited, the distribution of rates is expected, in part because of human comfort considerations, to be similar to residential structures when averaged over the United States for all four seasons of the year. Thus, a generic lognormal distribution has been assigned to the building exchange rate to represent 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 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 7.4-1 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.

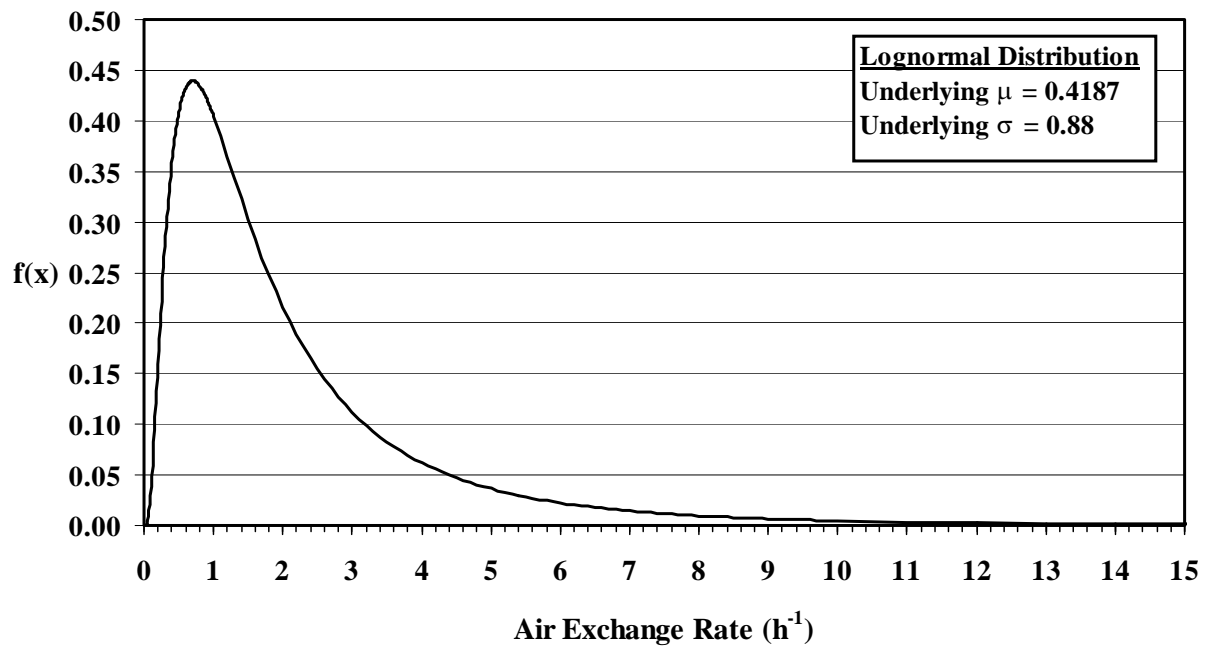


Figure 7.4-1 Building and Room Air Exchange Rate Probability Density Function

7.5 Deposition Velocity (Indoor)

Applicable Code: RESRAD-BUILD

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

Units: 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 decay rate, λ_d , of particles in indoor air due to deposition is often expressed as:

$$\lambda_d = \frac{v_d A_d}{V} , \quad (7.5-1)$$

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 7.5-1 presents an idealized representation of deposition velocity on a floor as a function of particle size on the basis of the methodology in Nazaroff and Cass (1989). A similar trend is observed for deposition of particles outdoors (Sehmel, 1980).

Because deposition velocities depend on particle size, it is expected that the probability density function distribution of deposition velocities is dependent on the particle size distribution. The particle size distribution in the atmosphere typically exhibits three modes (Seinfeld and Pandis, 1998). Fine particles (particles less than $2.5\ \mu\text{m}$ in diameter) can be divided into two modes, the nuclei mode and the accumulation mode. The nuclei mode (particles approximately 0.005 to $0.1\ \mu\text{m}$ in diameter) contains the largest number of particles in the atmosphere but represents only a few percent of the total mass of airborne particles (Seinfeld and Pandis, 1998). Nuclei mode particles are formed from condensation of atmospheric gases, such as combustion products. Depletion of nuclei mode particles occurs primarily through coagulation with larger particles. The accumulation mode (particles approximately 0.1 to $2.5\ \mu\text{m}$ in diameter) accounts for a large portion of the aerosol mass. Accumulation mode particles are formed through coagulation of particles in the nuclei mode and through condensation of gases onto smaller particles. Because removal mechanisms are not as efficient for this size range, particles tend to accumulate (hence the term “accumulation mode”). Coarse particles (diameters greater than $2.5\ \mu\text{m}$) 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 7.5-2 demonstrates the trimodal nature of the particle size distributions commonly found. Similar distributions are expected for indoor air concentrations, with the exception of some indoor source contributions, because, as discussed in Section 7.1, the building shell has been shown to be an insignificant barrier to particle sizes under $10\ \mu\text{m}$.

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 7.5-1 and 7.5-2, respectively) and taking into consideration the variability of each. Experimental estimates provide support for such an assumption, as shown in Tables 7.5-1 through 7.5-3. Also, because deposition is dependent on local airflow patterns (Nazaroff and Cass, 1989), 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 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 $2.7 \times 10^{-6}\ \text{m/s}$ and $2.7 \times 10^{-3}\ \text{m/s}$, respectively, as found in Tables 7.5-1 through 7.5-3. This distribution is shown in Figure 7.5-3.

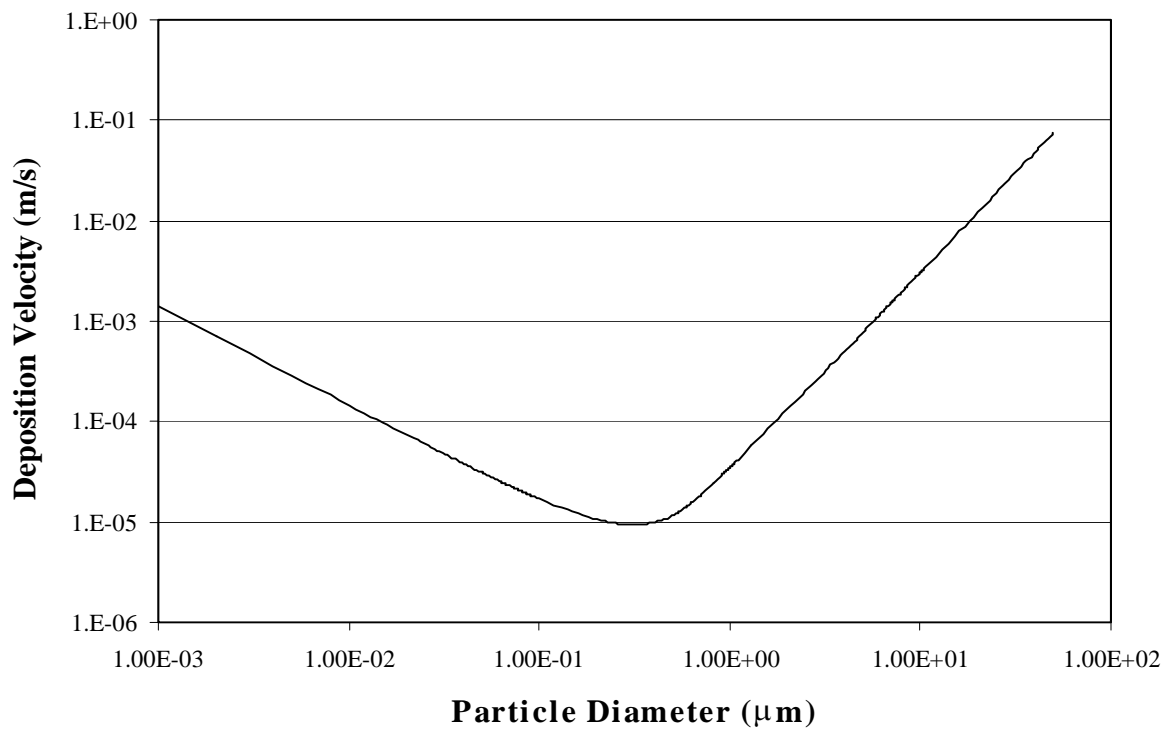


Figure 7.5-1 Idealized Representation of Indoor Particle Deposition Velocity

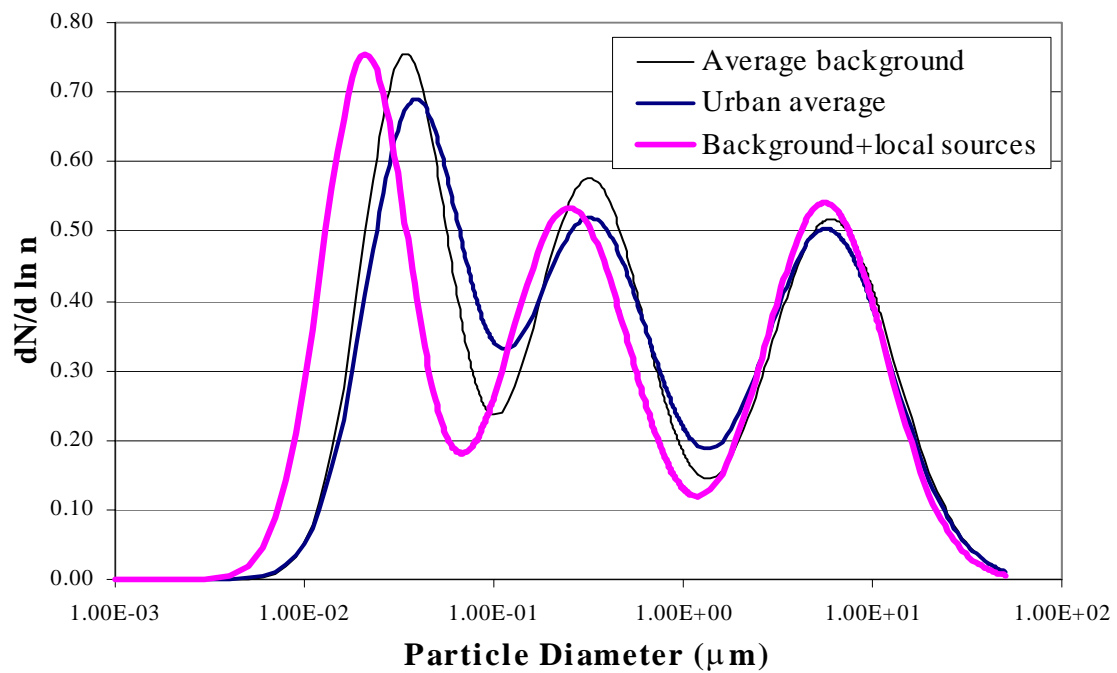


Figure 7.5-2 Trimodal Nature of Aerosol Particle Size Distribution

Table 7.5-1 Estimated Indoor Deposition Velocities by Particle Size

Particle Size (μm)	Deposition Velocity (m/s)	Comments	Reference
0.71	1.7×10^{-5}	^7Be with natural air exchange	Lang, 1995
1.4	1.3×10^{-5}		
2.8	6.7×10^{-5}		
0.71	1.33×10^{-4}	^7Be 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}	Data Set 2	
1-2	1.9×10^{-4}		
2-3	5.0×10^{-4}		
3-4	5.6×10^{-4}	Data Set 3	
4-6	1.2×10^{-3}		
1-5	3.1×10^{-4}		
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 Calcium ion particulates at two locations	Sinclair et al., 1985
2.5-15	1×10^{-2} and 2×10^{-3}		

Table 7.5-2 Estimated Deposition Velocities by Particle Size in Residences with and without Furniture

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

Source: Fogh et al. (1997).

Table 7.5-3 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).

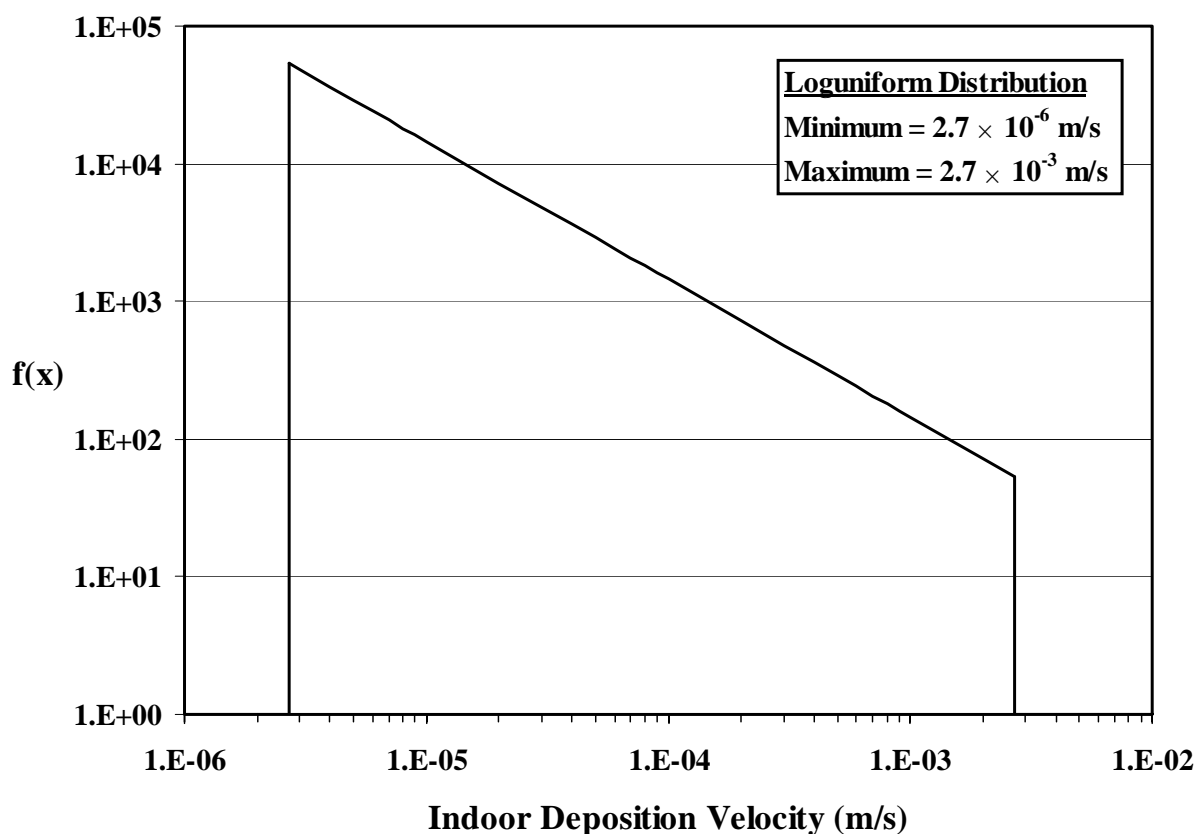


Figure 7.5-3 Indoor Deposition Velocity Probability Distribution

7.6 Indoor Fraction

Applicable Code: RESRAD, RESRAD-BUILD

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

Units: unitless

Probabilistic Input:

Distribution: user-defined continuous with linear interpolation

Defining Values for Distribution: See Table 7.6-1 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. (1998a) 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 7.6-2 was based on the assumption that full-time nonagricultural workers spent 35 hours or more a week at work. However, some workers may spend some time outside.

Table 7.6-1 Cumulative Distribution Functions for the Indoor Fraction

Cumulative Probability	Indoor Fraction	
	RESRAD	RESRAD-BUILD
0	0	0.003
0.05	0.375	0.0347
0.25	0.521	0.306
0.50	0.625	0.365
0.75	0.809	0.403
0.90	0.938	0.469
0.95	0.992	0.500
0.98	1.0	0.542
0.99	1.0	0.594
1.0	1.0	0.692

Table 7.6-2 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. (1998a).

The 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 7.6-3 summarizes a number of distributions, including distributions for time spent indoors at unspecified work locations in a plant/factory/warehouse. The distribution for full-time workers in the plant/factory/warehouse category is expected to be the best representation for workers in the building occupancy scenario and is the default for RESRAD-BUILD. For perspective, the 50th percentile value for this distribution, 0.365, corresponds to an 8.76-hour work day. The cumulative distribution function for the indoor fraction is shown in Figure 7.6-1.

For RESRAD, the indoor fraction is the fraction of time spent inside the building where the receptor is afforded shielding from the contaminated soil. This situation translates into the amount of time spent indoors at a residence when evaluating the residential farmer scenario. The EPA's comprehensive review of human activity patterns (EPA, 1997) also contains statistics on the amount of time spent indoors at a residence. Table 7.6-4 summarizes the relevant subset of distributions provided in the *Exposure Factors Handbook* (EPA, 1997) for this time fraction. The distribution chosen to represent the average members of the critical group (adult males) in the residential farmer scenario was that for the 18-64 year age group. This distribution is almost identical to that for the male population group and close to those for all subjects and the female population group. Figure 7.6-2 presents the cumulative distribution function for the indoor fraction parameter in RESRAD.

Table 7.6-3 Statistics for Fraction of Time Spent Indoors at Work

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).

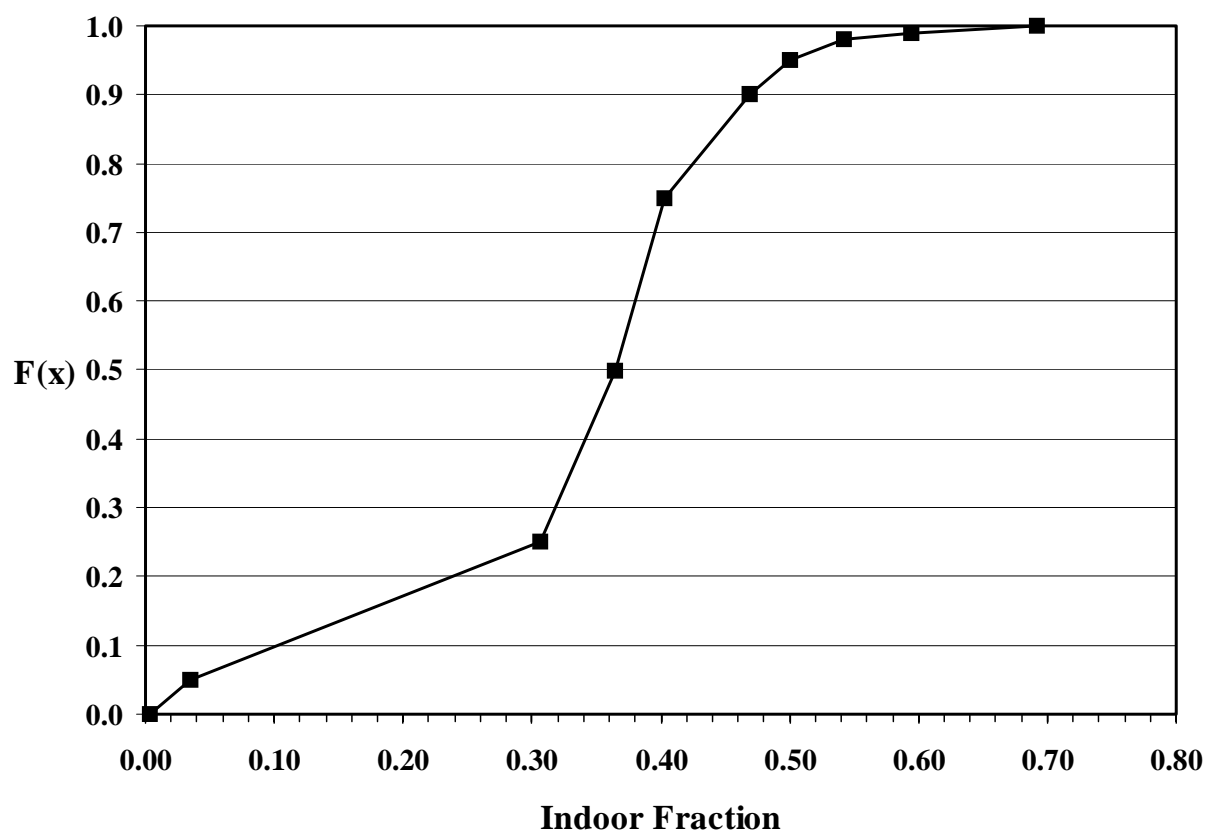


Figure 7.6-1 Indoor Fraction Cumulative Distribution Function for RESRAD-BUILD

Table 7.6-4 Statistics for Fraction of Time Spent Indoors in a Residence^a

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

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

^b Number of subjects in the survey.

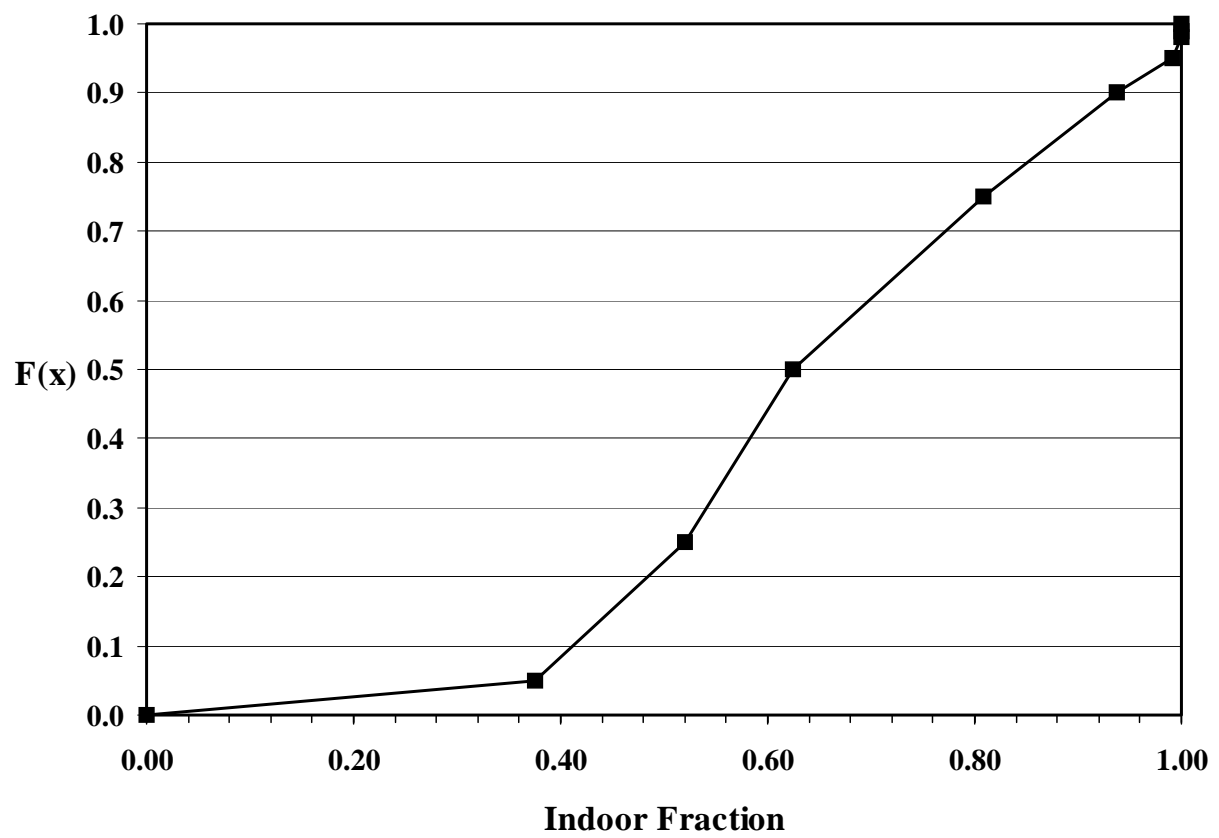


Figure 7.6-2 Indoor Fraction Cumulative Distribution Function for RESRAD

7.7 Room Area

Applicable Code: RESRAD-BUILD

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

Units: square meters (m^2)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 3 Maximum: 900 Most likely: 36

Discussion: The room area is used in determining 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. 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 $1.5 \times 2 \text{ m}$) 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 $10,000 \text{ ft}^2$) 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 , $3 \text{ m} \times 4 \text{ m}$) and is in the range of what might be expected for a multi-occupant office room. Figure 7.7-1 presents the probability density function suggested for the room area.

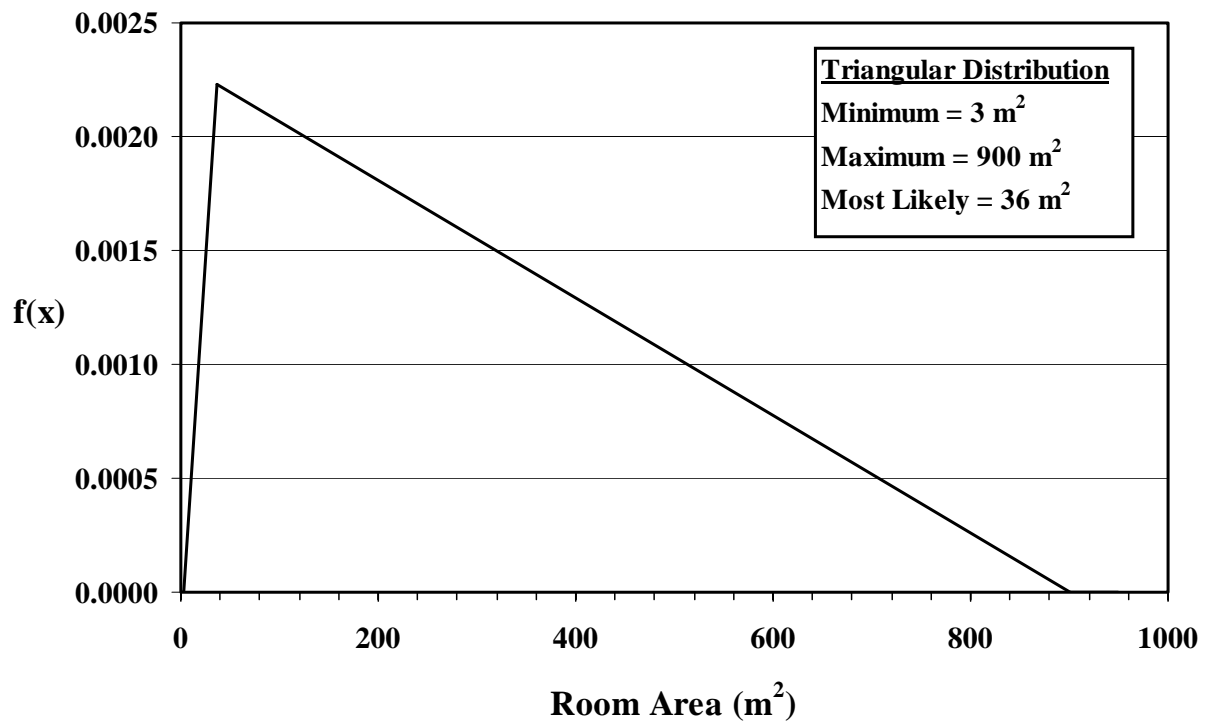


Figure 7.7-1 Probability Density Function for Room Area

7.8 Room Height

Applicable Code: RESRAD-BUILD

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

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 2.4 Maximum: 9.1 Most likely: 3.7

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 7.8-1. The 2.4-m (8 ft) height is considered to be typical of residential housing (EPA, 1997). Minimum room heights of 2.1 m (7 ft) below beams and girders are required by the Council of American Building Officials, with a ceiling height of not less than 2.3 m (7.5 ft) for half of the required area (National Association of Home Builders [NAHB], 1998). The U.S. Department of Housing and Urban Development requires a minimum ceiling height of not less than 2.1 m (7 ft) for at least half of the floor area and 1.9 m (6 ft 4 in.) under ducts and beams.

No comprehensive study of room height in commercial buildings exists. Room height can vary within the same occupational setting as well as between industries. Room height may also vary according to climate (because of energy efficiency considerations). A typical room height in commercial buildings is 3.7 m (12 ft) (EPA, 1997). A minimum of 2.4 m (8 ft) is found in smaller rooms, such as those used for individual offices or conference rooms. Larger room heights are found in warehousing (shipping/receiving) operations, which may have room heights of up to approximately 9.1 m (30 ft). Thus, for the occupational scenario, a triangular distribution is used for the room height, with a most likely value of 3.7 m and minimum and maximum values of 2.4 and 9.1 m, respectively. This distribution is a rough generalization, and site-specific data should be used when available. The probability density function is shown in Figure 7.8-1.

Table 7.8-1 Room Height in New Conventional and Manufactured Homes, 1996

Room Height (m) [ft]	Conventional Homes (First Floor), Percent of Total	Manufactured Homes, Percent of Total
≤ 2.1 [≤ 7]	0.1	48.2
2.3 [7.5]	1.6	37.4
2.4 [8.0]	57.8	5.1
2.6 [8.5]	0.8	1.5
2.7 [9.0]	24.2	7.7
> 2.7 [> 9]	15.5	—

Source: NAHB (1998).

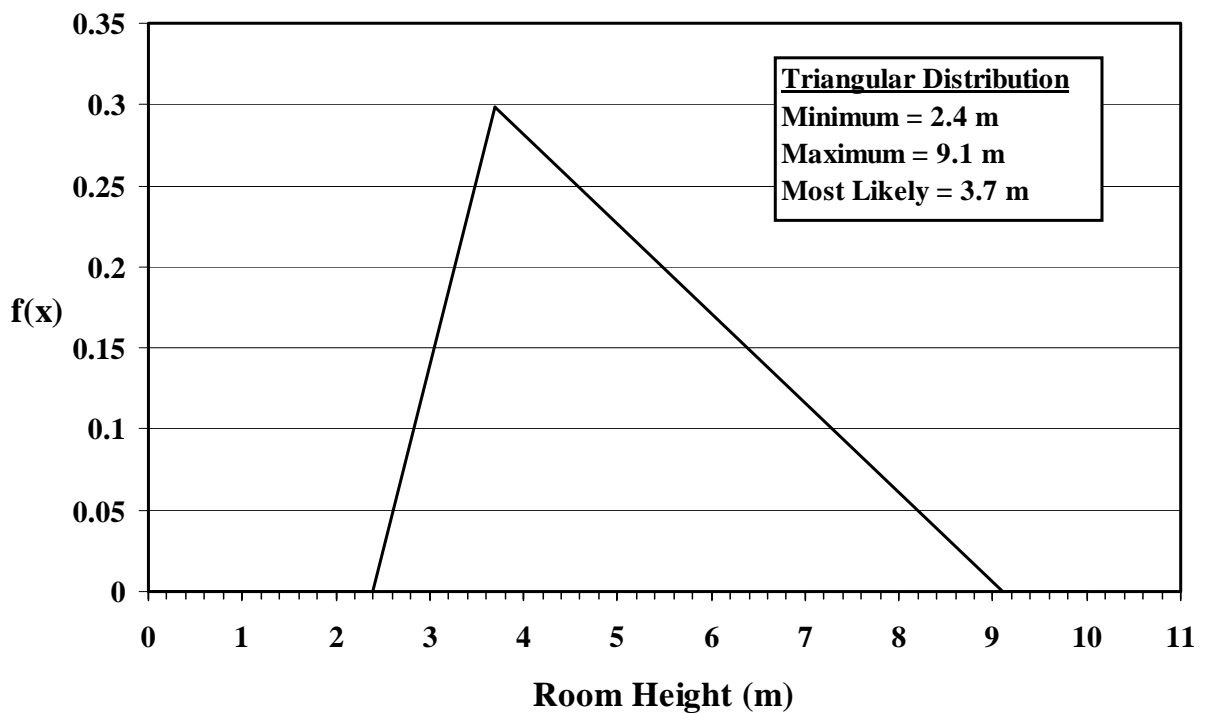


Figure 7.8-1 Room Height Probability Density Function

7.9 Shielding Thickness

Applicable Code: RESRAD-BUILD

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

Units: 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 where only air is present between the source and receptor, the shielding thickness is 0. The RESRAD-BUILD code requires the shielding thickness for every source and receptor pair (e.g., if there were 4 sources and 6 receptors, the code would require 24 [6×4] shielding thickness input values). The same shielding object might be assigned different thicknesses for different source-receptor pairs because of geometry considerations. It is highly recommended that the shielding thickness value be obtained from a direct measurement based on the site-specific condition. For example, to calculate dose for a receptor in a room other than the room in which the source is located, a shielding thickness equivalent to the wall thickness should be assumed.

Floor and wall thicknesses vary depending on the type of building and type of construction. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness approximates an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. A shielding thickness of 30 cm would reduce the dose significantly from the external exposure pathway for all radionuclides, including high-energy gamma emitters.

Little information is available for the shielding thicknesses in actual D&D situations; therefore, a triangular distribution is assumed. The maximum value is assumed to be 30 cm, the minimum value is chosen as 0 cm, and the most likely value also is chosen to be 0 cm (this assumption would yield most conservative dose results for the external exposure pathway). The probability density function is shown in Figure 7.9-1.

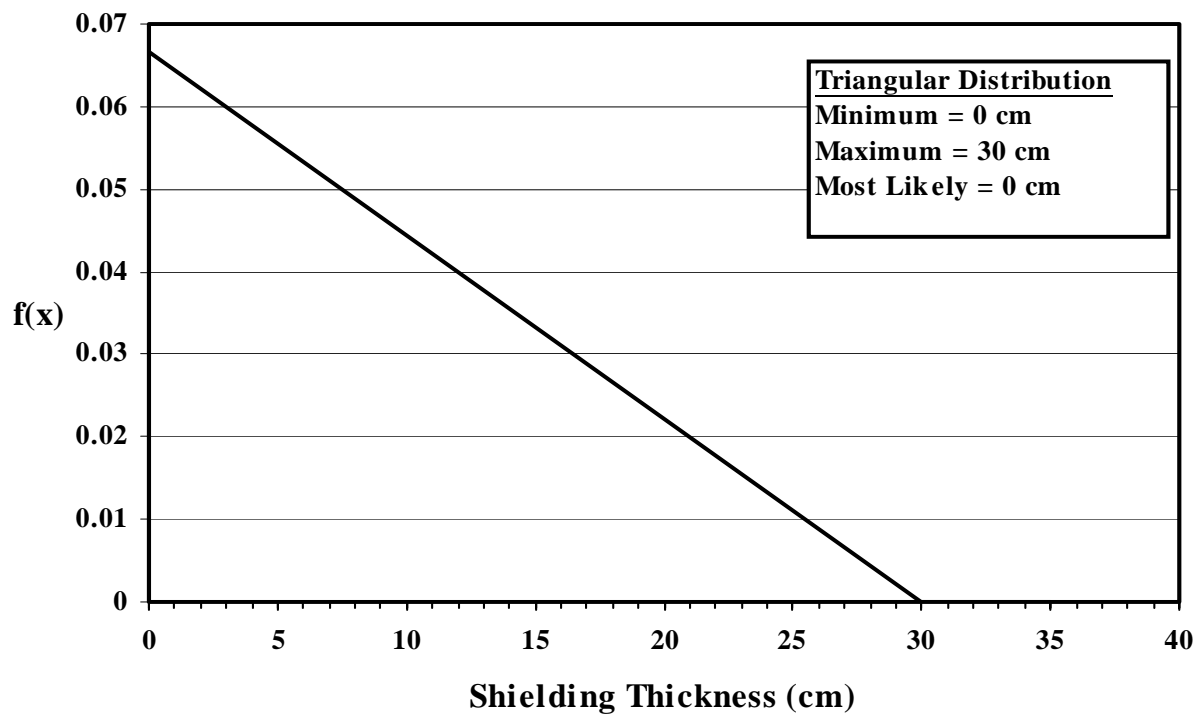


Figure 7.9-1 Shielding Thickness Probability Density Function

7.10 External Gamma Shielding Factor

Applicable Code: RESRAD

Description: The shielding factor for external gamma radiation is the ratio of the external gamma radiation level indoors on-site to the radiation level outdoors on-site. It is a function of the shielding that building materials provide against the penetration of gamma radiation.

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

Underlying mean value:	-1.3	Lower limit:	0.044 ¹
Underlying standard deviation:	0.59	Upper limit:	1

Discussion: A single external shielding factor is used to account for the attenuation of gamma radiation by building materials. The external shielding factor is the fraction of outdoor external gamma radiation level that is present indoors. The parameter can range from 0 (complete attenuation) to 1 (no attenuation).

Home construction type has a dramatic effect on the attenuation of gamma radiation. Concrete and brick attenuate gamma radiation more effectively than wood; hence, a house built on a concrete slab or built with a full basement will have a lower external shielding factor (i.e., will provide more protection) than a house built with a crawlspace without a finished concrete floor. Similarly a house that has exterior walls made of brick or stone will have a lower external shielding factor than a house with outer walls made of wood or other building materials. Data obtained from the U.S. Census Bureau indicates that approximately 20% of the new homes constructed during the years 1993-1999² were built on a crawlspace (U.S. Department of Housing and Urban Development, 1996,1999). Approximately 43% of homes constructed in the same period were built on a slab, and the remaining 37% of the homes were built either on a full or partial basement (U.S. Department of Housing and Urban Development, 1996, 1999). Data obtained from the same sources showed that 27% of the homes built in the U.S. between 1996-1999² used brick or stone as the principal building material for the exterior walls. Approximately

¹ Corresponds to the cumulative probability of 0.1%.

² Data from 1999 are only from the first three quarters of the year.

56% of the homes constructed within the same period had primary exterior walls made of either wood or vinyl/aluminum siding, while the remaining 17% had exterior walls made of stucco (U.S. Department of Housing and Urban Development, 1999).

External shielding factors were estimated for five different radioisotopes — Cs-137, Co-60, Mn-54, U-238, and Ra-226 — for four different home construction types. The types considered were (1) a brick home constructed over a full basement or on a slab, (2) a frame house constructed over a full basement or on a slab, (3) a frame house constructed with a crawlspace, and (4) a frame house constructed with a partial basement. The shielding factors were estimated with RESRAD-BUILD using five source geometries. The full basement/slab was modeled by placing a 15-cm (6-in.) concrete shield over the surface contamination, while the crawlspace was modeled by placing a 2.5-cm (1-in.) shield over the surface contamination. The brick and wooden walls were modeled using a 10-cm (4-in.) concrete and 2.5-cm (1-in.) wooden shield, respectively. It was assumed a person in the house spent 50% of the time completely shielded by the brick or wooden walls and 50% of the time by a window (essentially unshielded). The external shielding factors provided in Table 7.10-1 for the scenarios listed above are average values for the radionuclides that were analyzed. The shielding factors presented in the table were found to be consistent with those obtained from previous studies (NRC, 1975; Jensen, 1983; Golikov et al., 1999).

The probability distribution for the external shielding factor was obtained by combining the results from the RESRAD-BUILD computer code with the data obtained from the U.S. Department of Housing and Urban Development (1996, 1999). The external shielding factor was assumed to be distributed lognormally, and Bayesian techniques were used to estimate the parameters of the distribution. The posterior means of μ and σ were used to characterize the probability distribution for the external shielding factor. The probability density function is shown in Figure 7.10-1.

Table 7.10-1 External Shielding Factors

Scenario	External Shielding Factor
Brick House Constructed with a Slab or Full Basement	0.17
Frame House Constructed with a Slab or Full Basement	0.21
Frame House Constructed with a Crawlspace	0.81
Frame House Constructed with a Partial Basement	0.51

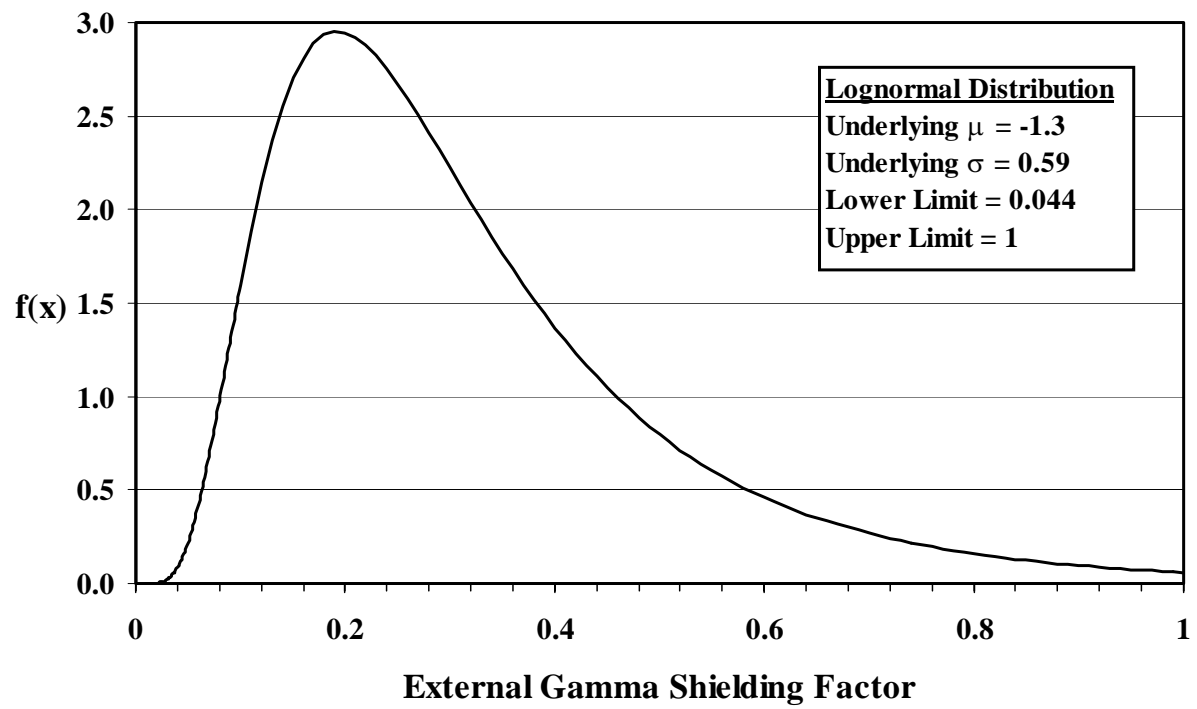


Figure 7.10-1 External Gamma Shielding Factor Probability Density Function

8 SOURCE CHARACTERISTICS PARAMETER DISTRIBUTIONS

8.1 Source Density, Volume Source

Applicable Code: RESRAD-BUILD

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

Units: 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 8.1-1 lists the density range (if appropriate) or a single value of density for the RESRAD-BUILD materials that have a narrow range of density (except concrete). The table lists a range for cast iron and a single value of density for each of the other materials. The values are taken from the *Health Physics and Radiological Health Handbook* (Shleien, 1992) and from the *CRC Handbook of Chemistry and Physics* (Lide, 1998) (for cast iron, uranium and tungsten). Table 8.1-2 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. The probability density function for the concrete source density is shown in Figure 8.1-1.

**Table 8.1-1 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).

Table 8.1-2 Concrete Density from Various Sources

Aggregate	Concrete Density (g/cm ³)		
	Shleien (1992)	Neville (1996)	Merritt et al. (1995)
Ordinary (silicacious) or normal weight	2.2-2.4	2.2-2.6	2.3
Heavy weight	— ^a	—	2.4-6.15
Limonite (goethite, hyd. Fe ₂ O ₃)	2.6-3.7	—	—
Ilmenite (nat. FeTiO ₃)	2.9-3.9	—	—
Magnetite (nat. Fe ₃ O ₄)	2.9-4.0	—	—
Limonite and magnetite	—	—	3.35-3.59
Iron (shot, punchings, etc.) or steel	4.0-6.0	—	4.0- 4.61
Barite	3.0-3.8	—	3.72
Lightweight	—	0.3-1.85	0.55-1.85
Pumice	—	0.8-1.8	1.45-1.6
Scoria	—	1.0-1.85	1.45-1.75
Expanded clay and shale	—	1.4-1.8	—
Vermiculite	—	0.3-0.8	0.55-1.2
Perlite	—	0.4-1.0	0.8-1.3
Clinker	—	1.1-1.4	—
Cinders without sand	—	—	1.36
Cinders with sand	—	—	1.75-1.85
Shale or clay	—	—	1.45-1.75
Cellular	—	0.36-1.55	—
No-fines	—	1.6-2.0	1.68-1.8
No-fines with light weight aggregate	—	0.64-higher	—
Nailing	—	0.65-1.6	—
Foam	—	—	0.3-1.75

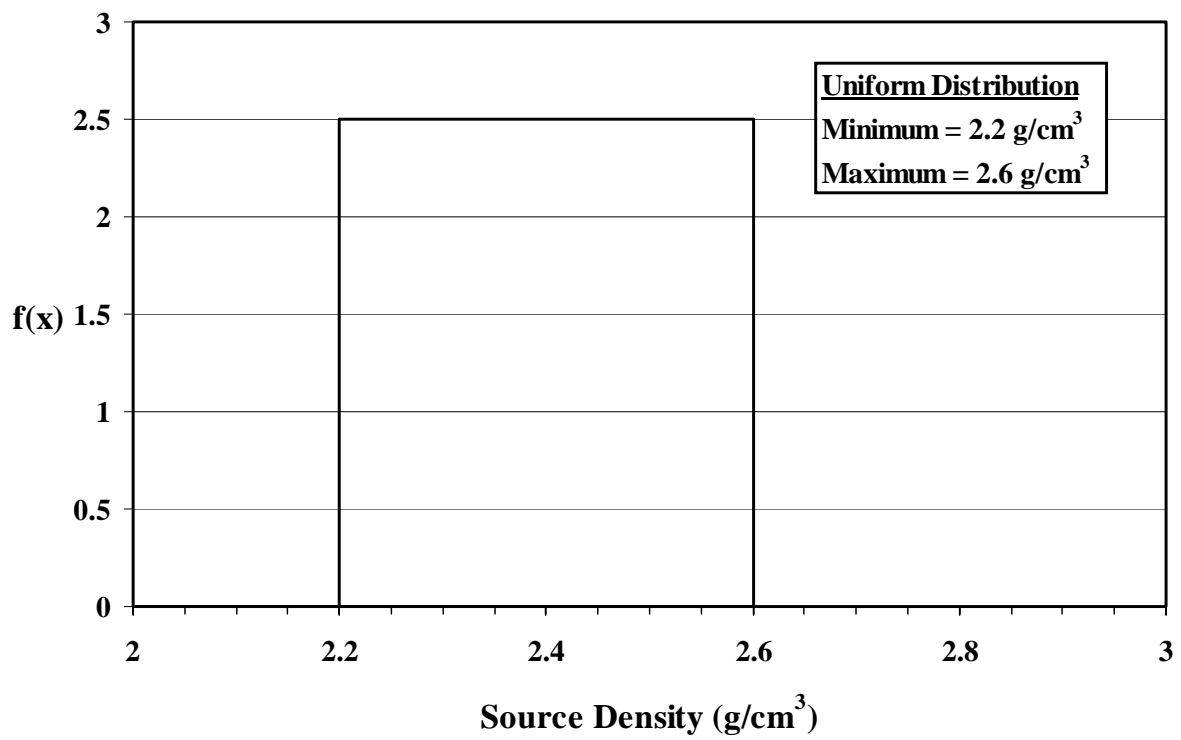


Figure 8.1-1 Concrete Source Density Probability Distribution Function

^a – = data not available.

8.2 Source Erosion Rate, Volume Source

Applicable Code: RESRAD-BUILD

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.

Units: 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 traffic or vehicle traffic, such as in warehousing operations. However, such areas are usually covered (carpet or tile), sealed, or waxed on a periodic basis, thus reducing the potential for erosion.

A triangular distribution was selected to represent the source erosion rate. A value of 0 was chosen for both the minimum and most likely values because contamination on both walls and floors in little-used areas can be expected to remain in place indefinitely. Even high-use areas may not experience erosion if they remain protected by paint or sealant. Under normal occupancy conditions (not remedial activities), a maximum value is expected as a result of traffic over floor areas. Contaminated wood, concrete, and (possibly) ceramic tile are expected to be the primary flooring materials affected. Contaminated carpet would be expected to have been removed by remedial activities. However, aside from studies on abrasion, little information is available in the general literature on normal wear of concrete or wood surfaces over extended periods of time.

A rough approximation for the maximum value can be obtained by considering that any eroded materials would become airborne for at least short periods of time. A

conservative assumption was made that all airborne indoor particulate matter is a result of erosion of the floor surface. Typically, outdoor air is a significant source of indoor air particulate concentrations (see Section 7.1), but this contribution was not considered. The erosion rate of a concrete floor was estimated to maintain an average particulate air concentration of $100 \mu\text{g}/\text{m}^3$ (Section 4.6) with a room air exchange rate of 1.52/h (Section 7.4). A floor area of 36 m^2 (Section 7.7), a room height of 3.7 m (Section 7.8, used to estimate the room volume), and a concrete density of $2.4 \text{ g}/\text{cm}^3$ (Section 8.1) were used. The estimated erosion rate was $5.6 \times 10^{-7} \text{ cm}/\text{d}$. Figure 8.2-1 shows the probability density function used for the source erosion rate.

In the case of renovation or remedial actions, the source erosion rate can be quite high. For example, thin-volume sources in wood or concrete could be removed in seconds with power sanders or sandblasting techniques. Other examples include the complete removal of wood, carpet, or drywall sections within seconds to minutes. For such a scenario, the user can input values appropriate to the contaminated source and removal technique under consideration.

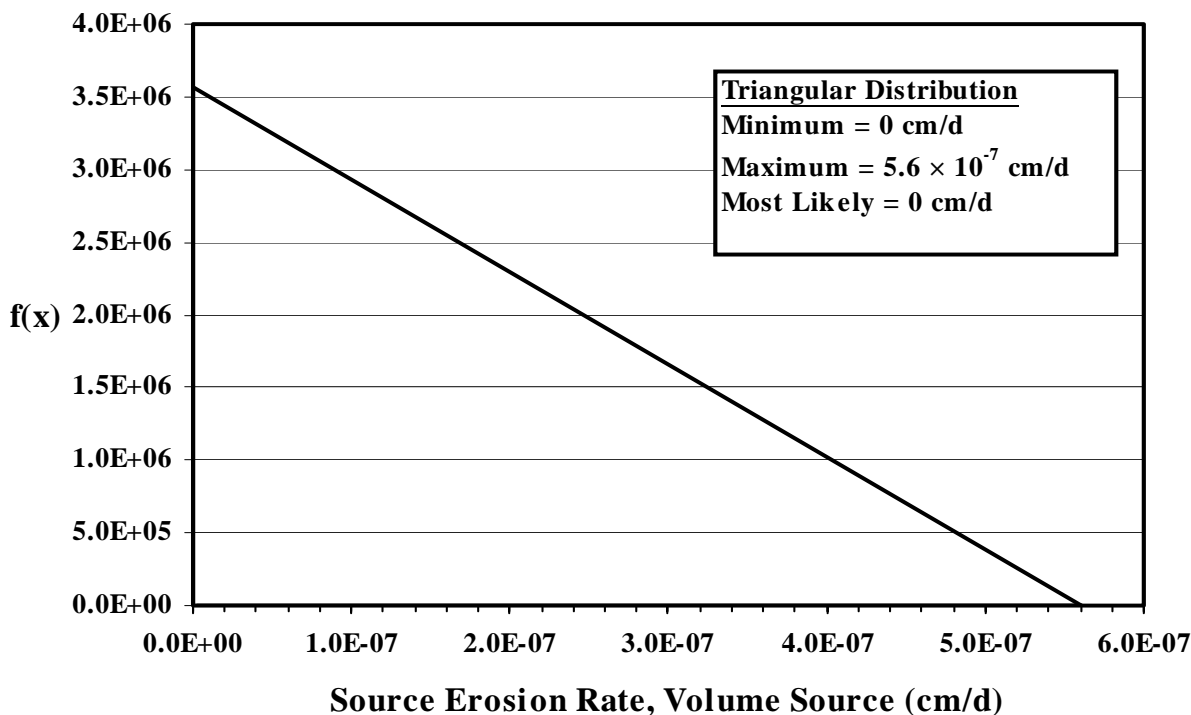


Figure 8.2-1 Source Erosion Rate Probability Density Function

8.3 Removable Fraction

Applicable Code: RESRAD-BUILD

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

Units: unitless

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum value: 0.0 Maximum value: 1.0 Most likely: 0.2

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 8.3-1 displays the distribution’s probability density function.

For most radionuclides, the DOE *Radiological Control Manual* (DOE, 1994a) allows a maximum removable concentration that is 20% of the maximum allowable total surface contamination for most radionuclides except for some transuranics and tritium (Table 2-2 in DOE, 1994a). 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, maximum acceptable removable concentrations are 20% of the average surface concentrations for all radionuclides (Table 1 in NRC, 1974), but like the DOE regulations, the removable fraction can be higher than 0.2 if overall surface concentrations are lower. Thus, a triangular distribution, as shown in Figure 8.3-1, is suggested for the removable fraction, with a most likely value of 0.2 and minimum and maximum values of 0 and 1, respectively, as discussed above.

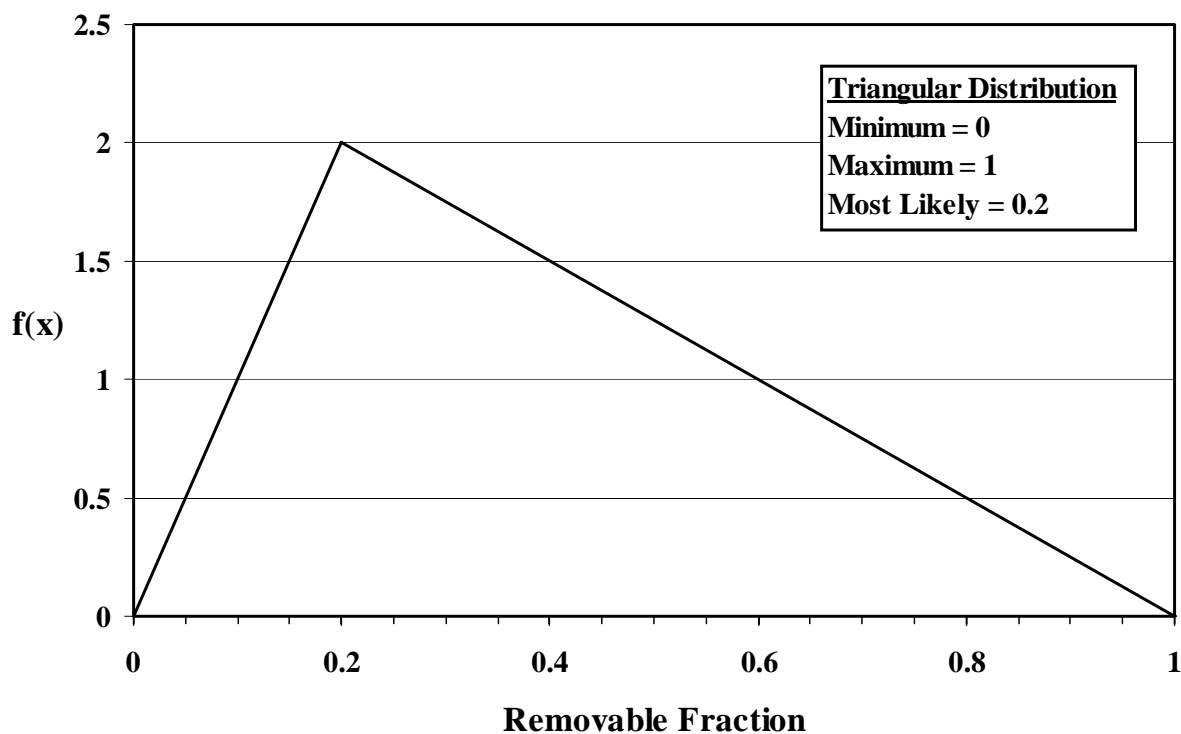


Figure 8.3-1 Removable Fraction Probability Distribution

For specific situations, a number of factors must be considered, including location of the contamination (e.g., wall or floor and proximity to human activity), the nature of the contaminated surface (e.g., type of material [chemical and physical properties]), the original form of the contaminant (chemical and physical properties [e.g., powder versus liquid and chemical reactivity]) and the removal mechanism (such as washing or foot traffic).

Smear tests are often used to determine the amount of “fixed” versus “non-fixed” (or removable) contamination (Frame and Abelquist, 1999). Although the definition of removable contamination varies, it applies to radioactive “contamination which is removable or 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 non-destructive means such as casual contact, wiping, brushing, or washing” (DOE, 1994a). 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 for the reasons listed above. Table 8.3-1 lists results from early experiments demonstrating that the nature of the contamination and of the surface can influence how easily removable the radioactive contamination can be. Thus, a specific distribution for the removable fraction must be

made on a case-by-case basis. Other measurement tests in the past have included tape and modified air sensor tests. Table 8.3-2 presents some results comparing these methods with smear tests on different surfaces.

Table 8.3-1 Influence of Surface and Contaminant Types on Smear Tests

Percentage Contamination Removed	Contamination	Surface	Comments	Reference
1 to 3	Low level from normal use	Granolithic concrete floor		Brunskill (1967)
50			Water wash of floor	
0.1 to 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 to 30		Polyvinyl chloride		
10 to 20	PuO ₂	Polyvinyl chloride		
20 to 30		Unwaxed linoleum		
50 to 60		Waxed and polished linoleum		

Table 8.3-2 Percent Removal of Contamination for Different Sampling Methods^a

Surface	Removal (%)		
	Adhesive Paper	Smear	Modified Air
Polyethylene	70.3	56.6	10.9
Glass	75.0	64.6	27.2
Plexiglass	78.0	71.3	15.8
Fiberboard (waxed)	53.8	44.3	10.2
Fiberboard (scrubbed)	56.9	23.5	9.0
Fiberboard (untreated)	73.4	23.5	6.6
Formica	73.4	70.6	26.5
Aluminum (painted)	70.0	50.3	24.8
Asphalt floor tile (untreated)	58.6	48.5	14.6
Asphalt floor tile (waxed)	74.5	74.5	30.3
Concrete (unsealed)	55.5	39.5	22.0
Concrete (sealed [seal and wax 1])	62.2	59.5	24.0
Concrete (sealed [seal and wax 2])	54.8	47.7	27.2
Concrete (greased)	43.5	37.5	1.32
Stainless steel	67.7	50.5	10.5

^a Modified air sampler (referred to as a “smair” sampler by the authors) causes air intake to blow across the sample surface when the sample head is pressed against a surface.

Source: Royster and Fish (1967); contamination was simulated by thorium dioxide dust particles approximately 1 μm in diameter at a concentration of about 1×10^6 particles per square centimeter.

8.4 Source Porosity

Applicable Code: RESRAD-BUILD

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

Units: unitless

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 are 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 8.4-1 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, ASTM has developed standard test methods for porosity of metal structure parts, and porosity tests for electrodeposits and related metallic coatings (<http://www.astm.org/sitemap.html>).

For generic applications, a uniform distribution from 0.04 to 0.25 is suggested for the source porosity for concrete. The minimum and maximum values were those reported by Frankowski et al. (1997) and Culot et al. (1976), respectively. The probability density function is shown in Figure 8.4-1.

Table 8.4-1 Bulk Density and Porosity of Rocks Commonly Used as Building Materials

Rock	Bulk Density (g/cm ³)	Porosity (%)
Granite	2.6-2.7	0.5-1.5
Basalt	2.8-2.9	0.1-1.0
Sandstone	2.0-2.6	0.5-25.0
Limestone	2.2-2.6	0.5-20.0
Gneiss	2.9-3.0	0.5-1.5
Marble	2.6-2.7	0.5-2.0

Source: Bever (1986).

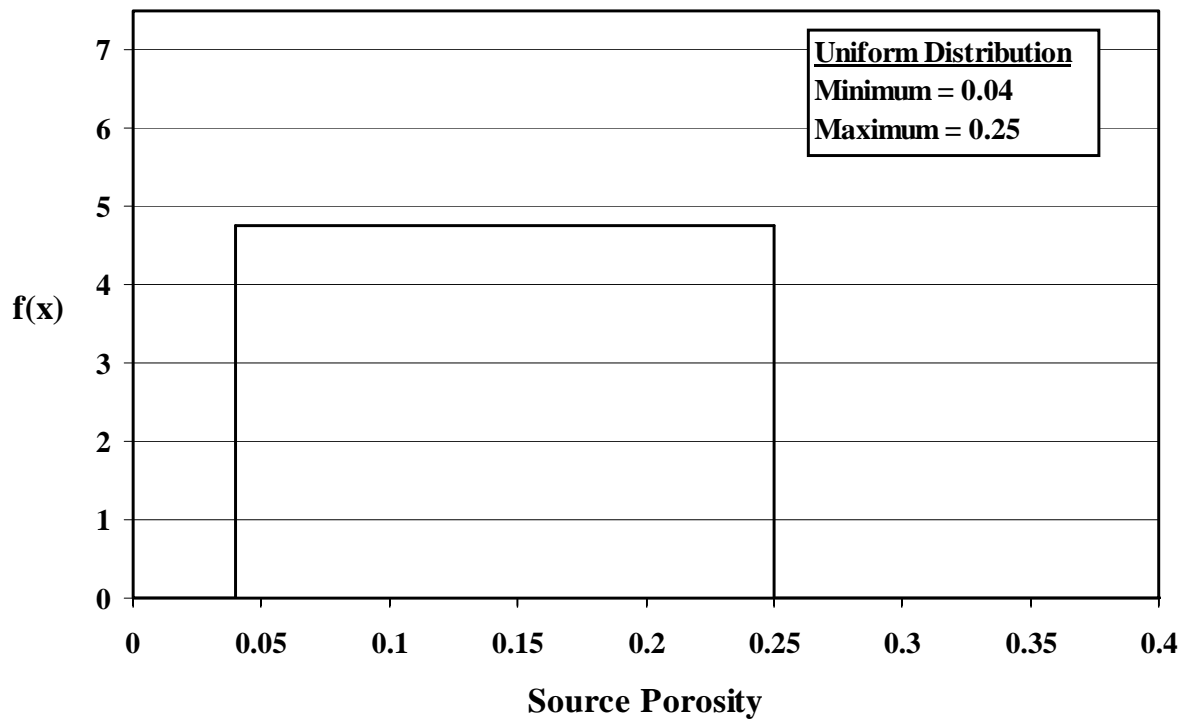


Figure 8.4-1 Concrete Source Porosity Probability Density Function

8.5 Volumetric Water Content

Applicable Code: RESRAD-BUILD

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

Units: unitless

Probabilistic Input (allowed only for concrete):

Distribution: uniform

Defining Values for Distribution:

Minimum value: 0.04

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 (Section 8.4). In any case, the maximum value assigned to the volumetric water content should not be greater than the maximum of the source porosity.

8.6 Air Release Fraction

Applicable Code: RESRAD-BUILD

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.

Units: 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. Note that if either the removable fraction or erosion rates are 0, the contributions from these pathways will be suppressed no matter what value is given to the air release fraction.

The DOE handbook on airborne release and respirable fractions (RFs) (DOE, 1994b) provides a compendium and analysis of experimental data from which airborne

release fractions¹ (ARFs) and RFs² 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 ANS has published an American National Standard for airborne release fractions at nonreactor nuclear facilities (ANS, 1998).

For materials in gaseous form, such as H-3, the recommended 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, 1994b).

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, 1994b). 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 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 ($0.1 \times 0.7 = 0.07$). The probability density function is displayed in Figure 8.6-1.

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- μ m aerodynamic equivalent diameter and less.

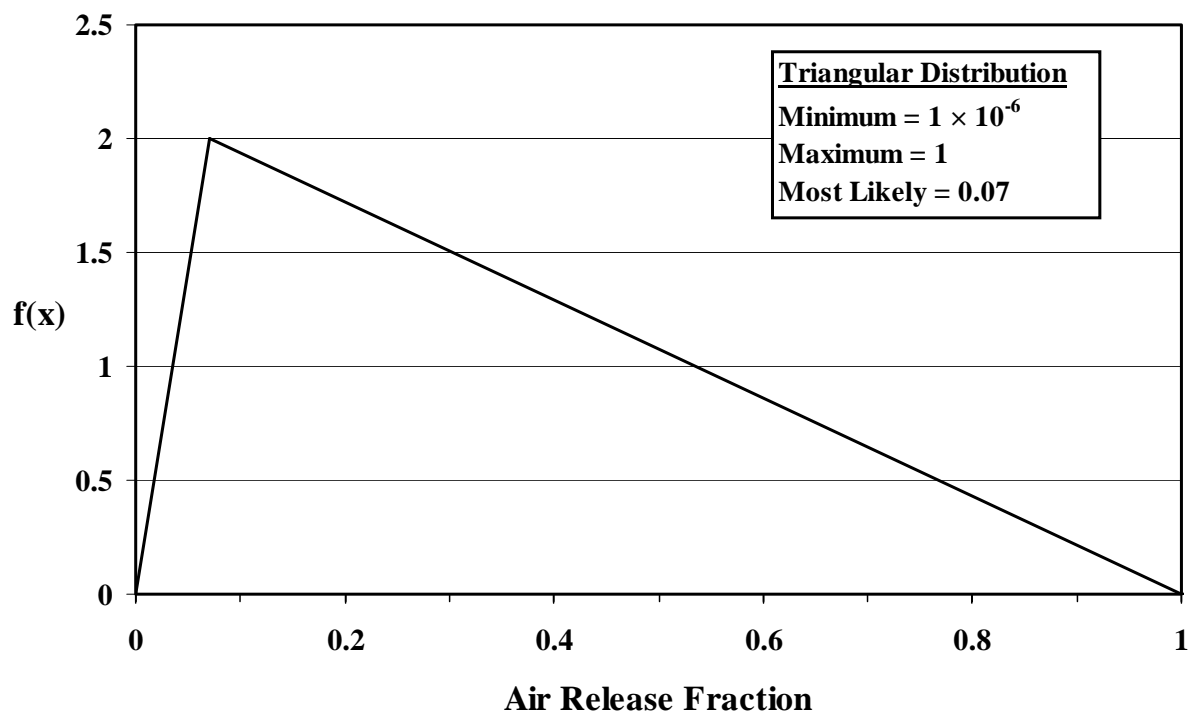


Figure 8.6-1 Air Release Fraction Probability Density Function

8.7 Wet + Dry Zone Thickness

Applicable Code : RESRAD-BUILD

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). On the other hand, HT can easily be converted to HTO in the environment. Experimental data concerning the tritium soaking effect on construction metals also showed that about 90% of the tritium desorbed from 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 ended.

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 8.10).

The diffusion of HTO is assumed to proceed like a peeling process in which the HTO molecules closer to the concrete-atmosphere interface will be released earlier than those farther from the interface. As the release process continues, a region free of free HTO molecules (i.e., the dry zone), will be formed, and its thickness will increase over time. The dry zone thickness then represents the path length for the subsequent diffusion. The region inside the concrete where the free HTO molecules are distributed is called the wet zone. As the dry zone becomes thicker, the thickness of the wet zone decreases accordingly. In fact, the sum of the dry zone thickness and the wet zone thickness is assumed to remain the same throughout the diffusion process.

Although diffusion of the HTO vapor to the bulk of concrete materials in a tritium handling facility is recognized (Wong et al., 1991), direct detection of the extent of spreading into the bulk (i.e., dry+ wet zone thickness) is not possible because of the short range of the beta radiation (DOE, 1991). However, judging by the high porosity of concrete materials, spreading of the HTO vapor throughout the entire thickness is possible if the exposure is of sufficient duration. Therefore, the thickness of the concrete wall is assumed for the “dry+wet zone thickness” parameter, which, on the basis of engineering judgments, can be as much as 30 cm. A low bound of 5 cm is selected because bulk contamination will not be extensive for a short exposure period. The probability density function is shown in Figure 8.7-1.

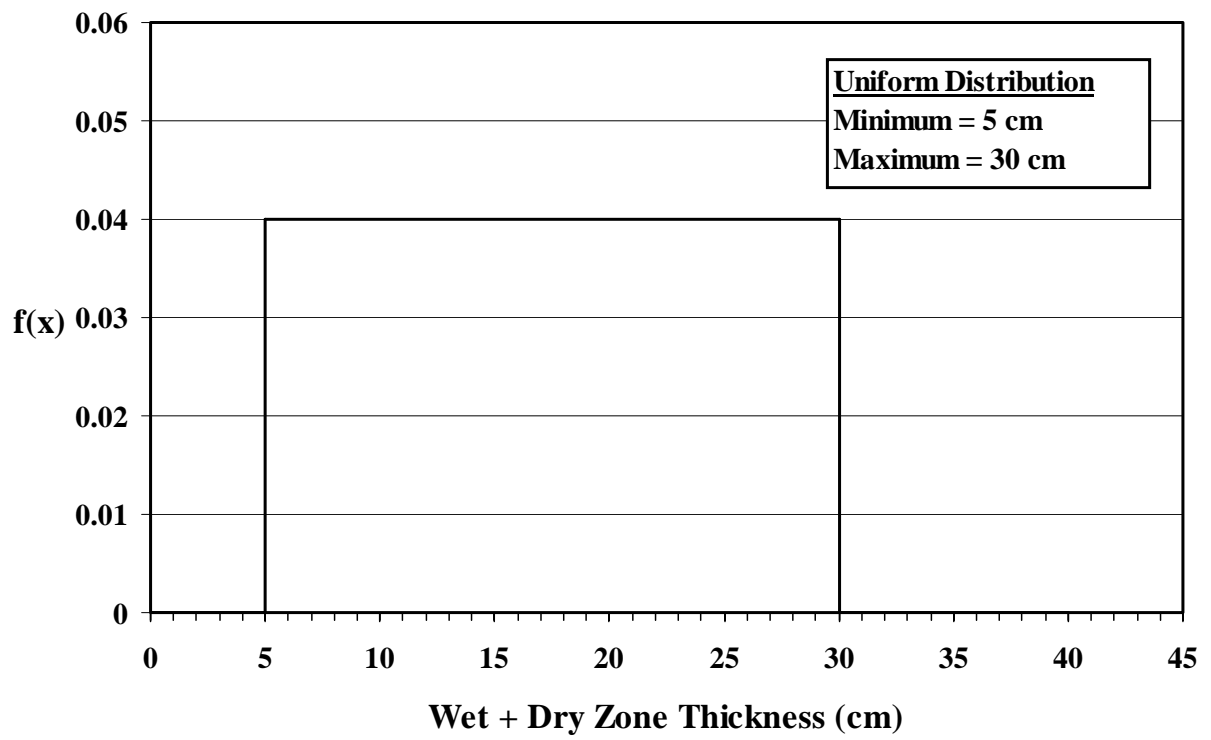


Figure 8.7-1 Wet + Dry Zone Thickness Probability Density Function

8.8 Time for Source Removal or Source Lifetime

Applicable Code : RESRAD-BUILD

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 8.3) and the “air release fraction” (Section 8.6) to obtain the emission rate of radionuclides into the indoor air.

Unit: days (d)

Probabilistic Input (allowed only for surface contamination):

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, an air release rate of $4 \times 10^{-5}/\text{h}$ is a conservative value for use in estimating the potential exposure resulting from 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 1,040 days (or 2.85 years). Although the loose particles on the contaminated source are not exactly the same as a pile of solid powders, the value for the free solid powders can be used to derive a lower bounding lifetime value for the loose materials.

Another suggestion by the ANS is an air release rate of $4 \times 10^{-6}/\text{h}$ 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 (~100,000 days) was assumed. The probability density function is shown in Figure 8.8-1.

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. Assuming a surface source on the floor with a removable fraction of 0.2 (Section 8.3) and an air release fraction of 0.07 (Section 8.6), the resuspension factor can be estimated from the source lifetime. A floor area of 36 m^2 (Section 7.7), a room height of 3.7 m (Section 7.8), and a room air exchange rate of 1.52 h^{-1} (Section 7.4) were used. In this case, the source lifetime of 10,000 days is equivalent to a resuspension factor of $1 \times 10^{-8}/\text{m}$.

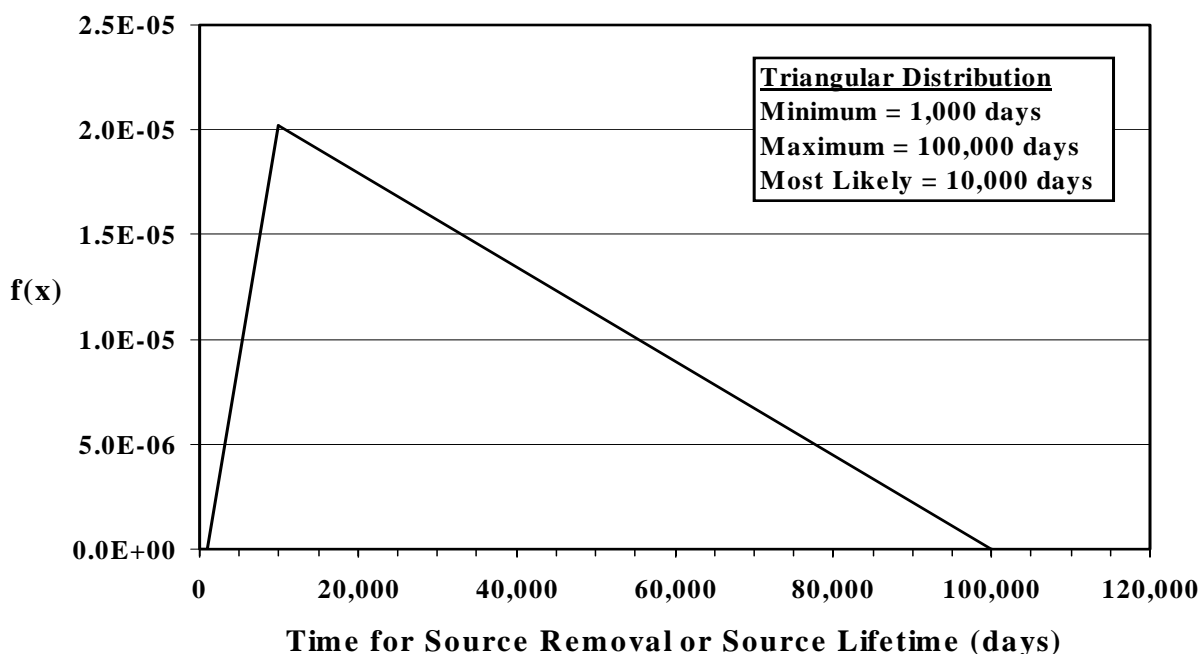


Figure 8.8-1 Time for Source Removal or Source Lifetime Probability Density Function

8.9 Source Thickness, Volume Source

Applicable Code: RESRAD-BUILD

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.

Units: centimeters (cm)

Probabilistic Input:

Distribution: triangular

Defining values for distribution:

Minimum: 2.5 Maximum: 30 Most likely: 15

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 upon the detail of modeling desired. For example, a wall could be modeled as a single layer or multiple layers (e.g., a sequence of paint, drywall, framing gap, drywall, and paint), with up to five layers per source. It is highly recommended that the source thickness be obtained from direct measurement or be estimated on the basis of the applicable building codes. The contaminated layer thickness and position should be based on site-specific measurement.

With the exception of sources resulting from neutron activation, most volume activity in buildings will be limited to small areas (hot spots) or rather shallow sources. For the case of neutron activation, volume sources could extend deep into the volume of a building structure. The thickness of building structure materials will place a limit on the potential thickness for volume sources. Ayers et al. (1999) noted that the contamination of concrete usually results from spills, contaminated dust, or other surficial deposition. In some instances, the contaminants may migrate into the concrete matrix, particularly over time and under environmental stresses. Cracks and crevices may also provide routes for contaminants to spread deeper into the concrete matrix. To estimate the total contaminated volume of concrete from DOE facilities, Ayers et al. (1999) assumed contamination to 1-in. (2.5-cm) depth and an average concrete thickness of 12 in. (30 cm) in a building. For external exposure calculations, this thickness will approximate an infinite thickness for alpha-emitters, beta-emitters, and X-ray or low-energy photon emitters. DandD and RESRAD-BUILD use 15 cm as the default source thickness for a volume source.

Little information is available for the source thicknesses in real decommissioning and decontamination situations; therefore, on the basis of above data, a triangular distribution is assumed for source thickness. The maximum value is assumed to be 30 cm, the minimum value is chosen as 2.5 cm, and the most likely value is the 15-cm default used in DandD and RESRAD-BUILD codes for volume sources. Figure 8.9-1 presents the probability density function for the source thickness.

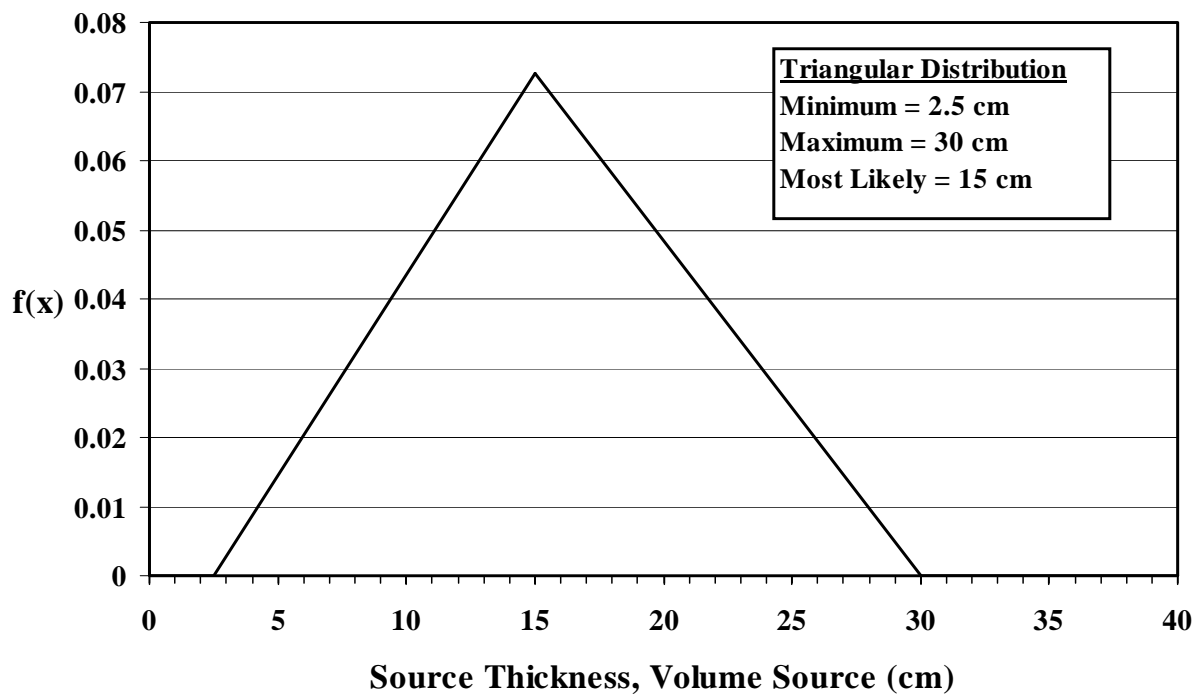


Figure 8.9-1 Source Thickness Probability Density Function

8.10 Water Fraction Available for Evaporation

Applicable Code : RESRAD-BUILD

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

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 desorb from the materials and released to the indoor air. This sorption/desorption process is generally referred to as the “tritium soaking effect” in tritium-handling facilities.

Tritium released from the tritium-handling facilities can be in different chemical forms; the most common ones are tritium gas (HT) and tritium oxide, or tritiated water (HTO). In general, sorption and desorption of HT occurs faster than that of HTO; however, the total amount sorbed and desorbed is greater for HTO than for HT (Wong et al., 1991; Dickson and Miller, 1992). On the other hand, HT can easily be converted to HTO in the environment. Experimental data concerning the tritium soaking effect on construction metals also showed that about 90% of the tritium desorbed from the metal samples was in the form of HTO, although the samples were exposed to atmosphere of HT (Dickson and Miller, 1992). Because of the conversion from HT to HTO and the potentially longer time required for degassing of HTO (desorption and subsequent release from the contaminated material to the indoor air), the tritium model incorporated in 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 HTO molecules from inside of the concrete matrix to the concrete-atmosphere interface.

The diffusion rate is estimated on the basis of information on extent of the contamination (thickness of dry zone, thickness of dry zone + wet zone, and area of contamination), characteristics of the source material (porosity and moisture content), tritium inventory (tritium concentration), and indoor humidity. Because not all the tritium in the source material is available for diffusion under ordinary building occupancy conditions, estimation of the release rate has to take into account the fraction of tritiated water available for evaporation and diffusion.

According to the experimental observations by 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 constitute 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 200°C. 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 30°C. Residual tritium sorbed was recovered by heating up the samples up to 800°C. Although the samples used by Ono et al. (1992) were different from the concrete samples used by Numata and Amano (1988), it is quite conclusive that some tritiated water can 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 tritiated water in concrete samples depended on duration of the previous exposure of the samples to tritiated water vapor. Shorter exposure duration resulted in 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 (1994b) regarding the air release fraction of tritiated water from concrete materials under accidental conditions that can cause the temperature to reach as high as 200°C. Tritiated water was assumed in the DOE report to be used in concrete formation, which is the same role as ordinary water in Numata and Amano's experiments.

It can be deduced from the above discussions 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 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 8.10-1.

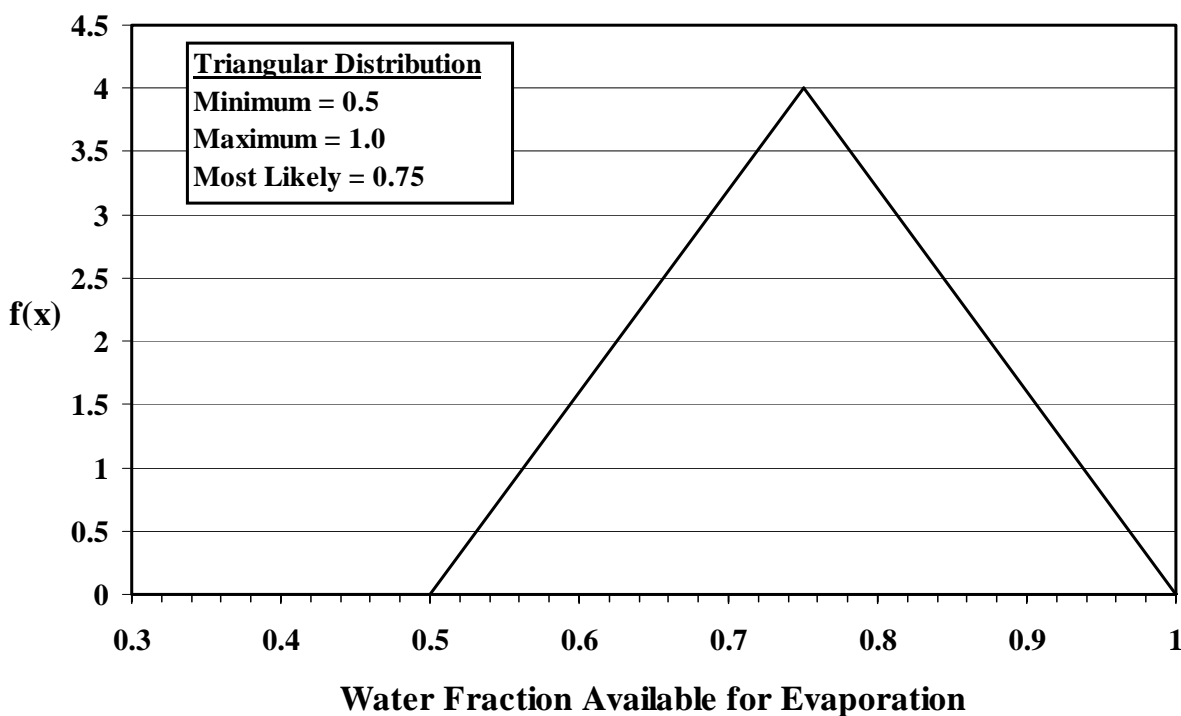


Figure 8.10-1 Water Fraction Available for Evaporation

8.11 C-14 Evasion Layer Thickness in Soil

Applicable Code: RESRAD

Description: This parameter represents the maximum soil thickness layer through which carbon-14 (C-14) can escape to the air by conversion to carbon dioxide (CO₂).

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.2 Maximum: 0.6 Most likely: 0.3

Discussion: One of the important pathways involving the radiological dose to humans from soil contaminated with C-14 is the plant ingestion pathway. In addition to direct root uptake from soil and foliar deposition of dust particles contaminated with C-14, carbon in gases volatilized from the soil is directly incorporated into the plant by the process of photosynthesis.

Inorganic and organic reactions convert most forms of soil carbon to CO₂. Because of the volatile nature of CO₂, soil carbon is usually lost to the air, where it becomes absorbed in plants through photosynthesis. The concentration of C-14 in air above a contaminated zone depends on the volatilization (evasion) rate of carbon from the soil, the size and location of the source area, and meteorological dispersion conditions.

Sheppard et al. (1991) measured the rate of C-14 loss from soils in outdoor lysimeter experiments and also investigated the vertical mobility of representative inorganic and organic C-14-labeled compounds in unsaturated soil for both net-leaching and net-capillary rise scenarios. The two soils (one retentive and other with low retention) chosen allowed investigation of the importance of organic matter and native carbonate content on C-14 mobility. The retentive soil was very fine sandy loam with high carbonate content, and the low retention acidic soil had no carbonate content (medium sand). Sheppard et al. (1991) observed upward movement of C-14 (perhaps linked to volatilization) up to the depth of 60 cm for the low retention acidic soil. Some upward movement was observed in all soil samples analyzed (activity ratio for the upward movement of 20 cm was >0.2). Amiro et al. (1991) assumed evasion layer thickness of 0.3 m in estimating C-14 flux from soil to the atmosphere.

On the basis of the above information, C-14 evasion layer thickness is assigned triangular distribution, with minimum of 0.2 m, a maximum value of 0.6 m, and a most likely value of 0.3 m. The probability density function is shown in Figure 8.11-1.

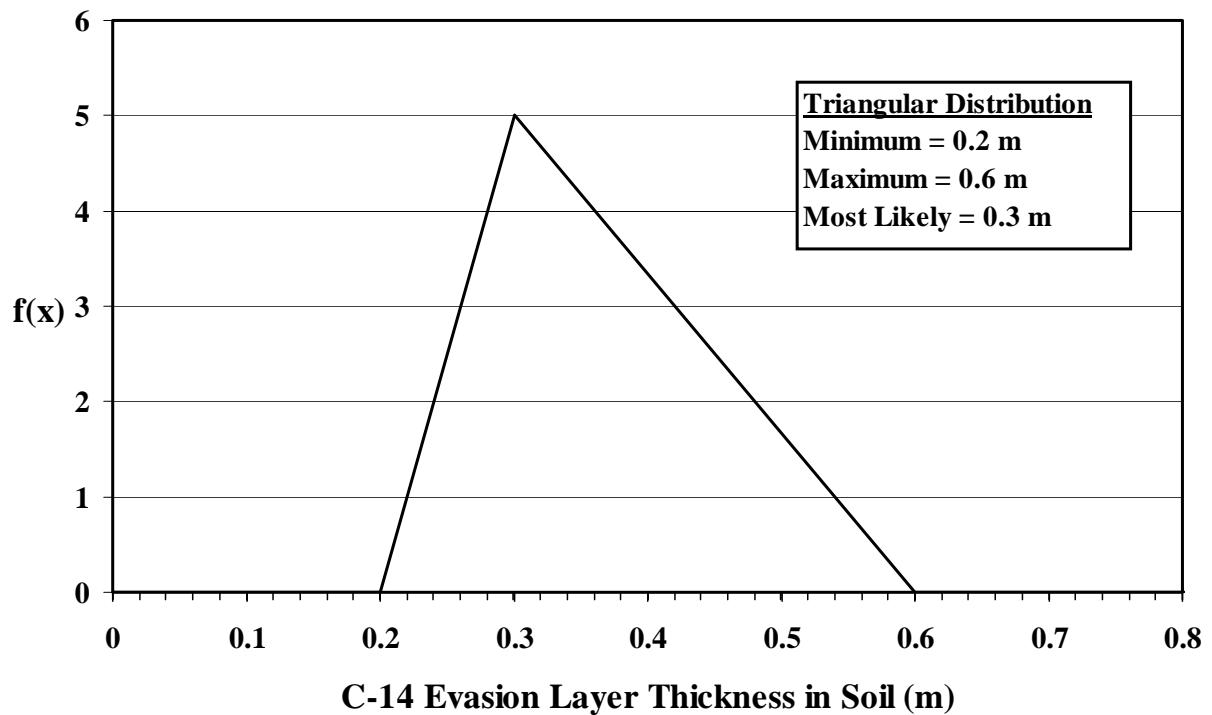


Figure 8.11-1 C-14 Evasion Layer Thickness in Soil Probability Density Function

9 REFERENCES

AIHC — See American Industrial Health Council.

Allen, R.R., et al., "Residual Deep Plowing Effects on Irrigation Intake for Pullman Clay Loam," *Soil Sci. Soc. Am. J.* 59:1424-1429, 1995.

Alzona, J., et al., "Indoor-Outdoor Relationships for Airborne Particulate Matter of Outdoor Origin," *Atmospheric Environment*, 13:55-60, 1979.

American Industrial Health Council, *Exposure Factors Sourcebook*, Washington, D.C., 1994.

American Nuclear Society, "Airborne Release Fractions at Non-Reactor Facilities, an American National Standard," ANSI/ANS-5.10-1998, prepared by the American Nuclear Society Standards Committee Working Group ANS-5.10, American Nuclear Society, La Grange Park, Ill., 1998.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., "1997 ASHRAE Handbook, Fundamentals," SI Ed., Atlanta, Ga., 1997.

Ames, L.L. and D. Rai, "Radionuclide Interactions with Soil and Rock Media," Vols. 1 and 2, EPA 520/6-78-007-b, U.S. Environmental Protection Agency, Office of Radiation Programs, Las Vegas, Nevada, 1978.

Amiro B.D., Y. Zhuang, and S.C. Sheppard, "Relative Importance of Atmospheric and Root Uptake Pathways for CO Transfer from Contaminated Soil to Plants," *Health Physics*, 61(6):825-829, 1991.

ANS — See American Nuclear Society.

ASHRAE — See American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Ayers, K.W. et al., "Reuse of Concrete from Contaminated Structures," prepared for the U.S. Department of Energy, Office of Science and Technology, by Department of Civil and Environmental Engineering, Vanderbilt University, Nashville, Tenn., 1999.

Baes, C.F., III and R.D. Sharp, "A Proposal for Estimation of Soil Leaching and Leaching Constants for Use in Assessment Models," *Journal of Environmental Quality*, 12(1):17, 1983.

Baes, C.F., III, et al., "A Review and Analysis of Parameters for Assessing Transport of Environmentally Released Radionuclides Through Agriculture," ORNL-5786, Health and Safety Division, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1984.

Baffault, C., M.A. Nearing, and G. Govers, "Statistical Distributions of Soil Loss from Runoff Plots and WEPP Model Simulations," *Soil Science Society of America Journal*, 62:756-763, 1998.

Beresford, N.A., et al., "The Effect of Treating Pastures with Bentonite on the Transfer of Cs-137 from Grazed Herbage to Sheep," *Journal of Environmental Radiation*, 9:251-264, 1989.

Berk, J.V., et al., "Impact of Energy-Conserving Retrofits on Indoor Air Quality in Residential Housing," LBL-12189, Lawrence Berkeley Laboratory, Berkeley, Calif., 1981.

Bever, M.B. (ed.-in-chief), *Encyclopedia of Materials Science and Engineering*, Vol. 5 O-Q, The MIT Press, Cambridge, Mass., 1986.

Beyeler, W.E., et al., "Review of Parameter Data for the NUREG/CR-5512 Building Occupancy Scenario and Probability Distributions for the DandD Parameter Analysis," letter report prepared by Sandia National Laboratories for U.S. Nuclear Regulatory Commission, January 1998a.

Beyeler, W.E., et al., "Review of Parameter Data for the NUREG/CR-5512 Residential Farmer Scenario and Probability Distributions for the DandD Parameter Analysis," letter report prepared by Sandia National Laboratories for U.S. Nuclear Regulatory Commission, January 1998b.

Binder, S. and D. Sokal, "Estimating Soil Ingestion: The Use of Tracer Elements in Estimating the Amount of Soil Ingested by Young Children," *Archives of Environmental Health*, 41(6):341-345, 1986.

BLS — See Bureau of Labor Statistics.

Brenk, H.D. and H. De Witt, "Indoor Inhalation Exposure after Nuclear Accidents," *Radiat. Prot. Dosim.*, 21:117-223, 1987.

Brown, J., et al., "Probabilistic Accident Consequence Uncertainty Analysis," NUREG/CR-6523, EUR 16771, SAND97-0335, Vol. 2, prepared by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission and the Commission of the European Communities, 1997.

Brunskill, R.T., "The Relationship Between Surface and Airborne Contamination," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 93-105, 1967.

Buckingham, F., *Tillage*, Deere & Company, Moline, Ill., 1984.

Bureau of Labor Statistics, "Annual Household Data," in *Employment and Earnings*, Vol. 43, No. 1, January 1996.

Calabrese, E.J. and E.J. Stanek, "Distinguishing Outdoor Soil Ingestion from Indoor Ingestion in a Soil Pica Child," *Regul. Toxicol. Pharmacol.*, 15:83-85, 1992.

Calabrese, E.J. and E.J. Stanek, "An Improved Method for Estimating Soil Ingestion in Children and Adults," *J. Environ. Sci. & Health, Pt. A-Environ. Sci. & Engr.*, 28(2):363-71, 1993.

Calabrese, E.J. and E.J. Stanek, "Resolving Intertracer Inconsistencies in Soil Ingestion Estimation," *Environmental Health Perspectives*, 103(5):454-57, 1995.

Calabrese, E.J., et al., "How Much Soil Do Young Children Ingest: An Epidemiologic Study," in *Petroleum Contaminated Soils*, Vol. 2, E.J. Calabrese and P.T. Kostecki (eds.), Lewis Publishers, Chelsea, Mich., 1989.

Calabrese, E.J., et al., "Preliminary Adult Soil Ingestion Estimates: Results of a Pilot-Study," *Regulatory Toxicology and Pharmacology*, 12(1):88-95, 1990.

Calabrese, E.J., E.J. Stanek, C.E. Gilbert, "Evidence of Soil-Pica Behavior and Quantification of Soil Ingested," *Hum. Exp. Toxicol.*, 10:245-249, 1991.

Calvin, C.L. and D.M. Knutson, *Modern Home Gardening*, John Wiley & Sons, Inc., New York, N.Y., 1983.

Carsel R.F. and R.S. Parrish, "Developing Joint Probability Distributions of Soil Water Retention Characteristics," *Water Resources Research*, 24:755-769, May 1988.

Cheng, J.-J., et al., "Selection of RESRAD and RESRAD-BUILD Input Parameters for Detailed Distribution Analysis," letter report (Revision 1) prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C., October 1999.

Christensen, G.C. and R. Mustonen, "The Filtering Effect of Buildings on Airborne Particles," *Radiat. Prot. Dosim.*, 21:125-128, 1987.

Cohen, A.F. and B.L. Cohen, "Infiltration of Particulate Matter into Buildings," NUREG/CR-1151, prepared by Sandia National Laboratories for U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., November 1979.

Culot, M.J.V., H. G. Olson, and K. J. Schiager, "Effective Diffusion Coefficient of Radon in Concrete, Theory and Method for Field Measurements," *Health Physics*, 30:263-270, 1976.

Davis, S. and P. Waller, "Quantitative Estimates of Soil Ingestion in Normal Children between the Ages of 2 and 7 Years: Population-Based Estimates Using Aluminum, Silicon, and Titanium as Soil Tracer Elements," *Archives of Environmental Health*, 45(2):112-122, 1990.

Dean, J.A., *Lange's Handbook of Chemistry*, 15th Edition, McGraw-Hill, Inc., New York, N.Y., 1999.

Dickson, R.S. and J.M. Miller, "Sorption of Tritium and Tritiated Water on Construction Materials," *Fusion Technology*, 21:850-855, 1992.

DOE — See U.S. Department of Energy.

Doyle, S.M., et al., "Time-Averaged Indoor Radon Concentrations and Infiltration Rates Sampled in Four U.S. Cities," *Health Physics*, 47:579-586, 1984.

Driscoll, F.G., *Groundwater and Wells*, 2nd Ed., Johnson Division, St. Paul, Minn., 1986.

Dunker, R.E., et al., "Deep Tillage Effects on Compacted Surface-Mined Land," *Soil Sci. Soc. Am. J.* 59:192-199, 1995.

Dunster, H.J., "Maximum Permissible Levels of Skin Contamination," AHSB(RP)R28, United Kingdom Atomic Energy Authority, London, 1962.

Engelmann, R.J., "Sheltering Effectiveness against Plutonium Provided by Buildings," *Atmospheric Environment*, 26A:2037-2044, 1992.

EPA — See U.S. Environmental Protection Agency.

Ershow, A.G. and K.P. Cantor, "Total Water and Tapwater Intake in the United States: Population-Based Estimates of Quantities and Sources," Life Sciences Research Office, Federation of American Societies for Experimental Biology, Bethesda, Md., May 1989 (as cited in Roseberry and Burmaster, 1992).

Finley, B., et al. "Recommended Distributions for Exposure Factors Frequently Used in Health Risk Assessment," *Risk Analysis*, 14(4):533-553, 1994.

Fish, B.R., et al., "Redispersal of Settled Particulates," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 75-81, 1967.

Fogh, C.L., et al., "Size Specific Indoor Aerosol Deposition Measurements and Derived I/O Concentrations Ratios," *Atmospheric Environment*, 31:2193-2203, 1997.

Foster, G.R., "Sediment Yield from Farm Fields: The Universal Soil Loss Equation and Onfarm 208 Plan Implementation," in *Universal Soil Loss Equation: Past, Present, and Future*, Soil Science Society of America Special Publication No. 8, Madison, Wis., pp. 17-24, 1979.

Frame, P.W. and E.W. Abelquist, "Use of Smears for Assessing Removable Contamination," *Health Physics*, 76(5):S57-S66, 1999.

Frankowski, Z., et al., "Properties of the Concrete from 80-Year-Old Structures of Facilities in the Radioactive Waste Repository," U.S. Department of Energy, Low-Level Radioactive Waste Management 18th Conference Proceedings, May 20-22, Salt Lake City, Utah, 1997.

Freeze, R.A. and J.A. Cherry, *Groundwater*, Prentice Hall, Inc., Englewood Cliffs, N.J., 1979.

Gallacher, J.E.J., et al., "Relation between Pica and Blood Lead in Areas of Differing Lead Exposure," *Archives of Disease in Childhood*, 59:40-44, 1984.

Gibson, J.A.B. and A.D. Wrixon, "Methods for the Calculation of Derived Working Limits for Surface Contamination by Low-Toxicity Radionuclides," *Health Physics* (36)3:311-321, 1979.

Gilbert, T.L., et al., "A Manual for Implementing Residual Radioactive Material Guidelines," ANL/ES-160, DOE/CH/8901, Argonne National Laboratory, Argonne, Ill., prepared for U.S. Department of Energy, Washington, D.C., June 1989.

Glauberger, H., W.R. Bootman, and A.J. Breslin, "Studies of the Significance of Surface Contamination," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 169-178, 1967.

Gnanapragasam, E.K. and C. Yu, "Application of the RESRAD Computer Code to VAMP Scenario S," ANL/EAD/TM-70, Argonne National Laboratory, Argonne, Ill., March 1997.

Godish, T., and J. Rouch, "Residential Formaldehyde Control by Mechanical Ventilation," *Applied Industrial Hygiene*, 3:93-96, 1988.

Godish, T., *Indoor Air Pollution Control*, Lewis Publishers, Chelsea, Mich., 1989.

Golikov, V. et al., "Model Validation for External Doses Due to Environmental Contamination by the Chernobyl Accident," *Health Physics*, 77(6): 664-661, 1999.

Grimsrud, D.T., et al., "Calculating Infiltration: Implications for a Construction Quality Standard," LBL-9416, Lawrence Berkeley Laboratory, Berkeley, Calif., 1983.

Grogan, H.A., "Concentration Ratios for BIOPATH: Selection of the Soil-to-Plant Concentration Ratios Database," Report EIR-Bericht Nr. 575, Swiss Federal Institute for Reactor Research, Geneva, Switzerland, 1985.

Grove Engineering Inc., "Microshield 4 Users Manual," Rockville Md., 1992.

Healy, J.W., "Surface Contamination: Decision Levels," LA-4558-MS, Los Alamos Scientific Laboratory, Los Alamos, N.M., 1971.

Hillel, D., *Fundamentals of Soil Physics*, Academic Press, Inc., New York, N.Y., 1980.

Hoffman, F.O. and C.F. Baes, III (eds.), "A Statistical Analysis of Selected Parameters for Predicting Food Chain Transport and Internal Dose of Radionuclides," NUREG/CR-1004, ORNL/NUREG/TM-282, prepared by Oak Ridge National Laboratory, Oak Ridge, Tenn., for U.S. Nuclear Regulatory Commission, Washington, D.C., 1979.

Hoffman, F., et al., "Variability in Dose Estimates Associated with the Food Chain Transport and Ingestion of Selected Radionuclides," NUREG/CR-2612, ORNL/TM-8099, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1982.

Hoffman, F.O., et al., "Comparison of Interception and Initial Retention of Wet-Deposited Contaminants on Leaves of Different Vegetation Types," *Atmos. Environ.*, 29(15):1771-1775, 1995.

Howard, B.J., et al., "Transfer of Radiocesium from Different Environmental Sources to Ewes and Suckling Lambs," *Health Physics*, 57:579-586, 1989.

IAEA — See International Atomic Energy Agency.

ICRP — See International Commission on Radiological Protection.

International Atomic Energy Agency, "Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Temperate Environments," Technical Reports Series No. 364, produced in collaboration with the International Union of Radioecologists, Vienna, 1994.

International Commission on Radiological Protection, "Report of the Task Group on Reference Man," Publication No. 23, Pergamon Press, Oxford, England, 1975.

International Organization for Standardization, "Evaluation of Surface Contamination-Part 1: Beta Emitters and Alpha Emitters," ISO-7503-1, Geneva, 1988.

ISO — See International Organization for Standardization.

Jensen, P.H., "Shielding Factors for Gamma Radiation from Activity Deposited on Structures and Ground Surfaces," *Nuclear Technology*, 68:28-39, 1983.

John, W., "The Characteristics of Environmental and Laboratory-Generated Aerosols," in *Aerosol Measurement, Principles, Techniques, and Applications*, Willeke, K. and P.A. Baron (eds.), John Wiley & Sons, Inc., New York, N.Y., pp. 54-76, 1993.

Johnson, J.E., et al., "Metabolism of Radioactive Cesium (Cs-134 and Cs-137) and Potassium of Dairy Cattle as Influenced by High and Lower Forage Diets," *Journal of Nutrition*, 94:282-288, 1968.

Johnson, M.E., *Multivariate Statistical Simulation*, John Wiley, New York, 1987.

Johnson, N.L. and S. Kotz, *Distributions in Statistics: Continuous Univariate Distributions*, Vol. 1, Houghton Mifflin Co., Boston, Mass., 1970.

Jones, I.S. and S.F. Pond, "Some Experiments to Determine the Resuspension Factor of Plutonium from Various Surfaces," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 83-92, 1967.

Justus, C.G., et al., "Nationwide Assessment of Potential Output from Wind-Powered Generators," *J. Appl. Meteor.*, 15(7):673-678, 1976.

Kamboj, S., et al., "Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes," letter report prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, September 1999.

Kennedy, W.E., and Streng, D.L., "Residual Radioactive Contamination from Decommissioning; A Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent," NUREG/CR-5512, PNL 7994, Vol. 1, prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, 1992.

Kennedy, W.E., Jr., et al., "A Review of Removable Surface Contamination on Radioactive Materials Transportation Containers," NUREG/CR-1859, PNL-3666, U.S. Nuclear Regulatory Commission, Washington, D.C., 1981.

Kimbrough, R.D., et al., "Health Implications of 2,3,7,8-Tetrachlorodibenzodioxin (TCDD) Contamination of Residential Soil," *Journal of Toxicology and Environmental Health*, 14:47-93, 1984.

Knight, M.J., "The Effect of Soil Erosion on the Long-Term Stability of FUSRAP Near-Surface Waste-Burial Sites," ANL/EIS-18, revised, prepared by Division of Environmental Impact Studies, Argonne National Laboratory, Argonne, Ill., for U.S. Department of Energy, Oak Ridge Operations Office, 1983.

Kocher, D.C., "Effects of Indoor Residence on Radiation Doses from Routine Releases of Radionuclides to the Atmosphere," *Nuclear Technology*, 48:171-179, 1980.

Konoplev, A.V., et al., "Influence of Agricultural Countermeasures on the Ratio of Different Chemical Forms of Radionuclides in Soil and Soil Solution," *Sci. Total Environ.* 137:147-162, 1993.

Koontz, M.D. and H.E. Rector, "Estimation of Distributions for Residential Air Exchange Rates," EPA Contract No. 68-D9-0166, Work Assignment No. 3-19, U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics, Washington, D.C., 1995.

Lamb, B., et al., "Air Infiltration Rates in Pre- and Post-Weatherized Houses," *JAPCA*, 35:545-551, 1985.

Lang, C., "Indoor Deposition and the Protective Effect of Houses Against Airborne Pollution," Ph.D Thesis Riso-R-780(en), ISBN 87-550-2024-0, 1995 (as cited in Fogh et al., 1997).

Layton, D.W., "Metabolically Consistent Breathing Rates for Use in Dose Assessments," *Health Physics*, 64(1):23-36, 1993.

Lepow, M.L., et al., "Investigations into Sources of Lead in the Environment of Urban Children," *Environ. Res.*, 10:414-426, 1975.

Lide, D.R. (ed.-in-chief), *CRC Handbook of Chemistry and Physics*, 79th ed., CRC Press, 1998.

Lipschutz, R.D., et al., "Infiltration and Indoor Air Quality in Energy Efficient Houses in Eugene, Oregon," LBL-12924, Lawrence Berkeley Laboratory, Berkeley, Calif., 1981.

Luna, R.E. and H.W. Church, "Estimation of Long Term Concentrations Using a 'Universal' Wind Speed Distribution," *J. Appl. Meteor.*, 13:910-916, 1974.

Maidment, D. R., *Handbook of Hydrology*, McGraw-Hill, New York, N.Y., 1992.

McKinley, I.G. and A. Scholtis, "Compilation and Comparison of Radionuclide Sorption Databases Used in Recent Performance Assessments in Radionuclide Sorption from the Safety Evaluation Perspective," *Proceedings of an NEA Workshop*, Interlaken, Switzerland, October 16-18, 1991.

Merritt, F.S., et al. (eds.), *Standard Handbook for Civil Engineers*, "Section 5, Construction Materials," McGraw-Hill, 1995.

Meyer, P.D. and G.W. Gee, "Information on Hydrologic Conceptual Models, Parameters, Uncertainty Analysis, and Data Sources for Dose Assessments at Decommissioning Sites," NUREG/CR-6656, Pacific Northwest National Laboratory, prepared for U.S. Nuclear Regulatory Commission, October 1999.

Meyer, P.D., M.L. Rockhold, and G.W. Gee, "Uncertainty Analyses of Infiltration and Subsurface Flow and Transport for SDMP Sites," NUREG/CR-6565, Pacific Northwest National Laboratory, prepared for U.S. Nuclear Regulatory Commission, September 1997.

Mitchell, R.N. and B.C. Eutsler, "A Study of Beryllium Surface Contamination and Resuspension," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 349-352, 1967.

Murray, D.M. and D.E. Burmaster, 1995, "Residential Air Exchange Rates in the United States: Empirical and Estimated Parametric Distributions by Season and Climatic Region," *Risk Analysis*, 15:459-465, 1995.

NAHB — See National Association of Home Builders.

National Association of Home Builders, "Factory and Site-Built Housing, A Comparison for the 21st Century," NAHB Research Center, Inc., Upper Marlboro, Md., prepared for the U.S. Department of Housing and Urban Development, Office of Policy Development and Research, Washington, D.C., October 1998.

National Climatic Data Center, "Comparative Climatic Data for the United States through 1998," National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 1999.

National Council on Radiation Protection and Measurements, "Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment," Report No. 76, 1984.

National Council on Radiation Protection and Measurements, "Screening Models for Releases of Radionuclides to Atmosphere, Surface Water, and Ground," Report No. 123, Vols. 1 and 2, 1996.

National Council on Radiation Protection and Measurements, "Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Issues," Report No. 129, 1999.

National Oceanic and Atmospheric Administration, "Comparative Climatic Data for the United States through 1998," <http://www.ncdc.noaa.gov/ol/climate/online/ccd/nrmlprcp.html>, 1999.

Nazaroff, W.W. and G.R. Cass, "Mass-Transport Aspects of Pollutant Removal at Indoor Surfaces," *Environ. Int.*, 15:567-584, 1989.

Nazaroff, W.W., A.J. Gadgil, and C.J. Weschler, "Critique of the Use of Deposition Velocity in Modeling Indoor Air Quality," in *Modeling of Indoor Quality and Exposure*, Nagda, N.L. (ed.), ASTM STP 1205, American Society for Testing and Materials, Philadelphia, Penn., pp. 148-165, 1993.

NCDC — See National Climatic Data Center.

NCRP — See National Council on Radiation Protection and Measurements.

NEA — See Nuclear Energy Agency.

Neville, A.M., *Properties of Concrete*, 4th Ed., John Wiley & Sons, Ltd., 1996.

Newell, C.J., L.P. Hopkins, and P.B. Bedient, "Hydrogeologic Database for Groundwater Modeling, Health and Environmental Sciences," American Petroleum Institute Publication 4476, February 1989.

Ng, Y.C., "Transfer Coefficients for Assessing the Doses from Radionuclides in Meat and Eggs," NUREG/CR-2976, UCID-19464, prepared by Lawrence Livermore National Laboratory, Livermore, Calif., for U.S. Nuclear Regulatory Commission, 1982.

NRC — See U.S. Nuclear Regulatory Commission.

Nuclear Energy Agency, "Sorption Data Base," Organization of Economic Cooperation and Development, 1989.

Numata S. and H. Amano, "Tritium Permeation into Concrete," *Fusion Technology*, Proceedings of the 15th Symposium on Fusion Technology, Utrecht, pp. 1260-1264, 1988.

Offermann, F.J., et al., "Low Infiltration Housing in Rochester, New York: A Study of Air-Exchange Rates and Indoor Air Quality," *Environment International*, 8:435-445, 1982.

Offermann, F.J., et al., "Control of Respirable Particles in Indoor Air with Portable Air Cleaners," *Atmos. Environ.*, 19:1761-1771, 1985.

Ono, F., et al., "Sorption and Desorption of Tritiated Water on Paints," *Fusion Technology*, 21:827-832, 1992.

Palmer, D.P., "Irrigation," in *Davis's Handbook of Applied Hydraulics*, Zipparro, V.J., et al. (eds.), 4th ed., McGraw Hill, New York, N.Y., 1993.

Pandian, M.D., W.R. Ott, and J.V. Behar, "Residential Air Exchange Rates for Use in Indoor Air and Exposure Modeling Studies," *Journal Exposure Analysis Environmental Epidemiology*, 3(4):407-416, 1993.

Peirce, L.C., *Vegetables, Characterization, Production, and Marketing*, John Wiley & Sons, Inc., New York, N.Y., 1987.

Persily, A.K. and R.A. Grot, "Ventilation Measurements in Large Office Buildings," *ASHRAE Trans.*, 91(2A):488-502, 1985.

Pimentel, D., "Land Degradation: Effects on Food and Energy Resources," *Science*, 194:149-155, 1976.

Poston, T.M. and D.C. Klopfer, "A Literature Review of the Concentration Ratios of Selected Radionuclides in Freshwater and Marine Fish," Report PNL-5484, Pacific Northwest Laboratory, Richland, Wash., 1986.

Prohl, G., et al., "Interception and Post-Deposition Retention of Radionuclides by Vegetation and Their Importance for Dose Assessment," in *Environmental Impact of Radioactive Releases*, proceedings of an international symposium on environmental impact of radioactive releases organized by the International Atomic Energy Agency, Vienna, 8-12 May, 1995, published by the IAEA, Vienna, October 1995.

Putnam, J., et al., "Food Consumption, Prices and Expenditures 1970-1997," U.S. Department of Agriculture, Statistical Bulletin No. 965, Washington D.C., 1999.

Rawls, W.J. and D.L. Brakensiek, "Prediction of Soil Water Properties for Hydrologic Modelling," *Proceedings of Symposium on Watershed Management*, American Society of Civil Engineering, New York, N.Y., pp. 293-299, 1985.

Robbins, C. and S.P. Phipps, "GIS/Water Resources Tools for Performing Floodplain Management Modeling Analysis," in *AWRA Symposium on GIS and Water Resources*, American Water Resources Association, September 1996 (accessed at: <http://awra.org/proceedings/gis32/woolprt3/>).

Roed, J. and R.J. Cannell, "Relationship between Indoor and Outdoor Aerosol Concentration Following the Chernobyl Accident," *Radiat. Prot. Dosim.*, 21:107-110, 1987.

Roseberry, A.M. and D.E. Burmaster, "Lognormal Distributions for Water Intake by Children and Adults," *Risk Analysis*, 12(1):99-104, 1992.

Roy, M. and C. Courtay, "Daily Activities and Breathing Parameters for Use in Respiratory Tract Dosimetry," *Radiation Protection Dosimetry*, 35(3):179-186, 1991.

Royster, Jr., G.W. and B.R. Fish, "Techniques for Assessing 'Removable' Surface Contamination," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 201-207, 1967.

Sayre, J., et al., "House and Hand Dust as a Potential Source of Childhood Lead Exposure," *Am. J. of Dis. Chil.*, 127:167-170, 1974.

Sedman, R.M. and R.J. Mahmood, "Soil Ingestion by Children and Adults Reconsidered Using the Results of Recent Tracer Studies," *Air and Waste Management Association*, 44:141-144, February 1994.

Sehmel, G.A., "Particle and Gas Dry Deposition: A Review," *Atmos. Environ.*, 14:983-1011, 1980.

Seinfeld, J.H. and S.N. Pandis, *Atmospheric Chemistry and Physics*, John Wiley & Sons, Inc., New York, N.Y., 1998.

Sheppard, M.I., "Radionuclide Partitioning Coefficients in Soils and Plants and Their Correlation," *Health Physics*, 49:106-115, 1985.

Sheppard, M.I. and D.H. Thibault, "Default Soil/Liquid Partition Coefficients, K_{ds}, for Four Major Soil Types: A Compendium," *Health Physics*, 59(4):471-482, 1990.

Sheppard, M.I., S.C. Sheppard, and B.D. Amiro, "Mobility and Plant Uptake of Inorganic C-14 and C-14-Labeled PCB in Soils of High and Low Retention," *Health Physics*, 6(4):481-492, 1991.

Sheppard, S.C., "Parameter Values to Model the Soil Ingestion Pathway," *Environmental Monitoring and Assessment*, 34:27-44, 1995.

Sheppard, S.C. and W.G. Evenden, "The Assumption of Linearity in Soil and Plant Concentration Ratios: An Experimental Evaluation," *Journal of Environmental Radioactivity*, 7:221-247, 1988.

Shleien, B. (ed.), *The Health Physics and Radiological Health Handbook*, Rev. Ed., Scinta Inc., Silver Spring, Md., 1992.

Silberstein, S. and R.A. Grot, "Air Exchange Rate Measurements in the National Archive Building," *ASHRAE Trans.*, 91, 1985.

Simon, S.L., "Soil Ingestion by Humans: A Review of History, Data, and Etiology with Application to Risk Assessment of Radioactively Contaminated Soil," *Health Physics*, 74(6):647-672, 1998.

Sinclair, J.D., L.A. Psota-Kelty, and C.J. Weschler, "Indoor/Outdoor Concentrations and Indoor Surface Accumulations of Ionic Substances," *Atmos. Environ.*, 19:315-323, 1985 (as cited in Nazaroff and Cass, 1989).

Spangler, G.W. and C.A. Willis, "Permissible Contamination Limits," in *Surface Contamination*, B.R. Fish (ed.), Pergamon Press, New York, N.Y., pp. 151-158, 1967.

Stanek, E.J. and E.J. Calabrese, "Soil Ingestion Estimates for Use in Site Evaluation Based on the Best Tracer Method," *Human and Ecological Risk Assessment*, 1:133-56, 1995.

Stanek, E.J., et al., "Soil Ingestion in Adults — Results of a Second Pilot-Study," *Ecotoxicology and Environmental Safety*, 36:249-257, 1997.

Sterling, E.M., et al., "Criteria for Human Exposure to Humidity in Occupied Buildings," *ASHRAE Transactions* 91(1B):611-622, 1985. [As cited in 1996 *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Systems and Equipment, SI Edition*, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Ga., 1996.]

Thatcher, T.L. and D.W. Layton, "Deposition, Resuspension, and Penetration of Particles within a Residence," *Atmos. Environ.*, 29(13):1487-1497, 1995.

Thibault, D.H., M.I. Sheppard, and P.A. Smith, "A Critical Compilation and Review of Default Soil Solid/Liquid Partition Coefficients, K_d , for Use in Environmental Assessments," AECL-10125, Atomic Energy of Canada Limited, 1990.

Thompson, K.M. and D.E. Burmaster, "Parametric Distributions for Soil Ingestion by Children," *Risk Analysis*, 11(2):339-342, 1991.

Tsang, A.M. and N.E. Klepeis, "Results Tables from a Detailed Analysis of the National Human Activity Pattern Survey (NHAPS) Response," draft report prepared for the U.S. Environmental Protection Agency by Lockheed Martin, Contract No. 68-W6-001, 1996.

Turk, B.H., et al., "Indoor Air Quality and Ventilation Measurements in 38 Pacific Northwest Commercial Buildings," LBL-22315, Lawrence Berkeley Laboratory, Berkeley, Calif., 1987.

USDA — See U.S. Department of Agriculture.

U.S. Department of Agriculture, "Food and Nutrient Intakes of Individuals in One Day in the United States, Spring 1977," Nationwide Food Consumption Survey 1977-1978, Preliminary Report No. 2, 1980.

U.S. Department of Agriculture, "Food and Nutrient Intakes of Individuals in the United States, One Day, 1987-88," Nationwide Food Consumption Survey 1987-1988, NFCS Report No. 87-I-1, 1992.

U.S. Department of Agriculture, "Food Consumption Prices and Expenditures (1970-1992)" Statistical Bulletin No. 867, Agriculture Research Service, 1993.

U.S. Department of Agriculture, "Continuing Survey of Food Intakes by Individuals and 1994 Diet and Health Knowledge Survey," Agriculture Research Service, Riverdale, Md., 1996a.

U.S. Department of Agriculture, "Continuing Survey of Food Intakes by Individuals and 1995 Diet and Health Knowledge Survey," Agriculture Research Service, Riverdale, Md., 1996b.

U.S. Department of Agriculture, "Vegetables: Final Estimates by States, 1992-1997," Statistical Bulletin No. 946, Agricultural Statistics Board, National Agricultural Statistics Service, January 1999.

U.S. Department of Energy, "Recommended Tritium Surface Contamination Release Guides," DOE Tritium Surface Contamination Limits Committee, Washington, D.C., February 1991.

U.S. Department of Energy, "Radiological Control Manual," Rev. 1, DOE/EH-0256T, Washington, D.C., 1994a.

U.S. Department of Energy, "DOE Handbook, Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities, Volume 1 – Analysis of Experimental Data," DOE-HDBK-3010-94, Washington, D.C., December 1994b.

U.S. Department of Housing and Urban Development, "Housing Completions," C22/96-12, U.S. Department of Commerce Economics and Statistics Administration, U.S. Census Bureau, December 1996.

U.S. Department of Housing and Urban Development, "Housing Completions," C22/99-9, U.S. Department of Commerce Economics and Statistics Administration, U.S. Census Bureau, September 1999.

U.S. Environmental Protection Agency, "Manual of Water Well Construction Practices," EPA 570/9-75-001, Office of Water Supply, Washington, D.C., 1975.

U.S. Environmental Protection Agency, "An Estimation of the Daily Food Intake Based on Data from the 1977-1978 USDA Nationwide Food Consumption Survey," EPA-520/1-84-021, Office of Radiation Programs, Washington, D.C., 1984 (as cited in EPA, 1989a).

U.S. Environmental Protection Agency, "Development of Statistical Distributions or Ranges of Standard Factors Used in Exposure Assessments," EPA/600/8-85/010, Office of Health and Environmental Assessment, Washington, D.C., 1985.

U.S. Environmental Protection Agency, "Exposure Factors Handbook," EPA/600/8-89/043, Office of Health and Environmental Assessment, Washington, D.C., 1989a.

U.S. Environmental Protection Agency, "Interim Final Guidance for Soil Ingestion Rates," OSWER Directive 9850.4, Office of Solid Waste and Emergency Response, Washington, D.C., 1989b

U.S. Environmental Protection Agency, "Risk Assessment Guidance for Superfund, Volume I, Human Health Evaluation Manual, Supplemental Guidance, Standard Default Exposure Factors," Interim Final, OSWER Directive 9285.6-03, Office of Emergency and Remedial Response, Washington, D.C., 1991.

U.S. Environmental Protection Agency, "PRZM-2, A Model for Predicting Pesticide Fate in the Crop Root and Unsaturated Soil Zones: Users Manual for Release 2.0," EPA/600/R-93/046, Washington, D.C., March 1993.

U.S. Environmental Protection Agency, "Exposure Factors Handbook, Update to Exposure Factors Handbook, EPA/600/8-89/043 — May 1989," EPA/600/P-95/002Fa,b&c, National Center for Environmental Assessment, Office of Research and Development, Washington, D.C., August 1997.

U.S. Environmental Protection Agency, "Understanding Variation in Partition Coefficient, K_d, Values, Volume I: The K_d Model, Methods of Measurement, and Application of Chemical Reaction Codes," EPA402-R-99-004A, cooperative effort by Office of Radiation and Indoor Air, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, and Office of Environmental Restoration, U.S. Department of Energy, Washington, August 1999a.

U.S. Environmental Protection Agency, "Understanding Variation in Partition Coefficient, K_d, Values, Volume II: Review of Geochemistry and Available K_d Values for Cadmium, Cesium, Chromium, Lead, Plutonium, Radon, Strontium, Thorium, Tritium (3H), and Uranium," EPA402-R-99-004B, a cooperative effort by Office of Radiation and Indoor Air, Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, and Office of Environmental Restoration, U.S. Department of Energy, Washington, August 1999b.

U.S. Environmental Protection Agency, "Air Quality Criteria for Particulate Matter," EPA 600/P-99/002, External Review Draft, Office of Research and Development, Washington, D.C., October 1999c.

U.S. Environmental Protection Agency, <http://www.epa.gov/airs/airs.html>, (home page for the AIRS database) [data downloaded on December 8], 1999d.

U.S. Nuclear Regulatory Commission, "Termination of Operating Licenses for Nuclear Reactors," Regulatory Guide 1.86, Washington, D.C., 1974.

U.S. Nuclear Regulatory Commission, "Reactor Safety Study; an Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Appendix G: Calculation of Reactor Accident Consequences," WASH-1400 (NUREG 75/014), Washington, D.C., 1975.

U.S. Nuclear Regulatory Commission, "Calculation of Annual Doses from Routine Releases of Reactor Effluents for the Purposes of Evaluating Compliance with 10 CFR Part 50, Appendix I," Regulatory Guide 1.109, Revision I, Washington D.C., 1977.

U.S. Nuclear Regulatory Commission, "Health Physics Surveys for Byproduct Materials at NRC-licensed Processing and Manufacturing Plants," Regulatory Guide 8.21, Washington, D.C., 1979a.

U.S. Nuclear Regulatory Commission, "Radiation Safety Surveys at Medical Institutions," Regulatory Guide 8.23, Washington, D.C., 1979b.

U.S. Nuclear Regulatory Commission, "Demonstrating Compliance with the Radiological Criteria for License Termination," Draft Regulatory Guide DG 4006, Office of Nuclear Regulatory Research, Washington, D.C., August 1998a.

U.S. Nuclear Regulatory Commission, "Decision Methods for Dose Assessment to Comply with Radiological Criteria for License Termination, Division of Regulatory Applications" (Draft Report for Comment) NUREG-1549, Office of Nuclear Regulatory Research, Washington, D.C., July 1998b.

Vanderploeg, H.A., et al., "Bioaccumulation Factors for Radionuclides in Freshwater Biota," ORNL-5002, EDS, Publication No. 783, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1975.

Van Wijnen, J.H., et al., "Estimated Soil Ingestion by Children," *Environmental Research* 51:147-162, 1990.

Wallace, L., "Indoor Particles: A Review," *J. Air & Waste Manage. Assoc.*, 46:98-126, 1996.

Walter, S.D., A.J. Yankel, and I.H. Von Lindern, "Age-Specific Risk Factors for Lead Absorption in Children," *Archives of Environ. Health*, 53(1):53-58, 1980.

Wang, Y.-Y., B.M. Biwer, and C. Yu, "A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk, and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code," ANL/EAIS/TM-103, Argonne National Laboratory, Argonne, Ill., prepared for the U.S. Department of Energy, August 1993.

Wernig, M.A., et al., "Residual Radioactive Contamination from Decommissioning; User's Manual," NUREG/CR-5512, Vol. 2, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, D.C., undated.

Weschler, C.J., H.C. Shields, and D.V. Naik, "Indoor Ozone Exposures," *JAPCA*, 39:1562-1568, 1989.

Whitby, K.T. and G.M. Sverdrup, "California Aerosols: Their Physical and Chemical Characteristics," in *The Character and Origins of Smog Aerosols*, G.M. Hidy, et al. (eds.), John Wiley & Sons, Inc., New York, N.Y., pg. 495, 1980 (as cited in John, 1993).

Wischmeier, W.H. and D.D. Smith, "Predicting Rainfall Erosion Losses - A Guide to Conservation Planning," Agricultural Handbook No. 537, prepared by Science and Education Administration for U.S. Department of Agriculture, Washington, D.C., 1978.

Wong, K.Y., et al., "Tritium Decontamination of Machine Components and Walls," *Fusion Engineering and Design*, 16(1991):159-172, 1991.

Wood, R.A. (ed.), "Weather of U.S. Cities," 5th ed., Gale Research Inc., Detroit, Mich., 1995.

Yocom, J.E., et al., "Indoor/Outdoor Air Quality Relationships," *J. Air Pollut. Control Assoc.*, 21:251-259, 1971.

Yu, C., et al., "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0," ANL/EAD/LD-2, Argonne National Laboratory, Argonne, Ill., September 1993a.

Yu, C., et al., "Data Collection Handbook to Support Modeling the Impacts of Radioactive Material in Soil," ANL/EAIS-8, Argonne National Laboratory, Argonne, IL, April 1993b.

Yu, C., et al., "RESRAD-BUILD: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material," ANL/EAD/LD-3, Argonne National Laboratory, Argonne, Ill., November 1994.

Vovk, I.F., et al., "Technical Approaches to Decontamination of Terrestrial Environments in the CIS (former USSR)," *Sci. Total Environ.* 137:49-63, 1993.

Zipparro, V.J., et al. (eds.), *Davis's Handbook of Applied Hydraulics*, McGraw Hill, New York, N.Y., 1993.

Zuzel, J.F., R.R. Allmaras, and R.N. Greenwalt, "Temporal Distribution of Runoff and Soil Erosion at a Site in Northeastern Oregon," *Journal of Soil and Water Conservation*, July-August 1993.

APPENDIX A:
PARAMETRIC DISTRIBUTION TYPES

APPENDIX A:

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 and RESRAD-BUILD codes. Table A.1 summarizes the continuous probability density distribution functions and the required input for the LHS module.

A.1 Beta Distribution

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

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

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

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

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

$$p = (\mu - A) \left[\frac{(\mu - A)(B - \mu) / \sigma^2 - 1}{B - A} \right], \quad (\text{A-3})$$

Table A.1 Continuous Probability Density Distribution Functions

Distribution	Input Variables			
Beta	A (minimum)	B (maximum)	p (shape factor)	q (shape factor)
Exponential Types				
Exponential	λ			
Bounded exponential	λ	A (minimum)	B (maximum)	
Truncated exponential	λ	lower quantile value	upper quantile value	
Gamma	α (shape factor)	β (scale factor)		
Inverse Gaussian	μ	λ		
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)	σ (standard deviation)		
Normal-b	value at 0.001 quantile	value at 0.999 quantile		
Bounded normal	μ (mean)	σ (standard deviation)	A (minimum)	B (maximum)
Truncated normal	μ (mean)	σ (standard deviation)	lower quantile value	upper quantile value
Pareto	α	β		
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	α	β		

and

$$q = \frac{(\mu - A)(B - \mu)}{\sigma^2} - 1 - p. \quad (\text{A-4})$$

A.2 Exponential Distribution

The probability density function for the exponential distribution is:

$$f(x) = \lambda e^{-\lambda x} \quad \text{for } x \geq 0, \quad (\text{A-5})$$

with the mean given by $1/\lambda$. The variable λ 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.

A.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:

$$f(x) = \frac{\beta^\alpha x^{(\alpha-1)} e^{-\beta x}}{\Gamma(\alpha)} \quad \text{with } x > 0, \alpha > 0, \beta > 0, \text{ and} \quad (\text{A-6})$$

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

where $\Gamma(\alpha)$ is the gamma function. The α parameter determines the shape of the function, and the β 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 α/β . The gamma distribution is appropriate for representing the time required for α independent events to take place for nonrandom events that occur at a constant arrival rate β . This distribution is often used to describe system reliability (the length of life of industrial equipment).

A.4 Inverse Gaussian

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

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

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).

A.5 Lognormal Distribution

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

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\frac{(\ln x - \mu)^2}{2\sigma^2}\right)} \quad \text{with } x > 0, \quad (\text{A-8})$$

where μ and σ 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).

A.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:

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

with the mean given by

$$\frac{b-a}{\ln b - \ln a}. \quad (\text{A-10})$$

A.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.

A.8 Normal Distribution

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

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)} \quad \text{with } -\infty < x < \infty, \quad (\text{A-11})$$

where μ is the mean ($-\infty < \mu < \infty$) and σ is the standard deviation ($\sigma > 0$) 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 $X = x \pm \mu$. 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 σ , 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

$$Z = \frac{(\bar{x} - \mu)\sqrt{n}}{\sigma}. \quad (\text{A-12})$$

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).

A.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:

$$f(x) = \frac{\alpha\beta^\alpha}{x^{\alpha+1}} \text{ for } x \geq \beta. \quad (\text{A-13})$$

The mean for the Pareto distribution is given by:

$$\mu = \frac{\alpha\beta}{\alpha-1} \text{ for } \alpha > 1. \quad (\text{A-14})$$

A.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:

$$f(x) = \begin{cases} \frac{2(x-a)}{(c-a)(b-a)} & a \leq x \leq b \\ \frac{2(c-x)}{(c-a)(c-b)} & b \leq x \leq c, \end{cases} \quad (\text{A-15})$$

with the mean given by:

$$\frac{a+b+c}{3}, \quad (\text{A-16})$$

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 $a \leq b \leq c$.

A.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:

$$f(x) = \frac{1}{b-a} \quad \text{for } a \leq x \leq b, \quad (\text{A-17})$$

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.

A.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:

$$f(x) = \left(\frac{\alpha}{\beta}\right) \left(\frac{x}{\beta}\right)^{(\alpha-1)} e^{-\left(\frac{x}{\beta}\right)^\alpha} \quad \text{for } \alpha > 0 \text{ and } \beta > 0, \quad (\text{A-18})$$

where α is the shape parameter and β is the scale parameter. When $\alpha = 1$, the Weibull distribution reduces to the exponential distribution. When $\alpha = 2$, the Weibull distribution has the form of the Rayleigh distribution.

A.13 References and Bibliography for Appendix A

Abramowitz, M. and I.A. Stegun, *Handbook of Mathematical Functions*, Dover Publications Inc., New York, N.Y., 1972.

Cullen, A.C. and H.C. Frey, *Probabilistic Techniques in Exposure Assessment*, Plenum Press, New York, N.Y., 1999.

Dougherty, E.R., *Probability and Statistics for the Engineering, Computing, and Physical Sciences*, Prentice Hall, Englewood Cliffs, N.J., 1990.

Hahn, G.J. and S.S. Shapiro, *Statistical Models in Engineering*, John Wiley & Sons, Inc., New York, N.Y., 1994.

Hoel, P.G., *Introduction to Mathematical Statistics*, John Wiley & Sons, Inc., New York, N.Y., 1971.

Johnson, N.L. and S. Kotz, *Continuous Univariate Distributions*, Vol. 2, John Wiley & Sons, Inc., New York, N.Y., 1970.

Johnson, N.L., S. Kotz, and N. Balakrishnan, *Continuous Univariate Distributions*, Vol. 1, John Wiley & Sons, Inc., New York, N.Y., 1994.

Lee, R.C. and W.E. Wright, "Development of Human Exposure-Factor Distributions Using Maximum-Entropy Inference," *J. Exp. Anal. Env. Epid.*, 4:329-341, 1994.

Ott, W.R., *Environmental Statistics and Data Analysis*, CRC Press, Boca Raton, Fla., 1995.

Wyss, G.D. and K.H. Jorgensen, "A User's Guide to LHS: Sandia's Latin Hypercube Sampling Software," SAND98-0210, Sandia National Laboratories, Albuquerque, N.M., 1998.

ATTACHMENT D

TESTING OF THE RESRAD PROBABILISTIC MODULES

Prepared by

D. LePoire, J. Arnish, E. Gnanapragasam, S. Kamboj,
B.M. Biwer, J. Cheng, C. Yu, A. Zielen, and S.Y. Chen
Environmental Assessment Division
Argonne National Laboratory

TABLE OF CONTENTS

ABBREVIATIONS	vii
1 INTRODUCTION	1
2 DEVELOPMENT UNIT TESTING	5
2.1 Testing the Probabilistic Inputs Sampling Program	5
2.1.1 Changes to the Computational Statements in the Code	5
2.1.2 Conditions on the Parameters Defining the Different Distributions	6
2.1.3 Verifying That the Samples Conformed to the Specified Distributions	6
2.1.4 Dimensioning Limits	7
2.1.5 Testing the Correlation and Regression Program	7
2.1.6 Verifying the Correlation and Regression Program	7
2.2 Calculation Integration Testing	8
2.2.1 Testing of Radionuclides	9
2.2.2 Testing of All Pathways	9
2.2.3 Testing of Input Correlations	9
2.2.4 Comparing Deterministic and Probabilistic Results	10
2.3 Output Interface Calculations	10
3 INTEGRATED TESTING	13
3.1 Calculations	13
3.1.1 Scenario Description	13
3.1.2 Case Implementation and Interpretation	13
3.1.3 Summary	18
3.2 Interface Testing	18
3.2.1 Data Input	18
3.2.2 Default Distribution Integration	23
3.2.3 Data Output	24
3.2.4 File Saving	25
3.2.5 Help	25
3.2.6 Manual	25
3.3 Distribution Testing	25
3.3.1 Creating the Distribution CD	25
3.3.2 Testing the Distribution CD	26
4 NRC BETA TESTING	28
4.1 Procedure	28
4.2 Summary of Comments and Resolution	28

CONTENTS (Cont.)

5	REFERENCES	29
Appendix A:	Argonne Responses to NRC Comments on Testing of the Draft (Release 1) Probabilistic RESRAD, Version 6.0, and RESRAD-BUILD, Version 3.0, Codes	A-1
Appendix B:	Argonne Responses to the Final NRC Comments on Evaluation and Beta Testing of the Draft (Release 2) Probabilistic RESRAD Version 6.0, and RESRAD-BUILD, Version 3.0, Codes	B-1

TABLES

2.1	Limits of the LHS Sampling Options	7
2.2	Comparison between Code-Calculated Coefficients and Coefficients Calculated Manually Using a Spreadsheet Program	8
2.3	Example Statistical Uncertainty Calculation of the Average Peak Dose	11
2.4	Example Statistical Uncertainty Calculation for the 50th Percentile	12
3.1	Input Parameters and Their Distributions Selected for Probabilistic Analysis	14
3.2	Partial Correlation Coefficients for Peak of the Mean Dose	19
3.3	Standardized Regression Coefficients for Peak of the Mean Dose	20
3.4	Partial Rank Correlation Coefficients for Peak of the Mean Dose	21
3.5	Standardized Rank Regression Coefficients for Peak of the Mean Dose	22

FIGURES

3.1	Scatter Plot of Indoor Time Fraction against Outdoor Time Fraction for a Rank Correlation Coefficient of -0.6	15
-----	--	----

FIGURES (Cont.)

3.2	Variation of the Peak of the Mean Dose at Graphical Times with Sample Size, for Seven Repetitions	16
3.3	Variation of 90% Dose at 299 Years with Sample Size, for Seven Repetitions	16
3.4	Variation of Median Dose at 299 Years with Sample Size, for Seven Repetitions	17
3.5	Scatter Plot of Drinking Water Intake and Peak Total Dose from All Pathways, All Repetitions Combined	23
3.6	Scatter Plot of Soil-to-Plant Transfer Factor for Lead and the Peak Dose from All Pathways, All Repetitions Combined	24

ABBREVIATIONS

CFR	Code of Federal Regulations
DCGL	derived concentration guideline level
DOE	U.S. Department of Energy
LHS	Latin hypercube sampling
NRC	U.S. Nuclear Regulatory Commission
PCC	partial correlation coefficient
PRCC	partial rank correlation coefficient
SRC	standardized regression coefficient
SRP	Standard Review Plan
SRRC	standardized rank regression coefficient
TEDE	total effective dose equivalent

TESTING OF THE RESRAD PROBABILISTIC MODULES

1 INTRODUCTION

On July 21, 1997, the U.S. Nuclear Regulatory Commission (NRC) published the License Termination Rule (Title 10, Code of Federal Regulations, Part 20 [10 CFR 20], Subpart E), which establishes requirements for nuclear facility licensees who are terminating their licensed operations. The NRC's approach to demonstrate compliance with the license termination rule is based on a philosophy of moving from simple, prudently conservative calculations toward more realistic simulations, as necessary, using dose modeling to evaluate exposure to residual radioactivity in soil and structures. Such potential exposures are evaluated for two scenarios: building occupancy (for contamination on indoor building surfaces) and residential (for contaminated soil).

The objective of dose modeling is to assess the total effective dose equivalent (TEDE) to an average member of the *critical group*¹ from residual contamination, including any contamination that has reached ground sources of drinking water. The assessment offers a reasonable translation of residual contamination into estimated radiation doses to the public. Compliance with the NRC-prescribed dose criteria can then be assessed from the modeling results.

As part of the development of site-specific implementation guidance supporting the License Termination Rule and development of a Standard Review Plan (SRP) on Decommissioning, the NRC recognized the need to perform probabilistic analysis with codes that could be used for site-specific modeling. Such modeling capabilities exist with the RESRAD (Yu et al., 1993) and RESRAD-BUILD (Yu et al., 1994) codes. These two codes were developed at Argonne National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE). These DOE codes possess the following attributes: (1) the software has been widely accepted and there is already a large user base, (2) the models in the software were designed for and have been successfully applied at sites with relatively complex physical and contamination conditions, and (3) verification and validation of the codes are well documented (Yu, 1999; NUREG/CP-0163 [NRC, 1998]). The RESRAD codes have been used primarily

¹ The *critical group* is defined as an individual or relatively homogenous group of individuals expected to receive the highest exposure under the assumptions of the particular scenario considered (NUREG/CR-5512 [Kennedy and Streng, 1992]). The average member of the critical group is an individual assumed to represent the most likely exposure situation on the basis of prudently conservative exposure assumptions and parameter values within the model calculations.

to derive site-specific cleanup guidance levels (the derived concentration guideline levels, or DCGLs) on the basis of the deterministic method.

In 1999, the NRC tasked Argonne to modify the RESRAD and RESRAD-BUILD codes for use with the NRC's license termination compliance process and SRP. For use in this NRC process, the codes must meet specifications consistent with the current NRC modeling guidelines. Thus, the primary objectives of this project are for Argonne to (1) develop parameter distribution functions and perform probabilistic analysis with the RESRAD and RESRAD-BUILD computer codes, and (2) develop necessary computer modules, external to the RESRAD and RESRAD-BUILD codes, that incorporate the parameter distribution functions for conducting the probabilistic analyses. These modules will contain user-friendly features based on a specially designed graphic-user interface (GUI). They will be tailored to use the RESRAD and RESRAD-BUILD codes to perform site-specific probabilistic dose assessments in support of decontamination and decommissioning of potentially radiologically contaminated sites.

This document reports on one of a series of steps undertaken by Argonne to meet NRC's requirements. The effort reported here builds on the information provided in a series of letter reports to the NRC leading to development of parameter distributions and the required probabilistic capabilities for RESRAD and RESRAD-BUILD. Those reports are described in the following paragraphs.

Parameter Categorization (Kamboj et al., 1999)²: All the input parameters used in the RESRAD and RESRAD-BUILD codes (totaling about 200 parameters) were listed, categorized, and defined. The parameters were classified as relating to physical, behavioral, or metabolic attributes. Any parameter that would not change if a different group of receptors was considered was classified as a physical parameter. Any parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. A parameter representing the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered was classified as a metabolic parameter.

Parameter Ranking (Cheng et al., 1999)³: A strategy was developed to rank the RESRAD and RESRAD-BUILD input parameters and identify parameters for detailed distribution analysis. The parameters were divided into three levels of priority: 1 (high priority), 2 (medium priority), and 3 (low priority). The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations, (2) variability of the radiation dose as a result of changes in the parameter value, (3) parameter type (physical, behavioral, or metabolic), and (4) availability of data on the parameter in the

²This report is included as Attachment A of the main document.

³This report is included as Attachment B of the main document.

literature. For each criterion, a numeric score (0-9) was assigned to each parameter, with a low score assigned to parameters with a higher priority and a high score assigned to parameters with lower priority under the considered criterion. The final priority ranking of each parameter was assigned on the basis of its total numeric score for the four ranking criteria. The lower the total score, the higher the priority assigned.

Parameter Distribution (Biwer et al., 2000)⁴: Value distributions were developed for those parameters identified as of high or medium priority in the RESRAD and RESRAD-BUILD codes. A total of about 70 parameters were selected for analysis. These parameters were deemed to be the ones most relevant to the NRC objective of demonstrating compliance with the radiological criteria for decommissioning and license termination. Development of distributions entailed gathering and analyzing relevant data from NRC-sponsored work and from an extensive literature search using library and Internet resources. However, it was recognized that many of the parameters in question have not been well tested or can vary significantly from site to site or even within the same site. Therefore, the focus was on analyzing the available data and making the most plausible distribution assignments for each selected parameter for use in an initial round of dose calculations.

Probabilistic Dose Analysis (Kamboj et al., 2000): The effects of parameter distribution on the estimated doses, taking into account parameter correlations, were assessed for the residential scenario with RESRAD and for the building occupancy scenario with RESRAD-BUILD. The interim versions of the probabilistic modules for the two codes (RESRAD version 5.95+ and RESRAD-BUILD version 2.9+) were used. The analysis took into account long-term transport of residual radionuclides in the environmental media and associated exposure pathways. For RESRAD, the peak dose within a 1,000-year time frame was captured, and for RESRAD-BUILD, the initial dose (i.e., at time 0) was calculated and used as the peak dose. The probabilistic analysis was performed by using the stratified sampling of the Latin hypercube sampling (LHS) method for a collection of input parameter distributions. The probabilistic analysis demonstrated the process of using the integrated RESRAD and RESRAD-BUILD codes and the probabilistic modules, together with the parameter distributions, for dose assessment at a relatively complex site.

⁴This report is included as Attachment C of the main document.

Probabilistic Modules (LePoire et al., 2000): The probabilistic modules developed for the RESRAD and RESRAD-BUILD codes are described and their use illustrated, including (1) description of the software design and requirements and (2) a user's manual for the probabilistic modules that facilitate the uncertainty analysis. The report is to be used in conjunction with the RESRAD and RESRAD-BUILD manuals (Yu et al., 1993, 1994), which describe the methods and parameters for those codes. A sample case and demonstration of the use of the probabilistic modules is provided. A detailed discussion of the LHS sampling method and a summary of parameter distributions are included in the appendixes.

Probabilistic Module Testing (this report): This report includes four major sections. Section 1 provides background information and summaries of the previous tasks accomplished in this project. Section 2 describes software component testing during development. The integrated system testing of the calculations, interface, and distribution are presented in Section 3. Section 4 provides the procedure and results from the beta testing phase. The NRC comments and Argonne responses regarding the beta testing phase are included in Appendix A.

2 DEVELOPMENT UNIT TESTING

Tests were performed as the components for the software system were under development. These components included the sampling method, the results calculations, and the results presentation. The testing of the sampling method and calculation of the results were nearly comprehensive in that they covered all possible variable distributions, all pathways, and most radionuclides. The results presentation was point checked for consistency of the different presentations of the same data in the interactive tables, interactive graphics, and reports. An example of the precision calculation is shown and compared with the software result.

2.1 Testing the Probabilistic Inputs Sampling Program

The Latin hypercube sampling (LHS) program used in this effort was developed by Sandia National Laboratories. The program, received in May 1999, had been written to run on different computer systems. It required some minor changes to run in the PC environment as Lahey Fortran 77 executable. A number of changes, primarily formatting, were also required to produce the desired LHS report. Three minor changes to the computational code were also necessary to overcome compilation errors and run time errors. This section describes the minor changes to the computational code and the testing of the resulting LHS executable to verify that the samples produced conformed to the specifications.

There are many ways to define and specify the parameters necessary to characterize a distribution. In most of the common cases (e.g., mean, standard deviation, minimum, maximum), these are unambiguous. However, some distributions use parameters such as alpha, beta, lambda, P, Q, and error factor whose definition may be neither obvious nor unique. Thus, it was necessary to understand the parameters as used in the LHS code and to describe them in the help screen to the probabilistic inputs screen. It was also necessary to verify that all the distributions were being sampled as intended, for quality control purposes.

2.1.1 Changes to the Computational Statements in the Code

The three changes made in computational statements are as follows:

- Subroutine BETALN (A,B)
The entry statement to GAMALN did not have any arguments; this caused a compilation error. When the necessary arguments were included, the compilation was successful. The computed value had to be named GAMALN. (It was called BETALN in the original code.)

- Subroutine CHKDAT (PAR, A, MAXA)
The code crashed when an attempt was made to sample a Beta distribution. The cause was as follows: This subroutine does the checks on the parameters for the distributions that have four or fewer parameters. The check on the parameters of the beta distribution was placed at the end of the original file after the checks for most of the other distributions. The variable PAR = "BETA " was five characters long (including the final blank character) for a beta distribution. The if blocks that tested the conditions for a number of distributions had the statement IF (PAR(1:6) .EQ..... This caused an error when executed on a PAR (= "BETA ") that was only five characters long. The check for the BETA parameters was moved ahead of the checks for all distributions that needed the IF (PAR(1:6) .EQ. statement.
- Subroutine NewCrd (Card, lunit, lend)
The variable Maxi was not defined before it was used in the first Do i=1, Maxi statement. It was defined following the aforementioned do loop. The definition was moved up.

2.1.2 Conditions on the Parameters Defining the Different Distributions

The subroutines in the LHS code that checked the inputs were studied to determine the conditions imposed on the parameters defining the different distributions. Some of these conditions are inherent to the distributions (e.g., the mean of a lognormal distribution has to be positive value), while others are due to the algorithms used in the code (e.g., the minimum and the maximum specified for the normal distribution can not be more than 4.75 standard deviations away from the mean). All conditions that are inherent to the distributions and the conditions imposed by the algorithms used in the code are described in the help screen to the probabilistic inputs screen. The input interface checks to make sure that these conditions are satisfied before accepting the values input by the user. The inputs that violate the conditions turn red when the update parameter distribution button or the previous/next parameter scroll button are pressed.

2.1.3 Verifying That the Samples Conformed to the Specified Distributions

An input file was created containing each of the 34 distributions available in the probabilistic interface of RESRAD and RESRAD-BUILD. Three repetitions of 250 samples were generated for each of these 34 distributions with the LHS code. The three cumulative distribution functions (cdf) of the samples generated for the three repetitions were compared with the cdf generated by other means (explicit directly evaluable analytical expressions of the cdf were use when available, otherwise the functions in Excel spreadsheet were used.) The cumulative distribution functions generated for all 34 distributions matched the cumulative distribution functions computed by other means.

2.1.4 Dimensioning Limits

The LHS program uses a number of arrays (subscripted variables) of fixed dimensions. These arrays impose limits on the number of uncertain variables, the number of observations, the number of non-zero correlations, and the product of the number of uncertain variables and the number of observations. The current limits are shown in Table 2.1. An LHS program with expanded limits (see Table 2.1) has also been compiled, but it is not included in the distribution file because of its large size.

2.1.5 Testing the Correlation and Regression Program

The Correlation and Regression (PCCSRC) program used was developed by Sandia National Laboratories. The program had been incorporated into RESRAD in the early 1990s. It has now been taken out of the RESRAD executable and is a separate executable. A number of variables in PCCSRC were changed to dynamic dimensioning so as not to restrict the number of observations or repetitions that could be used in the probabilistic analysis. A number of variables in the matrix inversion subroutine in PCCSRC were also changed to double precision to avoid round-off errors. The new Correlation and Regression program (CorrReg) also contains a number of subroutines to produce the necessary probabilistic input files and the probabilistic output file to produce the coefficients requested by the user.

2.1.6 Verifying the Correlation and Regression Program

The probabilistic inputs and the resulting probabilistic dose from a previous inter-model comparison exercise (BIOMOVs II Steering Committee, 1996) were processed by the correlation and regression program (CorrReg). The partial correlation coefficients (PCC), the standardized regression coefficients (SRC), the partial rank correlation coefficients (PRCC), and the standardized rank regression coefficients (SRRC) computed by the code (Table 2.2) agreed with those that had been previously computed manually using a spreadsheet program (PlanPerfect).

TABLE 2.1. Limits of the LHS Sampling Options

Quantity	Current limit	Expanded limit
Number of uncertain variables (Nvar)	501	701
Number of observations (Nobs)	2,001	2,001
Number of non-zero correlations (Ncv)	501	701
Nvar x Nobs	400,000	1,400,000
Size of LHS executable	6,140KB	17,287KB

TABLE 2.2. Comparison between Code-Calculated Coefficients and Coefficients Calculated Manually Using a Spreadsheet Program

	Code (CorrReg) Computed Coefficients					Coefficients Computed on Spreadsheet			
Variable	PCC	SRC	PRCC	SRRC		PCC	SRC	PRCC	SRRC
1	0.04	0.01	-0.02	-0.01		0.04	0.01	-0.01	-0.01
2	0.97	0.49	0.88	0.82		0.97	0.49	0.88	0.82
3	0.15	0.02	-0.02	-0.01		0.14	0.02	-0.03	-0.01
4	-0.2	-0.03	0.05	0.02		-0.20	-0.03	0.05	0.02
5	0.02	0	0.11	0.05		0.02	0.00	0.12	0.05
6	0.05	0.01	0.09	0.04		0.04	0.01	0.09	0.04
7	0.12	0.02	0.13	0.06		0.12	0.02	0.14	0.06
8	0.98	0.6	0.55	0.28		0.98	0.60	0.54	0.28
9	-0.02	0	-0.09	-0.04		-0.02	0.00	-0.09	-0.04
10	0.98	0.57	0.15	0.06		0.98	0.57	0.15	0.06
11	0.06	0.01	-0.06	-0.03		0.05	0.01	-0.06	-0.03
12	0.25	0.03	0.11	0.05		0.25	0.03	0.11	0.05
13	0.2	0.03	-0.06	-0.03		0.19	0.03	-0.06	-0.03
14	0.06	0.01	-0.02	-0.01		0.06	0.01	-0.01	-0.01
15	-0.2	-0.03	-0.2	-0.09		-0.21	-0.03	-0.20	-0.09
16	-0.1	-0.01	-0.08	-0.04		-0.13	-0.01	-0.08	-0.04
17	-0.02	0	0.02	0.01		-0.04	0.00	0.02	0.01
r ²	0.99	0.99	0.84	0.84			0.99		0.84

2.2 CALCULATION INTEGRATION TESTING

The probabilistic modules were tested during the development mode for their proper execution and for the reasonableness of the results. Most of the testing was done when the analysis for Subtask 1.4 was in progress. Many problems identified during the initial testing were later rectified. The modules were tested with all radionuclides in the RESRAD and RESRAD-BUILD databases. The testing was also done for all pathways. The rank correlation between input parameters was tested. The results obtained with the deterministic runs were compared with those from the probabilistic run.

2.2.1 Testing of Radionuclides

Testing was conducted to verify that the probabilistic modules would run with all the radionuclides in RESRAD and RESRAD-BUILD databases. For this testing, all the parameters assigned distributions in the Subtask 1.3 report (Biwer et al., 2000) were assumed to be uncertain in nature (i.e., those parameters were assigned distributions). It was found that the modules ran for all radionuclides except Cm-245 in RESRAD. Earlier, problems with branching radionuclides (Sb-125, Eu-152, Pu-241, etc.) were identified which were later rectified. The RESRAD code was also modified to handle large variations in Kd values in different zones and among progeny radionuclides. The Subtask 1.4 report (Kamboj et al., 2000) provides probabilistic results for all radionuclides except Cm-245 using interim versions of the RESRAD (version 5.95+) and RESRAD-BUILD (version 2.9+) codes. The code was modified to remove the problems with Cm-245.

2.2.2 Testing of All Pathways

The available pathways in RESRAD and RESRAD-BUILD were tested to verify that for individual pathways, only parameters expected to affect that pathway were actually found to be sensitive parameters. For the probabilistic dose analysis in Subtask 1.4, two scenarios — residential and building occupancy — were analyzed. The RESRAD code was used to analyze the residential scenario, and RESRAD-BUILD was used to analyze the building occupancy scenario. Except for radon, all pathways were active for the two scenarios. The results of the analyzes indicated that pathway doses were reasonable and that sensitive parameters and pathways were consistent (i.e., if external pathway was the dominant pathway, the most sensitive parameter was external gamma shielding factor, and if plant ingestion was the dominant pathway, the most sensitive parameter was the plant transfer factor).

2.2.3 Testing of Input Correlations

To test input correlations, some parameters were assigned rank correlations. The LHS output was checked to see the actual correlations used in the sample run. It was observed that unit positive or negative correlations (+1 or -1) could not be specified between the input parameters. The rank correlations >-1 and <1 are allowed in the probabilistic modules. Some parameters are highly correlated, such as total porosity and effective porosity. For those parameters, high input rank correlations should be used.

2.2.4 Comparing Deterministic and Probabilistic Results

Deterministic and probabilistic results were compared to ensure the proper integration of the probabilistic module with the RESRAD deterministic module. As mentioned in the Subtask 1.6 report (LePoire et al., 2000), when the user-specified case is run, the deterministic values are used to generate the standard deterministic analysis. The deterministic analysis uses no information from the specified probabilistic distributions. If probabilistic analysis has been specified by choosing one or more parameter for analysis and the number of observations and number of repetition is at least 1, then probabilistic calculations will also be performed.

In the probabilistic analysis, a probability distribution is specified for each input parameter of uncertain value. Samples (number equal to the number of observations times the number of repetitions in the probabilistic module) are generated from each of the input parameter distributions according to the sampling technique (LHS or Monte Carlo). One sample from each input parameter distributed is selected, depending on the specified correlations among the input uncertain parameters. This one sample constitutes a sample run. In this way, sample runs equal to the number of observations times the number of repetitions are generated.

The results from the probabilistic sample runs were compared with the deterministic RESRAD run. For that comparison, five parameters (density of contaminated zone, depth of roots, contaminated zone erosion rate, plant transfer factor, and external gamma shielding factor) were assigned probabilistic distribution. In all, 10 sample runs were performed in the probabilistic analysis (the radionuclide selected was Co-60). In the deterministic runs, the values of the uncertain parameters were chosen from the values in the probabilistic run (LHS sample input vectors from the LHS report). All 10 deterministic runs (equal to the number of sample runs) were performed. The resultant total dose and pathway doses from the deterministic runs were compared with the values from the probabilistic run. No significant differences were identified. This result means that the level of difference in the output (no differences within the first two or three significant figures) matches the level of differences in the input (no differences within the first two or three significant figures). The differences in the input are caused by the need to manually input numbers into the interface at the accuracy of 2 to 3 significant figures. This comparison verifies that the correct values from the probabilistic module are transferred to the RESRAD deterministic module.

2.3 OUTPUT INTERFACE CALCULATIONS

The percentile and statistics of the interactive tables and the report were compared. Slight differences were found in some circumstances. These differences are attributed to the slightly different calculational approaches. The interactive tables calculate statistics on the

basis of each repetition and then take the average of those values. The report calculates the statistics on the basis of the complete set of data over all the repetitions.

The tables and graphs were compared. The results were the same. It was decided to maintain the data point at the initial contamination placement (time = 0) in the plots with a logarithmic time scale. These data will be plotted on the far left axis, which usually also contains the data with the time equal to 1 year.

Correlations in the output report were reviewed. These calculations are performed by the suite of routines developed by Sandia to support the LHS method. It was found that some correlations were reported as zero when there was known to be a correlation. This situation was attributed to the nonconvergence of the routines within the software. The software was altered to support double precision calculations. This change yielded much better convergence and better reporting of the correlations.

Data stored in the database were analyzed and compared with the results of the “Quick Tour” case. In this example, there were 3 repetitions of 100 samples. The statistics for the average and 50% percentile were reported as 9.35 ± 1.04 and 5.56 ± 0.00957 , respectively. From the database, the average peak dose from the 100 samples in each repetition was calculated; results are shown in Table 2.3. The average of the averages matches the reported number. The standard deviation of the three numbers was also computed and then divided by the square root of the number of points to estimate the standard deviation of the underlying total average. This number (after dividing the sum by $2*3$) agrees with the report number.

From the database, the peak doses from the 100 samples in each repetition were sorted, and those with rank from 48 to 53 are shown in Table 2.4. The 50th percentiles have the rank of 50. The average of these 50th percentiles agrees with the reported number. The standard deviation of the three repetitions was also computed and then divided by the square root of the number of points to estimate the standard deviation of the underlying total average. The result agrees with that in the report.

Table 2.3. Example Statistical Uncertainty Calculation of the Average Peak Dose

Rep	Avg	($A_i - A_t$) ²
1	8.737	0.370881
2	11.366	4.0804
3	7.935	1.990921
Total	9.346	1.036195

TABLE 2.4. Example Statistical Uncertainty Calculation for the 50th Percentile

Ranked Sample Number	Repetition 1	Repetition 2	Repetition 3	Repetition Average	Precision
48	5.5560002	5.5279999	5.5510001	5.545	0.00704
49	5.5710001	5.5289998	5.5580001	5.552667	0.010136
50	5.5770001	5.5370002	5.5630002	5.559	0.009568
51	5.5900002	5.5469999	5.572	5.569667	0.01018
52	5.5929999	5.553	5.579	5.575	0.009568
53	5.6069999	5.559	5.5900002	5.585333	0.011473

3 INTEGRATED TESTING

The calculation, interface, and distribution aspects of the fully integrated system were tested. A scenario case is described and the results from the software are interpreted. The interface was reviewed with modern user interface heuristics as a guide. The distribution process was checked for completeness, compatibility, and security from viruses over a range of operating systems.

3.1 CALCULATIONS

This section analyzes a hypothetical test case to demonstrate the use of the various features of the probabilistic RESRAD code. The case that was used was selected because it is relatively simple but still illustrates the workings of the code.

3.1.1 Scenario Description

One radionuclide, Ra-226, is considered at initial concentrations of 30 pCi/g. Probabilistic analysis is performed on a total of eight input variables; details are given in Table 3.1.

While most of the distributions used here are those identified as national (default) distributions, the distributions for outdoor time fraction and indoor time fraction were specified for this illustrative example only. The variables selected for this simple case all have a linear effect on the dose; that is, the contributions of each of these variables to the total dose are additive. Knowing, a priori, how the variables influence the endpoint of interest, the peak of the mean doses at the graphical times used in this case helps illustrate the use of the various outputs available in RESRAD.

3.1.2 Case Implementation and Interpretation

The variables for the probabilistic analysis were specified by opening the input form containing the variable and then selecting that variable for uncertainty analysis. If a national (default) distribution was identified for that variable in Subtask 1.3, that distribution along with the defining parameters were automatically filled into the uncertainty input screen from the database. When a national (default) distribution was not available, a distribution was chosen from the drop-down list box, and appropriate defining parameters were input for this illustrative example.

TABLE 3.1. Input Parameters and Their Distributions Selected for Probabilistic Analysis

Input Variable	FORTTRAN Name	Distribution	Distribution's Statistical Parameters
Fish transfer factor for Ra	BBIO(88,1)	LOGNORMAL-N	3.9 1.1
Milk transfer factor for Ra	BRTF(88, 3)	LOGNORMAL-N	-6.91 0.47
Meat transfer factor for Ra	BRTF(88, 2)	LOGNORMAL-N	-6.91 0.693147
Plant transfer factor for Pb	BRTF(82,1)	LOGNORMAL-N	-5.52 0.916291
Fish transfer factor for Pb	BBIO(82,1)	LOGNORMAL-N	5.7 1.1
Outdoor time fraction	FOTD	UNIFORM	0.01 0.4
Indoor time fraction	FIND	UNIFORM	0.33 0.67
Drinking water intake	DWI	TRUNCATED LOGNORMAL-N	6.015 0.489 0.001 0.999

A negative correlation was specified between the indoor and outdoor time fractions because these two variables are likely to be inversely related. A negative correlation between the indoor and outdoor time fractions was also necessary to ensure that the total time fraction did not exceed 1. For the purpose of this example, a rank correlation coefficient of -0.75 was used. As shown in Figure 3.1, a rank correlation coefficient of -0.6 is sufficient to ensure that the time constraint is not violated.

Correlation between the drinking water intake and the outdoor time fraction was added to illustrate the care that needs to be taken when specifying multiple correlations for a given variable. If, for example, a rank correlation coefficient of 0.7 is specified between the drinking water intake and the outdoor time fraction, and no (or zero) correlation is specified between the drinking water intake and the indoor time fraction, then the sampling program will not be able to find a set of inputs that satisfy the specified correlations. This situation occurs because there will be some correlation between the drinking water intake (DWI) and the indoor time fraction (FIND) when the correlations specified between DWI and the outdoor time fraction (FOTD) and between the indoor and outdoor time fractions are satisfied. This situation will be indicated in the LHS report. The report will caution that the

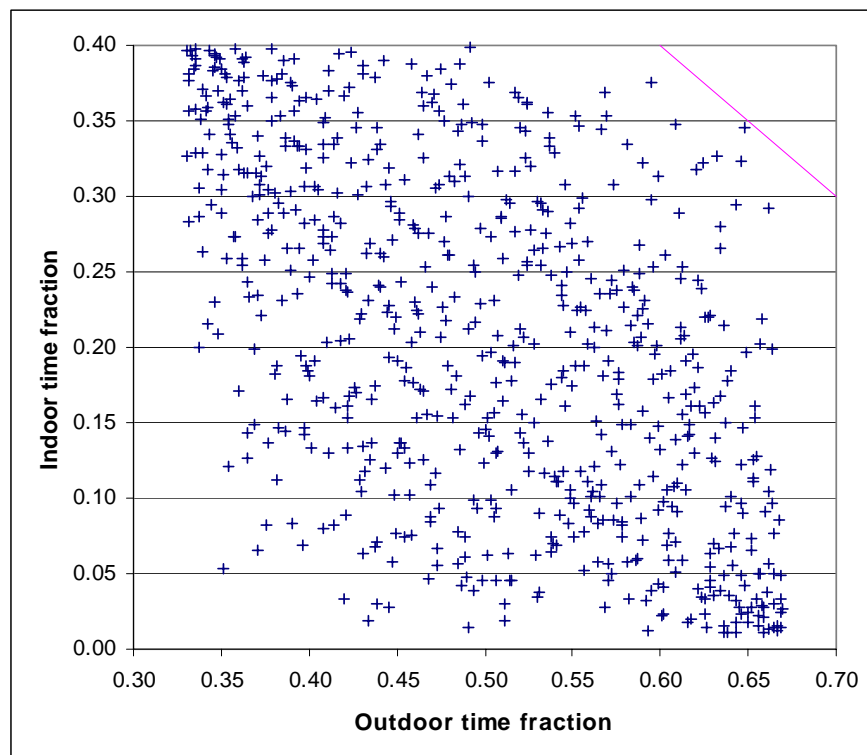


FIGURE 3.1 Scatter Plot of Indoor Time Fraction against Outdoor Time Fraction for a Rank Correlation Coefficient of -0.6

specified rank correlation matrix is not positive definite. It will suggest an adjusted rank correlation matrix. The rank correlations suggested by the code between the three pairs of variables in this case is: $\text{FIND} \leftrightarrow \text{FOTD} = -0.7345$, $\text{DWI} \leftrightarrow \text{FOTD} = +0.6856$, and $\text{DWI} \leftrightarrow \text{FIND} = -0.0105$. While the suggested adjusted rank correlation matrix is quite close to the specified one in this example, that does not always happen, and the user must look at the LHS report to ensure that any adjustments to the rank correlation matrix suggested by the code are acceptable.

The number of observations taken from each distribution affects the accuracy of the predicted probabilistic outputs. An indication of the accuracy of the prediction can be obtained by repeating the probabilistic runs with a different set of observations. The user can accomplish this by specifying the number of repetitions. The range of the predicted outputs for different sample sizes (i.e., number of observations) is shown in Figures 3.2 through 3.4. Five different sample sizes of 10, 12, 25, 50, and 100 were analyzed, each with seven repetitions. The three outputs considered were the peak of the mean dose at graphical times, the median dose at 299 years, and the 90% dose at 299 years. (The peak of the mean dose occurred at 299 years for all seven repetitions of each of the five sample sizes.) As would be expected, the predictions of the peak of the mean dose are of a

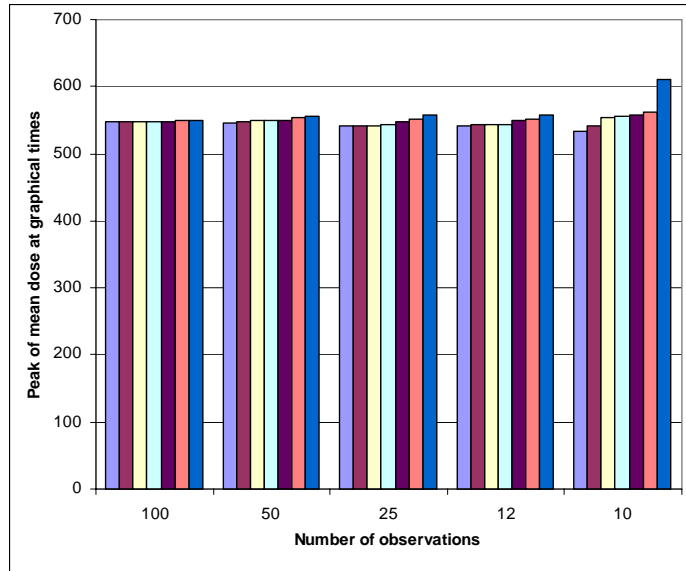


FIGURE 3.2 Variation of the Peak of the Mean Dose at Graphical Times with Sample Size, for Seven Repetitions

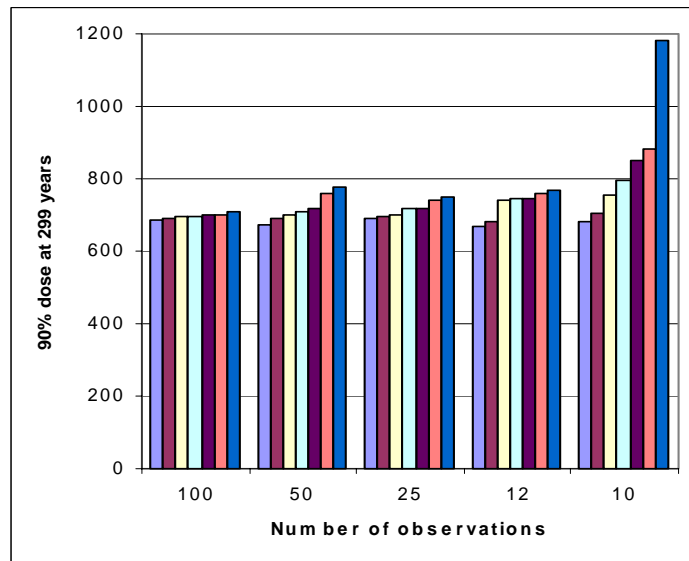


FIGURE 3.3 Variation of 90% Dose at 299 Years with Sample Size, for Seven Repetitions

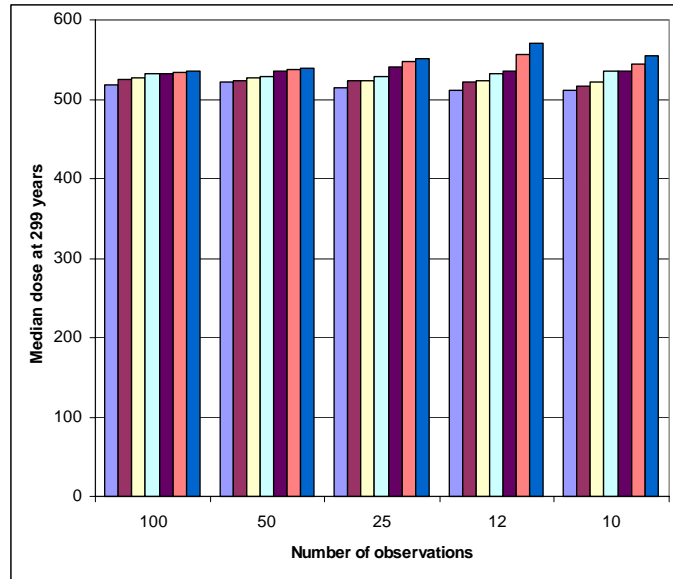


FIGURE 3.4 Variation of Median (50%) Dose at 299 Years with Sample Size, for Seven Repetitions

narrower range than the 90% dose for any given sample size. The user may wish to increase the sample size until the desired accuracy is achieved.

One way of judging the relative importance of the different probabilistic variables for their influence on the output is by the regression and correlation coefficients. The probabilistic RESRAD code offers the user a choice of four different coefficients: the partial correlation coefficient (PCC), the standardized regression coefficient (SRC), the partial rank correlation coefficient (PRCC), and the standardized rank regression coefficient (SRRC). Each is appropriate for different situations. In this example, the outputs are linearly related to the probabilistic input variables. The PCC and the SRC are more appropriate for a case where this relationship is linear or nearly so. On the other hand, the PRCC and the SRRC are suitable for cases where the output is nonlinearly related to the inputs. The user can decide on the set of parameters to be used by comparing the coefficient of determination (R-square) shown in the uncertainty report for the linear model and the nonlinear model. The coefficient of determination is a measure of the variation in the output that is explained by the probabilistic input variables. In this example, the coefficient of determination for the linear model is close to 1.0, while that for the nonlinear model is close to 0.9.

The selection of the appropriate model (linear or nonlinear) narrows the available coefficients to two. Each of the two are again suitable under different circumstances. This example was chosen so the outputs are strictly linear in the inputs. When the output is strictly linearly related to the inputs (or is very nearly so), the PCCs for all input variables will be unity (or very nearly so). In such a case, the SRC is the appropriate coefficient for

judging the relative importance of the influence of the input variables on the predicted output. Strong correlations between the input variable will give rise to large, spurious SRCs. When strong correlations exist between the input variables, the PCC would be a better indicator of their relative importance. Tables 3.2 through 3.5, extracted from the uncertainty output, show the coefficients for the case with 100 observations and 7 repetitions.

Another way of evaluating the influence of the input variables on the predicted output is to view the scatter plots between the output and each of the inputs. The interactive results screen of the code allows the user to view these scatter plots. Scatter plots of the two most significant parameters, on the basis of their influence on the peak dose from all pathways, are shown in Figures 3.5 and 3.6. These are the same two parameters that were identified as being the most significant by the SRC.

3.1.3 Summary

The identification of the parameters that have a significant influence on the chosen output is not always straightforward. RESRAD provides a number of tools, including scatter plots, temporal plots of the mean dose and selected dose percentiles, and four correlation and regression coefficients to facilitate their identification. Each of these tools is appropriate under different circumstances. Sometimes additional analysis is required to determine the significant parameters.

3.2 INTERFACE TESTING

Extensive testing was performed to check different aspects of the interface design as specified in the Subtask 1.6 report - "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes" (LePoire et al., 2000). A subsistence farmer scenario was used to test the RESRAD code. A building occupancy scenario was used to test the RESRAD-BUILD code. Because the testing followed the instructions provided in the user's manual (Subtask 1.6 report), the instructions themselves were tested for clarity and for consistency with the actual design.

3.2.1 Data Input

Data input to the uncertainty module include selection of input parameters and specification of sampling parameters, sampling technique, grouping of observations, desired probabilistic output, distribution characteristics, and correlation between parameters. Testing of data input was conducted to check the following: (1) acceptance of specification(s), (2) removal of specification(s), and (3) modification of specification(s). When more than one way exists for making a specification, all the available means were

TABLE 3.2. Partial Correlation Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	PCC 1		PCC 2		PCC 3		PCC 4		PCC 5		PCC 6		PCC 7	
	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
Variable														
BBIO(88,1)	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00	8	1.00
BRTF(88, 3)	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00	7	1.00
BRTF(88, 2)	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00	6	1.00
BRTF(82,1)	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
BBIO(82,1)	4	1.00	5	1.00	5	1.00	3	1.00	4	1.00	4	1.00	5	1.00
FOTD	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00	5	1.00
FIND	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
DWI	2	1.00	2	1.00	2	1.00	3	1.00	2	1.00	2	1.00	2	1.00
R-SQUARE		1.00		1.00		1.00		1.00		1.00		1.00		1.00

TABLE 3.3. Standardized Regression Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	SRC 1		SRC 2		SRC 3		SRC 4		SRC 5		SRC 6		SRC 7	
	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
Variable														
BBIO(88,1)	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00	8	0.00
BRTF(88, 3)	7	0.01	7	0.02	7	0.01	7	0.01	7	0.02	7	0.01	7	0.02
BRTF(88, 2)	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02	6	0.02
BRTF(82,1)	2	0.46	2	0.46	2	0.47	2	0.45	2	0.48	2	0.45	2	0.48
BBIO(82,1)	5	0.05	5	0.05	5	0.05	5	0.07	5	0.06	5	0.06	5	0.05
FOTD	4	0.14	4	0.14	4	0.14	4	0.13	4	0.15	4	0.14	4	0.13
FIND	3	0.35	3	0.35	3	0.35	3	0.33	3	0.37	3	0.34	3	0.33
DWI	1	0.75	1	0.76	1	0.77	1	0.74	1	0.80	1	0.74	1	0.78
R-SQUARE		1.00		1.00		1.00		1.00		1.00		1.00		1.00

TABLE 3.4. Partial Rank Correlation Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	PRCC 1		PRCC 2		PRCC 3		PRCC 4		PRCC 5		PRCC 6		PRCC 7	
	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
Variable														
BBIO(88,1)	6	-0.05	7	-0.05	8	-0.02	8	0.01	7	0.04	7	-0.04	7	-0.07
BRTF(88, 3)	8	0.02	5	-0.09	6	-0.11	3	0.20	4	0.25	6	-0.09	5	-0.10
BRTF(88, 2)	4	0.25	6	0.05	4	0.26	7	0.06	8	0.03	4	0.21	8	0.02
BRTF(82,1)	1	0.84	1	0.74	1	0.80	1	0.79	1	0.82	1	0.76	1	0.79
BBIO(82,1)	5	0.18	4	0.22	5	0.13	5	0.17	6	0.12	5	0.12	4	0.28
FOTD	7	0.03	8	0.01	7	0.03	6	-0.14	5	0.22	8	0.01	6	0.1
FIND	3	0.32	3	0.25	3	0.27	4	0.17	3	0.50	3	0.26	3	0.38
DWI	2	0.75	2	0.68	2	0.66	2	0.73	2	0.64	2	0.67	2	0.65
R-SQUARE		0.95		0.90		0.92		0.92		0.93		0.92		0.93

TABLE 3.5. Standardized Rank Regression Coefficients for Peak of the Mean Dose

Coefficient = Repetition =	SRRC ₁		SRRC ₂		SRRC ₃		SRRC ₄		SRRC ₅		SRRC ₆		SRRC ₇	
	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff	Sig	Coeff
Variable														
BBIO(88,1)	7	-0.01	7	-0.02	8	-0.01	8	0.00	7	0.01	7	-0.01	7	-0.02
BRTF(88, 3)	8	0.00	5	-0.03	7	-0.03	5	0.06	5	0.07	6	-0.03	6	-0.03
BRTF(88, 2)	4	0.06	6	0.02	4	0.08	7	0.02	8	0.01	4	0.06	8	0.01
BRTF(82,1)	2	0.36	2	0.35	2	0.38	2	0.37	3	0.40	2	0.33	3	0.36
BBIO(82,1)	5	0.04	4	0.07	6	0.04	6	0.05	6	0.03	5	0.03	5	0.08
FOTD	6	0.03	8	0.01	5	0.04	3	-0.17	4	0.27	8	0.01	4	0.12
FIND	3	0.27	3	0.26	3	0.27	4	0.15	2	0.53	3	0.28	2	0.38
DWI	1	0.85	1	0.85	1	0.80	1	0.96	1	0.66	1	0.86	1	0.76
R-SQUARE		0.95		0.90		0.92		0.92		0.93		0.92		0.93

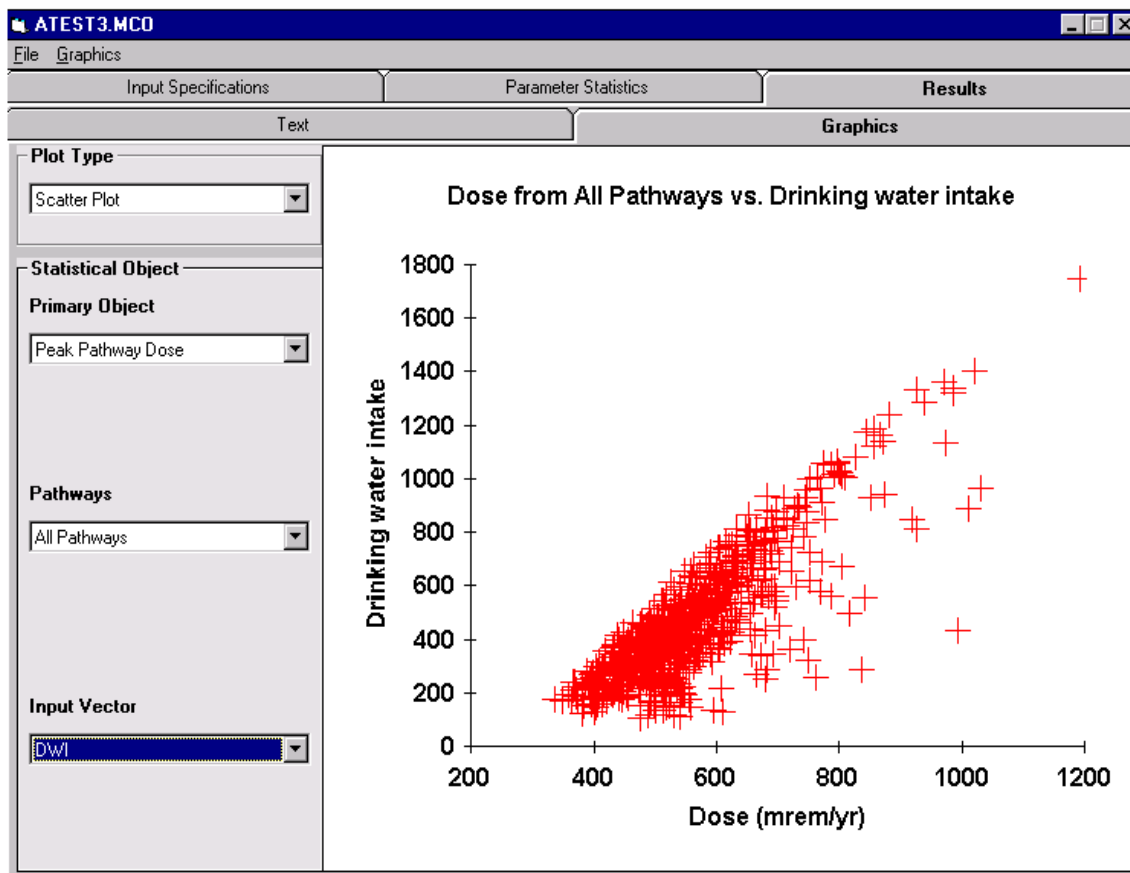


FIGURE 3.5 Scatter Plot of Drinking Water Intake and Peak Total Dose from All Pathways, All Repetitions Combined

tested. For example, selection of an input parameter can be done by pressing the F8 key, clicking the uncertainty analysis button on the menu bar, or viewing the uncertainty analysis summary after highlighting the desired parameter. The testing showed that both the RESRAD and RESRAD-BUILD codes successfully accepted data input for uncertainty analysis and allowed for modifications, as they were intended to.

3.2.2 Default Distribution Integration

Default distribution parameters were developed and documented in the Subtask 1.3 report (Biwer et al., 2000) for a total of 66 parameters (RESRAD and RESRAD-BUILD combined). The uncertainty analysis module incorporates all the default values and presents them as templates for modification. Testing of the uncertainty module was conducted to verify consistency between the suggested values in the document and the built-in values in the module. Some input parameters have values that are independent of radionuclides. Some input parameters, such as distribution coefficients, however, have values that are radionuclide-specific. For the first case, two or three radionuclides were

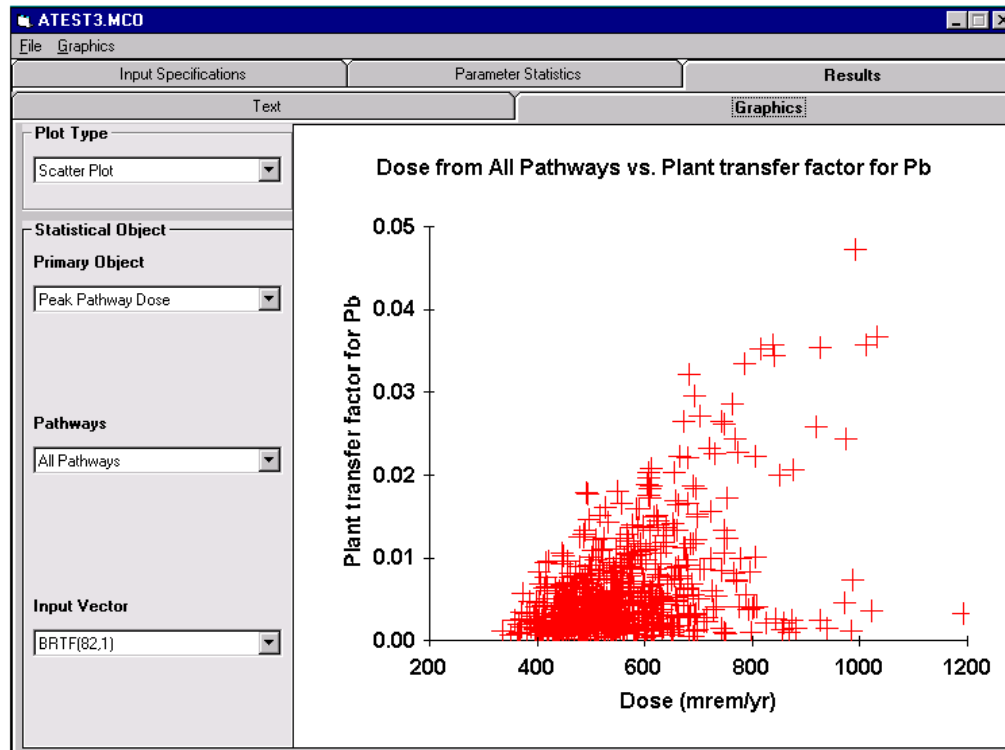


FIGURE 3.6 Scatter Plot of Soil-to-Plant Transfer Factor for Lead and the Peak Dose from All Pathways, All Repetitions Combined

randomly selected for testing. For the second case, each individual radionuclide was selected for testing. Test results showed that the suggested distribution parameters were accurately incorporated into the uncertainty analysis module.

3.2.3 Data Output

After input specifications are finished, the RESRAD and RESRAD-BUILD codes can be run to generate calculation results. The output includes two text report files and various graphic illustrations. Testing of the data output includes viewing, printing, and retrieving the generated text report files, obtaining statistical information on-line, and creating various graphic illustrations. The RESRAD and RESRAD-BUILD uncertainty modules perform these tasks successfully in accordance with the design principles specified in the user's manual. For graphic illustrations, the uncertainty module allows the user to edit the graphics (X-axis, Y-axis, title, and legend) and print them directly or copy and paste them to another document. This graphic editing feature is very useful for preparing risk assessment reports related to the use of RESRAD and RESRAD-BUILD codes.

3.2.4 File Saving

The input specifications to the uncertainty analysis module, as well as the calculational results, can be saved. The testing of the file-saving functions involved saving the input information both to an existing file and to a new file and saving the text results to a new file. The user can save the entire text report or just part of the report. Tables in the text report can also be manually exported to a Microsoft Excel spreadsheet for further editing and manipulation. The RESRAD and RESRAD-BUILD uncertainty modules performed these tasks successfully. In response to beta testing review comments, an easier way to save all files with a standard basename was implemented with a check box in the "Title" window.

3.2.5 Help

On-line help on manipulation of the uncertainty module, such as help in saving data and viewing results and definitions of the distribution parameters, is available in the RESRAD and RESRAD-BUILD codes. Testing of this feature focused on availability, clarity, and thoroughness of the help file. For the 67 parameters selected for uncertainty analysis in the testing, the uncertainty module was able to provide corresponding help content for the distribution characteristics specified. The help content is clear and useful.

3.2.6 Manual

The testing of various aspects of the uncertainty module was performed following instructions provided in the users manual (the Subtask 1.6 report). Although the manual does not cover and demonstrate every single feature incorporated in the interface design, it provides clear guidance on every major task that will be encountered when using the uncertainty analysis module. The features that are not covered (e.g., editing graphics), are self-explanatory and can be easily manipulated by a user with experiences in using commercial spreadsheets and graphic packages. In general, the manual is useful and is of sufficient depth for exploring each design feature.

3.3 DISTRIBUTION TESTING

3.3.1 Creating the Distribution CD

The computer codes RESRAD 6.0, Release 1, and RESRAD-BUILD 3.0, Release 1, and the corresponding sample files were distributed on CD-ROM. The files were distributed in the following manner. A self-extracting executable named *RESRAD 6.0 Beta.exe* was created for RESRAD by using the InstallShield computer code. A self-extracting executable

named *RESRAD-BUILD 3.0 Beta.exe* was created for the RESRAD-BUILD computer code. The sample files for RESRAD were compressed with WinZip, and the compressed file was named *RESRAD sample files.zip*. Similarly, the sample files for the RESRAD-BUILD computer code were compressed, and the compressed file was named *RESRAD-BUILD sample files.zip*. These files were then copied to a writable CD-ROM for access on any computer with either Windows 95, Window 98, Windows 2000, or Windows NT 4.0 (Service Pack 3 or later) operating system. The virus-detecting software Command Antivirus was then used to check the CD-ROM for known viruses. Similar procedures were followed for later versions.

3.3.2 Testing the Distribution CD

The files on the CD-ROM were tested for functionality on a Pentium 200 MHZ personal computer (PC) with 64 MB RAM, 3.6 gigabytes of hard disk space, and a 17-inch color monitor with a resolution of 800 x 600 dpi. The operating system loaded on the computer was Windows NT 4.0 (Service Pack 5). Before installation of the files, the hard disk drive of the PC was reformatted and Windows NT 4.0 (Service Pack 5) was reinstalled. The disk was partitioned into a single NTFS partition. Following the installation of the operating system, the program WinZip was installed so the sample files could be extracted.

The CD-ROM containing all files was placed into the CD-ROM reader, and the self-extracting executable *RESRAD 6.0 Beta.exe* was initialized to launch the RESRAD 6.0, Release 1, setup program. The instructions provided by the setup program were followed, and RESRAD was installed into the default subdirectory (c:\resrad). After this installation, the computer was restarted in accordance with instructions. Similar procedures were followed to setup RESRAD-BUILD 3.0, Release 1.

The RESRAD and RESRAD-BUILD sample files contained in *RESRAD sample files.zip* and *RESRAD-BUILD sample files.zip* were then extracted into c:\resrad and c:\winbld respectively.

The RESRAD 6.0 beta icon on the desktop was then double clicked and the RESRAD code was launched to ensure proper installation. The sample file *CO60UN9.RAD* was loaded from c:\resrad and the calculation was performed. After RESRAD completed the calculation, RESRAD was closed, and a similar procedure was used to test the installation of RESRAD-BUILD.

After documenting the successful installation of the two computer codes, RESRAD, RESRAD-BUILD, and all supporting files were removed from the PC using the uninstall program provided with RESRAD and RESRAD-BUILD. The hard disk drive of the PC was reformatted again, and Windows NT 4.0 (Service Pack 5) and WinZip were reinstalled. The distribution CD-ROM was inserted into the CD-ROM reader and the same procedures were

followed as described above; however, this time RESRAD-BUILD 3.0, Release 1, was installed first, followed by RESRAD 6.0, Release 1. Both computer codes installed and executed properly once again.

4 NRC BETA TESTING

4.1 PROCEDURE

The draft modules and user's manual were delivered to the NRC for a 1-month beta test. Early problems were identified through a videoconference soon after the delivery. Also at this time a demonstration was given to the interested NRC participants. The cover letter on the delivery of the draft requested that the comments be categorized into installation problems, serious errors that prevent further testing, calculational problems, annoyances, and misunderstandings. The first two types of problems were to be dealt with immediately, while the less severe problems would be dealt with in the course of the beta test. At the videoconference, no major installation issues were identified, but two serious problems were identified that resulted in software crashing. One of the two problems only occurred during unusual user entry for the deterministic setting. The other problem was irreproducible. Neither of these two problems delayed further beta testing of the software.

4.2 SUMMARY OF COMMENTS AND RESOLUTION

Some major changes made to the software package as a result of the comments from NRC testers included the following:

- The default distribution arguments for the mass loading factor for inhalation were changed. The beta version had inconsistent units for the distribution.
- The statistic definitions were tested.
- File management was enhanced by adding the probabilistic files to the list that gets renamed with the "Save All" command. A list of files was provided for users that want to zip the complete case into one file.
- Template files were provided that had probabilistic variables defined with correlations.
- The "Update Parameter Distribution" button was removed and that function is now performed automatically. This function had been the source of much confusion.
- Many other interface issues were fixed for a more robust and easier to use interface.

5 REFERENCES

BIOMOVs II Steering Committee. "Long-Term Contaminant Migration and Impacts from Uranium Mill Tailings," BIOMOVs II Technical Report No. 5. Stockholm, Sweden. 1996.

Biwer, B.M., et al. "Parameter Distributions for Use in RESRAD and RESRAD-BUILD Computer Codes, Revision 1." Letter report prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C. March 2000.

Cheng, J.-J., et al. "Selection of RESRAD and RESRAD-BUILD Input Parameters for Detailed Distribution Analysis, Revision 1." Letter report prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C. October 1999.

Kamboj, S., et al. "Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes." Letter report prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C. September 1999.

Kamboj, S., et al. "Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes." Prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C. May 2000.

Kennedy, W.E. and D.L. Streng. NUREG/CR-5512, PNL 7994, Vol. 1, "Residual Radioactive Contamination from Decommissioning; A Technical Basis for Translating Contamination Levels to Annual Total Effective Dose Equivalent." Prepared by Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission, Washington, D.C. 1992.

LePoire, D., et al. "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes." Prepared by Argonne National Laboratory, Argonne, Ill., for U.S. Nuclear Regulatory Commission, Washington, D.C. 2000.

Nielsen, J., "Usability Engineering," *AP Professional*, 1993.

Nuclear Regulatory Commission (U.S.) (NRC). NUREG/CP-0163, "Proceedings of the Workshop on Review of Dose Modeling Methods for Demonstration of Compliance with the Radiological Criteria for License Termination." NRC: Washington, D.C. May 1998.

Yu, C. "RESRAD Family of Codes and Comparison with Other Codes for Decontamination and Restoration of Nuclear Facilities." Chapter 11, pp. 207-231, in: *Decommissioning and Restoration of Nuclear Facilities*. M.J. Slobodien (Ed.). Medical Physics Publishing: Madison, Wisc. 1999.

Yu, C., et al. "Manual for Implementing Residual Radioactive Material Guidelines Using RESRAD, Version 5.0." ANL/EAD/LD-2. Argonne National Laboratory: Argonne, Ill. September 1993.

Yu, C., et al. "RESRAD-BUILD: A Computer Model for Analyzing the Radiological Doses Resulting from the Remediation and Occupancy of Buildings Contaminated with Radioactive Material." ANL/EAD/LD-3. Argonne National Laboratory: Argonne, Ill. 1994.

APPENDIX A:

**ARGONNE RESPONSES TO NRC COMMENTS ON TESTING OF
THE DRAFT (RELEASE 1) PROBABILISTIC RESRAD, VERSION 6.0,
AND RESRAD-BUILD, VERSION 3.0, CODES**

APPENDIX A:

ARGONNE RESPONSES TO NRC COMMENTS ON TESTING OF THE DRAFT (RELEASE 1) PROBABILISTIC RESRAD, VERSION 6.0, AND RESRAD-BUILD, VERSION 3.0, CODES

NRC staff conducted preliminary evaluation and testing of the beta version of the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 computer codes. Staff did not have sufficient time to critically test and evaluate these two codes for adequacy and consistency of the results generated. Therefore, the current comments are preliminary and will be refined and updated as staff continue to conduct additional testing, and evaluation, of the results generated using these two codes.

NRC staff is quite satisfied with the overall quality of the software developed by Argonne National Laboratory (ANL). ANL had integrated the deterministic RESRAD and RESRAD-BUILD codes with the probabilistic module and the Latin Hypercube Sampling (LHS) routine, in spite of the short turn around time and tight completion schedule. The newly developed integrated software system incorporated the default parameter distributions and contained input/output interfaces that appear to function well with RESRAD and RESRAD-BUILD software. Staff recognizes that the contractor, ANL expended significant efforts to develop additional outputs to support NRC's additional needs, especially those associated with the calculation of the peak values of averaged annual dose.

Based on staff's limited testing of the codes and review of the May 2000 Draft User's Guide/Report entitled: "Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes", the following comments are offered.

A.1 RESRAD VERSION 6.0

1. The code generated unusually high doses for analysis using U-234, U-235, U-238, and Th-232 radionuclides. The problem was traced to the assumed statistical distribution for the mass loading factor for inhalation which was determined to be in the wrong units. This needs to be corrected in the final version of the code or it will give results that are off by six orders of magnitude.

Response: This has already been fixed.

2. In a series of runs using different sample sizes, staff found that the difference between results, in some cases, were larger than what should have been expected based upon the calculated confidence in the result. This could point out a potential problem with the statistic being used to represent the confidence. Even if it is

determined that the right statistic is being used, it would appear that the use of 3 repetitions is too few to calculate a meaningful confidence (note: with the use of more repetitions, the confidence interval should be reduced, which will result in an even greater disparity between staff results and the calculated confidence levels in the results). It is recommended that at least 20 or 30 repetitions should be made before any confidence intervals are reported, otherwise this could lead to a false sense of confidence in the results. [See comment Number 35 for a related comment].

Response: Argonne will test and document in the Subtask 1.7 report. However, 20 to 30 repetitions seems to be quite high. We believe it would be better to use a combination of fewer repetitions and more observations (sample size). For example, instead of using 20 repetitions, one can use 7 repetitions and increase the number of observations by a factor of 3-4. This combination will provide a better measure of the range of the quantity of interest in about the same run time as using 20 repetitions with the smaller sample size.

3. Staff attempted to duplicate the exercise presented in “Appendix C: Quick Tour” of the draft report “Probabilistic Modules for the RESRAD and RESRAD-BUILD Computer Codes.” Staff used similar sensitivity and uncertainty conditions and input data as well as hardware compatible with that used by ANL. Staff noted the following observations in executing the code under similar conditions:
 - a) The time needed for executing the run lasted a few hours instead of 8 minutes, as was indicated in the draft report.
 - b) The estimated doses were much higher by approximately a factor of 10 than those reported in the draft report.
 - c) In certain runs, the execution was terminated early without completion of the run and the error message “floating point” was reported appeared on the screen.

Response: (a) The quick tour was performed using one dose integration point and one risk integration point as stated on page C.2, in order to quickly demonstrate the code. If the default settings of 17 dose integration points and 257 risk integration points are used, run time will be longer. Because dose is the desired output, it would be best to specify a maximum of 17 dose integration points and one risk integration point in a regular run. When the “quick” tour was rerun with a maximum of 17 dose integration points and one risk integration point, it took 1½ hours to execute. (b) Most of the probabilistic dose output values were lower than the single point dose outputs. The deviations were greater for the lower percentiles. The only dose quantity that was higher than the values reported in the Subtask 1.6 draft report was the standard deviation of the dose. (c) Argonne was not able to reproduce this error.

4. NRC staff will need more information on how the sensitivity analyses is being performed for the peak of the mean dose values in order to know whether or not the approach used is consistent with that recommended in the Standard Review Plan for Decommissioning (SRP). Specifically, in the SRP, we recommend that total doses at the time of the peak mean dose be used as the output measure in the sensitivity analysis.

Response: The correlation and regression statistics are generated by using the total dose (summed over all nuclides and all pathways) for each observation at the time of the peak of the mean total dose. This approach is consistent with the dose values recommended in the Standard Review Plan for Decommissioning (SRP).

5. In some cases, the code generated a run time error when users attempted to print a graph from the "Results/Graph" window (i.e., when clicking on Print Graph under Graphics). The code kicks you out of the graphics window and back to the RESRAD input screen.

Response: Argonne was not able to reproduce the problem.

6. Staff attempted to print text reports directly, from the Output menu. The following difficulties were encountered by certain users:
 - a. It was difficult to fit the text within the margins of the standard page.

Response: The fit to page button is on the toolbar. This function adjusts the font to fit all the pages in a report to one page width. This results in too small a font when there are many repetitions. The form of the report will be changed to print only one repetition per page.

- b. When printing the LHS report or the uncertainty report, staff noted multiple blank pages and/or printing one line only on a page.

Response: The LHS report is mostly generated from the Sandia post-processor and is in a slightly different format. The code has been changed to display this file in the standard Microsoft Notepad editor/viewer.

- c. General printing problems: selecting and retaining the selection of "landscape", printing all pages when all" is selected. Only the MS LineDraw font seems to correctly display/print the characters. Staff would like to have a print preview option to ensure print job is correctly configured.

Response: Argonne is unable to duplicate the landscape problem. The suggested method for printing the reports is to use MS LineDraw and select the "fit to page" toolbar option.

The user can still import the reports into other word-processors and handle the report. This option will be stated in the manual. Print previewing can be done in those software packages.

- d. In another experience, when the user attempted to print the file MCSUMMAR.REP from the print menu in the code, he got a blank paper only. When user tried to print only one page of this file, he got the whole file, also blank. However, staff had no trouble printing the file after reading it into WordPerfect 8.

Response: Argonne was unable to duplicate this problem. The print control worked fine with specified pages. The printing of blank pages may be related to the issues addressed in Comment 6a.

7. Staff had a difficult time getting the code to run to completion when attempting to perform analyses using more than four repetitions. For example, staff attempted to run the code using a single radionuclide (CI-36), 200 samples, on a computer with a Pentium III (400 MHZ) processor. The following are various error messages were noted:

RESWIN, Run-time error '70', Permission denied
Poly.dll floating point invalid
Run error

Response: Argonne will fix this by ensuring that the interactive output is closed before running or saving.

8. The current procedure to specify the default distribution for each parameter is extremely tedious. Given that the code is designed specifically for doing probabilistic analyses and will be largely used for that purpose, it should be designed so that the default distributions are automatically used. For the sake of efficiency and effectiveness in running the code in the probabilistic mode, if possible, staff suggest that the whole input file be made interactive.

Response: The suggestion made by NRC staff is good. However, to implement the suggestion will require modification of the code. In order to meet the deadline set by NRC, Argonne will provide a template file containing default distributions for all general (i.e., non-radionuclide-specific) parameters.

9. When a deterministic RESRAD run is completed, the five deterministic report files (*.rep) are generated, along with the deterministic graphics file, the output file (output.fil), and the message file (message.fil). Uncertainty report files from earlier runs are not deleted, and will appear if the user selects the option to view them.

Thus, following a run, a user may be viewing results from two different runs. This is further complicated if the user modifies data and updates an existing file.

Response: Argonne will modify the code so that the probabilistic results from a previous run will be deleted after the “Run” button is pressed.

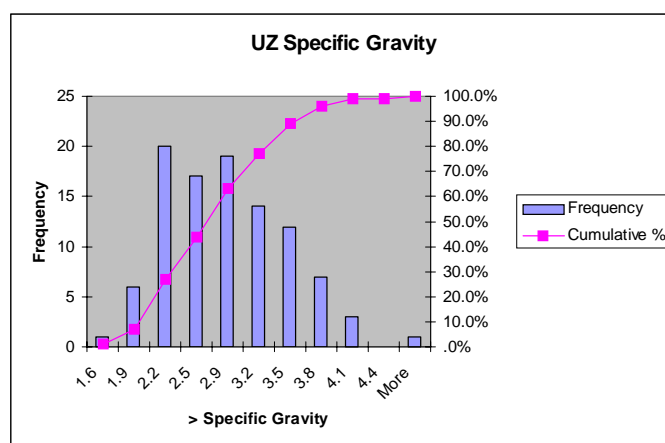
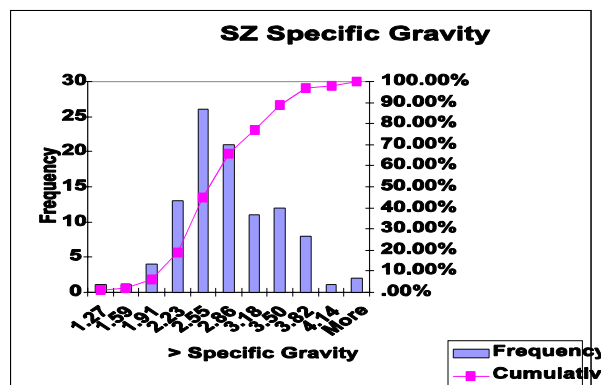
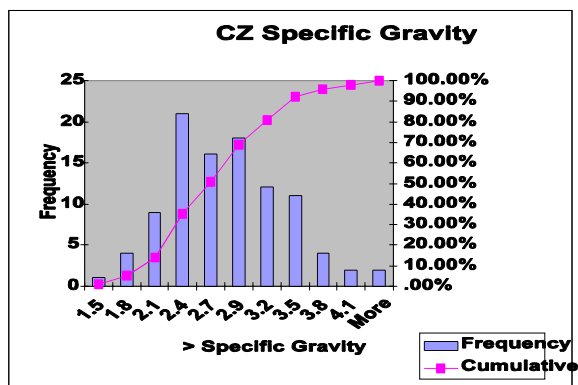
Also, when a user saves a file, only the input files are saved. The user must independently save each report file and the graphics files. If this is not done, some or all of the output files will be overwritten by the next run. This is a significant loss since the uncertainty runs take much longer than the deterministic runs to complete. In addition, while a user may open a new or existing input file, the results from the last run will still appear if view is selected. Further, when viewing an output file, the user has the option of saving that particular file, or the user may select “save all”. However, selecting “Save All” command would save only the five deterministic output report files (concen, daudose, detailed, intrisk, and summary). Thus, the “Save All” command has not been updated to also save the two uncertainty report files (lhs.rep and mcsummar.rep).

Response: The save all command will be modified to save the two uncertainty reports.

To solve this problem, staff suggests that the code save the report and graphics files with the input file, in a single file, with a single command. This would improve the transportability of the files (the input with all the results). This would also ensure that individual output files are not inadvertently lost, requiring the time-consuming runs to be re-run. This would also ensure that a user is not viewing results from two different runs at the same time. Before modifying an input file, the user should be prompted to save the existing input file and associated output files and warned that all existing output files will be cleared before proceeding.

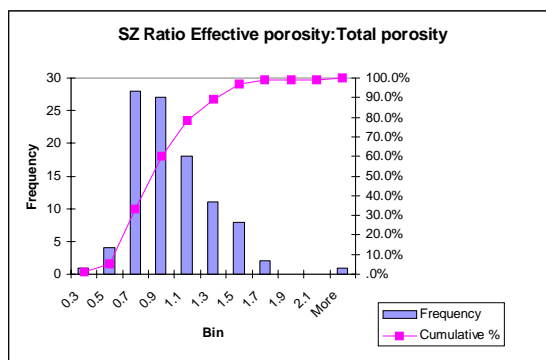
Response: This suggestion cannot be implemented, but we will modify the code to list files, and we will look into the ability of command line using WinZip to accomplish this.

10. Unless corrected by the user, the density, total porosity and effective porosity distributions for the contaminated zone, the saturated zone, and the unsaturated zone units are uncorrelated. This leads to unrealistic combinations of (1) density and total porosity and (2) effective porosity and total porosity within a given LHS input vector. To evaluate this, the LHS vector data for a single replication were evaluated. For the CZ, SZ and UZ, the implied specific gravity for each vector was calculated by from the density and the total porosity values:



The data indicates that the lack of correlation between the density and total porosity distributions leads to unrealistically low and high specific gravity values.

Similarly, for the SZ and UZ, the ratio of the effective porosity to the total porosity was calculated:



The data indicate that the lack of correlation between the effective porosity and total porosity distributions results in combinations where the effective porosity exceeds the total porosity.

Staff offers two suggested solutions: (1) Redefine the independent parameters to be specific gravity, total porosity and ratio of effective porosity to total porosity, and have density and effective porosity be internally calculated dependent parameters; (2) permanently and properly bound and correlate the distributions for density, total porosity and effective porosity.

Response: The first suggested solution will require (1) modification of the RESRAD code and (2) collection of distribution data for the ratio of effective porosity to total porosity. The second suggested solution of setting a default correlation for density, total porosity, and effective porosity can be done only for the default distributions. If the user changes the distributions, the default correlation may not work. Therefore, no default correction will be provided in the template file to be submitted to NRC. However, use of correlation coefficient among parameters has been discussed in the Subtask 1.4 report.

11. In the Monte Carlo summary report (i.e., MCSUMMAR.REP), the parameter Fortran labels should be replaced with more descriptive labels. In addition, the report should flag any default distribution that has been changed and it should identify any assumed correlations used in the analysis.

Response: All these features are in the interactive report, and the correlations are also listed in the LHS report. MCSUMMAR.REP may be modified in the future to include this information.

12. When the code gives an error message it refers the user to the OUTPUT.FIL file for further details; however, if the error occurs during the Monte Carlo runs, the only information provided is that the code is starting the uncertainty runs. The code should be designed to periodically dump information into the OUTPUT.FIL file while executing the uncertainty runs in an attempt to provide more information on the possible source of the error.

Response: This is a good suggestion. Argonne will incorporate this before 6.0 is finalized.

13. When highlighting a parameter (e.g., by pressing F8), the parameter is displayed in the parameter list. By pressing OK, highlighting the same parameter again, and pressing F8, the parameter is not displayed again. The parameter will not be re-displayed until after a different parameter is selected and F8 is pressed, and then the user returns to the original parameter.

Response: Argonne fixed this.

14. The Uncertainty Analyses Summary window cannot be closed without saving. Using "cancel current form" put the window in background, and it reappears when

executing Run. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: The values in the deterministic input screens are stored in a variable array, and it is possible to exit without saving the information in the deterministic screens. The information in the probabilistic input screen is not stored anywhere else; it is written to a file when the "save file" command is issued. Thus, if the user selects a variable and then does not want to perform uncertainty analysis on that variable, the user must use the "remove parameter" button to "remove the parameter" from the uncertainty screen. If the user does not want to run uncertainty analyses on all of the selected parameters, then the user could use the "suppress uncertainty analysis this session" option. Also see the response to Comment 30.

15. The Source window cannot be exited without saving changes. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: This comment is the same as Comment 14. See response to Comment 14.

16. When the program is opened, the radon pathway is not selected, by default. However, if New file is selected, the radon pathway is selected, by default. Having the radon pathway turned off should consistently be the default.

Response: This comment pertains to the regular RESRAD code. Argonne will look into this matter and make it consistent, if appropriate.

17. Staff performed probabilistic dose analysis using three default cases with both RESRAD 5.95 and 6: (1) Co-60, (2) U-238, and (3) Co-60 plus U-238. RESRAD 6 was run without uncertainty analysis (i.e., the default deterministic case). The results were identical. However, the speed was dramatically increased:

	RESRAD 5.95	RESRAD 6 (beta)
Co-60	8.23 seconds	2.47 seconds
U-238	25.21 seconds	3.11 seconds
Co-60 & U-238	41. 15 seconds	3.31 seconds

Response: The number of progress of computation messages has been reduced in version 6.0 to reduce execution time. The write to file operations were taking more time than the computations with the faster computers.

18. File management - User should have the option to delete files from with the “File Open” window by selecting the file, right-clicking, and selecting “Delete.”

Response: This feature is not supported in Visual Basic software that Argonne used.

19. When user selects a nuclide and then select distributions for parameters associated with that nuclide (e.g., Kd). Subsequently, when select another nuclide and deleting the first; the distributions associated with the first nuclide remain, and cause the run to fail after execution has started. Code should verify that distributions for nuclide-dependent parameters are included only if the nuclide is included.

Response: Argonne will look into this.

20. When the “Uncertainty” window is open; pressing F8 twice will result in a run-time error and the program will abort.

Response: Argonne will fix this.

21. When the Uncertainty window is closed, the last parameter on the list that does not have a distribution specified is deleted. However, if there is more than one parameter on the list that does not have a distribution specified, only the last on the list is removed; the others remain. ANL need to address this issue and resolve it if it has the potential to cause the code to crash or produce erroneous results.

Response: The “Update Parameter Distribution” button has been removed to address many problems users are having with the update of information on this form. This feature will be clarified further in the manual.

22. Uncertainty Graphics - Temporal plot: the user should be able to plot the mean and multiple percentiles at the same time, for a given repetition. Plotting the mean and multiple percentiles on the same graph allows the user to evaluate the spread of the dose results over time.

Response: This will be a good feature to add to the graphic output. Argonne will look into this but with a low priority.

23. After using the program for a while, the process of entering distributions becomes rather tedious. The user must move through each data window, select each parameter, press F8, and see if the uncertainty window comes up. If it does, there may or may not be a default distribution available. In all, there are approximately 127 non-radionuclide specific parameters; The program allows the user to specify distributions for 122 of these parameters. Of the 122 parameters, 40 have default

distributions. In addition, there are 13 parameters for which the user specifies values for each individual radionuclide. The user may specify distributions for twelve of these parameters. Of the twelve, seven have default distributions. The process of specifying distributions becomes a trial and error process. There is no efficient way to determine with confidence that all default distributions have been considered.

A possible solution is to add an "Uncertainty Analysis" button under the existing "C-14" button in the set of "Modify Data" buttons. This button would take the user to the Uncertainty Analysis window (the F8 window). There could be two parts to the Parameter Distribution tab: General parameters and Radionuclide-specific parameters. Under the General parameters tab, the user would be presented with a table of all 122 parameters for which distributions may be specified. Next to each, the currently specified deterministic value would appear with a check box. If a default distribution is available, that would also be shown, with a check box. Finally, a box labeled "user-specified distribution" would be shown, followed by the drop-down list of possible distribution types and space for the user to specify the values defining the selected distribution. This would allow the user, through a single step, to see all the parameters for which distributions may be specified and see which parameters have default distributions available. The user can quickly and systematically check off the default distributions they want or specify their own distributions. The user can quickly and confidently determine whether all default distributions have been considered. A similar tab would present similar information for each radionuclide in the inventory.

Response: This is an excellent suggestion. To implement this suggestion, extensive coding and redesigning of the input screen will be required. With time and budget constraints, Argonne will, instead, develop a template file that contains all the default distributions for the general parameters. See response to Comment 8.

24. The F8 window should indicate somewhere the units for each parameter.

Response: Argonne agrees with the comment. If time permits, Argonne will address this suggestion after higher priority issues have been addressed.

25. After an uncertainty run is completed, the deterministic reports are generated and are consistent with those generated in a deterministic run. However, the deterministic graphics ("Graphic Output" from the menu bar or "Standard Graphics") from the Navigator are not available and the following error message is displayed:



Response: Argonne is not able to reproduce this situation.

26. After completing an uncertainty run, staff viewed several reports. When staff selected the “Standard graphics” option the code displayed an error message as in comment 25 above. After staff viewed the report file, staff selected the “save all” option, and the code saved the five deterministic output report files. Then, when staff selected the interactive output button from the navigator, the code displayed the following window :



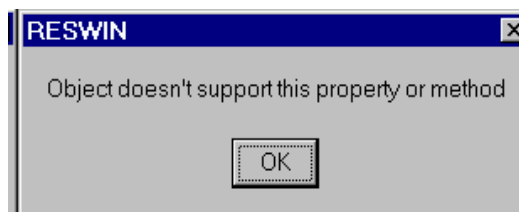
Response: Argonne is not able to reproduce this situation.

27. When staff selected the “Results” tab, the code displayed the following error message:



Response: This problem has been fixed.

28. General report viewing problems: The LHS report does not display correctly, page by page. Also, in moving from one page to the next, some data is repeated. When staff attempted to highlight text in the LHS report and convert to Excel; the following error message appeared:



The viewer then locked up, and after several other error messages, the viewer and RESRAD code shut down.

Response: The "Export to Excel" feature will be removed. The user can still copy and paste text between applications and then parse the data.

29. One of the default distributions differs slightly from the Subtask 1.3 report: Wind.

Response: Argonne will look into this.

30. If a parameter is chosen for uncertainty analysis that does not have a default distribution the variable description nor the user selected distribution will not be "held" in the tab window called parameter distributions if the user selects the tab window "Input Rank Correlations". This can be recreated by 1. selecting modifying data. 2. select Contaminated zone parameters 3. Select Area of contaminated zone. 4. Press F8 or hit the uncertainty button. 5. select the parameter distributions tab 6. input a distribution 7. go to the Input Rank Correlations tab. 8. go back to Parameter distributions and the variable is lost.

Response: The user inputs in and changes to the information in the statistics of uncertain variable frame of the parameter distribution tab will be stored in the form only if the update parameter distribution button is pressed or if the previous/next parameter scroll button is pressed. This in essence is the way to cancel changes. Argonne will clarify this in the Subtask 1.6 manual.

31. The uncertainty button does not work consistently. Start RESRAD. 1. Select modify data. 2. Select contaminated zone parameters. 3. Select area of contaminated zone. 4. Press the uncertainty button. 5. No variables were given in the parameter distributions tab. The same thing happens if you go directly from a parameter with a default distribution to one with no default distribution and if the

user press the “uncertainty” button. ANL need to correct this problem as appropriate.

Response: Argonne will clarify this issue in the Subtask 1.6 manual. The variable is shown in the parameter distribution tab, but it will be removed if the user does not specify a distribution and the associated parameters. See also response to Comment 30.

32. If the parameter cell is highlighted and deleted and the mouse is moved to the top of the screen the code crashes with the error: “Run-time error '400' Form already displayed; can't show modally.”

Response: Argonne will fix this.

33. The distribution help screen in the uncertainty analysis window does not turn off after hitting the black “close X” in the upper right hand corner. If you click on the “X”, every two times you modify the parameters in the distribution, the help screen reappears or every time you select the distribution type it will reappear. ANL need to fix this problem as appropriate.

Response: Argonne will fix this.

34. When staff tried to save the input file after changing it from 3 to 1 repetition; the message “access denied” was reported and then the code bombed off. ANL definitely need to fix this problem as appropriate.

Response: Argonne could not replicate this problem. Please provide input files and Argonne will look into this issue.

35. This comment represent an individual NRC staff’s (Dr. Richard Codell’s) view or idea regarding alternate approach for deriving confidence level. It is recognized that the current schedule may not allow performing significant modification in the current mathematical formulation. However, ANL may evaluate the merits of the proposed idea. Staff believes that the current method of making multiple Monte Carlo repetitions for the LHS set to show the confidence in the results is tedious. Staff believes that this is a time-consuming way of showing the result. Staff believes that ANL can show confidence in a single repetition. To get a quantitative estimate of confidence using the multiple-repetition method would require many repetitions, not the 3 to 7 used as given in the draft report example. Staff believes that ANL should add the following, straightforward statistics to each repetition so that one can get a measure of the confidence in the mean and the percentiles of the distributions.

- a) Confidence in the mean - For a normally distributed quantity, the confidence in the mean can be expressed (Bowen and Bennett, 1988, Section 3.5.2):

$$\bar{X} - t_{1-\frac{\alpha}{2}}(n-1) \frac{S}{\sqrt{(n)}} \leq \mu \leq \bar{X} + t_{1-\frac{\alpha}{2}}(n-1) \frac{S}{\sqrt{(n)}}$$

where \bar{X} = the sample mean, μ = the population mean, S = the sample standard deviation, and $t_p(n-1)$ = the value of the Student's t distribution for probability p , and $n-1$ degrees of freedom. For samples of 100 or more, you can substitute the normal variate for the t distribution. For 95% confidence, this would be approximately 1.96, so the confidence limits would be

$$\bar{X} \pm 1.96 \frac{S}{\sqrt{(n)}}$$

Although this strictly applies to only the normal distribution, it is approximately correct even if the distribution is not normal.

- a) Confidence in the percentiles of the distribution.

For the order statistics of the distribution, assuming a large sample (100 or more) points, the probability that the actual 90th (or other) percentile falls between two particular order statistics is:

$$F\left(\frac{H-.5-pn}{S}\right) - F\left(\frac{L-.5-pn}{S}\right)$$

where F = the cumulative normal distribution function, H and L are the order in the sorted distribution of values, p = percentile, and S = sample standard deviation. For the 95% confidence bounds, the first term is 0.975 and the second term is 0.025, and the arguments of F are 1.96 and -1.96, respectively. Solving for H , therefore, which is the order where the upper bound confidence is 95%:

$$H = 1.96 S + 0.5 + pn$$

Staff did not have an opportunity to demonstrate these results, but it would be interesting to compare the results from the multiple repetitions to the direct method.

[Dr. Codell's follow-up question on comment 35 during the 6/1/2000 teleconference with ANL is as follows:

Does the 90th percentile dose presented in the code output file represent the 90th percentile of each realization or of the peak dose?]

Response: Argonne will test different methods and report in the Subtask 1.7 report. Some of the statistics might not apply to the non-randomly sampled LHS observations. Regarding Dr. Codell's question, the answer depends on the quantity to which the percentile refers to: (1) The previously existing output in the uncertainty report (mcsummary.rep) with the heading "MC Cumulative probability summary for total dose over pathways" combines the observations (realizations) of all repetitions to produce single estimates of the 90% of the dose from all pathways due to all the nuclides at each of the user-specified times. (2) The new output in the uncertainty report (mcsummary.rep) with the heading "Summary of dose at graphical times, repetition I" uses the observations (realizations) of the Ith repetitions to produce estimates of the 90% of the dose from all pathways due to all the nuclides at each of the graphical times. Thus, there will be as many estimates of the 90% dose at each graphical time as there are repetitions.

36. Saving files is not discussed in the users manual. There was uncertainty in how the files could be saved after the computer calculations. The main, or data, files were identified in the manual as the only files that were to be saved. Saving the files as .MCO and by using the File/Save All and File/View Another File in the View-SUMMARY.REP is not addressed in the manual. The files generated by the probabilistic calculations appear not to be saved making it difficult to retrieve probabilistic reports a week or two after the calculations have been performed. In addition, there needs to be a easier way to save all files generated after a computer calculation. One way to do this is to have a SAVE command that would save all files after any calculation.

Response: Argonne will add discussion in the manual regarding saving input and output files.

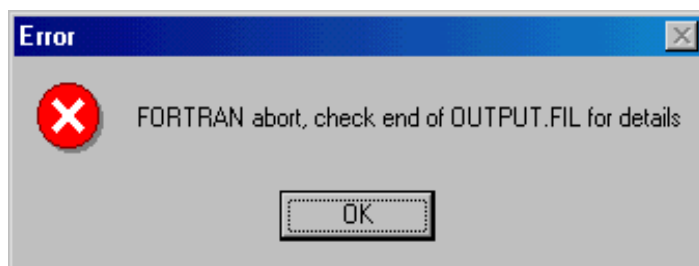
37. Some calculations terminated unexpectedly before the run was completed. One calculation involving secular equilibrium using U238, U234, Th230, Ra226 and Pb210 at concentrations of 100 pCi/g for all radionuclides terminated before running Ra226. The Error Message said: FORTRAN Abort, Check end of OUTPUT.FIL for details. Examination of this file indicated the run terminated with the statement "Starting uncertainty analysis..." The computer was turned off, RESRAD was ran again using the same problem and the dose calculation was completed. It may have been a memory problem. The computer that ran the calculation had 96 MB of RAM.

Response: Argonne was unable to replicate this problem. Please provide input data files.

38. RESRAD does not display the Dose, Risk etc. calculated results for all the dose pathways, External, Ingestion and Inhalation. These pathways are identified on the Navigator Dialog Box under the Pathway/Input Tab on the main RESRAD screen, but only selected pathways are calculated and displayed via the probabilistic Interactive Output/Results/Text output (All Pathways) and the deterministic Standard Graphics/Pathway (External and Inhalation; no Ingestion) output. The printed Summary Files reports apparently provide only ingestion and inhalation dose results (as indicated by the dose conversion factors on page 2 for these pathways), but on page 7 the table summarizing the pathway selections shows direct mostly gamma (external) radiation and inhalation exposure pathways. The results would be more useful to the dose analyst, if both the probabilistic and deterministic text outputs report the dose for the inhalation, ingestion and direct gamma (external) radiation exposure pathways.

Response: Argonne will consider NRC staff's suggestions.

39. The error dialog box appeared after a run stayed on the screen for more than fifteen minutes. Access to the Interactive/Output/Results was denied and the following dialog box appeared:

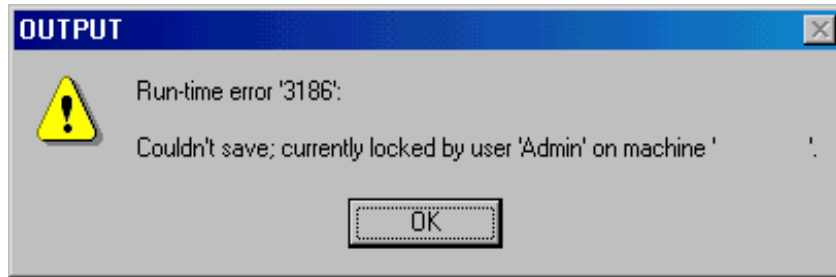


Response: Argonne was not able to duplicate this problem.

40. The user's manual needs to provide a discussion of the risk calculations and the conversion factors for determining excess cancer risks.

Response: The calculation of risk and risk coefficients is explained in detail in the next version of the RESRAD manual.

41. The following error appeared while attempting to run RESRAD while WordPerfect 8 was open and being used. The OUTPUT.FIL indicated the uncertainty analysis would not start



Response: Argonne was unable to duplicate this problem.

42. The Interactive Output/Results/Text output screen show the results up to 90th percentile level. We would like to see 95-Th percentile results displayed also.

Response: Argonne will try to implement this suggestion, but as a low-priority task.

43. Could RESRAD be modified to calculate the dose as CCDF type output?. NRC's Advisory Committee for Nuclear Waste (ACNW) has recommended this type of output for risk-informed performance assessments in accordance with current NRC policy.

Response: RESRAD reports CDF. $CCDF = 1 - CDF$. So it would be a simple matter for the user to use the CDF plots to find the CCDF of interest.

44. Page 3 references NUREG/CR-5512 as the reference for the term "critical group". The reference should be the report in which this term first appeared. That would be in the National Academy of Science/National Research Council report on High-Level Radioactive Waste.

Response: NUREG/CR-5512 is the reference that has been used in the previous NUREG and Letter Reports.

45. In the "HELP on Statistical Distribution" screen from the Uncertainty Analysis Input Summary, there are no distributions shown for Kds for U238, U234 and Th230. Please provide the distributions as appropriate.

Response: The distribution is shown, but it hugs the two axes when liner scale is used because this is a log normal distribution with a range of many (8 to 10) orders of magnitude. It might show better on a log scale, which currently is not an option in the code.

46. Has the RESRAD output been tested by a hand calculation to ensure the calculated results are indeed the actual results? Have validation and testing of the

code been sufficient and comprehensive enough to ensure that the calculated results are indeed reasonably accurate, of good quality and technically defensible?

Response: The deterministic results of RESRAD have been verified, and Argonne has performed manual testing of probabilistic aspects. This testing will be reported in the Subtask 1.7 letter report.

47. The solubility options appears to work fine. Using radionuclide solubility data for U238 in the test case described in Appendix C, RESRAD version 6.0 gave lower dose values compared to those values obtained when using Kds for U238. The May 2000 draft user's manual/report should be revised so that it provide a short write up on the use of solubility data and indicate how the results would vary from those obtained using the default Kd values. The only difficulty encountered was how to add probabilistic data for radionuclide solubilities. Staff would welcome any ANL suggestions or technical guidance in the user's manual and improvement in the code features to overcome this difficulty.

Response: The use of the solubility option in RESRAD is described in the RESRAD Manual. Currently the solubility variable is not supported for probabilistic analysis.

48. The source term option was difficult to use. Using the fraction method is probably not a good way to go. If possible, staff suggest that the model uses absolute release rates in units of Ci/year or pCi/year.

Response: This is functionality of the deterministic RESRAD code.

49. If one changes the default values to provide user data, it's not clear how the user adds the probabilistic data to the model. When the default Kd data for U238 was changed by adding different Kd data, the calculated dose were different. But the code appeared to use the same probabilistic data. Is this consistent with the code's intent ? How does the user provide their own probabilistic data to the code for calculations? This should be discussed clearly in the user's manual and an example should be provided to illustrate the method for inputting such data into the code for performing dose analysis.

Response: Argonne will clarify in the user's guide the relationship between deterministic values and probabilistic values.

A.2 RESRAD-BUILD, VERSION 3

1. Version 3.0 lacks a good user's guide. The last manual, published in 1994, described methods, parameters, and detailed mathematical models for

Version 1.5. ANL need to develop a comprehensive and friendly user's guide to include practical examples (variations of source types, wall regions, etc.). In addition to a description of capabilities, scenarios, ANL need to develop probabilistic and LHS features especially, considering the anticipated availability of the code to the public.

Response: Argonne is currently updating the RESRAD and RESRAD-BUILD deterministic manuals under DOE contract. The LHS features in RESRAD and RESRAD-BUILD are discussed in the Subtask 1.6 NUREG report

2. The graphic user-interface, layout, and report generation of the beta code appears to be identical (except for integration of probabilistic and LHS capabilities) to that of its predecessor, which is expected to be welcomed by veteran users. Similarity of the two codes will minimize the learning curve for users unfamiliar with the probabilistic distribution functions and analyses integrated into the latest version.

Response: Comment noted; no action required.

3. Test cases "co603.inp", "co606.inp", "u2383.inp", and "u2386.inp" were unzipped from the CD-ROM and run using the parameter values saved in the respective input files. The conceptual model or basis for the various parameter selections in the files were not apparently provided in the May 2000 draft report or CD-ROM, and, therefore, it was unclear as to why certain parameter values (i.e., time, building, receptor, and source parameters) were changed from their default settings. The resulting outputs are attached, but were not reviewed due to insufficient time.

Response: These files are from the Subtask 1.4 analysis and are discussed in the Subtask 1.4 report.

4. The interactive output of the "Uncertainty Analysis Parameter Input Summary" window and various tabs was very user-friendly. Yellow highlighting of defaults in the "Variable Description" in the "Parameter distributions" tab clearly demonstrated its usefulness and purpose.

Response: Comment noted; no action required.

5. The basis for selecting the various parameter default distributions and other values in the "Sample specifications", "Parameter distributions", "Input Rank Correlations", and "Output Specifications" tabs in the "Uncertainty Analysis Parameter Input Summary" window was assumed to be reviewed by NRC staff and documented, and, therefore, was not looked at in detail due to insufficient time.

Response: No action necessary.

6. The “Doing Calculations” window, which displays the number of Monte Carlo samples, and estimated and real times appears to be very helpful in optimizing a run, even though the estimated time seemed to be very conservative as compared to the actual run time.

Response: Comment noted; no action required.

7. It is unclear what report the radionuclide inventory in the code’s database was obtained. Is the radionuclide inventory in RESRAD-BUILD Version 3.0 consistent with RESRAD Version 6.0? If not (this is believed to be the case), will it be possible to add radionuclides via a patch without creating a new version?

Response: The number of radionuclides in the RESRAD and RESRAD-BUILD codes are different. It is possible to add radionuclides to RESRAD-BUILD and make it consistent with RESRAD. However, this can not be done via a patch. Adding radionuclides to RESRAD-BUILD is beyond the scope of the current task assignment.

8. Will the cumulative probability, scatter, and temporal plots be available in the final version of the code? If so, will NRC staff have an opportunity to review this?

Response: These features are included in the Release 1 of the beta version of the codes.

9. It would be interesting to compare calculated surface contamination levels for the radionuclides published in 63 FR 64134 (Nov. 18, 1998) using the probabilistic RESRAD-BUILD V3.0 and DandD V2.01 beta codes (as performed with the DandD screen V1.01 code and DandD V2.01 beta code). This comparison was not conducted due to insufficient time.

Response: No action necessary.

10. The output text report is titled “RESRAD-BUILD Program Output, Version 2.36.” This title should be changed to Version 3.0.

Response: Argonne will fix this.

11. The highlights of the fixed versus the uncertain parameters with, or without, defaults are unclear. In other words, users cannot identify which parameters are fixed or uncertain and which parameters have default distributions.

Response: This would be a nice feature to have, but there is not enough time to incorporate it for this version.

12. The three parameters: resuspension rate, deposition velocity, and the air flow/exchange rates should be correlated. It is unclear how these parameters will maintain realistic values or ranges through the probabilistic analysis.

Response: Some correlations among parameters were discussed in the Subtask 1.4 report.

13. To be consistent with NRC's 10 CFR Part 20, Subpart E regulatory requirements, ANL need to mention the NRC's "25 mrem dose limit" with appropriate verbiage to distinguish it from the U.S. Department of Energy (D.O.E's) "30 mrem dose limit" that appeared in this RESRAD-BUILD version 3.0.

Response: The U.S. Department of Energy is also using 25 mrem/yr dose limit in the proposed 10 CFR Part 834. The new RESRAD and RESRAD-BUILD manuals and codes will use 25 mrem/yr as the default dose limit.

APPENDIX B:

**ARGONNE RESPONSES TO THE FINAL NRC COMMENTS
ON EVALUATION AND BETA TESTING OF THE DRAFT
(RELEASE 2) PROBABILISTIC RESRAD VERSION 6.0,
AND RESRAD-BUILD, VERSION 3.0, CODES**

APPENDIX B:

ARGONNE RESPONSES TO THE FINAL NRC COMMENTS ON EVALUATION AND BETA TESTING OF THE DRAFT (RELEASE 2) PROBABILISTIC RESRAD VERSION 6.0, AND RESRAD-BUILD, VERSION 3.0, CODES

NRC staff appreciate Argonne National Laboratory's (ANL) continuous efforts and cooperation to address staff concerns and comments to optimize the performance of these widely used and important codes. Staff conducted additional evaluation and testing of the beta version (Release 2) of the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 computer codes. Staff noted that many of the previous comments made on Release 1 beta version of the codes have been resolved whereas others remained unresolved. Staff understands the time and resource constraints to resolve all comments, especially those comments pertaining to certain code enhancement (i.e. nice to have features but not really important nor would necessarily lead to more accurate results) and ease of execution. However, staff believes that ANL should strive to optimize the codes' essential performance aspects and eliminate any serious bugs affecting proper (i.e. correct or technically sound) and effective code execution. In addition, the code should perform well for simultaneous handling of uncertainty of all sensitive parameters with default distributions as well as other uncertain parameters with no pre-defined distributions. The comments listed below include unresolved comments that were identified previously for Release 1 (May 5, 2000) code versions, as well as new comments from testing the Release 2 (June 28, 2000) versions of the codes.

B.1 NRC/NMSS COMMENTS

1. The code would not allow treatment of certain parameters that did not have default parameter distributions as uncertain (i.e., staff could not assign specific parameter distributions), when all the default distributions are used. For example, when staff treated the source concentration as uncertain, in one analysis, it would not allow treatment of the well pumping rate as uncertain. In another example, the code would not allow treatment of any of the C-14 data (e.g., C-14 concentration, fraction of vegetation that absorb carbon, evasion flux, etc.) as uncertain. Staff believes that this is a new problem with Release 2 of the code.

Response: During the video conference, the circumstances surrounding this problem were duplicated (i.e., not going to the output specification tab). This problem will be fixed.

2. The current default values of time integration parameter (e.g., the maximum number of points) for the dose and the risk are 17 and 257 respectively. These values caused the code to execute for several hours instead of several minutes. In some instances, the execution was terminated early without completion of the run and an error message “floating point” was reported on the screen. It appears to staff that using the combination of default values of 17 and 257 may have caused this problem.

Response: There are two places where the user can control the number of the integrated points: (1) the user can set preference in the title screen not to do time-integrated probabilistic risk by unchecking the “time-integrated probabilistic risk” check box. If this box is unchecked, the number of time integration points is set to one, not only for the current run, but also for all subsequent probabilistic runs. So, if probabilistic risk was never the desired output, the user can set this preference option. (2) The user can also suppress time-integrated probabilistic risk for a given session by unchecking the “Total risk at each of the user specified times” box in the Output specification tab of the uncertainty form. Using smaller numbers of integration points may reduce the accuracy of the calculated dose and risk. Therefore, the default values will remain the same, yet users will be provided with instructions and multiple options as discussed above.

3. The same chemical compounds of the same element should have the same geochemical properties. For example, all uranium radionuclides with the same physicochemical composition should have the same distribution coefficient (K_d) and solubility. It is possible to use the correlation to account for this but it is very awkward and slow.

Response: This problem is understood, but because of time and budget constraints, it was agreed not to address this issue now.

4. If you start to specify a correlation, you have to complete it. There is no way to escape, except to complete it and then to delete it. It is awkward, because you cannot **easily realize ahead of time** what variable you are using since the code only displays the short name or acronym. It will give you the complete description of the variable, but in order to see it, you must start the correlation input procedure. If it turned out to be something you did not want, you have to complete the correlation calculations first before you can try another correlation calculation with another set of parameters.

Response: The code has been modified to allow users to change the selection of the first and second variables. The instructions in the manual will also clarify this issue.

5. Staff see no good way to specify the time duration (i.e. the number of years the waste was buried. There is a place for it under the specification of nuclides, but the number of years seems to be unchangeable. Staff cannot find a good explanation for this. ANL staff need to explain, remove, reconcile and correct this undesirable inflexibility and limitation of the code.

Response: During the video conference the circumstances surrounding this problem were duplicated (time since placement set, water concentration set, time zeroed out). This problem will be fixed.

6. The Uncertainty Analyses Summary window cannot be closed without saving. Using "Cancel current form" put the window in background, and it reappears when executing "Run." There should be a button on every window/form that provide the user the option of exiting without saving changes.

Response: This situation is an inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now.

7. The Source window cannot be exited without saving changes. There should be a button on every window/form providing the user the option of exiting without saving changes.

Response: This situation also is an inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now.

8. General printing problems: selecting and retaining the selection of "landscape", printing all pages when "all" is selected. Only the MS Line Draw font seems to correctly display/print the characters. Suggest having a print preview option to ensure print job is correctly configured.

Response: Several code modifications have been made to resolve these issues:

1. *The "Printer Setup" option from the menu was not saving the landscape/portrait option. However, the "Print" option from the menu or the toolbar allowed access to the printer properties. These properties include the landscape/portrait option that are saved and used. We have removed the "Printer Setup" option from the menu. This change ensures reliable printing without removing any features.*
2. *The option to print all pages was not working properly. This problem has been fixed.*

3. *All fonts except MSLine Draw and Courier New will be removed from the font list.*
9. File management - User should have the option to delete files from the File Open window by selecting the file, right-clicking, and selecting Delete.

Response: This option is not a standard feature of the development environment (Visual Basic 4). The lack of this feature is a user inconvenience that would take much effort to change. It was agreed to not pursue this issue now.

10. Select a nuclide. Select distributions for parameters associated with the nuclide (e.g., Kd). Select another nuclide and delete the first. The distributions associated with the first nuclide remain, and cause the run to fail after execution has started. Code should verify that distributions for nuclide-dependent parameters are included only if the nuclide is included.

This was tested again and the program crashed. This appears to be an obvious “bug” that ANL need to fix.

Response: The ability to delete a nuclide with uncertainty parameters already set was demonstrated in the video conference. NRC will review this problem to see if there are special circumstances in which this fix does not work. It is true that the parameters associated with the deleted nuclide remain in the uncertainty form (at least for the current session in the case of Kd values), but this does not cause the code to crash. The parameters are left in so the user can reselect the nuclide and perform analysis on the nuclide properties during the same session.

11. When the uncertainty window is closed, the last parameter on the list that does not have a distribution specified is deleted. However, if there is more than one parameter on the list that does not have a distribution specified, only the last on the list is removed; the others remain. This was tested again and the program crashed. This again appears to be an obvious “bug” that ANL need to fix.

Response: This problem has been recognized and has been fixed in a version later than beta release 2.

12. When a deterministic RESRAD run is completed, the five deterministic report files (*.rep) are generated, along with the deterministic graphics file, the output file (output.fil), and the message file (message.fil). Uncertainty report files from earlier runs are not deleted, and will appear if the user selects the option to view them. Thus, following a run, a user may be viewing results from two different runs. This is further complicated if the user modifies data and updates an existing file.

When a user saves a file, only the input files are saved. The user must independently save each report file and the graphics files. If this is not done, some or all of the output files will be overwritten by the next run. This is a significant loss since the uncertainty runs take much longer than the deterministic runs to complete.

While a user may open a new or existing input file, the results from the last run will still appear if view is selected.

Also, when viewing an output file, the user has the option of saving that particular file, or the user may select "save all". However, "save all" saves only the five deterministic output report files (concen, daudose,detailed, intrisk and summary). Please reconcile.

Suggestion: Save the report and graphics files with the input file, in a single file, with a single command. This would improve the transportability of the files (the input with all the results). This would also ensure that individual output files are not inadvertently lost, requiring the time-consuming runs to be repeated. This would also ensure that a user is not viewing results from two different runs at the same time. Before modifying an input file, the user should be prompted to save the existing input file and associated output files and warned that all existing output files will be cleared before proceeding.

ANL's resolution of the problem in Release 2 of the codes is not clear. Using "Save All" now saves the MC and LHS reports in addition to the five deterministic reports. With respect to clearing out probabilistic results from the preceding run with the execution of each new run (deterministic or probabilistic), it is not clear that the problem has been fixed. Problems identified and communicated by NRC staff to ANL for resolution after the testing of the Release 1 version of the codes still seem to exist. Please reconcile.

Response: (1) The code has been modified so that "Save All" now saves 10 files, including the five deterministic report files (summary.rep, concent.rep, daudose.rep, detailed.rep, intrisk.rep), the deterministic graphics file (graphics.asc), the two probabilistic report files (mcsummar.rep, lhs.rep), and the two files that contain the raw uncertainty data (uncgrpto.bin, uncpeak.asc). The four probabilistic files from the previous runs are deleted when the run command is issued. (2) Those users who want the "Save All" command to be issued automatically after each run can set this preference in the "Title" form. If the "Save All files after each run" box is checked these 10 files (6 for deterministic runs) will be saved automatically after all subsequent runs until this preference is changed. (3) The file used by the interactive output is always saved. (4) Files from previous runs will still be available if saved; however, access to

them will be gained by explicitly specifying the case name. The probabilistic graphics file will be cleared so that the user is assured that the files readily accessible from the results interface will be for the current case.

13. Uncertainty Graphics - Temporal plot: The user should be able to plot the mean and multiple percentiles at the same time, for a given repetition. Plotting the mean and multiple percentiles on the same graph allows the user to evaluate the spread of the dose results over time. Providing this user suggested practical display feature would greatly improve the usefulness of this code output feature.

Response: This situation is a user inconvenience that would take much effort to change. It was agreed in the video conference to not pursue this issue now. The uncertainty output report (MCSUMMAR.REP) contains tables of the minimum, maximum, mean, median, 90%, 95%, 97.5%, and 99% dose at each graphical time for each repetition. Look for "Summary of dose at graphical times, repetition 1" in the index of that report.

14. After using the program for a while, the process of entering distributions becomes rather tedious. The user must move through each data window, select each parameter, press F8, and see if the uncertainty window comes up. If it does, there may or may not be a default distribution available. In all, there are approximately 127 non-radionuclide specific parameters. The program allows the user to specify distributions for 122 of these parameters. Of the 122 parameters, 40 have default distributions. In addition, there are 13 parameters for which the user specifies values for each individual radionuclide. The user may specify distributions for twelve of these parameters.

Of the twelve, seven have default distributions. The process of specifying distributions becomes a trial and error process. There is no efficient way to determine with confidence that all default distributions have been considered. Staff suggest that ANL attempt to make this procedure for entering the parameter distributions more systematic, comprehensive, efficient and effective than the trial and error method that the user (s) have to go through.

NRC staff would like to propose the following possible solution: Add a "Uncertainty Analysis" button under the existing "C-14" button in the set of "Modify Data" buttons. This button would take the user to the Uncertainty Analysis window (the F8 window). There could be two parts to the Parameter Distribution tab: General parameters and Radionuclide-specific parameters. Under the General parameters tab, the user would be presented with a table of all 122 parameters for which distributions may be specified. Next to each, the currently specified deterministic value would appear with a check box. If a default distribution is available, that would also be shown, with a check box.

Finally, a box labeled “user-specified distribution” would be shown, followed by the drop-down list of possible distribution types and space for the user to specify the values defining the selected distribution. This would allow the user, through a single step, to see all the parameters for which distributions may be specified and see which parameters have default distributions available. The user can quickly and systematically check off the default distributions they want or specify their own distributions. The user can quickly and confidently determine whether all default distributions have been considered. A similar tab would present similar information for each radionuclide in the inventory.

*Response: This issue has been addressed through the development and distribution of the template file NONNUCL.TEM, in both RESRAD and RESRAD-BUILD. It will be made more visible placed by including *.TEM files in the file dialog box.*

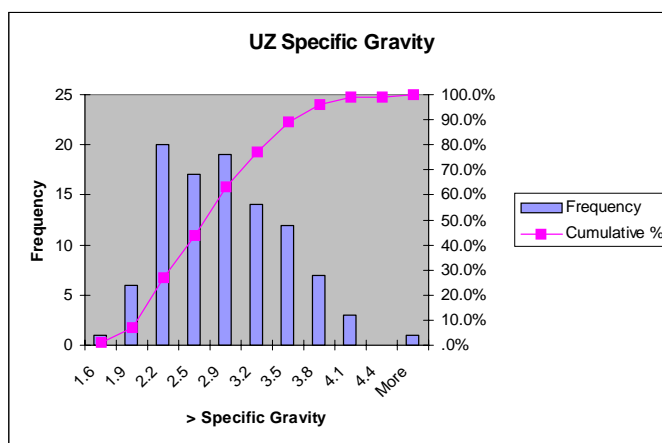
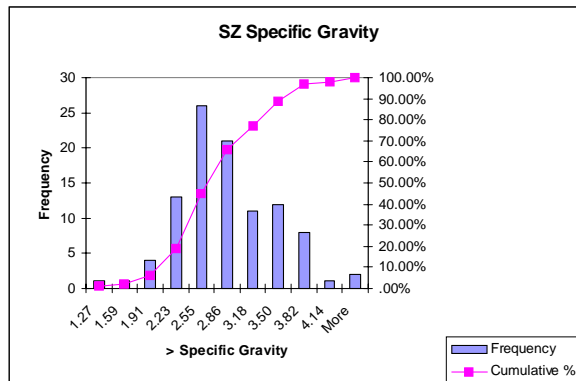
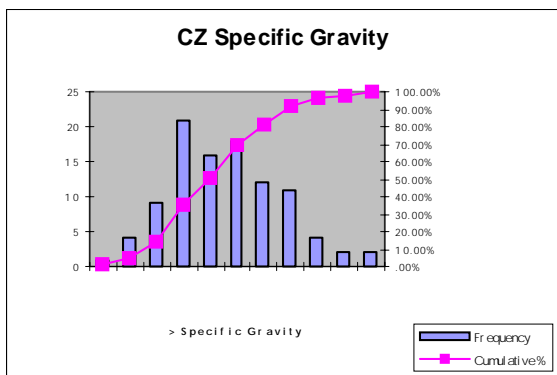
15. The F8 window should indicate somewhere the units for each parameter.

Response: It was agreed in the video conference to not pursue this issue now.

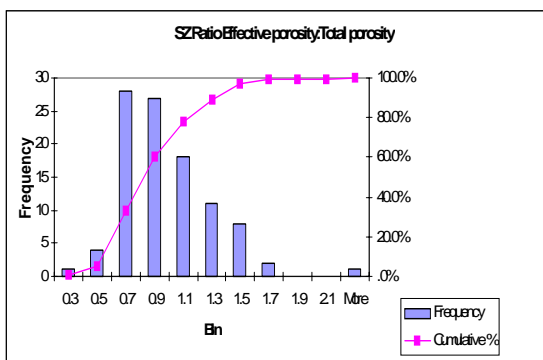
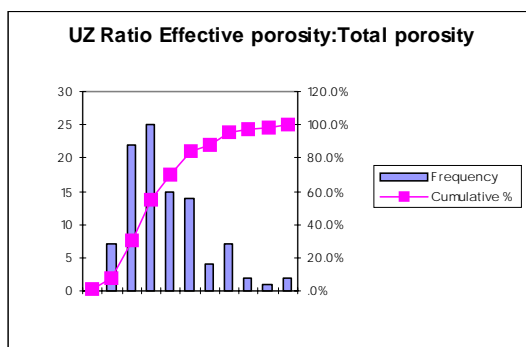
16. Unless corrected by the user, the density, total porosity and effective porosity distributions for the contaminated zone, the saturated zone, and the unsaturated zone units are uncorrelated. This leads to unrealistic combinations of (1) density and total porosity and (2) effective porosity and total porosity within a given LHS input vector. It appears that this problem was brought to ANL staff attention for resolution in previous reviews of project reports and after the testing of the Release 1 versions of the codes on June 1, 2000. If possible, ANL need to address and resolve this problem.

To evaluate this, the LHS vector data for a single replication were evaluated. For the CZ, SZ and UZ, the implied specific gravity for each vector was calculated by using the density and the total porosity values. The results are presented below in graphical form.

The results indicate that the lack of correlation between the density and total porosity distributions leads to unrealistically low and high specific gravity values.



Similarly, for the SZ and UZ, the ratio of the effective porosity to the total porosity was calculated and the results are presented below in graphical form.



The results indicate that the lack of correlation between the effective porosity and total porosity distributions led to combinations where the effective porosity exceeds the total porosity.

NRC staff would like to suggest two solutions: (1) Redefine the independent parameters to be specific gravity, total porosity and ratio of effective porosity to total porosity, and have density and effective porosity be internally calculated dependent parameters; (2) permanently and properly bound and correlate the distributions for density, total porosity and effective porosity.

Response: This issue is understood and has been previously discussed. It would take much effort to change. It was agreed in the video conference to not pursue this issue now.

17. One of the default distributions differs slightly from the Subtask 1.3 report: Wind. Default values for “wind” still inconsistent. Please reconcile.

Response: It was explained that the limits of the distribution in the Subtask 1.3 report could not be represented with the LHS sampling routine. The distribution limits were set as close to the Subtask 1.3 reported values as possible and still maintain a distribution that LHS could handle.

18. Staff recommend that ANL generate a template file to include all sensitive parameters with default distributions. This file is necessary to reduce the burden on the users of going through each specific input parameter.

Response: This suggestion has been done; please see response to comment 14 above.

B.2 NRC/RES/DRAA COMMENTS

1. The user’s manual should provide more background information on the Cut-off Half, Graphical Parameters and Time integration Parameters listed under “**Change Title**”. In addition, the manual should provide some guidance on what numbers should be chosen for the Maximum numbers of points for both Dose and Risk as the choice of these two values can considerably effect the time RESRAD runs an application.

Response: These issues will be addressed in the new RESRAD and RESRAD-BUILD manuals to be issued by DOE.

2. The manual is still not clear on how the user would add probabilistic data to situations where (a) there is a default value, but no probabilistic data are provided and (b) where the user has better probabilistic data than the default probabilistic data and (c) in the situations where there are no default data and no probabilistic numbers(e.g., cover depth, solubility limit). Do the users have to contact the code developers to change or add probabilistic data or can the users do it themselves? How would the user's do it?

Response: The user's guide covers these issues, and it will be reviewed for clarity. Also, a brief help message pops up when the user selects a parameter for which no default exists.

3. On page 10, second column, third paragraph seem to indicate if the user wants to have all non-nuclide specific parameters that have defined default distributions to be set for probabilistic analysis, a template file should be used. The template to be found in "**File\Open\NonNucl.tem.NonNucl.Tem**" could not be found under "**File\Open**".

Response: A template file is provided; please see the previous response to Comment 14 in Section B.1.

4. Add title, date, RESRAD version to "**lhs.rep**" and "**filename.smp**" report. Both start out with just "**Random Seed = 1000.**"

Response: This suggestion has been done.

5. The user's manual should indicate the LHS Report (LHS REP) for each case needs to be saved separately in the "**lhs.rep**" using "**File\Save As...**" We could not locate files with the "**.lhs**" extension. Apparently "lhs" reports are not saved with an ".lhs" extension but they are saved here as "**.rep.txt**" reports. Using "**Save All**" in the Summary or Uncertainty Report doesn't save the "**lhs**" reports. It's also noted the "**.smp**" report appears to include the input Latin hypercube sampling (LHS) data.

*Response: The manual describes how the "Save All" command works and the file descriptions. The *.lhs files are not output files but are the probabilistic input files created when the user saves the input data.*

6. Page 16. Table 2. List of Probabilistic Files. Could not locate "**.buo files**". The "**.buo**" files are not listed in the Summary reports when "**Save All**" is used. Also, add "**.lhs**" if files are save with an "**.lhs**" extension. For "**.prb**", add "**and Uncertainty Analysis**".

Response: BUO files are generated only for RESRAD-BUILD runs, as is specified in the user's manual.

7. We notice the Pathways in Interactive Output\Results are indicated as "All Pathways", but there are no categories specifically listed for specifying the dose for ingestion, exposure, and inhalation. We especially need the dose for the ingestion pathway listed separately because this is the pathway most likely to contribute to the total dose.

Response: The interactive output contains options for looking at each pathway and at combinations of pathways.

8. **The following comment is from Dr. Phil Meyer of the Pacific Northwest Laboratory:**
"Writing the detailed output to a database file is a good idea and we're happy the full set of output data is easily accessible for additional analysis. We had a problem once when Access for Office 2000 tried to convert the **.mco** file to **.mdb** and wasn't successful. We actually had to rerun a Monte Carlo simulation because Access overwrote and corrupted the **.mco** file during the attempted conversion. We were wondering why the output database file isn't written in the more recent **.mdb** format."

Response: At the time the probabilistic versions were developed, MS Access 97 was the latest version. The software uses Access 2 because of the compatibility with the development environment (Visual Basic 4). To upgrade the software to a MS Access 97 would require significant effort. A workaround was found for the identified problem — first convert the database file to Access 97 and then convert the Access 97 database to Access 2000. The inability to convert the database file directly to Access 2000 is an issue for Microsoft. This issue should be included in a readme file or the user's manual.

9. ANL Note: The following comments have been addressed in the previous Response to Comments after Beta Release 1. There are no further comments or responses.
 1. Both RESRAD-BUILD Versions 2.37, and 3.0 lacks a good user's guide. The last manual, published in 1994, described methods, parameters, and detailed mathematical models for Version 1.5. A comprehensive user's guide to include practical examples (variations of source types, wall regions, etc.) in addition to a description of capabilities, scenarios, probabilistic and LHS features needs to be developed especially considering the anticipated availability of the code to the public.

2. The graphic user-interface, layout, and report generation of the beta code appears to be identical (except for integration of probabilistic and LHS capabilities) to that of its predecessor, which is expected to be welcomed by veteran users. Similarity of the two codes will minimize the learning curve for users unfamiliar with the probabilistic distribution functions and analyses integrated into the latest version.
3. Test cases "co603.inp", "co606.inp", "u2383.inp", and "u2386.inp" were unzipped from the CD-ROM and run using the parameter values saved in the respective input files. The conceptual model or basis for the various parameter selections in the files were not apparently provided in the May 2000 draft report or CD-ROM, and, therefore, it was unclear as to why certain parameter values (i.e., time, building, receptor, and source parameters) were changed from their default settings. The resulting outputs are attached, but were not reviewed due to insufficient time.
4. The basis for selecting the various parameter default distributions and other values in the "Sample specifications", "Parameter distributions", "Input Rank Correlations", and "Output Specifications" tabs in the "Uncertainty Analysis Parameter Input Summary" window was assumed to be reviewed by NRC staff and documented for previous subtasks of the project, and, therefore, was not looked at in detail due to insufficient time.
5. It is unclear from what report the radionuclide inventory in the code's database was obtained. Is the radionuclide inventory in RESRAD-BUILD Version 3.0 consistent with RESRAD Version 6.0? If not (this is believed to be the case), will it be possible to add radionuclides via a patch without creating a new version? It would be interesting to compare calculated surface contamination levels for the radionuclides published in 63 FR 64134 (Nov. 18, 1998) using the probabilistic RESRAD-BUILD V3.0 and DandD V2.01 beta codes (as performed with the DandD screen V1.01 code and DandD V2.01 beta code). This comparison may be useful in testing the performance of RESRAD-BUILD 3.0 Release 2 version.
6. It will be interesting to test the performance of the code using common building occupancy scenario (NUREG/CR-5512 Vol. 1) and sensitive parameters related to suspension rate and resuspension factor.
7. The highlights of the fixed versus the uncertain parameters with, or without, defaults are unclear. In other words, users cannot identify which parameters are fixed or uncertain and which parameters have default distributions.

8. The three parameters: resuspension rate, deposition velocity, and the air flow/exchange rates should be correlated. It is unclear how these parameters will maintain realistic values or ranges throughout the probabilistic analysis calculations.

B.3 NRC/NMSS COMMENTS ON THE JUNE 2000 DRAFT LETTER REPORT “TESTING OF THE RESRAD PROBABILISTIC MODULES”

1. The report states that the correlation analysis agreed with those previously computed manually; however, it does not provide any specific examples of such analysis and the results to support this statement. For example, what is being defined by “agreed”. More elaboration should be provided on the comparison.

Response: The test report will be reviewed and elaborated on as necessary.

2. The report states that no significant differences were found in comparing the deterministic and probabilistic results. However, again it is not clear what is meant by “no significant difference”. Additional elaboration should be provided.

Response: The test report will be reviewed and elaborated on as necessary.

3. The report did not include vivid examples to demonstrate actual performance of the code. In other words, the integrated testing was conducted on Ra-226 only rather than on radionuclide mixtures representing typical inventory, and residual radioactivity at nuclear facilities and competing environmental pathways. Therefore, testing of parameter uncertainties and their impacts on dose outputs are not adequately addressed. In addition, evaluation of code performance regarding approaches to uncertainty treatment for dose compliance is lacking. Please reconcile.

Response: The test report Section 2.2.1 states that all nuclides except one were tested and reported in Subtask 1.4. Since the calculational aspects of the code were not changed, these results stand. The detailed analysis later in the test report was meant to clarify analysis issues, not to be a comprehensive test over all input conditions. No modifications are necessary.

