NUREG/CR-6676
ANL/EAD/TM-89

Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes

Argonne National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555-0001

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at NRC's Public Electronic Reading Room at www.nrc.gov/NRC/ADAMS/index.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and *Title 10, Energy*, in the Code of *Federal Regulations* may also be purchased from one of these two sources.

1. The Superintendent of Documents
   U.S. Government Printing Office
   P. O. Box 37082
   Washington, DC 20402–9328
   www.access.gpo.gov/su_docs
   202–512–1800
2. The National Technical Information Service
   Springfield, VA 22161–0002
   www.ntis.gov
   1–800–553–6847 or, locally, 703–605–6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: Office of the Chief Information Officer,
Reproduction and Distribution
Services Section
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
E-mail: DISTRIBUTION@nrc.gov
Facsimile: 301–415–2289

Some publications in the NUREG series that are posted at NRC's Web site address www.nrc.gov/NRC/NUREGS/indexnum.html are updated regularly and may differ from the last printed version.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, and transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852–2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036–8002
www.ansi.org
212–642–4900

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX), (4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of NRC's regulations (NUREG–0750).

NUREG/CR-6676
ANL/EAD/TM-89

Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes

Manuscript Completed: May 2000
Date Published: July 2000

Prepared by
S. Kamboj, D. LePoire, E. Gnanapragasam,
B. M. Biwer, J. Cheng, J. Arnish, C. Yu, S. Y. Chen

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

T. Mo, NRC Project Manager

Prepared for
Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code Y6112

ABSTRACT

The existing RESRAD 6.0 and RESRAD-BUILD 3.0 codes for site-specific radiation dose modeling applications are being developed and adapted for use with the U.S. Nuclear Regulatory Commission's (NRC's) Standard Review Plan for decommissioning and as tools for demonstrating compliance with the license termination rule in a risk-informed manner. Computer interfaces and software modules have been developed under NRC sponsorship to perform the probabilistic simulation of dose. RESRAD and RESRAD-BUILD are part of the RESRAD family of codes that have been developed by the U.S. Department of Energy (DOE) and for many years have been successfully applied to cleanup efforts at sites contaminated with radioactive materials. Specifically, the RESRAD code applies to cleanup of soil, and RESRAD-BUILD applies to the cleanup of buildings and structures at a site. This report describes the use of these codes to perform probabilistic dose analysis. The dose analysis presented in this report has fully demonstrated the process of using the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 codes and the probabilistic modules, together with distributions of input parameters, for dose assessment at a relatively complex site. This demonstration enables site-specific application of the codes for dose analysis where pertinent parameters and their distributions are available or can be developed. Results of the uncertainty analysis and sensitivity analysis of dose to input parameter values indicated that because the dependence of dose on the input parameters is complex, no single correlation or regression coefficient can be used alone to identify sensitive parameters in all cases. However, the results could give an indication of the degree of sensitivity of the calculated dose to changes in input parameter values for each exposure situation. Therefore, the coefficients are useful guides, but they have to be used in conjunction with the other aids, such as scatter plots and further analysis, to accurately identify the sensitive parameters.

CONTENTS

CONTENTS (Continued)

APPENDICES

FIGURES

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

FIGURES (Continued)

TABLES

TABLES (Continued)

TABLES (Continued)

EXECUTIVE SUMMARY

In 1999, the U.S. Nuclear Regulatory Commission (NRC) tasked Argonne National Laboratory (Argonne) to adapt the existing RESRAD and RESRAD-BUILD codes for use in site-specific modeling with the NRC's license termination compliance process and the Standard Review Plan (SRP) on Decommissioning. The RESRAD code has been used extensively for dose analysis in cleanup of sites, and the RESRAD-BUILD code is used in cleanup of buildings. For use in this NRC process, the codes are being revised to be consistent with the current NRC guidance for dose modeling being developed in the SRP on Decommissioning. Thus, the primary objectives of Argonne's effort are to (1) develop parameter distribution functions and parametric analysis for the RESRAD and RESRAD-BUILD codes and (2) develop necessary computer modules for conducting probabilistic analyses.

The RESRAD and RESRAD-BUILD computer codes have been developed by Argonne under sponsorship of the U.S. Department of Energy (DOE) for use in evaluating radioactively contaminated sites and structures, respectively. Both are widely used in cleanup operations in the United States and abroad. The two codes are 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 are being developed for RESRAD and RESRAD-BUILD. The modules are further equipped with user-friendly input and output interface features to accommodate numerous parameter distribution functions and result display requirements. The integrated system, consisting of the codes and the interface modules, is designed to operate on Microsoft Windows™ 95, 98, and NT platforms.

Completion and publication of the entire code system is scheduled for a later date. For the analysis described in this report, a preliminary version of the system was used.

This report emphasizes probabilistic dose analysis using parameter distributions developed for the RESRAD and RESRAD-BUILD codes. The objective is to establish and demonstrate the process for site-specific analysis using the integrated code system. This site-specific approach is emphasized despite the fact that the parameter distributions have been compiled from national databases. In the future, when site-specific distributions are available for an actual application, the same process can be readily used with site-specific data.

Development of distributions contained in this report has 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) combined with an extensive literature search using 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 distribution assignments for each selected parameter for use in dose calculations. A total of about 200 parameters are used in the RESRAD and RESRAD-BUILD codes for describing the exposure pathways and the associated exposure conditions. The data distribution for these parameters has been developed through the following three steps.

Step 1: Parameter Categorization (Kamboj et al., 1999) — 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: Parameter Ranking (Cheng et al., 1999) — A strategy was developed to rank the input parameters and identify parameters according to their importance for 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 remainder of 120 as "low priority" for RESRAD and RESRAD-BUILD combined.

Step 3: Parameter Distribution (Biwer et al., 2000) — Parameter distributions were developed for a total of 73 parameters identified as high or medium priority in Step 2. The data were obtained from a variety of published information representative of a national distribution. Potential correlation among parameters was also studied and discussed in the report (Biwer et al., 2000).

For this probabilistic dose analysis report, RESRAD was used to analyze a residential scenario, and RESRAD-BUILD was used to analyze a building occupancy scenario. These are the same baseline scenarios (together with assumptions) used for the NRC screening analysis (Wernig et al., 1999). As is the case for parameter distributions, such generic scenarios serve only as a baseline exercise for analytical purposes. For site-specific applications, more detailed descriptions, including the use of site-specific input parameters such as thickness and area of contamination, as well as the soil cover and shielding factors, are to be used. It should be noted that the parameter sensitivities for doses are influenced by the input assumptions selected.

The analysis takes 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. In the dose assessment, the total effective dose equivalent (TEDE) to the average member of the critical group under the scenarios analyzed was estimated.

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 LHS method provides a rather efficient process for multiparameter sampling. The dose estimate is generated in quantile value (at 50th percentile and 90th percentile) of the resulting analysis. Dose spread for different radionuclides was identified by the ratio of dose at 99th percentile to that at the 50th percentile for the residential scenario and by the ratio of dose at 95th percentile to that at the 50th percentile for the building occupancy scenario. Regression analysis was used to identify sensitive parameters. As an example, the partial rank correlation coefficients (PRCCs) and standardized rank regression coefficients (SRRCs) were used in residential and building occupancy scenarios, respectively. The effects of sensitive parameters on dose distribution were studied for selected radionuclides.

To illustrate the sensitivity of site-specific parameters such as source area and thickness, three source configurations were analyzed in RESRAD: (1) area of 100 m^2 and thickness of 15 cm; (2) area of 2,400 m^2 and thickness of 15 cm; (3) area of 10,000 m^2 and thickness of 2 m. For RESRAD-BUILD, three different areas (36 m^2, 200 m^2, and 900 m^2) were analyzed for area sources, and the same three areas (36 m^2, 200 m^2, and 900 m^2) along with the probability distribution on source thickness were used for volume sources. Results for the residential scenario indicate that a change from the baseline configuration (i.e., source configuration 1) to an increased area (i.e., source configuration 2) could produce a 19-fold increase in the estimated dose, while a change from the baseline case to an extended thickness and area (i.e., source configuration 3) could lead to a 100-fold increase in the estimated dose. Similarly for the building occupancy scenario, a change in source area could lead to a 25-fold increase in the estimated dose.

The analysis has 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 demonstration enables a site-specific application where pertinent site data can be developed.

Results of the analysis indicated that no single correlation or regression coefficient (e.g., PRCC, SRRC) 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.

Probabilistic dose analysis conducted with RESRAD for 90 principal radionuclides in three source configurations for the residential scenario indicated that the resulting doses appear reasonable and show a consistent pattern. The ratio between the 99th percentile dose and 50th percentile dose ranges from 2.0 to 79, depending on the source configurations and on the type of radionuclide. External shielding factor was the most sensitive parameter in many cases where the external exposure pathway was the dominant pathway. Plant transfer factor was the most sensitive parameter in many cases where plant ingestion was the dominant pathway. The total dose variability could be explained by just the variability in the external shielding factor or the plant transfer factor in those cases.

Probabilistic dose analyses for 67 principal radionuclides for two source types (volume and area) with three source areas were performed for the building occupancy scenario with RESRAD-BUILD. For radionuclides with a dominant external exposure pathway, shielding thickness between the source and receptor was the dominant contributor to the dose variability for volume and area sources for the building occupancy scenario. For radionuclides with a dominant inhalation pathway, for a volume source, the room area and source erosion rate were the two most sensitive parameters. In area sources, the room area, removable fraction, and source lifetime all contributed to the dose variability.

For radionuclides with a dominant ingestion pathway, apart from the sensitive parameters identified for the inhalation pathway, deposition velocity and resuspension rate also contributed to dose variability for the building occupancy scenario.

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.

ACKNOWLEDGMENTS

The authors 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 NMSS/RES Standard Review Plan (SRP) Dose Modeling Working Group (DMWG), and his helpful guidance in ensuring the high quality and timeliness of the work performed and the project deliverables.

We also would like to thank 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), at NRC 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, 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 Owen Hoffman and Kathleen Thiessen of SENES Oak Ridge, Inc., Center for Risk Analysis, for performing a peer review of Argonne's work at the initial phase of the project and to Christine Daily, the NRC RES Project Manager for the SENES peer review project, whose efforts made this important peer review possible in a timely manner. The authors' thanks next go to Douglas Brosseau and Walter Beyeler of Sandia National Laboratories (SNL) 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 SNL for performing parameter analysis for the DandD computer code.

Marianne Riggs and Margaret Farr, Program Management, Policy Development and Analysis Staff (RES/PMPDAS) of NRC, 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.

The authors would like to thank Alexander Williams, RESRAD project manager of the Office of Environmental Management (EM) of the U.S. Department of Energy (DOE); Andrew Wallo, Director of Air, Water and Radiation Division; and Harold Peterson in the Office of Environmental Health (EH) of DOE 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 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, Technical Editor at Argonne, for their thorough review and helpful suggestions. We also thank the staff of the Document Processing Center of Argonne's Information and Publishing Division for preparing the manuscript.

ABBREVIATIONS

CDF	cumulative distribution function
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
dpm	disintegration(s) per minute
EDE	effective dose equivalent
g	gram(s)
GI	gastrointestinal
GUI	graphic-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)
μg	microgram(s)
mrem	millirem
NRC	U.S. Nuclear Regulatory Commission
PCC	partial correlation coefficient
pCi	picocurie(s)
PRCC	partial rank correlation coefficient
s	second(s)
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 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 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, 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, 1998c]). The RESRAD codes have been used primarily to derive site-specific cleanup guidance levels (the derived concentration guideline levels, or DCGLs) based on the deterministic method.

In 1999, the NRC tasked Argonne to modify 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 radioactively contaminated sites.

---

[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). 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.

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): 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): 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 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): 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. The parameter distributions are summarized in Section 6 of this report.

Probabilistic Dose Analysis (current report): This report presents probabilistic dose analysis and evaluation of the results for the derived parameter distributions for the RESRAD and RESRAD-BUILD codes. This effort entails the application of the probabilistic modules being developed for the two codes. Since the development of the modules is not yet final, interim RESRAD version 5.95+ and RESRAD-BUILD version 2.9+ were used for this analysis. The report focuses on the effects of parameter distributions on the distribution of estimated doses, taking into account parameter correlations.

This report is organized into nine major sections. Section 1 (the current section) provides background information and summarizes the previous tasks accomplished in this project. Section 2 describes the scope and purpose of the parameter analysis. Overviews of the RESRAD and RESRAD-BUILD computer codes are provided in Section 3. Section 4 discusses the two scenarios (residential and building occupancy) evaluated in license termination dose analyses and lists the input parameters. Section 5 discusses the probabilistic analysis methodology. Parameter distributions used in the analysis are described in Section 6. Results of the analyses are discussed in Section 7. Section 8 provides an overall summary of the results. References cited are listed in Section 9. Appendix A presents the details of the probabilistic module used to evaluate dose distribution. Appendix B contains tables and figures for parameter distribution used in probabilistic dose analyses. Appendix C contains the detailed results of the sensitivity analyses.

For residential scenario, this report calculates the peak dose over 1,000 years for each sample run and focuses on several percentile values characterizing the distribution of peak doses. The RESRAD uncertainty module can also calculate the mean dose at each specified time from all sample runs (i.e., the mean dose can be reported as a function of time). From this time-dependent mean dose, the peak of the mean can be identified. Probabilistic analysis can be conducted for the time when the peak of the mean dose occurs.

For both analyses, peak dose for each sample run and the peak of the mean dose will provide similar results if the peak always occurs at the same time (say at time zero or at 1,000 years) from all sample runs. The results of the analysis may be different if the peak time is different for any sample run. Therefore, for radionuclides such as Co-60 and Cs-137, for which the peak dose always occurs at time zero (water-dependent pathways are not significant in any sample run), there will not be any significant difference in the two analyses. On the other hand, for radionuclides such as Th-232 and U-238, for which the peak dose occurs at different times (water-dependent pathways may become significant in any sample run), there will be differences in the two analyses. The probabilistic dose analyses done for the peak dose will be more conservative than the analyses done for the peak of the mean dose.

2 SCOPE AND PURPOSE OF THE PROBABILISTIC DOSE ANALYSIS

Deterministic analysis (as previously employed in the RESRAD and RESRAD-BUILD codes) uses a single value for each parameter, resulting in a single dose value. The probabilistic approach uses systematic uncertainty analysis to quantify the uncertainty in dose estimates due to uncertainty in the input parameters. Figure 2.1 shows the concept of parameter uncertainty analysis.

In the probabilistic analysis, a probability distribution is specified for each model input parameter of uncertain value (Figure 2.1). Samples are generated from each of the input distributions. One sample from each input distribution is selected. A model is run repeatedly (for a specified number of iterations), each time using different values for each of the uncertain input parameters. The model results are stored. Instead of obtaining a single number for model outputs as in a deterministic run, a set of outputs (equal in number to the number of iterations) is obtained. These outputs can be represented as probability density functions (PDFs) and as cumulative distribution functions (CDFs). The CDF helps provide quantitative insight regarding the percentiles of the distributions. Although the generation of sample values for model input parameters is probabilistic, the execution of the model for a given set of samples in a repetition is deterministic.

Probabilistic analysis is a tool that can be used to support the decision-making process by showing changes in potential doses for a range of possible input parameter values. Probabilistic analysis in RESRAD and RESRAD-BUILD codes is discussed in Section 5.

An external module (a preprocessor and a postprocessor) equipped with probabilistic sampling and analytical capabilities is being developed for RESRAD and RESRAD-BUILD. The module is further equipped with user-friendly input and output features to accommodate numerous parameter distribution functions and display requirements. The integrated system, consisting of the codes and interface modules, is designed to operate on Microsoft Windows™ 95, 98, and NT platforms. Completion and publication of the entire code system is scheduled for a later date. For the analysis described in this report, a preliminary version of the system was used. Appendix A describes the probabilistic module used to evaluate dose distribution.

The objective of the probabilistic dose analyses discussed in this report is to use parameter distributions developed for the RESRAD and RESRAD-BUILD codes to establish and demonstrate the process for site-specific analysis using the integrated code system. RESRAD was used to analyze a residential scenario, and RESRAD-BUILD was used to analyze a building occupancy scenario. The RESRAD and RESRAD-BUILD codes are described in Section 3. The two scenarios, residential and building occupancy, evaluated as part of the NRC's license termination process are described in Section 4. Detailed discussion on the approach used for the analysis is provided in the following subsections.

2.1 PROBABILISTIC DOSE ANALYSIS APPROACH FOR SCREENING ANALYSIS

The site-specific modeling approach complements the generic screening approach described in NUREG/CR-5512 (Kennedy and Strenge, 1992). The screening analysis approach is evaluated to contrast similarity and differences in areas that are common to the site-specific analysis discussed in Section 2.2.

Because the underlying premise of a screening model analysis is to make an informed decision

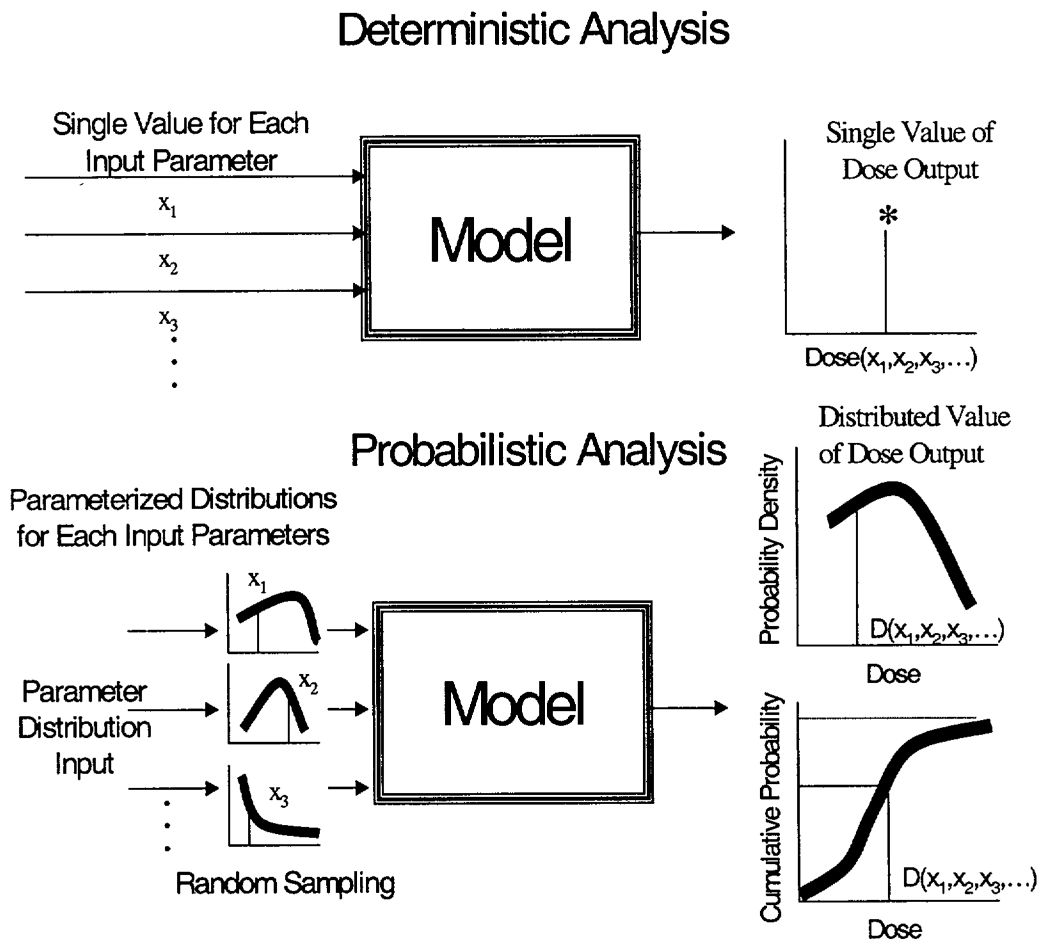

Figure 2.1 Concepts of Deterministic and Probabilistic Analyses

on the basis of a minimal amount of user input data, those data used in the model that are not input by the user must ensure a certain level of conservatism. In the case of the DandD code (Wernig et al., 1999), such a default parameter set was developed through an analysis of radionuclide-specific dose distributions. The dose distributions were obtained with a modified Monte Carlo approach using Latin hypercube sampling (LHS) (Beyeler et al., 1999).

In the screening methodology used for the DandD code, model parameters representing the physical characteristics of a site were assigned default values by using the following steps:

- The parameters were assigned input distributions deemed to be representative of conditions across all contaminated sites.
- Using these input distributions, a distribution of doses was obtained for each potential radionuclide contaminant.
- Each subset of values sampled from the input distributions (a sample vector, one set of all input parameters) that resulted in a dose greater than or equal to a specific percentile value was identified for each radionuclide.
- Those subsets that satisfied the condition for *all* radionuclides would be those best

suited to be a deterministic default set of parameters for use in the screening model.

The use of such subsets would result in conservatively high doses. Thus, sites with estimated doses below regulatory limits have a high probability of meeting the limits if a site-specific analysis were to be performed.

On the other hand, a site-specific analysis, as performed by RESRAD or RESRAD-BUILD, requires input distributions that best characterize the variability found at a given site rather than those that maximize dose. The site-specific approach strives to calculate more realistic estimates of dose for each particular site. As discussed below, the site-specific approach relies on the same LHS sampling method as the screening approach. However, in the site-specific analysis, the distributions of the inputs capture the expected variability and the uncertainty in the inputs at a particular site (as opposed to the screening approach, which accounts for variability across sites).

2.2 PROBABILISTIC DOSE ANALYSIS APPROACH FOR SITE-SPECIFIC ANALYSIS

The RESRAD and RESRAD-BUILD codes were designed to consider a relatively complex contamination situation and incorporate relatively complex transport mechanisms to simulate partitioning of contaminants in the environment. Therefore, they can be used for site-specific analysis to obtain more realistic dose estimates. To determine the potential dose distributions, the same LHS sampling methods used in the screening analysis should be used. However, parameter distributions that best characterize the variability found at a given site, rather than those that maximize dose, should be used.

The dose distribution analysis conducted for this report used the generic distributions developed in the Parameter Distribution Report (Biwer et al., 2000) to test the distribution data and to demonstrate the capability of RESRAD and RESRAD-BUILD to perform a site-specific analysis. The specific strategy used to select the input values depended on the parameter category.

Parameters representing metabolic characteristics were defined by the average values for the general population (International Commission on Radiological Protection [ICRP], 1984). These values would not be expected to change for a site-specific analysis because they would be independent of site conditions.

The behavioral parameters used in a site-specific analysis characterize the average member of the "critical group" (as defined in Section 1) at the site. Default values for behavioral parameters were defined by stipulating a generic group for the scenario, which was a site-independent population appropriate for use at all sites. Therefore, behavioral parameters were set at mean values or at a median value of probability distributions. However, behavioral parameter distributions could vary among different population groups. The user should confirm the appropriateness of the parameters for the population being considered.

Physical parameters can vary from site to site, and to capture the variability in estimated doses due to variability in such parameters, probability distributions for those parameters that were analyzed in the Parameter Distribution Report (Biwer et al., 2000) were used in the analysis. For other physical parameters not assigned distributions, RESRAD and RESRAD-BUILD default values were used, or in cases of overlap among RESRAD, RESRAD-BUILD, and DandD input parameters, DandD default input parameter values were used if appropriate.

As was noted in the Parameter Ranking Report (Cheng et al., 1999), some site-specific parameters have significant impacts on estimated radiation doses. For those parameters, site-specific information should always be used in dose calculations, and thus no distributions were provided for them in the Parameter Distribution Report (Biwer et al., 2000). For RESRAD, such parameters include radionuclide concentrations, source area, and source thickness. For RESRAD-BUILD, such parameters include radionuclide concentrations and source area. The radionuclide concentration would affect the dose linearly, whereas the effect of source area and thickness may not be linear. For RESRAD, this report analyzes three source configurations: (1) area of 100 m^2 and thickness of 15 cm; (2) area of 2,400 m^2 and thickness of 15 cm; (3) area of 10,000 m^2 and thickness of 2 m. For RESRAD-BUILD, three different areas (36 m^2, 200 m^2, and 900 m^2) are analyzed for area sources, and the same three areas (36 m^2, 200 m^2, and 900 m^2) along with the probability distribution on source thickness were used for volume sources.

Parameter Distribution Report (Biwer et al., 2000) indicated that some input parameters are clearly related, such as effec ;e 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 performing dose variability in this task.

The stratified Monte-Carlo LHS technique was used to sample the assigned parameter distributions in estimating the dose distribution functions.

2.3 HIGHLIGHTS OF DOSE DISTRIBUTION ANALYSIS

Some key elements for the site-specific analysis are furnished by the major attributes of the RESRAD and RESRAD-BUILD codes. This section highlights these attributes together with considerations specific to probabilistic analysis:

- RESRAD was used to analyze the residential scenario, and RESRAD-BUILD was used to analyze the building occupancy scenario.
- Probabilistic analysis was performed for the radionuclides in the RESRAD and RESRAD-BUILD databases. RESRAD has 91 principal radionuclides in its database, and RESRAD-BUILD has 67 principal radionuclides.
- Three source configurations were analyzed for the residential scenario.
- Two source types (volume and area) with three source areas were analyzed for the building occupancy scenario.
- The time frame used for the residential scenario was 0-1,000 years.
- For the physical parameters, distributions presented in the Parameter Distribution Report (Biwer et al., 2000) were used in the analysis. For the metabolic and behavioral parameters, mean or median values of the distributions were used.
- A total of 300 samples each were generated for RESRAD and RESRAD-BUILD with the LHS technique.
- Parameters were divided into radionuclide-independent and radionuclide-dependent categories. Input files were created for all radionuclides.
- Quantile values (at 50th percentile and 90th percentile) of unit-source dose distributions were generated. For the residential scenario, the dose distribution is for the peak dose over each 1,000-year period, and for the building occupancy scenario, it is for the dose at time zero.
- Regression analysis was used to identify sensitive parameters.
- The effect of sensitive parameters on dose distribution was studied for selected radionuclides.
- The effect of correlation of input parameters on dose distribution was studied.

3 OVERVIEW OF RESRAD AND RESRAD-BUILD CODES

RESRAD (Yu et al., 1993) and RESRAD-BUILD (Yu et al., 1994) computer codes have been developed by Argonne National Laboratory (Argonne) under sponsorship of 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 (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 total effective dose equivalent (TEDE).

To perform probabilistic dose analyses, external modules (a preprocessor and a post-processor) for both RESRAD and RESRAD-BUILD were developed to serve as "drivers" for providing an input/output and sampling mechanism. Appendix A describes the probabilistic module, and Section 5 describes the sampling mechanism.

3.1 RESRAD

RESRAD (Yu et al., 1993) 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 3.1 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 population 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 three-dimensional 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.

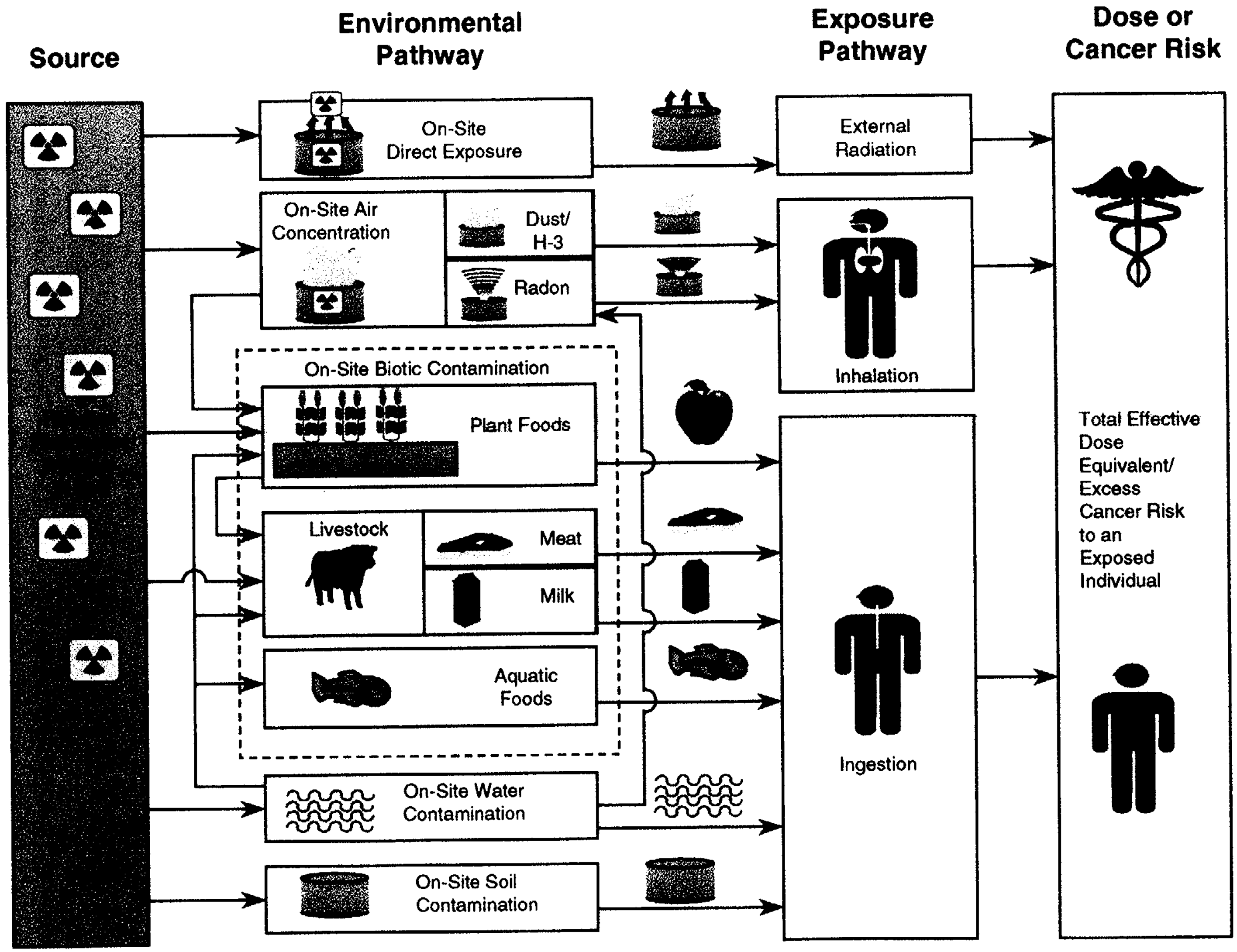

Figure 3.1 Graphical Representation of Pathways Considered in RESRAD

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 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 3.1 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.

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 and uncertainty analysis for various parameters. A probabilistic interface for the RESRAD is being enhanced (Appendix A).

Table 3.1. List of Principal Radionuclides[a] in RESRAD and RESRAD-BUILD					
Source ID	Radionuclide	Source ID	Radionuclide	Source 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.

[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.

3.2 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.

Seven exposure pathways are considered in RESRAD-BUILD: (1) external exposure directly from the source; (2) external exposure to materials deposited on the floor; (3) external exposure due to air submersion; (4) inhalation of airborne radioactive particulates; (5) inhalation of aerosol indoor radon progeny; (6) inadvertent ingestion of radioactive material directly from the sources; and (7) inadvertent ingestion of materials deposited on the surfaces of the building rooms or compartments. Figure 3.2 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).

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. 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 3.1 lists radionuclides in both the RESRAD-BUILD and RESRAD databases. A probabilistic interface for the RESRAD-BUILD is being enhanced (Appendix A).

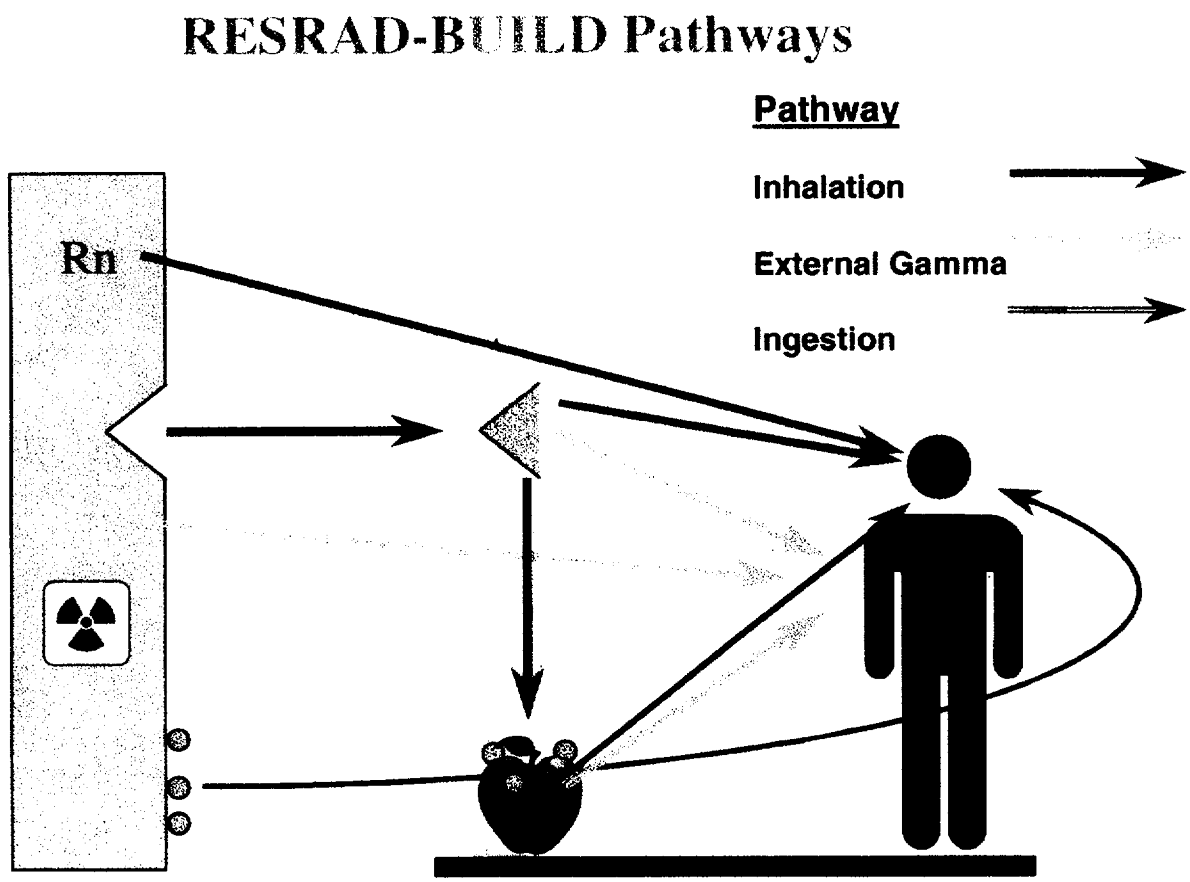

Figure 3.2 Graphical Representation of Pathways Considered in RESRAD-BUILD

4 SCENARIOS USED IN ESTIMATING DOSE DISTRIBUTIONS

As mentioned in Section 1, to assess compliance with the NRC's prescribed dose criteria for decommissioning and license termination of a facility, potential doses to an average member of the critical group should be evaluated for realistic future use scenarios involving a number of possible exposure pathways. For sites with residual contamination in soil, a "residential scenario" is evaluated. For a building with residual contamination indoors, a "building occupancy" scenario is evaluated.

Significant assumptions made for these two scenarios are summarized in the following subsections. These are the same baseline scenarios (together with the assumptions) used for the NRC screening analysis. As is the case for parameter distributions, such generic scenarios serve only as a baseline exercise for analytical purposes. For site-specific analyses, more detailed descriptions, including site-specific data for input parameters such as thickness and area of contamination, as well as the soil cover and shielding factors, are to be used.

4.1 RESIDENTIAL SCENARIO ASSUMPTIONS

The residential scenario model, as defined in NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992) as the baseline screening scenario, is based on the following assumptions. These assumptions are followed in the RESRAD analysis for this report:

- Radioactive contamination occurs in a surface soil layer.

- The property can be used for residential and light farming activities.

- Residency can occur immediately after release of the property.

- Radioactive dose results from exposure via external exposure, inhalation, and ingestion. The model includes 12 exposure pathways created by the activities considered in the scenario:

  - external exposure to penetrating radiation from volume soil sources while outdoors,
  - external exposure to penetrating radiation from volume sources while indoors,
  - inhalation exposure to resuspended soil while outdoors,
  - inhalation exposure to resuspended soil while indoors,
  - inhalation exposure to resuspended surface sources of soil tracked indoors,
  - direct ingestion of soil,
  - inadvertent ingestion of soil tracked indoors,
  - ingestion of drinking water from a contaminated groundwater source,
  - ingestion of plant products grown in contaminated soil,
  - ingestion of plant products irrigated with contaminated groundwater,
  - ingestion of animal products (meat and milk) grown on the site, and
  - ingestion of fish from a contaminated surface water source.

It should be noted that the RESRAD code considers all the above pathways, although some pathways are considered through the use of occupancy, shielding, and filtration factors. RESRAD also considers the following three pathways:

- inhalation of indoor radon aerosol,
- inhalation of outdoor radon aerosol, and
- ingestion of drinking water from a surface water source.

Although RESRAD can calculate radon inhalation doses, they were not included in this analysis. Figure 4.1 conceptually illustrates the exposure pathways in a typical residential scenario. The time frame used is up to 1,000 years, and the peak dose in this time horizon (0 - 1,000 years) is used in the analysis.

4.2 BUILDING OCCUPANCY SCENARIO ASSUMPTIONS

The building occupancy scenario, as defined in NUREG/CR-5512, Volume 1 (Kennedy and Strenge, 1992) as the baseline screening scenario, is based on the following assumptions. These assumptions are followed in the RESRAD-BUILD analysis for this report:

- Radioactive dose results from exposure via three major exposure pathways:
    - external exposure to penetrating radiation from surface sources,
    - inhalation of resuspended surface contamination, and
    - inadvertent ingestion of surface contamination.
- The building will be commercially used after decommissioning.
- The occupancy of the building will occur immediately after its release.
- The residual contamination will be represented by a thin surface layer left on the inner building surfaces.
- The exposure type will be a long-term chronic exposure to low-level radioactive contamination because major contamination will have been cleaned up before decommissioning of the building.

It should be noted that the RESRAD-BUILD code considers all the above pathways and the following three additional pathways:

- external exposure during submersion in airborne radioactive dust,
- external exposure from deposited material, and
- inhalation of indoor radon aerosol.

However, radon inhalation doses were not included in this analysis.

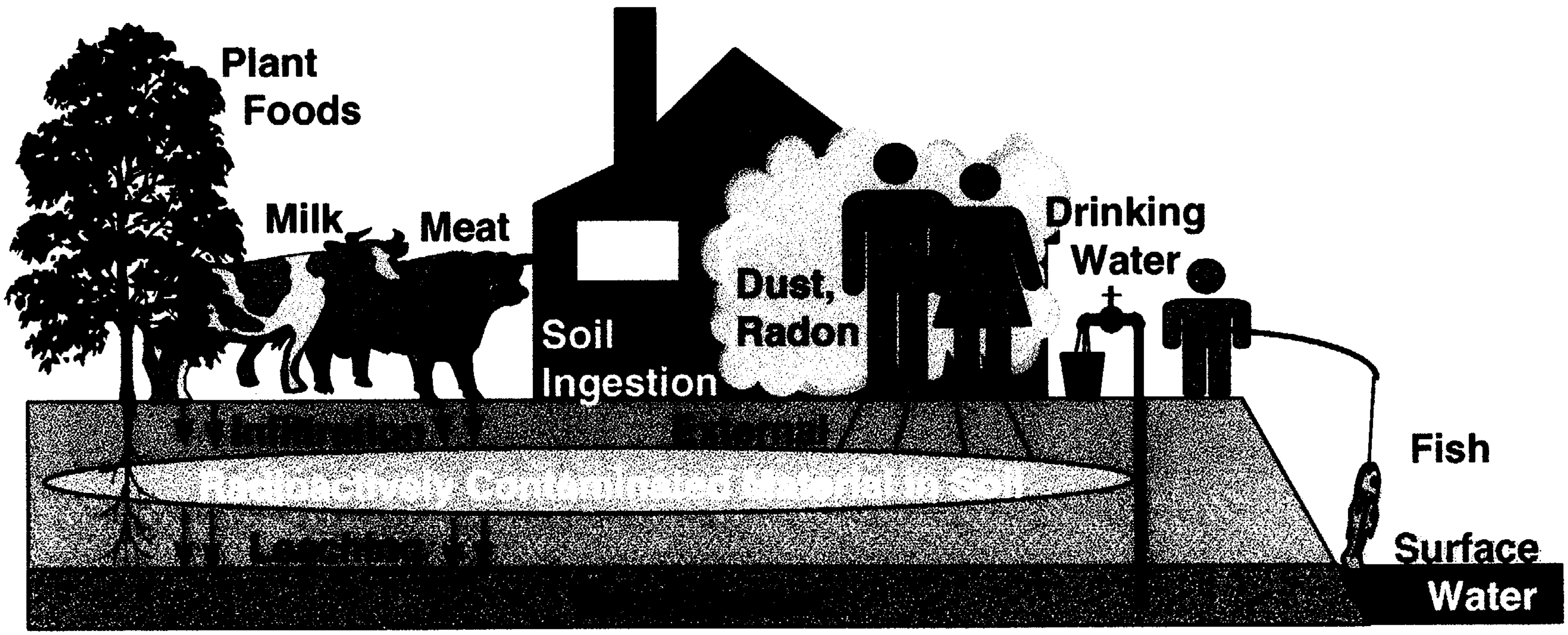

Figure 4.1 Schematic Representation of Exposure Pathways in a Typical Residential Scenario

5 PROBABILISTIC ANALYSIS IN RESRAD AND RESRAD-BUILD

Probabilistic analysis in RESRAD or RESRAD-BUILD is the computation of the total uncertainty induced in the output (resultant dose) as a result of either the uncertainty in or the variability of the input parameters. This kind of quantitative analysis helps determine the relative importance of the contributions of the uncertainties in the input parameters to the total uncertainty. Also, the results of probabilistic analysis can be used as a basis for determining the cost-effectiveness of obtaining additional information or data on input parameters. The analysis can be conducted by using correlations and rank correlations based on regression methodology to examine how much of the uncertainty in the results is attributable to which input parameters.

A pre-processor and a post-processor are being 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.

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 obtained and presented in a tabular form in terms of percentile values. Further analysis using regression methods is performed to find the correlation of the resultant doses (peak dose over 1,000-year period for RESRAD and dose at time zero for RESRAD-BUILD) with the input parameters. Partial correlation coefficients, partial rank correlation coefficients, standardized partial regression coefficients, and partial ranked regression coefficients are computed and ranked to provide a tool for determining the relative importance of input parameters in influencing the resultant dose.

5.1 SAMPLING METHOD

Samples of the input parameters are generated with an updated version of the LHS computer code (Iman and Shortencarierm, 1984). The uncertainty input form 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 5.1 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

Table 5.1. Listing of Input Data and Information Needed for Sample Generation	
Input Data	**Description**
Sampling Parameters	
Random Seed	Determines the series of random numbers generated.
Number of Observations	Number of sample values to be generated for each input variable for each repetition.
Number of Repetitions	Number of times probabilistic analysis is repeated.
Sampling Techniques	
Latin Hypercube	The distribution to be sampled is split into a number of equally probable distribution segments; the number being equal to desired number of observations.
Monte Carlo	The desired number of observations are obtained at random from the whole distribution.
Grouping of Observations	
Correlated or Uncorrelated	The samples of each variable are grouped together according to the specified correlation or are not correlated at all.
Random	The samples of each variables are grouped together at random.
Statistical Distributions	
Variable Descriptions	List of parameters for which distributions are specified.
Statistics of Uncertain Variable	Assigned distribution for the uncertain variable and the statistical parameters for the distribution.
Input Rank Correlations	
Variable 1, Variable 2	Two variables for which rank correlation is specified.
RCC	The specified input rank correlation coefficient between two variables.

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 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 the 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. For the residential and building occupancy scenario analyses, few input parameters were correlated (seven for the residential scenario and none for the building occupancy scenario). The code checks whether the user-specified rank correlation matrix is positive definite and suggests an alternative rank correlation matrix if necessary. It then groups the samples so that the rank correlation matrix is as close as possible to the one specified. Both matrices are in the LHS.REP file (which is generated by the RESRAD or RESRAD-BUILD code after the probabilistic analysis is run), and the 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 doses and risk vary with the number of samples chosen. The accuracies of the mean dose and of the dose values for a particular percentile are dependent on the percentile of interest and on the number of samples. The confidence interval or the (upper or lower) confidence limit of the mean can be determined from the results of a single set of samples. Distribution-free upper (u%, v%) statistical tolerance limits can be computed by using the SRS technique according to the methodology in IAEA Report No. 100 (IAEA, 1989).

If LHS is used, the best way to determine the statistical accuracy is to run the same problem and only vary the initial seed value of the random number generator. For this analysis, the same problem was run with different random seed values, and the number of observations was changed from 100 sample runs to 300. For the few radionuclides tested, it was found that 300 sample runs would give 5% accuracy in the 50th percentile and 90th percentile dose values if the run was repeated with different random numbers.

5.2 DISTRIBUTION OF PARAMETERS

A set of input parameters for uncertainty analysis is chosen through the code's interface. Each parameter may have a probability distribution assigned to it and may be correlated with other input parameters included in the uncertainty analysis. A total of 34 different distribution types are available for selection. The distribution of parameters required for the uncertainty analysis depend on the selected distribution type. Table A.1 in the Parameter Distribution Report (Biwer et al., 2000) 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." This technique of using correlation on ranks rather than on actual data is used because, in general, linear relationships among parameters may not exist. For the residential scenario analyses, rank correlations between density and total porosity, density and effective porosity, and total porosity and effective porosity were used.

5.3 PROBABILISTIC RESULTS

The results of the probabilistic analysis handled by the post-processor are presented in the summary text files MCSUMMAR.REP in RESRAD and RESBMC.RPT in RESRAD-BUILD. In each case, the file contains statistical data for a collection of resultant doses as a function of time, pathway, and radionuclide. 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%. Tabulations of the correlation of the resultant doses with the input parameters using regression methods are provided. 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 analysis of the input parameters and the resultant dose (peak dose over 1,000-year period for RESRAD and dose at time zero for RESRAD-BUILD) is based on the methodology of Iman et al. (1985). The correlation results in RESRAD and RESRAD-BUILD include a table for PCC, SRC, partial rank correlation coefficients (PRCCs), and the standardized rank regression coefficient (SRRC), and 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 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 the rank 1, the next smallest value is assigned rank 2, and so on up to the largest value, which is assigned the 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, PRCC and SRRC are recommended over PCC and SRC when nonlinear relationships, widely disparate scales, or long tails are present in the inputs and outputs.

Table 5.2 compares the approaches available for correlating the uncertainty in the distribution of doses to the uncertainty in the input parameter.

Table 5.2. 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 is 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).		

6 OVERVIEW OF PARAMETER DISTRIBUTION ASSIGNMENT

The parameter distributions assigned in the Parameter Distribution Report (Biwer et al., 2000) 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 most recent data were gathered for the selected input parameters. The starting point for this step was NUREG/CR-5512 (Kennedy and Strenge, 1992) and 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 process that was used in prioritizing parameters and assigning distribution is summarized below.

6.1 PARAMETERS ASSIGNED DISTRIBUTION

In the Parameter Ranking Report (Cheng et al., 1999), 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 (Biwer et al., 2000) 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 6.1 lists the parameters assigned distributions; it also lists the parameter type and assigned distribution type for each.

6.2 ASSIGNMENT OF DISTRIBUTIONS

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 where available. However, data are often lacking for environmental exposure pathways. As fewer data became available, secondary types of information were used in conjunction with existing sample data in the distribution assignment task.

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. Goodness-of-fit may have been determined through the use of probability plots or other graphical representations.

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

Table 6.1. Parameters Assigned Probability Density Functions		
Parameter	**Parameter Type[a]**	**Assigned Distribution Type**
RESRAD		
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 depth (m)	P	None recommended
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 ($\mu g/m^3$)	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

Table 6.1. Parameters Assigned Probability Density Functions (Continued)		
Parameter	**Parameter Type[a]**	**Assigned Distribution Type**
Well pumping rate (m^3/yr)	B, P	None recommended
Well pump intake depth (below water table) (m)	P	Triangular
Wet foliar interception fraction for leafy vegetables	P	Triangular
Wet-weight crop yields for non-leafy vegetables (kg/m^2)	P	Lognormal
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
RESRAD-BUILD		
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
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	B	None recommended
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 next is secondary (Kamboj et al., 1999).

Source: Modified from Biwer et al. (2000), Table 2.1-1.

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.

For the parameters not assigned distributions, RESRAD and RESRAD-BUILD default values were used, or in cases of overlap among RESRAD, RESRAD-BUILD, and DandD input parameters, the DandD default values were used if appropriate. Table B.1 in Appendix B lists the assigned distributions for the Priority 1 and 2 parameters in the RESRAD and the RESRAD-BUILD codes.

7 RESULTS OF PROBABILISTIC DOSE ANALYSES

The results of the probabilistic dose analyses are presented in this section. The analyses were conducted to assess the effects of parameter distribution on estimated doses from residual radionuclides for the residential and building occupancy scenarios. The total effective dose equivalent (TEDE) was estimated for an average member of the critical group. The RESRAD code was used to analyze the residential scenario, and RESRAD-BUILD was used to analyze the building occupancy scenario.

The uncertainty module used for evaluating dose variability included the input interface and the calculational components of sample generation, calculation for each sample, and compilation of the results. The results were accessible through a set of files that contained the user's input, the sample vectors, and the output dose results for each sample. Supplemental software was developed to extract, manage, analyze, and aggregate the data.

7.1 RESIDENTIAL SCENARIO

As noted in the Parameter Ranking Report (Cheng et al., 1999), certain parameters have significant impacts on calculated radiation doses, and site-specific information for those parameters should always be used in dose calculations. The parameters with significant effect on dose include radionuclide concentrations, source area, and source thickness. Radionuclide concentration would affect the dose linearly, whereas the effect of source area and source thickness may not be linear. For the residential scenario, this report analyzes the influence of parameter values on peak dose for three source configurations: (1) area of 100 m^2, thickness of 15 cm; (2) area of 2,400 m^2, thickness of 15 cm; and (3) area of 10,000 m^2, thickness of 2 m).

Table B.2 (Appendix B) lists the parameter values and distribution types used in the analysis. A stratified Monte-Carlo technique, Latin hypercube sampling (LHS), was used to estimate the dose distribution functions from the assigned parameter distribution functions. Three hundred sample values were generated for each input variable. This set of inputs was then used to generate a set of outputs from which the probability statistics were generated. For the physical parameters, assigned distributions were used in the analysis. For the metabolic and behavioral parameters, mean or median values of the distributions were used. For the parameters not assigned distributions, RESRAD default values were used, or in cases of overlap between RESRAD and DandD input parameters, DandD default input parameter values were used if appropriate.

The results of the parameter sampling are illustrated in Figures B.1 through B.32 in Appendix B. Those figures compare the input frequency of the physical parameter values based on LHS sampling and the probability density of the parameter. Because of the large number of element-specific parameters, distributions for the distribution coefficients and transfer factors (plant, meat, milk, and bioaccumulation) are not shown.

7.1.1 Parameter Correlations

The Parameter Distribution Report (Biwer et al., 2000) indicated that some input parameters in RESRAD are correlated. For some parameters, such as effective porosity and total porosity, strong correlations were indicated. Distributions were not provided for some of the parameters, such as irrigation rate. Some parameters were behavioral parameters, such as soil ingestion rate and drinking water intake. For behavioral parameters, mean or median values were used in the analysis. For these cases, no correlation analysis was performed.

In cases for which a clear relationship was identified, such as density and porosity and effective porosity and total porosity, strong rank correlations were used as input. A rank correlation value of 0.96 between porosity and effective porosity ensured pairing of high porosity value with high effective porosity. In no case among the 300 samples generated by LHS was effective porosity higher than the total porosity. Figure 7.1 shows the scatter plot of effective porosity and total porosity with rank correlation of 0.96. Similarly, a negative rank correlation of 0.99 ensured proper pairing between total porosity and bulk density. The average particle density, calculated on the basis of the total porosity and bulk density sample data set, was 2.64 g/cm^3, with a 0.06 standard deviation. Figure 7.2 shows the scatter plot of sample input for bulk density and total porosity. Figure 7.3 shows the cumulative probability of the sampled particle density with a rank correlation of -0.99. All values are within 2.48 to 2.81 g/cm^3.

7.1.2 Dose Analysis Results

For each set of sampled parameter values, dose to the average member of the critical group was calculated for unit concentrations of each radionuclide. For each source, the distribution describing possible doses to the average member of the critical group was then constructed from these calculated doses. From the resulting dose distributions, the dose quantiles were estimated. The distribution of the dose is the distribution of the peak dose over each 1,000-year period. In all, 90 radionuclides were analyzed for three source configurations (total of 270 radionuclide-source configurations).

Table 7.1 lists the quantile values (at 50th percentile and 90th percentile) of unit-source distribution for three source configurations (source configuration 1: source area = 100 m^2 and thickness = 15 cm; source configuration 2: source area = 2,400 m^2 and thickness = 15 cm; and source configuration 3: source area = 10,000 m^2 and thickness = 2 m) in the residential scenario. Table 7.1 also shows the ratio of the 99th percentile dose to the 50th percentile (median) dose. The dose ratio shows the dose spread for different radionuclides. Dose values at the selected quantiles can be used to calculate the source concentration equivalent to a dose value of 25 mrem/yr.

For source configuration 1, the dose ratio varies from 2.2 (Cs-134, Cs-137, Pu-244, Ru-106, Se-75, and Th-229) to 79 (C-14). For source configuration 2, the dose ratio varies from 2.1 (Am-243) to 39 (S-35). For source configuration 3, the dose ratio varies from 2.0 (H-3) to 28 (S-35). For some radionuclides, the dose ratio remains almost the same for all three source configurations (e.g., Ag-108m, Ag-110m, Al-26, Ba-133, Bi-207, Ce-141, Ce-144, Co-57, Co-60, Eu-152, Eu-154, Eu-155, and Fe-59). Wide variations occur for other radionuclides (e.g., Ac-227, Am-241, Am-243, C-14, Ca-41, and Ca-45). Figures 7.4 to 7.13 show the dose variability for Am-241, C-14, Co-60, Cs-137, H-3, Pu-239, Ra-226, Sr-90, Th-230, and U-238 in the residential scenario for all three source configurations.

For 90 radionuclides and 3 source configurations, there are a total of 270 radionuclide-source configurations. For 186 of these radionuclide-source configurations, peak dose was always at time 0 from all 300 sample runs. For 41 radionuclide-source configurations, peak dose was at time 0 more than 90% of the time (< 30 sample runs). For 41 radionuclide-source configurations, more than 30 samples (10%) produced peak dose at times other than time 0 (>30 - <300 sample runs). In some cases (2 radionuclide-source configurations), peak dose was always at a time other than time 0 (all 300 sample runs). Therefore, the results indicate that in most cases, the peak dose occurred at time zero. The reason was that for most radionuclides, water-dependent pathways were either not significant or the transport time was greater than 1,000 years.

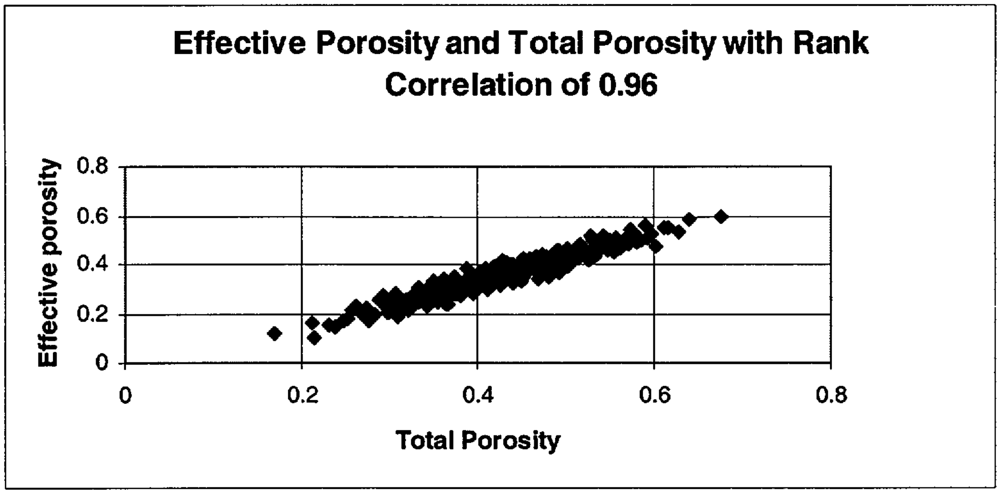

Figure 7.1 Scatter Plot of Effective and Total Porosity in Sample Input with Rank Correlation of 0.96

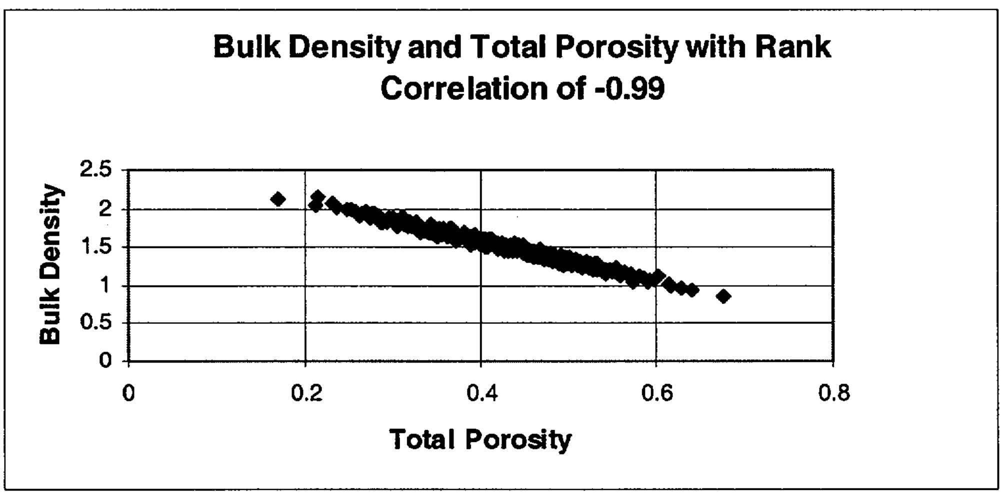

Figure 7.2 Scatter Plot of Bulk Density and Total Porosity in Sample Input with Rank Correlation of -0.99

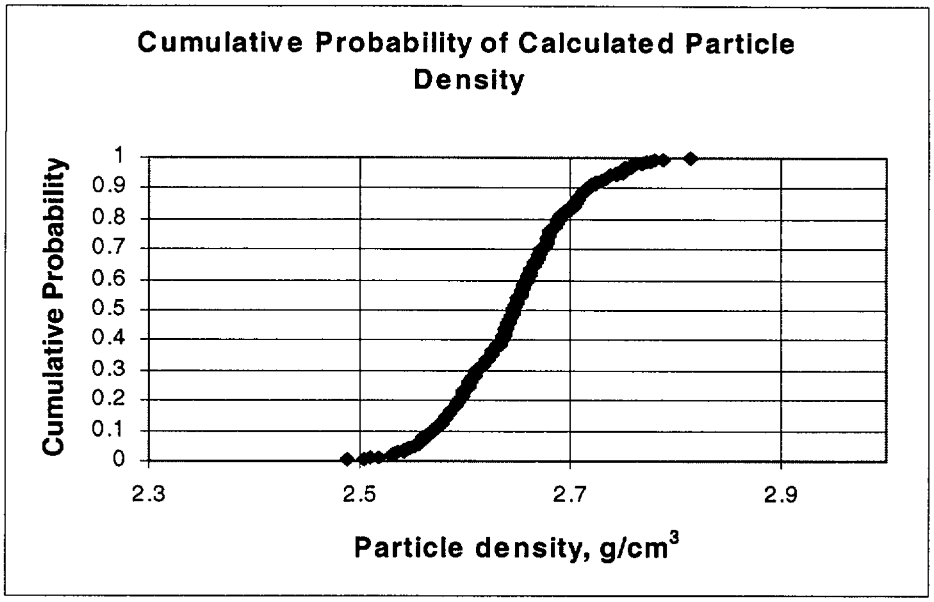

Figure 7.3 Cumulative Probability of Calculated Particle Density

Tables 7.2 through 7.4 give the range of sample runs when the peak dose was at times other than time 0 for the three source configurations. Sensitive parameters for the radionuclides that have peak dose at time other than 0 will change with the dose percentile values.

7.1.3 Dominant Pathways and Sensitive Parameters

The results of the probabilistic dose analysis indicated that the dominant pathways generally were external exposure and plant ingestion at high dose percentiles. The external exposure pathway was dominant because in the residential scenario analyzed, there was no cover present; if cover was present, the dominant pathways and sensitive parameters would be different. The reason plant ingestion was the dominant pathway was that the plant transfer factor has large variability, which results in high plant ingestion doses at high dose percentiles.

The results can be used to identify parameters controlling dose variability for each radionuclide. The dependence of dose on the model parameter values is complex; total dose may depend non-monotonically on the parameter value, or may be sensitive to the parameter value only within certain limits, or only in conjunction with certain ranges of values for other parameters. Because of these complexities, a single regression analysis can not be used to identify the sensitive parameters. RESRAD output provides partial correlation coefficient (PCC), standard regression coefficient (SRC), partial rank correlation coefficient (PRCC), and standardized rank regression coefficient (SRRC) values and scatter plots. (These terms are explained in Section 5.) Sensitive parameters can be identified by the use of these aids along with expert judgment.

The ranking of parameters may be different if different regression analysis, such as PCC, SRC, PRCC, or SRRC, is used. Tables 7.2 through 7.4 list the four most sensitive parameters on the basis of PRCC, along with the dominant pathway for three source configurations. The detailed regression analysis results with PRCC values are provided in

Table 7.1. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per pCi/g) for Three Source Configurations in the Residential Scenario									
	Source Configurations								
	Area = 100 m^2; Thickness = 15 cm			Area = 2,400 m^2; Thickness = 15 cm			Area = 10,000 m^2; Thickness = 2 m		
Radionuclide	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%
Ac-227	5.00E-01	7.90E-01	2.30E+00	8.80E-01	1.40E+00	3.80E+00	2.10E+00	6.30E+00	7.10E+00
Ag-108	2.00E+00	3.20E+00	2.30E+00	2.40E+00	3.90E+00	2.30E+00	2.70E+00	4.30E+00	2.30E+00
Ag-110	2.20E+00	3.50E+00	2.30E+00	2.60E+00	4.20E+00	2.30E+00	3.00E+00	4.90E+00	2.30E+00
Al-26	3.30E+00	5.50E+00	2.30E+00	4.00E+00	6.60E+00	2.30E+00	4.80E+00	7.80E+00	2.40E+00
Am-241	2.00E-02	3.30E-02	3.30E+00	8.00E-02	2.00E-01	5.70E+00	3.60E-01	9.70E-01	7.80E+00
Am-243	2.20E-01	3.50E-01	2.30E+00	3.20E-01	5.20E-01	2.10E+00	6.50E-01	1.20E+00	4.40E+00
Au-195	2.60E-02	4.30E-02	2.50E+00	3.00E-02	4.90E-02	2.40E+00	4.10E-02	6.80E-02	2.70E+00
Ba-133	4.10E-01	6.80E-01	2.30E+00	4.80E-01	7.90E-01	2.30E+00	5.40E-01	8.70E-01	2.30E+00
Bi-207	1.80E+00	2.90E+00	2.40E+00	2.10E+00	3.50E+00	2.40E+00	2.70E+00	4.20E+00	2.30E+00
C-14	1.90E-04	1.00E-03	7.90E+01	8.00E-03	2.90E-02	2.40E+01	6.60E-01	1.10E+00	1.00E+01
Ca-41	4.80E-04	2.50E-03	2.30E+01	4.80E-03	2.30E-02	2.30E+01	6.30E-02	2.70E-01	1.00E+01
Ca-45	6.00E-04	3.30E-03	2.40E+01	6.00E-03	3.30E-02	2.40E+01	7.70E-02	3.40E-01	1.10E+01
Cd-109	6.40E-03	2.20E-02	1.50E+01	4.00E-02	2.00E-01	2.40E+01	4.70E-01	2.10E+00	1.10E+01
Ce-141	1.00E-02	1.60E-02	2.30E+00	1.20E-02	1.90E-02	2.30E+00	1.20E-02	2.00E-02	2.30E+00
Ce-144	4.40E-02	7.20E-02	2.30E+00	5.30E-02	8.60E-02	2.20E+00	6.40E-02	1.00E-01	2.20E+00
Cf-252	2.30E-03	5.50E-03	7.60E+00	1.80E-02	5.00E-02	9.50E+00	9.20E-02	3.30E-01	1.20E+01
Cl-36	3.80E-02	2.50E-01	3.30E+01	4.90E-01	3.00E+00	3.10E+01	1.30E+01	5.80E+01	1.30E+01
Cm-243	1.40E-01	2.30E-01	2.40E+00	2.10E-01	3.30E-01	2.80E+00	4.20E-01	8.90E-01	4.20E+00
Cm-244	4.60E-03	9.80E-03	9.40E+00	3.90E-02	8.70E-02	1.10E+01	2.00E-01	5.60E-01	7.80E+00
Cm-246	8.60E-03	1.80E-02	5.60E+00	7.00E-02	1.70E-01	6.60E+00	3.50E-01	1.10E+00	6.90E+00
Cm-247	4.20E-01	6.80E-01	2.40E+00	5.60E-01	8.90E-01	2.30E+00	9.00E-01	1.60E+00	3.20E+00
Cm-248	3.20E-02	6.80E-02	5.60E+00	2.60E-01	6.20E-01	6.80E+00	1.30E+00	3.80E+00	8.30E+00
Co-57	7.60E-02	1.20E-01	2.40E+00	8.80E-02	1.40E-01	2.30E+00	1.10E-01	1.80E-01	2.30E+00
Co-60	2.90E+00	4.80E+00	2.30E+00	3.50E+00	5.80E+00	2.30E+00	4.80E+00	7.80E+00	2.30E+00
Cs-134	1.70E+00	2.70E+00	2.20E+00	2.10E+00	3.30E+00	2.20E+00	3.00E+00	5.00E+00	2.50E+00
Cs-135	3.30E-04	1.30E-03	1.60E+01	4.40E-03	1.60E-02	1.40E+01	6.50E-02	2.30E-01	8.60E+00
Cs-137	7.00E-01	1.10E+00	2.20E+00	8.90E-01	1.40E+00	2.40E+00	1.50E+00	2.60E+00	3.30E+00
Eu-152	1.30E+00	2.20E+00	2.40E+00	1.60E+00	2.60E+00	2.40E+00	1.90E+00	3.10E+00	2.30E+00
Eu-154	1.40E+00	2.40E+00	2.30E+00	1.70E+00	2.90E+00	2.30E+00	2.00E+00	3.30E+00	2.30E+00
Eu-155	4.00E-02	6.50E-02	2.40E+00	4.50E-02	7.30E-02	2.40E+00	4.90E-02	7.90E-02	2.30E+00
Fe-55	2.90E-06	5.40E-06	4.30E+00	5.30E-05	1.00E-04	3.50E+00	3.70E-04	6.70E-04	3.20E+00
Fe-59	2.70E-01	4.40E-01	2.30E+00	3.20E-01	5.30E-01	2.30E+00	3.80E-01	6.20E-01	2.30E+00

Table 7.1. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per pCi/g) for Three Source Configurations in the Residential Scenario (Continued)									
	Source Configurations								
	Area = 100 m^2; Thickness = 15 cm			Area = 2,400 m^2; Thickness = 15 cm			Area = 10,000 m^2; Thickness = 2 m		
Radionuclide	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%
Gd-152	1.40E-03	3.10E-03	9.80E+00	7.10E-03	1.80E-02	1.40E+01	4.20E-02	1.50E-01	9.60E+00
Gd-153	3.60E-02	5.90E-02	2.40E+00	4.00E-02	6.60E-02	2.40E+00	4.40E-02	7.10E-02	2.30E+00
Ge-68	7.30E-01	1.20E+00	2.40E+00	8.80E-01	1.40E+00	2.50E+00	1.40E+00	2.50E+00	4.80E+00
H-3	3.40E-05	1.80E-04	1.80E+01	3.00E-04	8.40E-04	6.80E+00	1.40E-02	2.20E-02	2.00E+00
I-125	1.20E-03	2.10E-03	3.20E+00	4.40E-03	1.10E-02	8.40E+00	4.30E-02	1.30E-01	6.60E+00
I-129	1.10E-02	9.90E-02	7.80E+01	1.00E-01	4.60E-01	3.10E+01	1.40E+00	5.70E+00	1.30E+01
Ir-192	2.80E-01	4.60E-01	2.30E+00	3.30E-01	5.40E-01	2.30E+00	3.70E-01	6.00E-01	2.30E+00
K-40	1.90E-01	3.10E-01	2.40E+00	3.00E-01	5.30E-01	4.20E+00	1.10E+00	3.70E+00	8.60E+00
Mn-54	7.10E-01	1.20E+00	2.30E+00	8.50E-01	1.40E+00	2.30E+00	1.10E+00	1.70E+00	2.20E+00
Na-22	2.30E+00	3.70E+00	2.40E+00	2.80E+00	4.50E+00	2.30E+00	3.60E+00	5.80E+00	2.20E+00
Nb-93	3.60E-05	5.90E-05	3.00E+00	7.50E-05	2.30E-04	1.20E+01	4.60E-04	1.70E-03	8.40E+00
Nb-94	1.90E+00	3.20E+00	2.30E+00	2.30E+00	3.80E+00	2.30E+00	2.70E+00	4.30E+00	2.30E+00
Nb-95	1.40E-01	2.30E-01	2.30E+00	1.60E-01	2.70E-01	2.30E+00	1.90E-01	3.00E-01	2.30E+00
Ni-59	9.90E-06	4.10E-05	1.70E+01	1.30E-04	4.60E-04	1.60E+01	1.70E-03	5.50E-03	7.60E+00
Ni-63	2.70E-05	1.10E-04	1.70E+01	3.50E-04	1.30E-03	1.60E+01	4.60E-03	1.50E-02	7.50E+00
Np-237	3.40E-01	6.30E-01	6.60E+00	1.00E+00	3.50E+00	1.00E+01	8.50E+00	2.80E+01	1.00E+01
Pa-231	3.00E-01	7.60E-01	5.00E+00	1.20E+00	4.70E+00	1.20E+01	1.10E+01	4.00E+01	1.20E+01
Pb-210	4.30E-02	1.50E-01	7.70E+00	4.50E-01	1.50E+00	7.60E+00	4.20E+00	1.00E+01	5.80E+00
Pm-147	1.40E-05	2.50E-05	2.60E+00	4.60E-05	1.10E-04	6.00E+00	2.40E-04	8.10E-04	9.60E+00
Po-210	8.30E-03	3.30E-02	1.60E+01	9.50E-02	3.50E-01	1.40E+01	9.30E-01	3.10E+00	8.10E+00
Pu-238	7.60E-03	1.40E-02	8.70E+00	6.20E-02	1.30E-01	1.00E+01	3.20E-01	9.20E-01	6.20E+00
Pu-239	8.30E-03	2.10E-02	5.50E+00	6.50E-02	1.90E-01	6.70E+00	3.50E-01	9.30E-01	7.90E+00
Pu-240	8.30E-03	1.80E-02	7.20E+00	6.90E-02	1.70E-01	8.60E+00	3.40E-01	1.00E+00	7.10E+00
Pu-241	4.10E-04	6.80E-04	3.20E+00	1.90E-03	4.30E-03	5.70E+00	1.30E-02	3.40E-02	6.40E+00
Pu-242	7.80E-03	1.60E-02	7.60E+00	6.50E-02	1.50E-01	8.30E+00	3.40E-01	9.50E-01	7.40E+00
Pu-244	1.60E+00	2.60E+00	2.20E+00	2.00E+00	3.20E+00	2.20E+00	2.60E+00	4.20E+00	2.20E+00
Ra-226	2.30E+00	3.70E+00	2.30E+00	3.50E+00	6.00E+00	2.60E+00	1.30E+01	2.50E+01	3.90E+00
Ra-228	1.90E+00	3.10E+00	2.40E+00	2.70E+00	5.00E+00	2.70E+00	7.10E+00	1.90E+01	6.70E+00
Ru-106	1.90E-01	3.20E-01	2.20E+00	2.40E-01	3.90E-01	2.30E+00	3.40E-01	5.50E-01	2.20E+00
S-35	1.80E-03	1.00E-02	2.80E+01	2.60E-02	1.70E-01	3.90E+01	7.60E-01	4.20E+00	2.80E+01
Sb-124	5.30E-01	8.70E-01	2.30E+00	6.30E-01	1.00E+00	2.30E+00	7.60E-01	1.20E+00	2.30E+00
Sb-125	4.60E-01	7.30E-01	2.40E+00	5.40E-01	8.70E-01	2.40E+00	6.10E-01	1.00E+00	2.30E+00
Sc-46	7.90E-01	1.30E+00	2.30E+00	9.50E-01	1.60E+00	2.30E+00	1.10E+00	1.80E+00	2.30E+00
Se-75	1.90E-01	3.00E-01	2.20E+00	2.30E-01	3.70E-01	2.30E+00	4.00E-01	9.10E-01	7.30E+00
Se-79	1.00E-03	5.00E-03	2.00E+01	1.60E-02	7.20E-02	2.00E+01	2.90E-01	1.40E+00	2.00E+01
Sm-147	8.70E-04	2.10E-03	1.60E+01	7.00E-03	1.90E-02	1.70E+01	4.70E-02	1.70E-01	9.90E+00
Sm-151	1.60E-06	4.10E-06	1.50E+01	1.40E-05	4.00E-05	1.60E+01	9.80E-05	3.50E-04	9.70E+00

Table 7.1. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per pCi/g) for Three Source Configurations in the Residential Scenario (Continued)

	Source Configurations								
	Area = 100 m^2; Thickness = 15 cm			Area = 2,400 m^2; Thickness = 15 cm			Area = 10,000 m^2; Thickness = 2 m		
Radionuclide	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 99%/ Dose @ 50%
Sn-113	1.30E-01	2.10E-01	2.30E+00	1.60E-01	2.50E-01	2.40E+00	2.30E-01	3.90E-01	3.50E+00
Sr-85	1.50E-01	2.50E-01	2.30E+00	1.90E-01	3.00E-01	2.30E+00	2.30E-01	3.80E-01	2.20E+00
Sr-89	9.00E-04	2.70E-03	1.10E+01	5.10E-03	2.40E-02	1.90E+01	6.00E-02	2.40E-01	9.90E+00
Sr-90	4.00E-02	1.70E-01	1.90E+01	3.70E-01	1.70E+00	2.20E+01	4.90E+00	1.90E+01	1.00E+01
Ta-182	6.20E-01	1.00E+00	2.30E+00	7.50E-01	1.20E+00	2.30E+00	8.90E-01	1.40E+00	2.40E+00
Tc-99	2.80E-03	1.70E-02	2.90E+01	2.70E-02	1.70E-01	3.10E+01	5.60E-01	2.10E+00	8.20E+00
Te-125	9.90E-04	1.60E-03	2.40E+00	1.80E-03	4.40E-03	8.70E+00	9.50E-03	3.50E-02	9.50E+00
Th-228	1.60E+00	2.60E+00	2.30E+00	2.00E+00	3.20E+00	2.20E+00	2.50E+00	4.00E+00	2.30E+00
Th-229	3.70E-01	5.90E-01	2.20E+00	5.30E-01	8.30E-01	2.20E+00	9.30E-01	1.70E+00	3.40E+00
Th-230	3.20E-02	4.20E-01	3.30E+01	6.00E-02	9.60E-01	3.30E+01	2.20E+00	5.80E+00	5.80E+00
Th-232	2.40E+00	4.00E+00	2.60E+00	3.50E+00	5.80E+00	2.70E+00	1.00E+01	2.20E+01	4.60E+00
Ti-204	1.50E-03	3.50E-03	8.60E+00	6.60E-03	3.10E-02	2.00E+01	8.60E-02	3.90E-01	1.40E+01
U-232	1.30E+00	2.30E+00	2.80E+00	1.60E+00	2.90E+00	2.80E+00	2.90E+00	4.60E+00	2.30E+00
U-233	2.10E-03	7.70E-03	2.10E+01	1.10E-02	4.00E-02	2.00E+01	9.10E-02	2.50E-01	1.80E+01
U-234	1.50E-03	3.70E-03	1.40E+01	9.90E-03	2.60E-02	1.40E+01	7.20E-02	2.10E-01	9.60E+00
U-235	1.70E-01	2.70E-01	2.30E+00	2.10E-01	3.20E-01	2.30E+00	3.40E-01	5.80E-01	4.00E+00
U-236	1.30E-03	3.60E-03	1.20E+01	9.10E-03	2.50E-02	7.70E+00	6.20E-02	1.90E-01	1.00E+01
U-238	2.90E-02	4.90E-02	3.40E+00	4.30E-02	7.40E-02	4.30E+00	1.00E-01	2.30E-01	1.30E+01
Zn-65	4.40E-01	7.50E-01	2.30E+00	6.10E-01	1.00E+00	2.50E+00	1.80E+00	4.40E+00	5

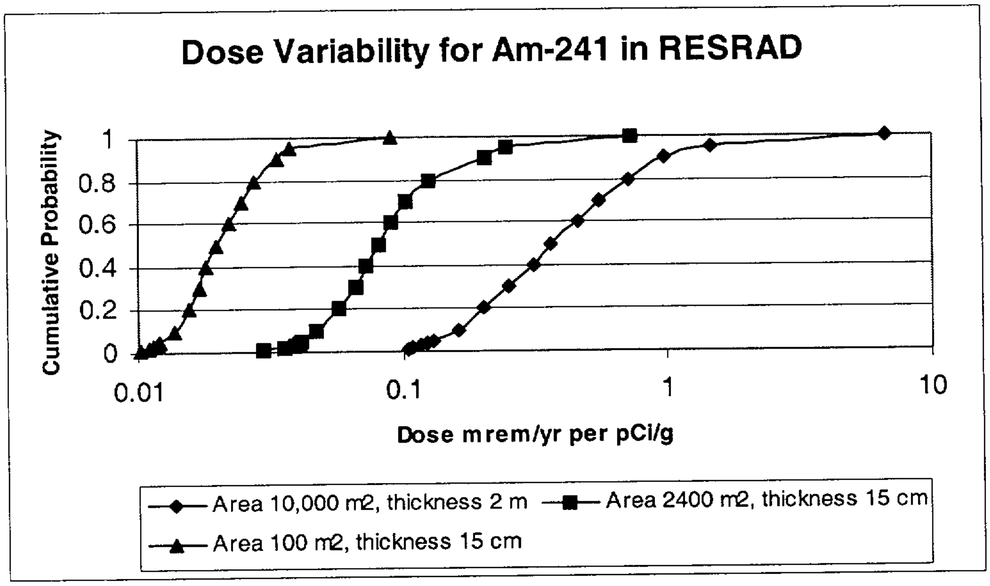

Figure 7.4 Dose Variability of Am-241 for Three Source Configurations in RESRAD

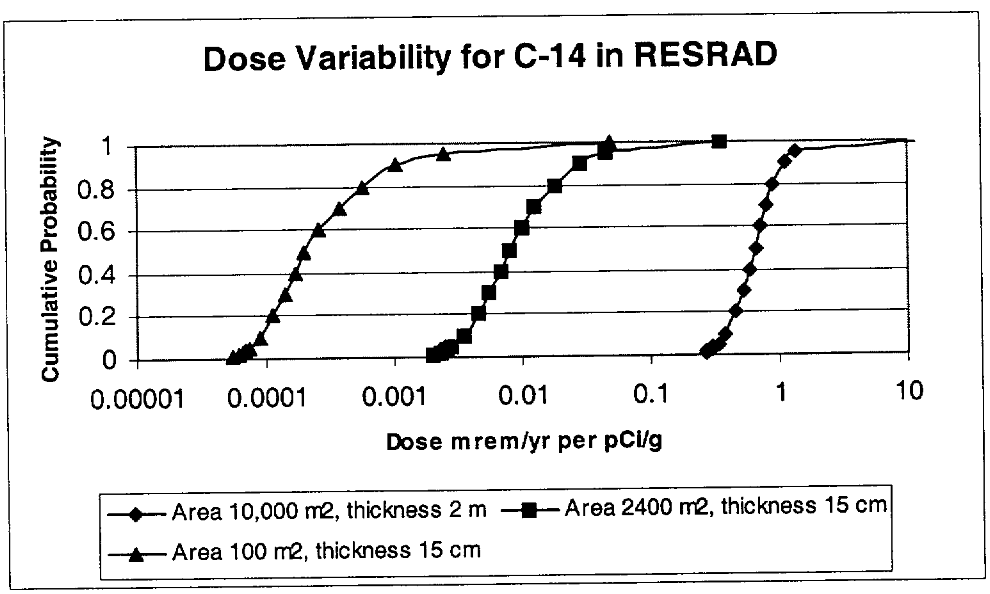

Figure 7.5 Dose Variability of C-14 for Three Source Configurations in RESRAD

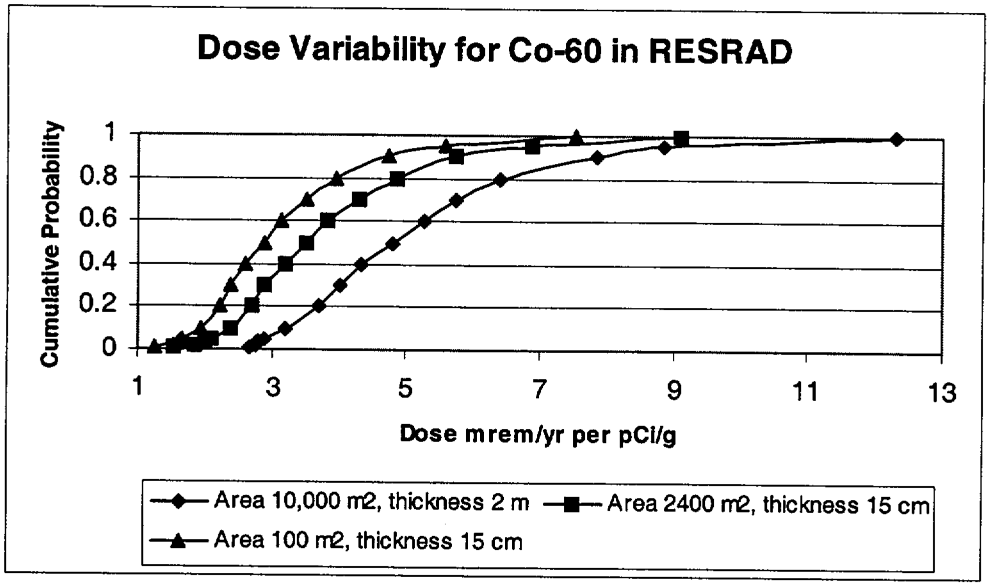

Figure 7.6 Dose Variability of Co-60 for Three Source Configurations in RESRAD

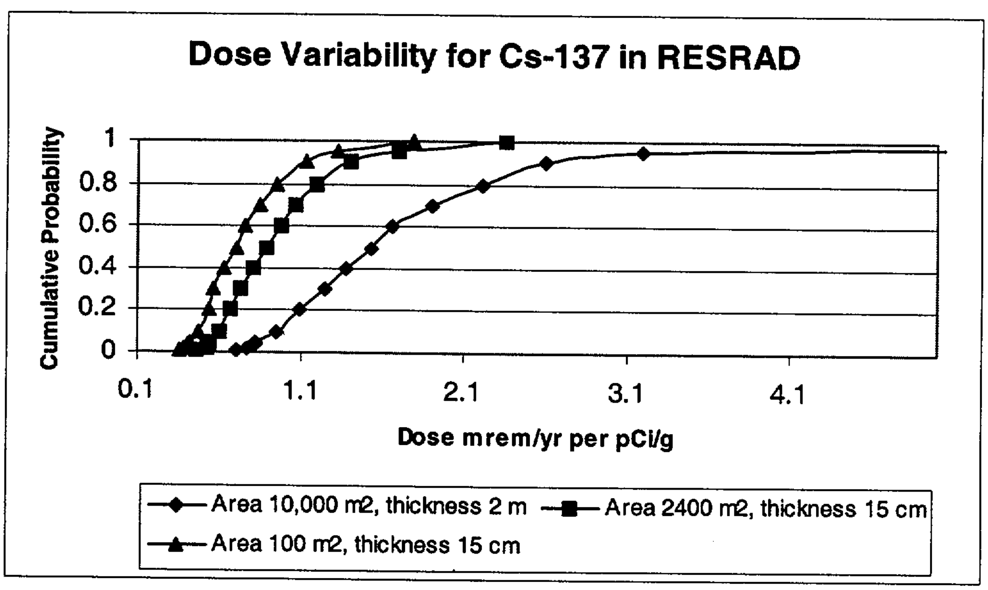

Figure 7.7 Dose Variability of Cs-137 for Three Source Configurations in RESRAD

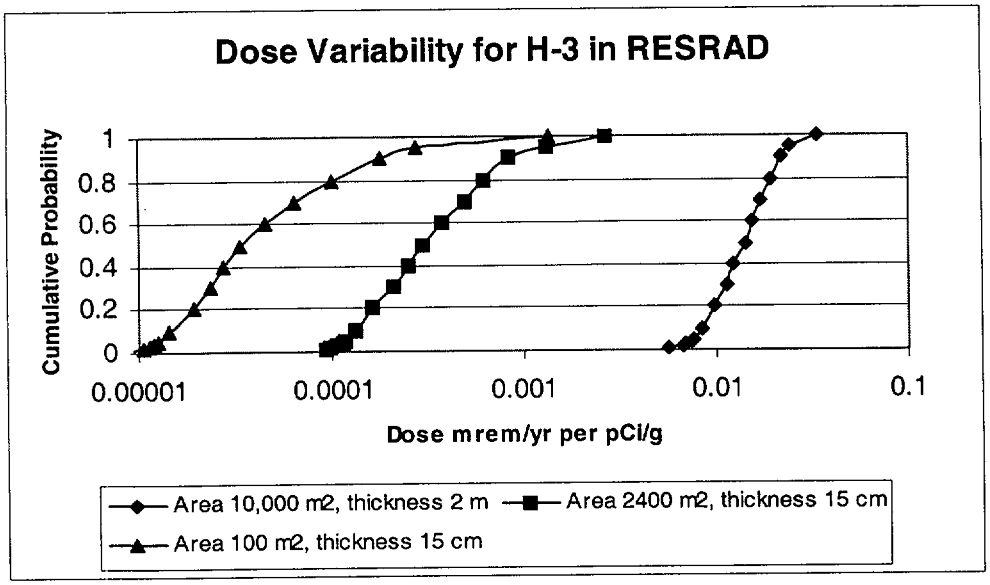

Figure 7.8 Dose Variability of H-3 for Three Source Configurations in RESRAD

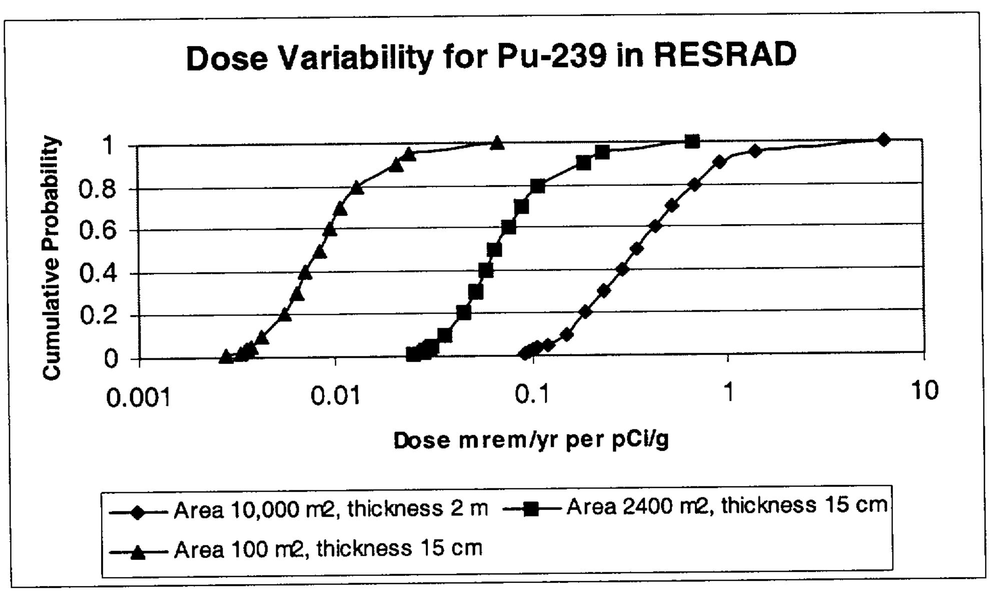

Figure 7.9 Dose Variability of Pu-239 for Three Source Configurations in RESRAD

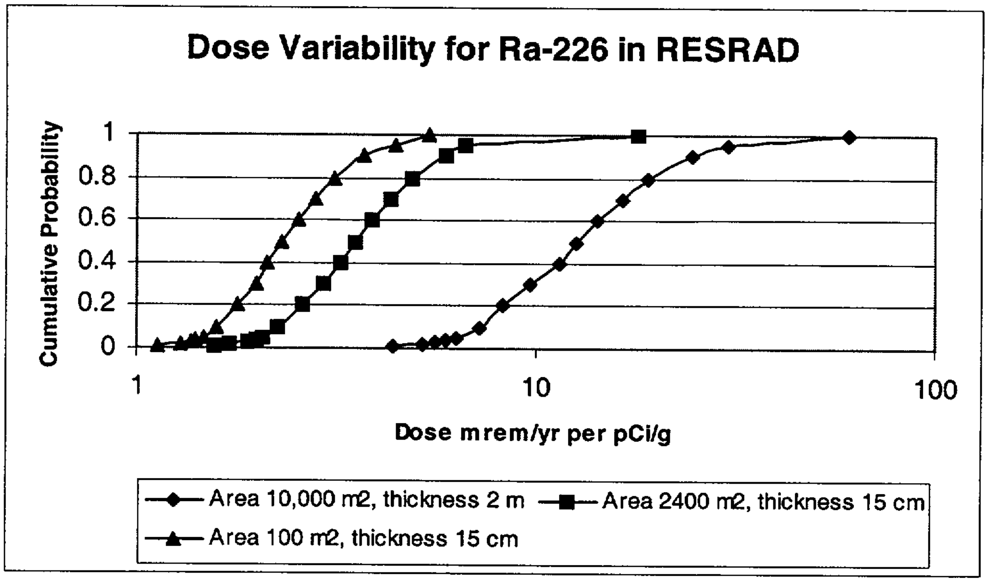

Figure 7.10 Dose Variability of Ra-226 for Three Source Configurations in RESRAD

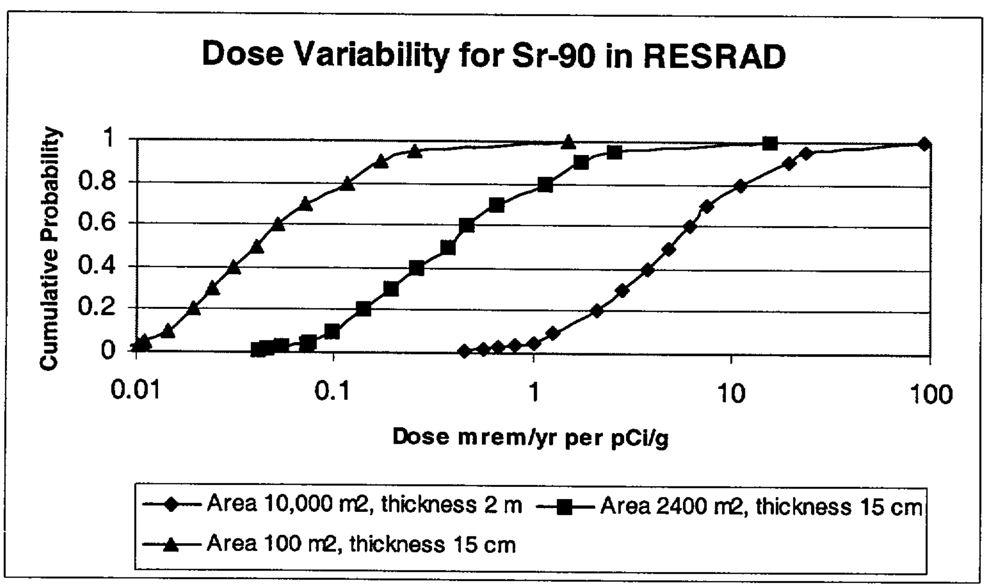

Figure 7.11 Dose Variability of Sr-90 for Three Source Configurations in RESRAD

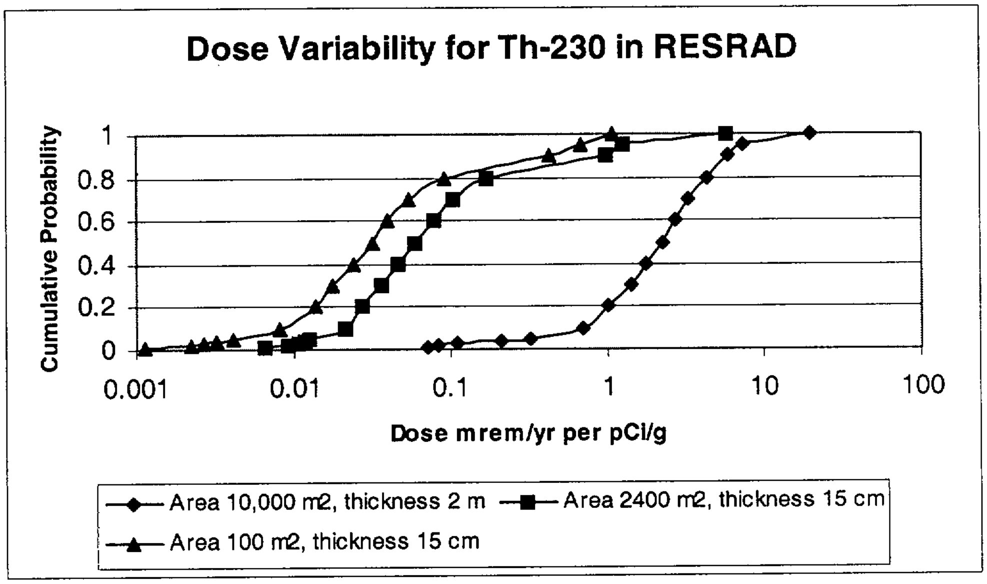

Figure 7.12 Dose Variability of Th-230 for Three Source Configurations in RESRAD

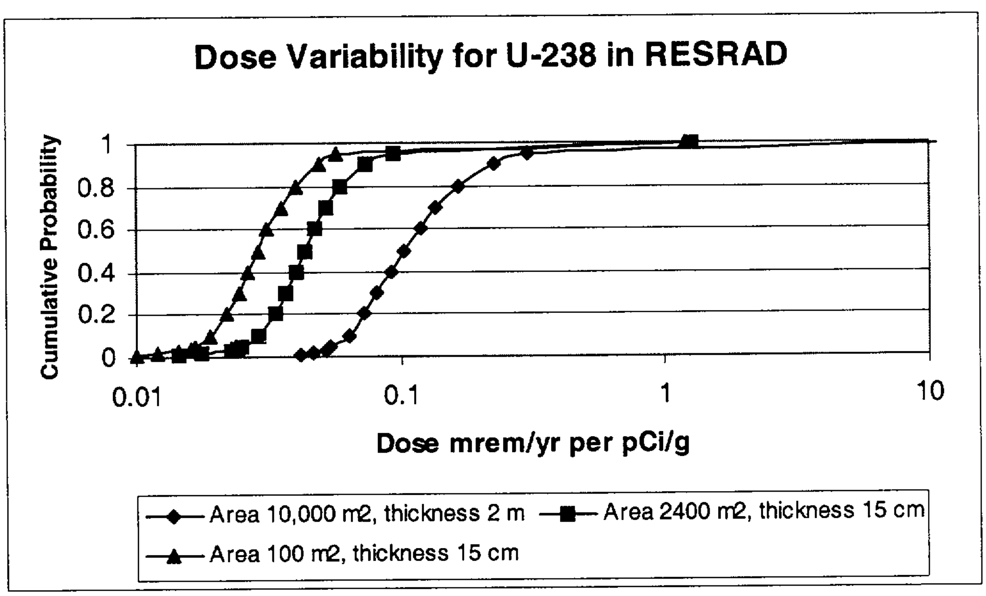

Figure 7.13 Dose Variability of U-238 for Three Source Configurations in RESRAD

Table 7.2. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 100 m^2 with Source Thickness of 15 cm

Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis			
			1	2	3	4
Ac-227+D[c]	ext	None	SHF1	DCACTC(1)	BRTF(89,1)	DM
Ag-108m+D	ext	None	SHF1	DCACTC(1)		
Ag-110m+D	ext	None	SHF1	DCACTC(1)		
Al-26	ext	None	SHF1	DCACTC(1)		
Am-241	plant + ext	< 30	SHF1	BRTF(95,1)	DROOT	DM
Am-243+D	ext	None	SHF1	DROOT		
Au-195	ext	None	SHF1	DCACTC(1)		
Ba-133	ext	None	SHF1	DCACTC(1)		
Bi-207	ext	None	SHF1	DCACTC(1)		
C-14	plant	> 30 - < 300	DROOT	DMC	DCACTS(1)	DCACTU1(1)
Ca-41	plant	> 30 - < 300	BRTF(20,1)	DROOT	HCSZ	
Ca-45	plant	None	BRTF(20,1)	DROOT		
Cd-109	plant	None	BRTF(48,1)	DROOT	DCACTC(1)	SHF1
Ce-141	ext	None	SHF1			
Ce-144+D	ext	None	SHF1			
Cf-252	plant	None	BRTF(98,1)	DM	DROOT	MLINH
Cl-36	plant	< 30	BRTF(17,1)	DROOT	DCACTC(1)	RUNOFF
Cm-243	ext	None	SHF1	BRTF(96,1)	DROOT	DM
Cm-244	plant	None	BRTF(96,1)	DM	DROOT	SHF3
Cm-246	plant	None	BRTF(96,1)	DROOT	DM	WIND
Cm-247	ext	< 30	SHF1	BRTF(96,1)	VCZ	
Cm-248	plant	None	BRTF(96,1)	DROOT	DM	MLINH
Co-57	ext	None	SHF1	DCACTC(1)		
Co-60	ext	None	SHF1	DCACTC(1)		
Cs-134	ext	None	SHF1	DCACTC(1)		
Cs-135	plant	< 30	BRTF(55,1)	DROOT	BRTF(55,2)	DM
Cs-137+D	ext	None	SHF1	DCACTC(1)		
Eu-152	ext	None	SHF1	DCACTC(2)		
Eu-154	ext	None	SHF1	DCACTC(1)		
Eu-155	ext	None	SHF1	DCACTC(1)		
Fe-55	meat + plant	None	DM	BRTF(26,2)	BRTF(26,1)	DROOT
Fe-59	ext	None	SHF1	DCACTC(1)		
Gd-152	plant + inh	< 30	BRTF(64,1)	DM	MLINH	DROOT
Gd-153	ext	None	SHF1	DCACTC(1)		
Ge-68+D	ext	None	SHF1	DCACTC(1)		
H-3	water + plant	> 30 - < 300	DROOT	HCSZ	HGWT	H(1)
I-125	ext	None	SHF1	BRTF(53,1)	DCACTC(1)	DROOT
I-129	water + plant	> 30 - < 300	BRTF(53,1)	DROOT	DCACTC(1)	HCSZ
Ir-192	ext	None	SHF1	DCACTC(1)		
K-40	ext	None	SHF1	DCACTC(1)	BRTF(19,1)	RUNOFF
Mn-54	ext	None	SHF1	DCACTC(1)		

Table 7.2. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 100 m² with Source Thickness of 15 cm (Continued)

Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis			
			1	2	3	4
Na-22	ext	None	SHF1	DCACTC(1)		
Nb-93m	ext + plant	None	SHF1	BRTF(41,1)	DROOT	DCACTC(1)
Nb-94	ext	None	SHF1	DCACTC(1)		
Nb-95	ext	None	SHF1	DCACTC(1)		
Ni-59	plant	None	BRTF(28,1)	DROOT	BRTF(28,3)	
Ni-63	plant	None	BRTF(28,1)	DROOT	BRTF(28,3)	
Np-237+D	plant + ext	< 30	BRTF(93,1)	SHF1	DROOT	DCACTC(1)
Pa-231	plant	> 30 - < 300	BRTF(91,1)	DCACTC(2)	VCZ	DROOT
Pb-210+D	plant	> 30 - < 300	DROOT	BRTF(82,1)	BRTF(84,1)	DM
Pm-147	ext + plant	None	SHF1	BRTF(61,1)	DROOT	BCZ
Po-210	plant	None	BRTF(84,1)	DROOT	DM	BRTF(84,2)
Pu-238	plant	None	BRTF(94,1)	DM	DROOT	MLINH
Pu-239	plant	None	BRTF(94,1)	DM	DROOT	MLINH
Pu-240	plant	None	BRTF(94,1)	DM	DROOT	MLINH
Pu-241+D	plant	> 30 - < 300	VCZ	SHF1	DCACTC(1)	DROOT
Pu-242	plant	None	BRTF(94,1)	DM	DROOT	MLINH
Pu-244+D	ext	None	SHF1	VCZ		
Ra-226+D	ext	< 30	SHF1	BRTF(88,1)	DROOT	VCZ
Ra-228+D	ext	> 30 - < 300	SHF1	VCZ	DROOT	BRTF(88,1)
Ru-106+D	ext	None	SHF1	DCACTC(1)		
S-35	plant + meat	None	BRTF(16,1)	DROOT	BRTF(16,2)	DCACTC(1)
Sb-124	ext	None	SHF1	DCACTC(1)		
Sb-125+D	ext	None	SHF1	DCACTC(2)		
Sc-46	ext	None	SHF1	DCACTC(1)		
Se-75	ext	None	SHF1			
Se-79	plant	None	BRTF(34,1)	DROOT	BRTF(34,2)	
Sm-147	plant	< 30	BRTF(62,1)	DROOT	DM	MLINH
Sm-151	plant	< 30	BRTF(62,1)	DROOT	DM	BRTF(62,2)
Sn-113	ext	None	SHF1	DCACTC(1)		
Sr-85	ext	None	SHF1	DCACTC(1)		
Sr-89	plant	None	BRTF(38,1)	DROOT	SHF1	DCACTC(1)
Sr-90+D	plant	< 30	BRTF(38,1)	DROOT	DCACTC(1)	SHF1
Ta-182	ext	None	SHF1	DCACTC(1)		
Tc-99	plant	< 30	BRTF(43,1)	DROOT	DCACTC(1)	RUNOFF
Te-125m	ext	None	SHF1	BRTF(52,1)	DCACTC(1)	DROOT
Th-228+D	ext	None	SHF1	DCACTC(1)		
Th-229+D	ext	None	SHF1	DCACTC(1)		
Th-230+D	ext	> 30 - < 300	VCZ	DCACTC(4)	SHF1	
Th-232	ext	> 30 - < 300	SHF1	VCZ	DCACTC(3)	
Tl-204	plant	None	BRTF(81,1)	SHF1	DROOT	DCACTC(1)
U-232	ext	> 30 - < 300	SHF1	DCACTC(2)	VCZ	
U-233	ext + plant	> 30 - < 300	DCACTC(2)	VCZ	BRTF(92,1)	DROOT
U-234	plant	> 30 - < 300	BRTF(92,1)	DROOT	DM	VCZ
U-235+D	ext	< 30	SHF1	DCACTC(3)		
U-236	plant	< 30	BRTF(92,1)	DROOT	DM	MLINH
U-238+D	ext	< 30	SHF1	DCACTC(6)		

Table 7.2. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 100 m^2 with Source Thickness of 15 cm (Continued)						
Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis 1	2	3	4
Zn-65	ext	None	SHF1	DCACTC(1)		
Zr-93	water	>30 - < 300	HCSZ	HGWT	H(1)	VCZ
Zr-95	ext	None	SHF1	DCACTC(3)		

[a] Pathways: ext = external, inh = inhalation, plant = plant ingestion, meat = meat ingestion, fish = fish ingestion, water = water ingestion.

[b] Parameters are listed only if PRCC was greater than 0.25. Descriptive name of the parameters is provided in Table B.1 in Appendix B. There are two indexes associated with BRTF, the first index represents the listing order of the responsible radionuclide in the RESRAD database and the second index represents whether it is plant ingestion (1), meat ingestion (2), or milk ingestion (3). DCACT's have one index associated with them, it indicates whether it is a principal radionuclide (index of 1) or a progeny in the chain.

[c] +D indicates, that associated radionuclides with half-lives less than 30 days are in secular equilibrium with the principal radionuclide.

Tables C.1 through C.3 in Appendix C. These tables also list radionuclides with their dominant pathways. Our analysis of the results indicated that only PRCC values of greater than 0.25 were significant; therefore, only the sensitive parameters with PRCC values of 0.25 or greater are listed in Tables 7.2 through 7.4 and Tables C.1 through C.3 in Appendix C.

For the external exposure pathway, the external gamma shielding factor was found to be the main contributor to dose variability. Three radionuclides (Co-60, Na-22, and Ag-108) for which external exposure was the dominant pathway were selected to study the effects of shielding factor on dose variability. Uncertainty runs were performed after removing the uncertainty on shielding factor for Co-60, Na-22, and Ag-108 for all three source configurations. It was observed that the dose variability was significantly reduced. Figure 7.14 shows the dose ratio (99th percentile dose to 50th percentile dose) with and without the shielding factor uncertainty.

For the plant ingestion pathway, plant transfer factors were found to be the main contributors to the dose variability. Three radionuclides (Ca-41, Sr-90, and Cm-244) for which plant ingestion was the dominant pathway were selected to study the effect of the plant transfer factor. Uncertainty runs were performed after removing the uncertainty on plant transfer factor for Ca-41, Sr-90, and Cm-244 for all three source configurations. The dose variability was significantly reduced. Figure 7.15 shows the dose ratio (99th percentile dose to 50th percentile dose) with and without the plant transfer factor uncertainty. It was observed that for radionuclides for which peak dose was always at time 0, it was possible to get more than 90th percentile dose by just setting the external gamma shielding factor, plant transfer factor, and meat transfer factor at 90th percentile values (all other parameters were set at mean or median values).

As mentioned above, no single correlation or regression coefficient can be used to identify sensitive parameters in all the cases. The rankings based on the SRRC were not reliable in the residential scenario because of the strong input correlations between total porosity, effective porosity, and bulk density. It was observed that a large numerical value of SRRC for one parameter was being negated or

Table 7.3. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 2,400 m^2 with Source Thickness of 15 cm						
Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis			
			1	2	3	4
Ac-227+D[c]	plant	None	SHF1	BRTF(89,1)	DROOT	DM
Ag-108m+D	ext	None	SHF1	DCACTC(1)		
Ag-110m+D	ext	None	SHF1	DCACTC(1)		
Al-26	ext	None	SHF1	DCACTC(1)		
Am-241	plant	None	BRTF(95,1)	DROOT	DM	SHF1
Am-243+D	ext	None	SHF1	BRTF(95,1)	DROOT	DM
Au-195	ext	None	SHF1	DCACTC(1)		
Ba-133	ext	None	SHF1	DCACTC(1)		
Bi-207	ext	None	SHF1	DCACTC(1)		
C-14	plant	> 30 - < 300	DROOT	DMC	WIND	DCACTU1(1)
Ca-41	plant	< 30	BRTF(20,1)	DROOT	DCACTC(1)	HCSZ
Ca-45	plant	None	BRTF(20,1)	DROOT		
Cd-109	plant	None	BRTF(48,1)	DROOT	DCACTC(1)	
Ce-141	ext	None	SHF1			
Ce-144+D	ext	None	SHF1			
Cf-252	plant	None	BRTF(98,1)	DROOT	DM	
Cl-36	plant	None	BRTF(17,1)	DROOT	DCACTC(1)	BRTF(17,2)
Cm-243	ext	None	SHF1	BRTF(96,1)	DROOT	DM
Cm-244	plant	None	BRTF(96,1)	DROOT	DM	
Cm-246	plant	None	BRTF(96,1)	DROOT	DM	
Cm-247	ext	< 30	SHF1	BRTF(96,1)	DROOT	DM
Cm-248	plant	None	BRTF(96,1)	DROOT	DM	
Co-57	ext	None	SHF1	DCACTC(1)		
Co-60	ext	None	SHF1	DCACTC(1)		
Cs-134	ext	None	SHF1	DCACTC(1)	BRTF(55,1)	
Cs-135	plant	< 30	BRTF(55,1)	DROOT	BRTF(55,2)	DM
Cs-137+D	ext	None	SHF1	BRTF(55,1)	DCACTC(1)	DROOT
Eu-152	ext	None	SHF1	DCACTC(2)		
Eu-154	ext	None	SHF1	DCACTC(1)		
Eu-155	ext	None	SHF1	DCACTC(1)		
Fe-55	meat	None	DM	BRTF(26,2)	BRTF(26,1)	DROOT
Fe-59	ext	None	SHF1	DCACTC(1)		
Gd-152	plant	< 30	BRTF(64,1)	DROOT	DM	BRTF(64,2)
Gd-153	ext	None	SHF1	DCACTC(1)		
Ge-68+D	ext	None	SHF1	DCACTC(1)		
H-3	plant	> 30 - < 300	DROOT	RUNOFF	HCSZ	H(1)
I-125	plant	None	BRTF(53,1)	DROOT	DCACTC(1)	DM
I-129	water + plant	> 30 - < 300	BRTF(53,1)	DROOT	DCACTC(1)	HCSZ
Ir-192	ext	None	SHF1	DCACTC(1)		
K-40	ext + plant	None	SHF1	BRTF(19,1)	DROOT	DCACTC(1)
Mn-54	ext	None	SHF1	DCACTC(1)		
Na-22	ext	None	SHF1	DCACTC(1)		

Table 7.3. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 2,400 m^2 with Source Thickness of 15 cm (Continued)						
Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis 1	2	3	4
Nb-93m	plant	None	BRTF(41,1)	DROOT	SHF1	DCACTC(1)
Nb-94	ext	None	SHF1	DCACTC(1)		
Nb-95	ext	None	SHF1	DCACTC(1)		
Ni-59	plant	None	BRTF(28,1)	DROOT	BRTF(28,3)	DM
Ni-63	plant	None	BRTF(28,1)	DROOT	BRTF(28,3)	DM
Np-237+D	plant	< 30	BRTF(93,1)	DROOT	DCACTC(1)	SHF1
Pa-231	plant	> 30 - < 300	BRTF(91,1)	DROOT	VCZ	DCACTC(2)
Pb-210+D	plant	> 30 - < 300	DROOT	BRTF(82,1)	BRTF(84,1)	DM
Pm-147	plant	None	BRTF(61,1)	DROOT	DM	BRTF(61,2)
Po-210	plant	None	BRTF(84,1)	DROOT	BRTF(84,2)	DM
Pu-238	plant	None	BRTF(94,1)	DROOT	DM	
Pu-239	plant	None	BRTF(94,1)	DROOT	DM	
Pu-240	plant	None	BRTF(94,1)	DROOT	DM	
Pu-241+D	plant	> 30 - < 300	DROOT	DM	BRTF(94,1)	BRTF(95,1)
Pu-242	plant	None	BRTF(94,1)	DROOT	DM	
Pu-244+D	ext	None	SHF1	BRTF(94,1)	DROOT	
Ra-226+D	ext + plant	> 30 - < 300	SHF1	BRTF(88,1)	DROOT	
Ra-228+D	ext + plant	> 30 - < 300	SHF1	BRTF(88,1)	DROOT	VCZ
Ru-106+D	ext	None	SHF1	BRTF(44,1)	DCACTC(1)	DROOT
S-35	meat	None	BRTF(16,1)	BRTF(16,2)	DROOT	DCACTC(1)
Sb-124	ext	None	SHF1	DCACTC(1)		
Sb-125+D	ext	None	SHF1	DCACTC(2)		
Sc-46	ext	None	SHF1	DCACTC(1)		
Se-75	ext	None	SHF1	BRTF(34,1)	DROOT	BRTF(34,2)
Se-79	meat	None	BRTF(34,1)	DROOT	BRTF(34,2)	DM
Sm-147	plant	< 30	BRTF(62,1)	DROOT	DM	BRTF(62,2)
Sm-151	plant	< 30	BRTF(62,1)	DROOT	BRTF(62,2)	DM
Sn-113	ext	None	SHF1	BRTF(50,1)	DCACTC(1)	DROOT
Sr-85	ext	None	SHF1	DCACTC(1)	RUNOFF	
Sr-89	plant	None	BRTF(38,1)	DROOT		
Sr-90+D	plant	None	BRTF(38,1)	DROOT	DCACTC(1)	
Ta-182	ext	None	SHF1	DCACTC(1)		
Tc-99	plant	< 30	BRTF(43,1)	DCACTC(1)	DROOT	RUNOFF
Te-125m	plant	None	BRTF(52,1)	DROOT	SHF1	DCACTC(1)
Th-228+D	ext	None	SHF1	DCACTC(1)		
Th-229+D	ext	None	SHF1	BRTF(90,1)	DROOT	DM
Th-230+D	ext	> 30 - < 300	VCZ	DCACTC(4)	SHF1	DROOT
Th-232	ext	> 30 - < 300	SHF1	VCZ	DCACTC(3)	BRTF(88,1)
Tl-204	plant	None	BRTF(81,1)	DROOT	DCACTC(1)	BRTF(81,2)
U-232	ext	> 30 - < 300	DCACTC(2)	SHF1	VCZ	
U-233	plant	> 30 - < 300	BRTF(92,1)	DROOT	DM	DCACTC(2)
U-234	plant	< 30	BRTF(92,1)	DROOT	DM	
U-235+D	ext	< 30	SHF1	DCACTC(3)	BRTF(92,1)	
U-236	plant	< 30	BRTF(92,1)	DROOT	DM	DCACTC(4)
U-238+D	ext + plant	< 30	SHF1	BRTF(92,1)	DROOT	DCACTC(6)
Zn-65	ext	None	SHF1	BRTF(30,1)	DCACTC(1)	DROOT

Table 7.3. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 2,400 m^2 with Source Thickness of 15 cm (Continued)

Radionuclide	Dominant Pathway[a]	Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis 1	2	3	4
Zr-93	water	> 30 - < 300	HCSZ	HGWT	H(1)	VCZ
Zr-95	ext	None	SHF1			

[a] Pathways: ext = external, inh = inhalation, plant = plant ingestion, meat = meat ingestion, fish = fish ingestion, water = water ingestion.

[b] Parameters are listed only if PRCC was greater than 0.25. Descriptive name of the parameters is provided in Table B.1 in Appendix B. There are two indexes associated with BRTF, the first index represents the listing order of the responsible radionuclide in the RESRAD database and the second index represents whether it is plant ingestion (1), meat ingestion (2), or milk ingestion (3). DCACT's have one index associated with them, it indicates whether it is a principal radionuclide (index of 1) or a progeny in the chain.

[c] +D indicates, that associated radionuclides with half-lives less than 30 days are in secular equilibrium with the principal radionuclide.

countered by the contributions of other correlated parameters for many radionuclides. Analysis of U-233 is presented as an example. Table 7.5 gives the PRCC and SRRC values for the four top ranked parameters for U-233 in two source configurations (100 m^2 area with a thickness of 15 cm and 10,000 m^2 area with a thickness of 2 m).

For the first source configuration (area = 2,400 m^2 and thickness = 15 cm), SRRC identified density of unsaturated zone (DENSUZ), total porosity of unsaturated zone (TPUZ), plant transfer factor for U-233 [BRTF(92,1)], and effective porosity of the unsaturated zone (EPUZ) as the top four ranked parameters. PRCC identified plant transfer factor for U-233 [BRTF(92,1)], depth of roots (DROOT), depth of mixing layer (DM), and distribution coefficient of contaminated zone [DCACTC(2)] as the top four ranked parameters. Figures 7.16 through 7.19 show the scatter plots of the four top ranked parameters identified by SRRC with the total dose. Scatter plots of DENSUZ (Figure 7.17), TPUZ (Figure 7.18), and EPUZ (Figure 7.19) show no clear relationship between dose and the respective parameter. High SRRC values are the artifact of the strong correlation between bulk density, total porosity, and effective porosity. The scatter plot of plant transfer factor for U-233 (Figure 7.16) shows some relationship with total dose.

For the second source configuration (area = 10,000 m^2 and thickness = 2 m) SRRC identified density of the saturated zone (DENSAQ), effective porosity of the saturated zone (EPSZ), total porosity of the saturated zone (TPSZ), and plant transfer factor for U-233 [BRTF(92,1)] as the top four ranked parameters. PRCC identified plant transfer factor for U-233 [BRTF(92,1)], depth of roots (DROOT), distribution coefficient of contaminated zone [DCACTC(2)], and erosion rate of contaminated zone (VCZ) as the top four ranked parameters. Figures 7.20 through 7.23 show the scatter plots of the four top ranked parameters identified by SRRC with the total dose. Scatter plots of DENSAQ (Figure 7.21), EPSZ (Figure 7.22), and TPSZ (Figure 7.23) show no clear relationship between dose and the respective parameter. High SRRC values are the artifact of the strong correlation between bulk density, total porosity, and effective porosity. The scatter plot of plant transfer factor for U-233 (Figure 7.20) shows some relationship with total dose.

Table 7.4. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 10,000 m^2 with Source Thickness of 2 m						
		Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis			
Radionuclide	Dominant Pathway[a]		1	2	3	4
Ac-227+D[c]	plant	None	BRTF(89,1)	SHF1	DROOT	
Ag-108m+D	ext	None	SHF1	DCACTC(1)		
Ag-110m+D	ext	None	SHF1			
Al-26	ext	< 30	SHF1	DCACTC(1)		
Am-241	plant	< 30	BRTF(95,1)	DROOT		
Am-243+D	plant	< 30	BRTF(95,1)	SHF1	DROOT	
Au-195	ext + plant	None	SHF1	BRTF(79,1)	DROOT	
Ba-133	ext	None	SHF1	BRTF(56,1)	DCACTC(1)	
Bi-207	ext	None	SHF1	BRTF(83,1)	DCACTC(1)	
C-14	plant	< 30	WIND	DROOT	DMC	DCACTS(1)
Ca-41	plant	> 30 - < 300	BRTF(20,1)	DROOT	BBIO(20,1)	HCSZ
Ca-45	plant	None	BRTF(20,1)	DROOT	BRTF(20,3)	
Cd-109	plant	None	BRTF(48,1)	DROOT	BRTF(48,3)	
Ce-141	ext	None	SHF1	BRTF(58,1)		
Ce-144+D	ext	None	SHF1	BRTF(58,1)		
Cf-252	plant	None	BRTF(98,1)	DROOT		
Cl-36	meat	None	BRTF(17,1)	BRTF(17,2)	DROOT	BRTF(17,3)
Cm-243	plant	None	BRTF(96,1)	SHF1	DROOT	BRTF(95,3)
Cm-244	plant	None	BRTF(96,1)	DROOT		
Cm-246	plant	None	BRTF(96,1)	DROOT		
Cm-247	plant	> 30 - < 300	BRTF(96,1)	SHF1	DROOT	
Cm-248	plant	None	BRTF(96,1)	DROOT		
Co-57	ext	None	SHF1	BRTF(27,1)	BRTF(27,2)	DROOT
Co-60	ext	None	SHF1	BRTF(27,1)	BRTF(27,2)	
Cs-134	ext	None	SHF1	BRTF(55,1)	DROOT	BRTF(55,2)
Cs-135	meat	None	BRTF(55,1)	BRTF(55,2)	DROOT	BRTF(55,3)
Cs-137+D	plant + ext	None	BRTF(55,1)	SHF1	DROOT	BRTF(55,2)
Eu-152	ext	None	SHF1	DCACTC(2)		
Eu-154	ext	None	SHF1	DCACTC(1)		
Eu-155	ext	None	SHF1	BRTF(63,1)	DCACTC(1)	
Fe-55	meat	None	BRTF(26,2)	BRTF(26,1)	DROOT	
Fe-59	ext	None	SHF1			
Gd-152	plant	< 30	BRTF(64,1)	BRTF(64,2)	DROOT	
Gd-153	ext	None	SHF1	BRTF(64,1)	DCACTC(1)	
Ge-68+D	ext + meat	None	SHF1	BRTF(32,1)	BRTF(32,2)	DROOT
H-3	plant	< 30	DROOT	RUNOFF	HCCZ	DCACTC(1)
I-125	plant+meat	None	BRTF(53,1)	BRTF(53,2)	DROOT	BRTF(53,3)
I-129	meat + water	> 30 - < 300	BRTF(53,1)	BRTF(53,2)	DROOT	HCSZ
Ir-192	ext	None	SHF1	BRTF(77,1)	DCACTC(1)	
K-40	plant	< 30	BRTF(19,1)	DROOT	SHF1	BRTF(19,3)
Mn-54	ext	None	SHF1	BRTF(25,1)	DROOT	
Na-22	ext	None	SHF1	BRTF(11,1)	DCACTC(1)	
Nb-93m	plant	None	BRTF(41,1)	DROOT	SHF1	

Table 7.4. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 10,000 m^2 with Source Thickness of 2 m (Continued)						
		Sample Runs with Peak Doses at Times Other Than Zero	Four Most Sensitive Parameters[b] Based on PRCC Analysis			
Radionuclide	Dominant Pathway[a]		1	2	3	4
Nb-94	ext	< 30	SHF1	DCACTC(1)		
Nb-95	ext	None	SHF1	BRTF(41,1)	DCACTC(1)	
Ni-59	plant	None	BRTF(28,1)	BRTF(28,3)	DROOT	BRTF(28,2)
Ni-63	plant	None	BRTF(28,1)	BRTF(28,3)	DROOT	BRTF(28,2)
Np-237+D	plant	< 30	BRTF(93,1)	DROOT	HCSZ	
Pa-231	plant	> 30 - < 300	BRTF(91,1)	DROOT	BRTF(89,1)	
Pb-210+D	plant	> 30 - < 300	BRTF(82,1)	BRTF(84,1)	DROOT	BRTF(84,2)
Pm-147	plant	None	BRTF(61,1)	BRTF(61,2)	DROOT	
Po-210	plant	None	BRTF(84,1)	DROOT	BRTF(84,2)	
Pu-238	plant	None	BRTF(94,1)	DROOT		
Pu-239	plant	None	BRTF(94,1)	DROOT		
Pu-240	plant	None	BRTF(94,1)	DROOT		
Pu-241+D	plant	> 30 - < 300	BRTF(95,1)	BRTF(94,1)	DROOT	
Pu-242	plant	< 30	BRTF(94,1)	DROOT		
Pu-244+D	ext	> 30 - < 300	SHF1	BRTF(94,1)	DROOT	
Ra-226+D	plant	> 30 - < 300	BRTF(88,1)	DROOT	BRTF(82,1)	BRTF(84,1)
Ra-228+D	plant	>30 - < 300	BRTF(88,1)	DROOT	SHF1	
Ru-106+D	ext + plant	None	SHF1	BRTF(44,1)	DROOT	
S-35	meat	None	BRTF(16,1)	BRTF(16,2)	DROOT	
Sb-124	ext	None	SHF1	BRTF(51,1)	DCACTC(1)	
Sb-125+D	ext	None	SHF1	BRTF(52,1)	DCACTC(2)	
Sc-46	ext	None	SHF1	DCACTC(1)	TPUZ(1)	
Se-75	meat	None	BRTF(34,1)	SHF1	BRTF(34,2)	DROOT
Se-79	meat	None	BRTF(34,1)	BRTF(34,2)	DROOT	BRTF(34,3)
Sm-147	plant	< 30	BRTF(62,1)	BRTF(62,2)	DROOT	
Sm-151	plant	< 30	BRTF(62,1)	BRTF(62,2)	DROOT	
Sn-113	ext + plant	None	SHF1	BRTF(50,1)	DROOT	BRTF(50,2)
Sr-85	ext	None	SHF1	BRTF(38,1)	DROOT	
Sr-89	plant	None	BRTF(38,1)	DROOT	BRTF(38,2)	
Sr-90+D	plant	None	BRTF(38,1)	DROOT	BRTF(38,2)	
Ta-182	ext	None	SHF1	DCACTC(1)		
Tc-99	plant	< 30	BRTF(43,1)	DROOT	DCACTC(1)	EVAPTR
Te-125m	plant	None	BRTF(52,1)	DROOT	BRTF(52,2)	SHF1
Th-228+D	ext	None	SHF1	BRTF(90,1)		
Th-229+D	plant	None	BRTF(90,1)	SHF1	DROOT	
Th-230+D	plant	> 30 - < 300	VCZ	DROOT	DCACTC(4)	BRTF(88,1)
Th-232	plant	300	BRTF(88,1)	SHF1	DROOT	BRTF(90,1)
Tl-204	plant+meat	None	BRTF(81,1)	BRTF(81,2)	DROOT	
U-232	ext	300	SHF1	DCACTC(2)	BRTF(92,1)	DROOT
U-233	plant	> 30 - < 300	BRTF(92,1)	DROOT	DCACTC(2)	VCZ
U-234	water + plant	> 30 - < 300	BRTF(92,1)	DROOT	DCACTU1(5)	
U-235+D	plant	> 30 - < 300	SHF1	BRTF(92,1)	BRTF(91,1)	DCACTC(3)
U-236	plant	< 30	BRTF(92,1)	DROOT		
U-238+D	plant	< 30	BRTF(92,1)	SHF1	DROOT	

Table 7.4. Four Most Sensitive Parameters Based on PRCC Analysis, Dominant Pathways, and Number of Sample Runs with Peak Dose at Times Other Than Time Zero for Source Area of 10,000 m^2 with Source Thickness of 2 m (Continued)

Zn-65	meat	None	BRTF(30,1)	SHF1	DROOT	BRTF(30,2)
Zr-93	water	> 30 - < 300	H(1)	HCSZ	HGWT	FR9
Zr-95	ext	None	SHF1			

[a] Pathways: ext = external, inh = inhalation, plant = plant ingestion, meat = meat ingestion, fish = fish ingestion, water = water ingestion.

[b] Parameters are listed only if PRCC was greater than 0.25. Descriptive name of the parameters is provided in Table B.1 in Appendix B. There are two indexes associated with BRTF, the first index represents the listing order of the responsible radionuclide in the RESRAD database and the second index represents whether it is plant ingestion (1), meat ingestion (2), or milk ingestion (3). DCACT's have one index associated with them, it indicates whether it is a principal radionuclide (index of 1) or a progeny in the chain.

[c] +D indicates, that associated radionuclides with half-lives less than 30 days are in secular equilibrium with the principal radionuclide.

The example shown for U-233 illustrates that no single correlation or regression coefficient can be used to rank parameters in all cases. For some cases, SRRC would be appropriate, for example when the input parameters are not strongly correlated. Sometimes, PRCC would be appropriate, for example when nonlinear relationships are present. In still other cases, especially when combinations are involved, none of the correlation or regression coefficients may give an indication of the most significant parameter.

7.2 BUILDING OCCUPANCY SCENARIO

As was noted in the Parameter Ranking Report (Cheng et al., 1999), certain parameters have profound impacts on radiation doses, and for those parameters, site-specific information should always be used in dose calculations. For use of RESRAD-BUILD in evaluating the building occupancy scenario, such parameters include radionuclide concentrations and source area. The radionuclide concentration would affect the dose linearly, while the effect of source area may not be linear. This report analyzes the effect of parameter values on dose for area and volume sources for three different areas (36 m^2, 200 m^2, and 900 m^2).

Table B.3 (Appendix B) lists the parameter values and distribution types used in the analysis. As for the residential scenario using RESRAD, the stratified Monte-Carlo technique, LHS, was used with RESRAD-BUILD to estimate the dose distribution functions from the assigned parameter distribution functions. For each input variable, 300 sample values were generated. This set of inputs was then used to generate a set of outputs from which the probability statistics were generated. For the physical parameters, assigned distributions were used in the analysis. For the metabolic and behavioral parameters, mean or median values of the distributions were used. For the parameters not assigned distributions, RESRAD-BUILD default values were used, or in cases of overlap between RESRAD-BUILD and DandD input parameters, DandD default input parameter values were used if appropriate.

The results of the parameter sampling for the volume source for the building occupancy scenario are illustrated in Figures B.33 through B.41 in Appendix B. Two of the input parameters for the area source in the building occupancy scenario are different from the volume source. These two are the removable fraction and source lifetime; they are illustrated in Figures B.42 and B.43. Tritium volume source has a few different parameters, such as wet + dry zone thickness. Those parameters are illustrated in Figures B.44 through B.48. All those figures compare the sampling frequency or the cumulative probability of the physical

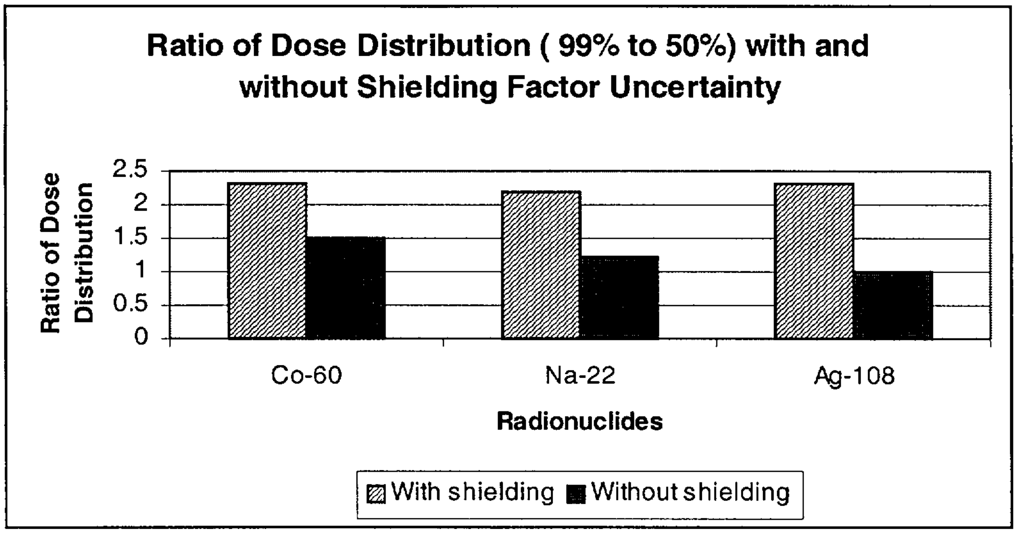

Figure 7.14 Ratio of Dose Distribution with and without Shielding Factor Distribution Uncertainty

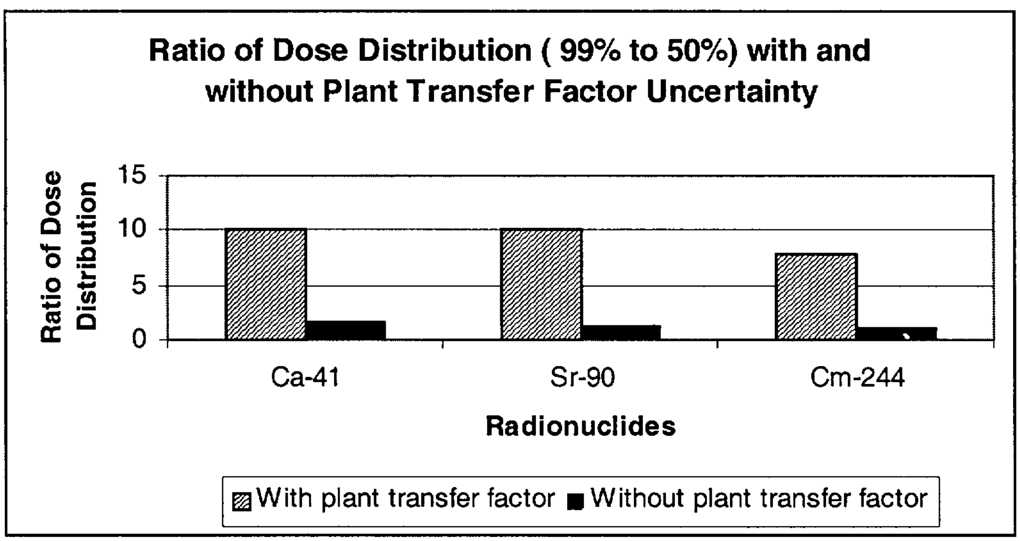

Figure 7.15 Ratio of Dose Distribution with and without Plant Transfer Factor Uncertainty

Table 7.5. PRCC and SRRC for Four Top Ranked Parameters for U-233 in Two Source Configurations								
Coefficient	Parameter	Coefficient Value	Parameter	Coefficient Value	Parameter	Coefficient Value	Parameter	Coefficient Value
Source Configuration: Area = 2,400 m², thickness = 15 cm								
PRCC	BRTF(92,1)	0.67	DROOT	-0.58	DM	-0.45	DCACTC(2)	0.29
SRRC	DENSUZ(1)	0.98	TPUZ(1)	0.55	BRTF(92,1)	0.52	EPUZ(1)	0.49
Source Configuration: Area = 10,000 m², thickness = 2 m								
PRCC	BRTF(92,1)	0.78	DROOT	-0.40	DCACTC(2)	0.38	VCZ	-0.32
SRRC	DENSAQ	-1.58	EPSZ	-0.83	TPSZ	-0.82	BRTF(92,1)	0.67

parameter values based on LHS sampling and the probability density or the cumulative distribution function of the parameter.

7.2.1 Parameter Correlations

The Parameter Distribution Report (Biwer et al., 2000) identified correlations among the input parameters in RESRAD-BUILD. The parameters identified were air release fraction, deposition velocity, direct ingestion rate, indirect ingestion rate, indoor fraction, resuspension rate, source erosion rate, and source lifetime. The air release fraction, direct and indirect ingestion rate, and indoor fraction are behavioral parameters. These parameters were kept at a fixed value in the analysis. Source erosion rate and source lifetime are correlated with the fixed behavioral parameters. Positive correlation between deposition velocity and resuspension rate was studied for selected radionuclides. Results of the correlation analyses are presented in Section 7.2.4. However, no correlations were used in the dose distribution analyses for the radionuclides.

7.2.2 Dose Analysis Results

For each set of sampled parameter values, the dose to the average member of the critical group was calculated for unit concentrations of each radionuclide. For each source, the distribution describing possible doses to the average member of the critical group was then constructed from these calculated doses. The dose quantiles were estimated from the resulting dose distributions. The resultant dose distribution is for the dose at time zero. In all, 67 radionuclides for three source configurations (each for area and volume source) were analyzed.

7.2.2.1 Volume Source Analysis

Table 7.6 lists the quantile values (at 50th percentile and 90th percentile) of unit-source distribution for three volume sources (source1: source area = 36 m^2; source 2: source area = 200 m^2; and source 3: source area = 900 m^2) in the building occupancy scenario. Table 7.6 also shows the ratio of dose at the 95th percentile to that of the 50th percentile (median) dose. The dose ratio shows the dose spread for different radionuclides. Dose values at the selected quantiles can be used to calculate the source concentration equivalent to a dose value of 25 mrem/yr.

For source 1, the dose ratio varies from 3.35 (U-232) to 501 (I-129). For source 2, the dose ratio varies from 3.38 (Th-232) to 180 (I-129). For source 3, the dose ratio varies from 3.15 (U-232) to 144 (Au-195). For some radionuclides, the dose ratio remains almost the same for the three source configurations (e.g., Ca-41, Cm-244, Cm-248, Fe-55, Gd-152, H-3, Ni-59, and Ni-63), while wide variations are observed for others (e.g., C-14, Am-241,

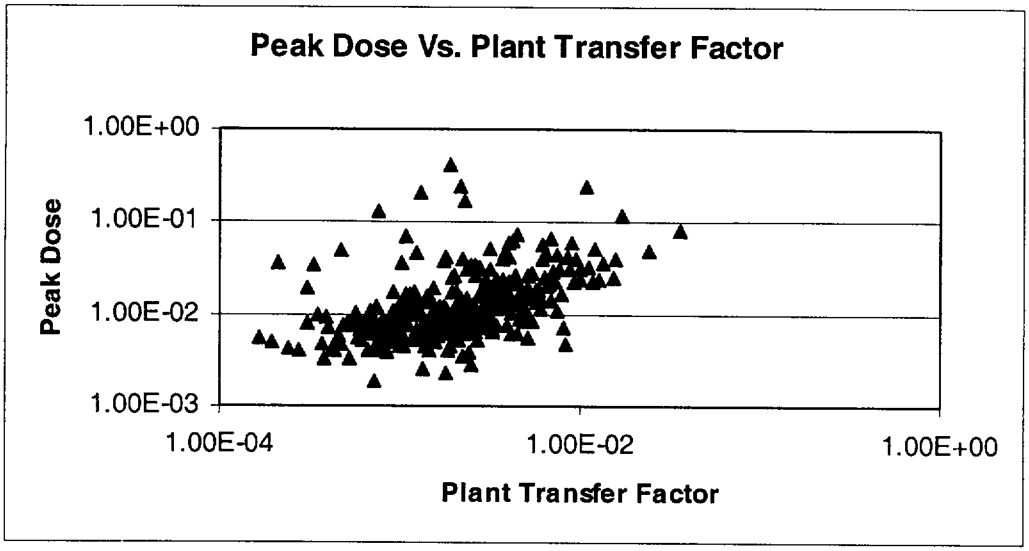

Figure 7.16 Scatter Plot of the Peak Dose vs. U-233 Plant Transfer Factor for Source Area = 2,400 m^2 and Thickness = 15 cm

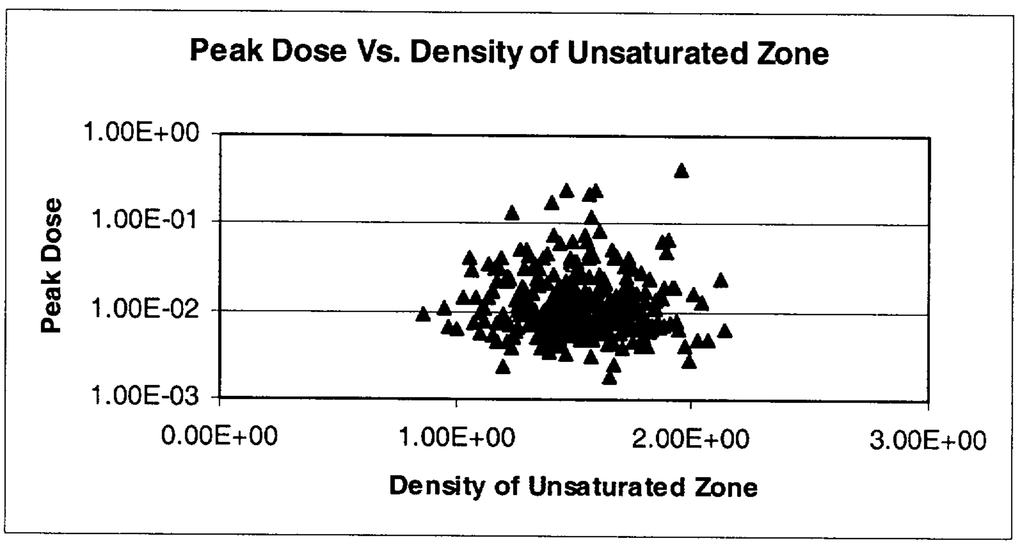

Figure 7.17 Scatter Plot of the Peak Dose vs. Density of Unsaturated Zone for Source Area = 2,400 m^2 and Thickness = 15 cm

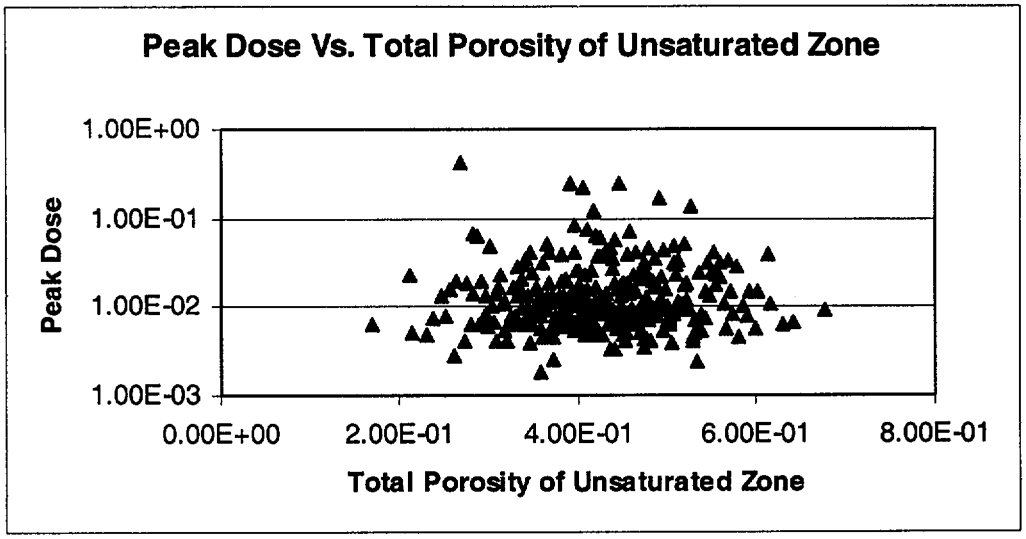

Figure 7.18 Scatter Plot of the Peak Dose vs. Total Porosity of Unsaturated Zone for Source Area = 2,400 m^2 and Thickness = 15 cm

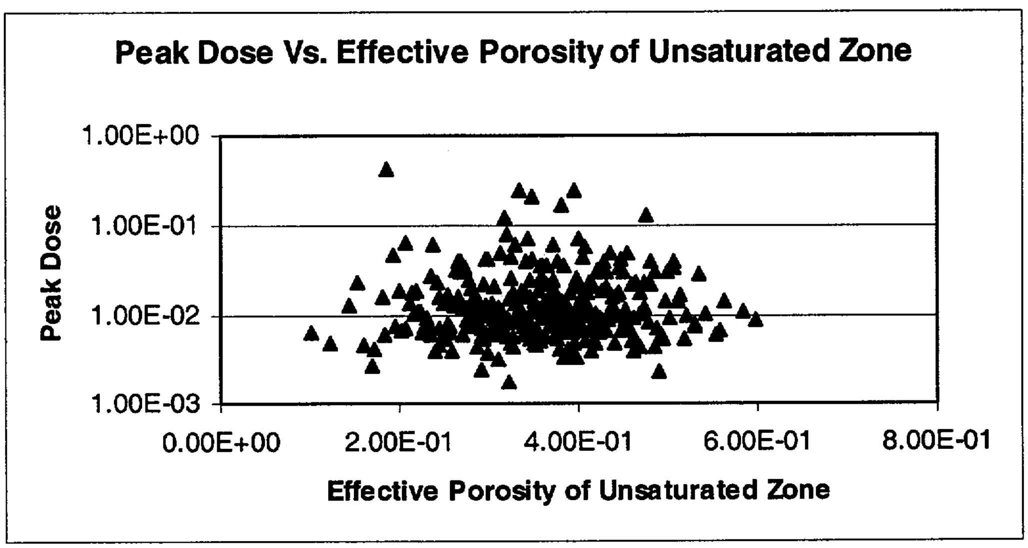

Figure 7.19 Scatter Plot of the Peak Dose vs. Effective Porosity of Unsaturated Zone for Source Area = 2,400 m^2 and Thickness = 15 cm

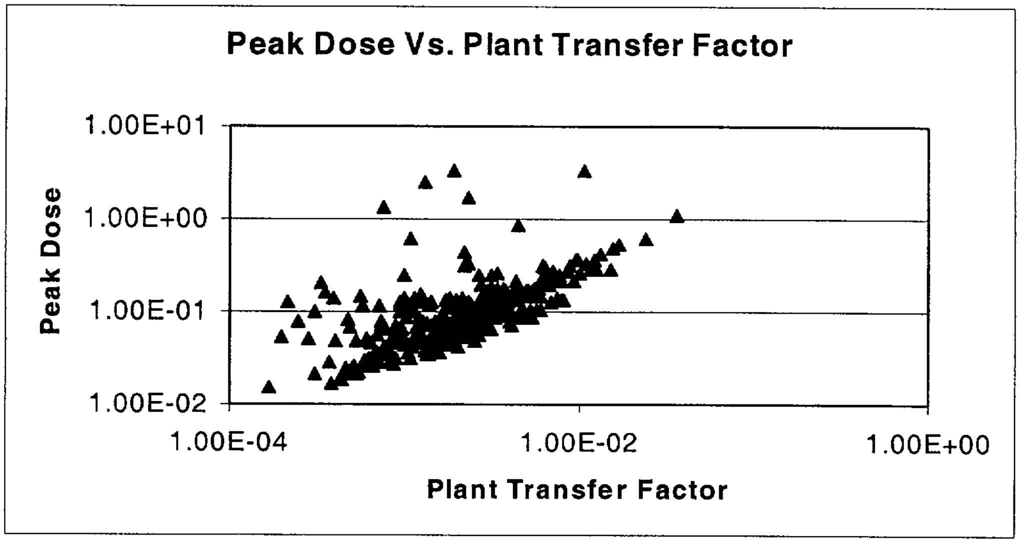

Figure 7.20 Scatter Plot of the Peak Dose vs. U-233 Plant Transfer Factor for Source Area = 10,000 m^2 and Thickness = 2 m

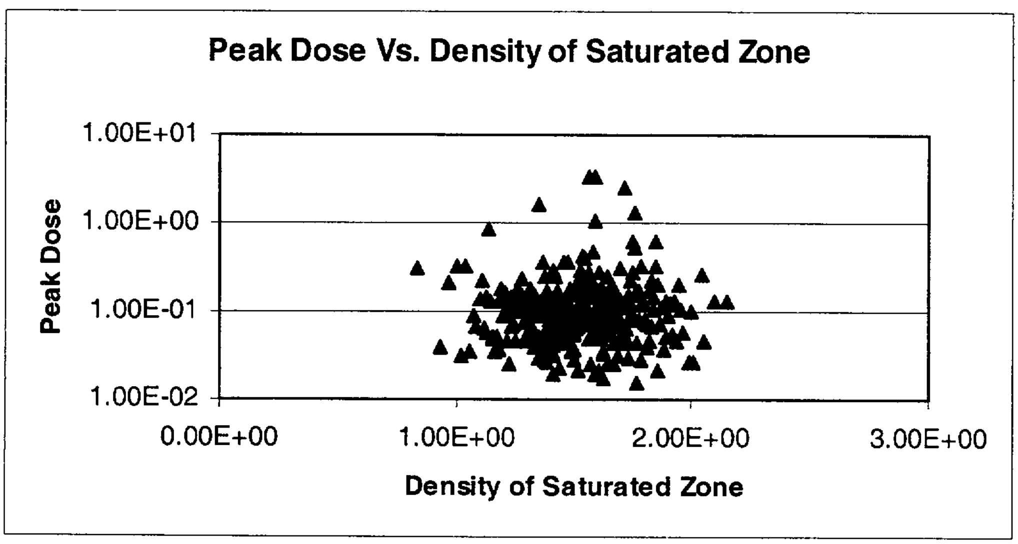

Figure 7.21 Scatter Plot of the Peak Dose vs. Density of Saturated Zone for Source Area = 10,000 m^2 and Thickness = 2 m

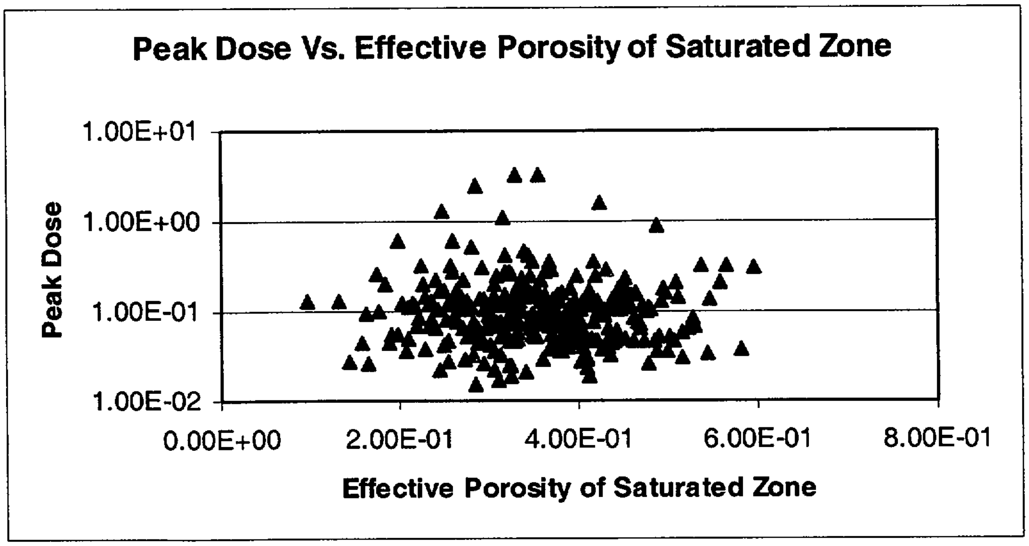

Figure 7.22 Scatter Plot of the Peak Dose vs. Effective Porosity of Saturated Zone for Source Area = 10,000 m² and Thickness = 2 m

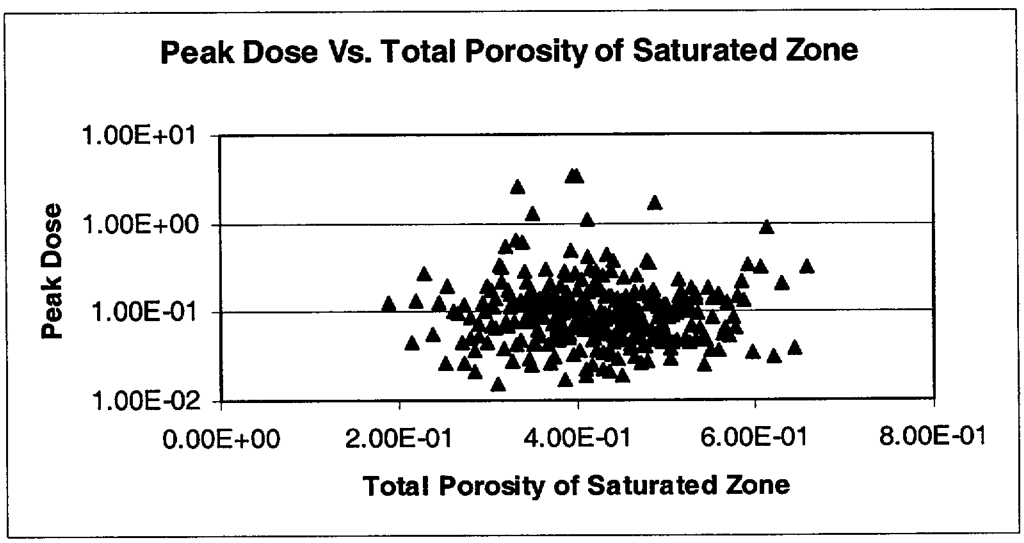

Figure 7.23 Scatter Plot of the Peak Dose vs. Total Porosity of Saturated Zone for Source Area = 10,000 m² and Thickness = 2 m

Table 7.6. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per pCi/g) for Three Source Areas for a Volume Source in the Building Occupancy Scenario

Radionuclide	Source 1: Area = 36 m^2			Source 2: Area = 200 m^2			Source 3: Area = 900 m^2		
	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%
Ac-227	7.44E-02	3.72E-01	5.86E+00	1.34E-01	5.21E-01	4.68E+00	2.88E-01	8.73E-01	4.38E+00
Ag-108	4.39E-01	1.85E+00	4.83E+00	4.40E-01	2.11E+00	5.75E+00	4.40E-01	2.16E+00	5.95E+00
Ag-110	5.62E-01	2.10E+00	4.23E+00	5.67E-01	2.42E+00	4.97E+00	5.67E-01	2.51E+00	5.24E+00
Al-26	1.05E+00	3.40E+00	3.59E+00	1.07E+00	3.97E+00	4.23E+00	1.07E+00	4.05E+00	4.39E+00
Am-241	6.75E-04	4.80E-03	1.03E+01	2.94E-03	1.20E-02	7.28E+00	1.16E-02	5.10E-02	7.91E+00
Am-243	1.12E-02	1.35E-01	1.48E+01	1.68E-02	1.56E-01	1.15E+01	3.55E-02	1.88E-01	6.39E+00
Au-195	1.16E-04	9.77E-03	1.33E+02	1.16E-04	1.00E-02	1.43E+02	1.16E-04	1.00E-02	1.44E+02
Bi-207	4.63E-01	1.80E+00	4.38E+00	4.78E-01	2.07E+00	5.02E+00	4.78E-01	2.12E+00	5.36E+00
C-14	1.56E-08	7.59E-07	7.18E+01	4.46E-08	1.20E-06	4.91E+01	1.50E-07	2.00E-06	3.82E+01
Ca-41	2.00E-09	3.53E-08	6.80E+01	1.11E-08	1.96E-07	6.79E+01	4.99E-08	8.82E-07	6.79E+01
Cd-109	2.26E-05	8.91E-04	5.66E+01	2.31E-05	9.35E-04	6.10E+01	2.86E-05	9.74E-04	4.97E+01
Ce-144	9.28E-03	3.85E-02	4.74E+00	9.85E-03	4.43E-02	5.34E+00	9.85E-03	4.53E-02	5.56E+00
Cf-252	1.24E-04	5.21E-04	8.05E+00	6.82E-04	2.90E-03	8.06E+00	3.06E-03	1.30E-02	8.10E+00
Cl-36	5.23E-05	3.96E-04	9.22E+00	5.25E-05	4.57E-04	1.09E+01	5.33E-05	4.91E-04	1.11E+01
Cm-243	1.09E-02	9.68E-02	1.06E+01	1.43E-02	1.14E-01	9.65E+00	2.61E-02	1.34E-01	6.09E+00
Cm-244	2.24E-04	9.68E-04	8.17E+00	1.24E-03	5.38E-03	8.23E+00	5.56E-03	2.42E-02	8.24E+00
Cm-248	1.64E-03	7.68E-03	8.29E+00	9.11E-03	4.27E-02	8.32E+00	4.10E-02	1.92E-01	8.32E+00
Co-57	3.07E-03	4.82E-02	1.97E+01	3.07E-03	5.14E-02	2.22E+01	3.07E-03	5.14E-02	2.30E+01
Co-60	9.37E-01	2.98E+00	3.52E+00	9.53E-01	3.47E+00	4.14E+00	9.53E-01	3.54E+00	4.30E+00
Cs-134	3.87E-01	1.56E+00	4.57E+00	3.98E-01	1.80E+00	5.23E+00	3.98E-01	1.83E+00	5.55E+00
Cs-135	8.43E-08	2.88E-06	4.93E+01	1.85E-07	4.47E-06	4.03E+01	4.54E-07	6.72E-06	4.38E+01
Cs-137	1.60E-01	6.52E-01	4.64E+00	1.61E-01	7.47E-01	5.45E+00	1.61E-01	7.64E-01	5.73E+00
Eu-152	3.72E-01	1.31E+00	3.98E+00	3.75E-01	1.52E+00	4.67E+00	3.75E-01	1.55E+00	4.91E+00
Eu-154	4.10E-01	1.39E+00	3.85E+00	4.15E-01	1.62E+00	4.51E+00	4.15E-01	1.66E+00	4.80E+00
Eu-155	5.07E-04	1.74E-02	4.97E+01	5.07E-04	1.79E-02	5.40E+01	5.08E-04	1.80E-02	5.43E+01
Fe-55	2.58E-09	1.15E-08	8.49E+00	1.43E-08	6.40E-08	8.46E+00	6.45E-08	2.87E-07	8.47E+00
Gd-152	2.28E-04	9.66E-04	8.03E+00	1.27E-03	5.37E-03	8.03E+00	5.70E-03	2.42E-02	8.04E+00
Gd-153	2.53E-04	1.28E-02	7.75E+01	2.53E-04	1.29E-02	8.14E+01	2.53E-04	1.29E-02	8.14E+01
Ge-68	1.64E-01	7.16E-01	5.02E+00	1.64E-01	8.24E-01	6.03E+00	1.64E-01	8.32E-01	6.22E+00
H-3	1.74E-04	1.40E-03	1.44E+01	9.68E-04	7.80E-03	1.44E+01	4.35E-03	3.51E-02	1.44E+01
I-129	5.79E-07	8.17E-05	5.01E+02	2.78E-06	2.46E-04	1.80E+02	9.70E-06	5.05E-04	1.29E+02
K-40	6.48E-02	2.03E-01	3.46E+00	6.71E-02	2.37E-01	4.02E+00	6.71E-02	2.43E-01	4.20E+00
Mn-54	1.78E-01	6.81E-01	4.32E+00	1.82E-01	7.84E-01	5.01E+00	1.82E-01	8.06E-01	5.33E+00

Table 7.6. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per pCi/g) for Three Source Areas for a Volume Source in the Building Occupancy Scenario (Continued)

Radionuclide	Source 1: Area = 36 m^2			Source 2: Area = 200 m^2			Source 3: Area = 900 m^2		
	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%
Na-22	6.26E-01	2.35E+00	4.23E+00	6.30E-01	2.70E+00	4.97E+00	6.30E-01	2.76E+00	5.24E+00
Nb-94	4.71E-01	1.87E+00	4.52E+00	4.92E-01	2.17E+00	5.10E+00	4.92E-01	2.21E+00	5.43E+00
Ni-59	3.12E-09	2.23E-08	1.48E+01	1.73E-08	1.24E-07	1.49E+01	7.79E-08	5.58E-07	1.48E+01
Ni-63	7.20E-09	4.81E-08	1.39E+01	4.00E-08	2.67E-07	1.40E+01	1.80E-07	1.20E-06	1.39E+01
Np-237	3.02E-02	1.99E-01	7.68E+00	3.63E-02	2.29E-01	7.63E+00	6.14E-02	2.65E-01	5.15E+00
Pa-231	1.00E-02	4.36E-02	5.04E+00	2.15E-02	6.70E-02	4.02E+00	5.00E-02	1.69E-01	5.98E+00
Pb-210	1.19E-04	6.98E-04	7.68E+00	3.17E-04	1.81E-03	8.90E+00	8.78E-04	7.62E-03	1.45E+01
Pm-147	1.58E-07	4.27E-06	3.68E+01	3.84E-07	4.77E-06	1.79E+01	1.11E-06	6.68E-06	7.98E+00
Pu-238	3.78E-04	1.64E-03	8.28E+00	2.07E-03	9.13E-03	8.41E+00	9.31E-03	4.11E-02	8.41E+00
Pu-239	4.52E-04	1.99E-03	7.85E+00	2.37E-03	1.11E-02	8.31E+00	1.07E-02	4.98E-02	8.29E+00
Pu-240	4.26E-04	1.99E-03	8.33E+00	2.37E-03	1.10E-02	8.31E+00	1.07E-02	4.96E-02	8.29E+00
Pu-241	8.95E-06	3.32E-05	7.39E+00	4.37E-05	1.84E-04	8.08E+00	1.93E-04	8.30E-04	8.13E+00
Pu-242	4.08E-04	1.91E-03	8.33E+00	2.27E-03	1.06E-02	8.33E+00	1.02E-02	4.77E-02	8.32E+00
Pu-244	3.73E-01	1.51E+00	4.56E+00	3.83E-01	1.73E+00	5.22E+00	4.01E-01	1.79E+00	5.31E+00
Ra-226	6.24E-01	2.16E+00	3.91E+00	6.35E-01	2.53E+00	4.58E+00	6.35E-01	2.58E+00	4.72E+00
Ra-228	3.79E-01	1.37E+00	4.09E+00	3.86E-01	1.59E+00	4.77E+00	3.86E-01	1.64E+00	5.00E+00
Ru-106	4.33E-02	1.80E-01	4.73E+00	4.35E-02	2.06E-01	5.61E+00	4.35E-02	2.10E-01	5.86E+00
Sb-125	9.11E-02	4.13E-01	5.24E+00	9.13E-02	4.75E-01	6.25E+00	9.13E-02	4.78E-01	6.42E+00
Sm-147	7.04E-05	3.07E-04	8.01E+00	3.91E-04	1.71E-03	8.01E+00	1.76E-03	7.68E-03	8.01E+00
Sm-151	3.06E-08	1.37E-07	8.07E+00	1.69E-07	7.50E-07	8.11E+00	7.42E-07	3.38E-06	8.33E+00
Sr-90	1.89E-04	1.77E-03	1.24E+01	2.12E-04	1.77E-03	1.11E+01	3.17E-04	1.86E-03	7.54E+00
Tc-99	3.83E-07	1.25E-05	4.62E+01	5.74E-07	1.39E-05	3.48E+01	1.10E-06	1.60E-05	1.89E+01
Th-228	5.34E-01	1.66E+00	3.43E+00	5.69E-01	1.95E+00	3.88E+00	5.84E-01	2.00E+00	3.99E+00
Th-229	5.30E-02	2.79E-01	6.28E+00	7.77E-02	3.49E-01	5.34E+00	1.51E-01	4.65E-01	4.05E+00
Th-230	5.37E-04	1.61E-03	5.07E+00	1.94E-03	7.58E-03	7.27E+00	7.99E-03	3.40E-02	7.75E+00
Th-232	2.46E-02	7.57E-02	3.53E+00	3.93E-02	1.06E-01	3.38E+00	7.56E-02	2.12E-01	4.55E+00
Tl-204	7.24E-06	3.51E-04	7.25E+01	7.25E-06	3.59E-04	7.82E+01	7.38E-06	3.59E-04	7.71E+01
U-232	9.58E-02	2.92E-01	3.35E+00	1.09E-01	3.47E-01	3.67E+00	1.42E-01	3.93E-01	3.15E+00
U-233	2.07E-04	6.55E-04	5.41E+00	7.75E-04	3.18E-03	7.60E+00	3.35E-03	1.41E-02	7.67E+00
U-234	1.32E-04	5.50E-04	7.80E+00	7.19E-04	3.06E-03	7.75E+00	3.13E-03	1.36E-02	7.96E+00
U-235	1.29E-02	1.27E-01	1.18E+01	1.41E-02	1.46E-01	1.26E+01	2.08E-02	1.53E-01	8.94E+00
U-236	1.25E-04	5.21E-04	7.65E+00	6.59E-04	2.88E-03	7.97E+00	2.96E-03	1.29E-02	7.97E+00
U-238	6.59E-03	2.37E-02	4.14E+00	7.64E-03	2.76E-02	4.42E+00	1.22E-02	3.56E-02	3.75E+00
Zn-65	1.27E-01	4.45E-01	3.96E+00	1.29E-01	5.21E-01	4.66E+00	1.29E-01	5.34E-01	4.82E+00

Cs-135, I-129, and Pm-147). Figures 7.24 through 7.33 show the dose variability for Am-241, C-14, Co-60, Cs-137, H-3, Pu-239, Ra-226, Sr-90, Th-230, and U-238 in the building occupancy scenario for all three volume sources.

7.2.2.2 Area Source Analysis

Table 7.7 lists the quantile values (at 50th percentile and 90th percentile) of unit-source distribution for three area sources [source 1: source area = 36 m^2; source 2: source area = 200 m^2; and source 3: source area = 900 m^2] in the building occupancy scenario. Table 7.7 also shows the ratio of dose at the 95th percentile to that at the 50th percentile (median). The dose ratio shows the dose spread for different radionuclides. Dose values at the selected quantiles can be used to calculate the source concentration equivalent to a dose value of 25 mrem/yr.

For source 1, the dose ratio varies from 2.55 (K-40) to 135 (Au-195). For source 2, the dose ratio varies from 3.34 (Ra-228) to 121 (Au-195). For source 3, the dose ratio varies from 4.50 (K-40) to 81.9 (Au-195). For some radionuclides, the dose ratio remains almost the same in all three source configurations (e.g., Am-241, Ca-41, Cm-244, and Cm-248), while wide variations are observed for others (e.g., Au-195, C-14, and Cs-135). Figures 7.34 through 7.43 show the dose variability for Am-241, C-14, Co-60, Cs-137, H-3, Pu-239, Ra-226, Sr-90, Th-230, and U-238 in the building occupancy scenario for all three area sources.

7.2.3 Dominant Pathways and Sensitive Parameters

The results of the probabilistic dose calculations can be processed to identify parameters controlling dose variability for each radionuclide. The dependence of dose on the model parameter values is complex; total dose may depend non-monotonically on the parameter value, or may be sensitive to the parameter value only within certain limits, or only in conjunction with certain ranges of values for other parameters. Because of these complexities, no single regression analysis can be used to identify the sensitive parameters. RESRAD-BUILD output provides PCC, SRC, PRCC, and SRRC values and scatter plots. These aids, along with expert judgment, should be used to identify sensitive parameters. In this analysis, SRRC was used as an example to identify sensitive parameters. The effect of sensitive parameters was then studied for selected radionuclides by determining the dose variability with and without the uncertainty of the sensitive parameter. For the RESRAD-BUILD code, either the default value or the mean value of the distribution of the sensitive parameter was used to determine sensitivity on these parameters.

7.2.3.1 Dominant Pathways and Sensitive Parameters in Volume Source

Tables 7.8 through 7.10 list the four most sensitive parameters based on SRRC along with the dominant pathway for three sources. Tables C.4 through C.6 in Appendix C present detailed information, including SRRC values. Only sensitive parameters with SRRC values of 0.1 or greater are listed in these tables. An SRRC value of 0.1 means that one standard deviation change in the parameter value will change the resultant dose by 0.1 times the standard deviation of the dose.

For radionuclides for which external exposure was the dominant pathway, shielding thickness was found to be the dominant contributor to the dose variability. Three radionuclides (Cs-137, Mn-54, and Pu-244) were selected to study the effect of shielding thickness. It was observed after removing the shielding thickness from the uncertainty analysis that dose variability was significantly reduced. The dose ratio (95th percentile dose to 50th percentile dose) with

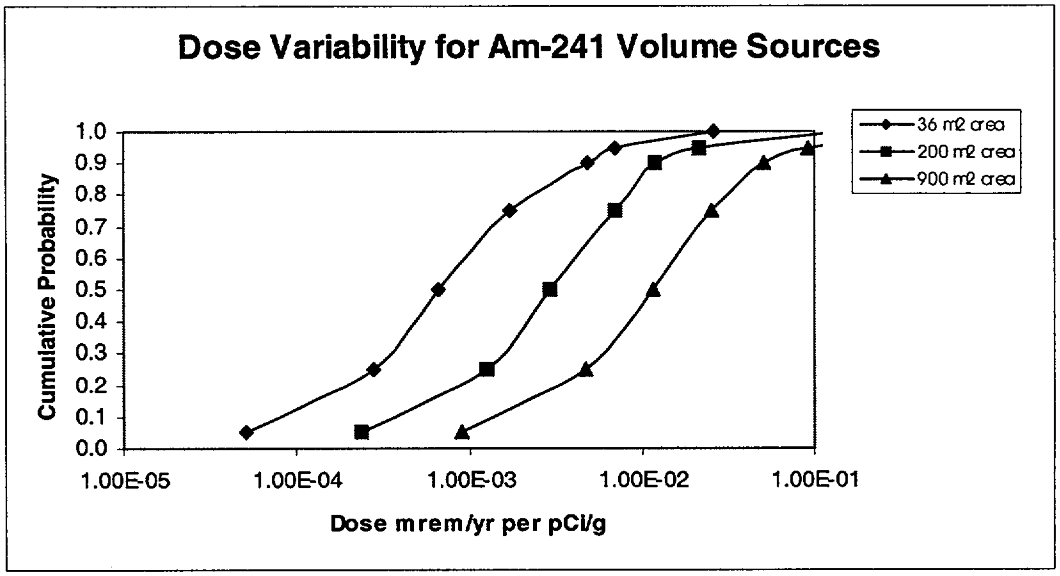

Figure 7.24 Dose Variability of Am-241 for a Volume Source with Three Source Areas in Building Occupancy Scenario

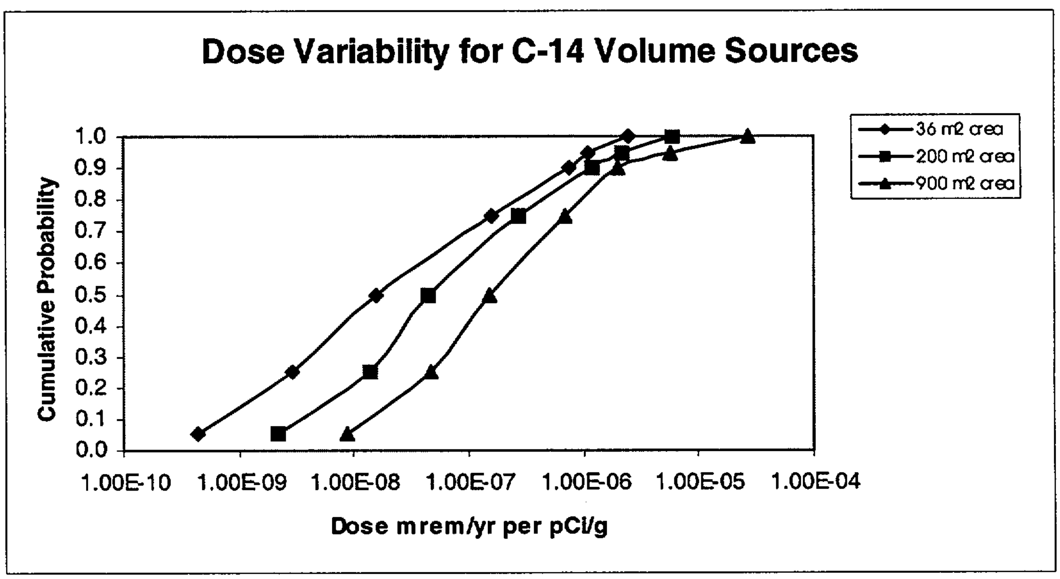

Figure 7.25 Dose Variability of C-14 for a Volume Source with Three Source Areas in Building Occupancy Scenario

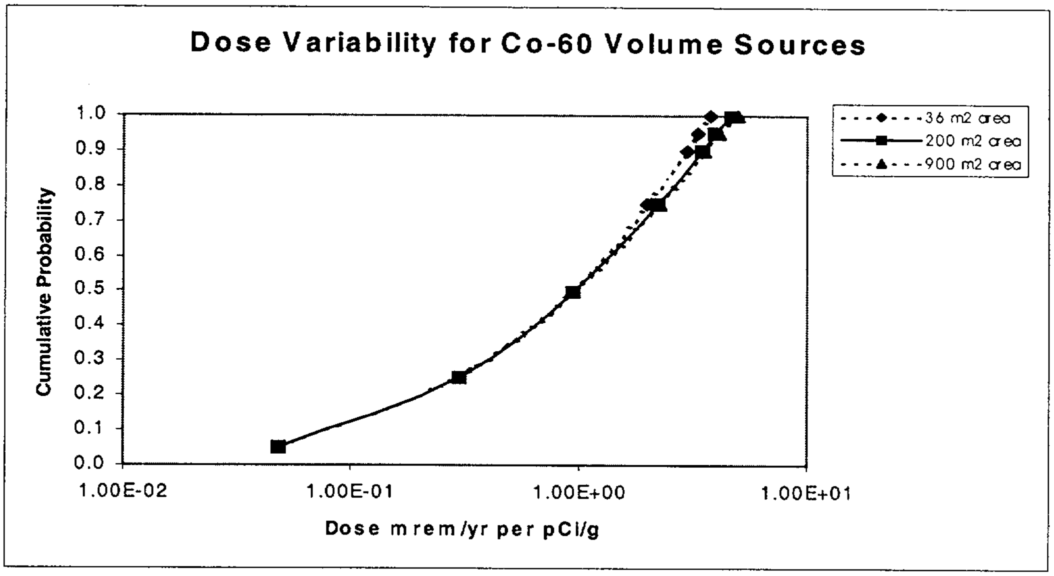

Figure 7.26 Dose Variability of Co-60 for a Volume Source with Three Source Areas in Building Occupancy Scenario

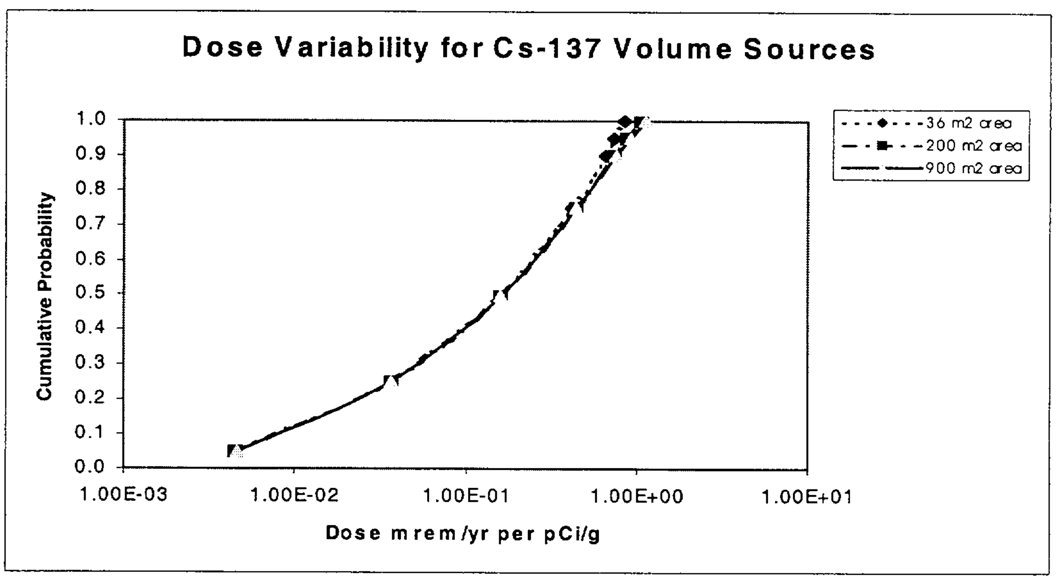

Figure 7.27 Dose Variability of Cs-137 for a Volume Source with Three Source Areas in Building Occupancy Scenario

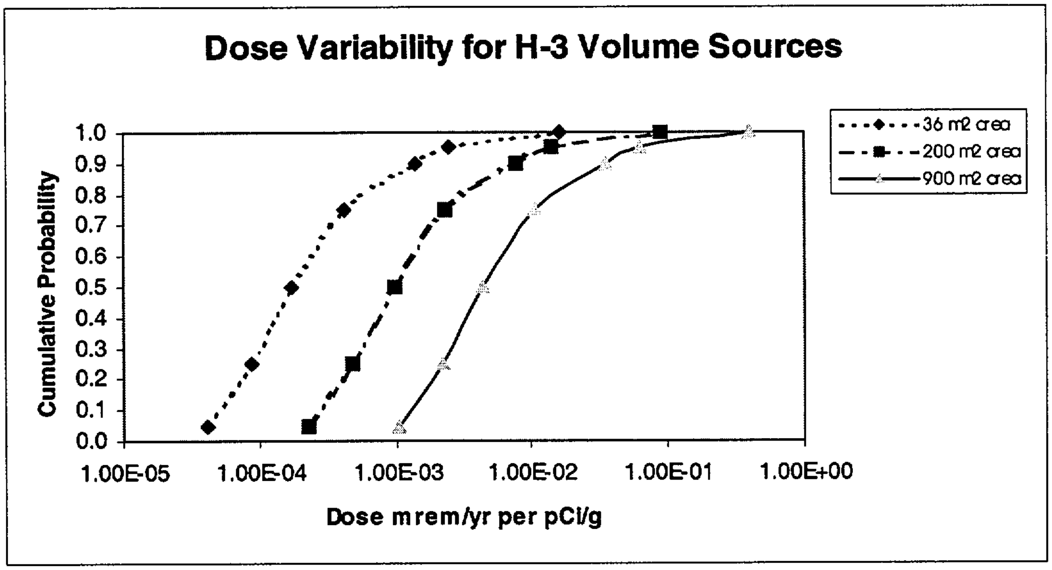

Figure 7.28 Dose Variability of H-3 for a Volume Source with Three Source Areas in Building Occupancy Scenario

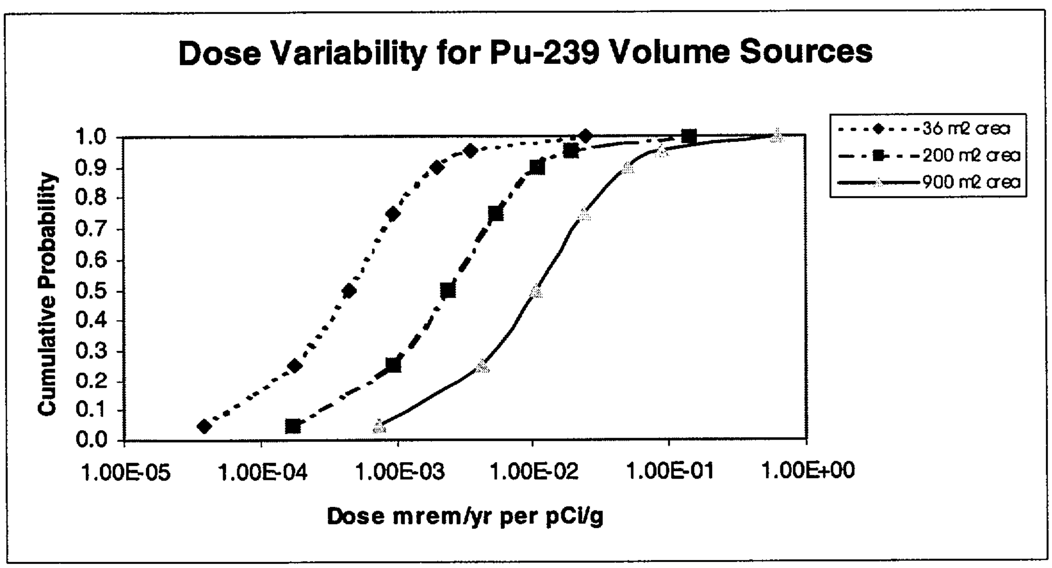

Figure 7.29 Dose Variability of Pu-239 for a Volume Source with Three Source Areas in Building Occupancy Scenario

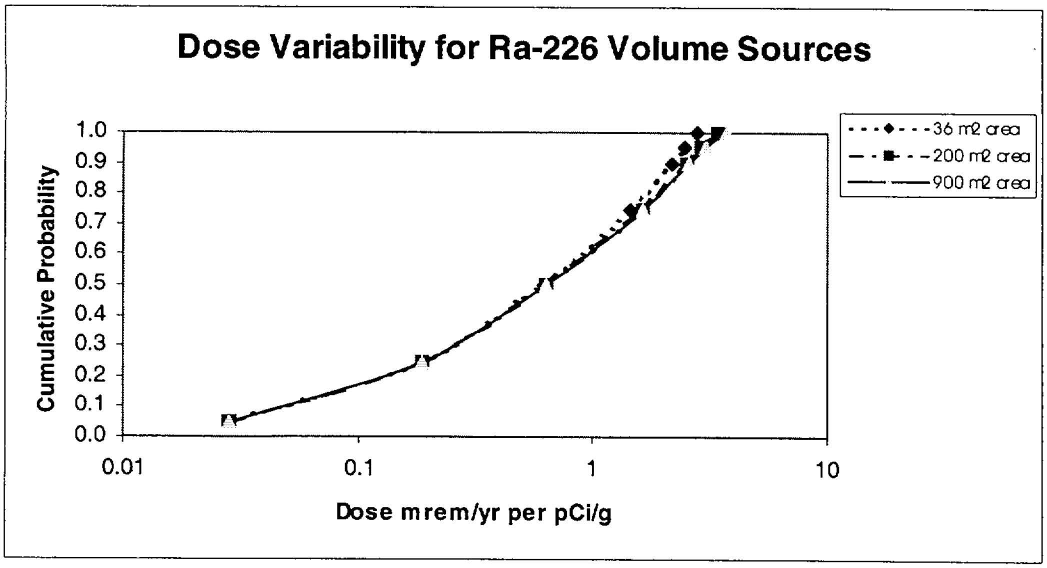

Figure 7.30 Dose Variability of Ra-226 for a Volume Source with Three Source Areas in Building Occupancy Scenario

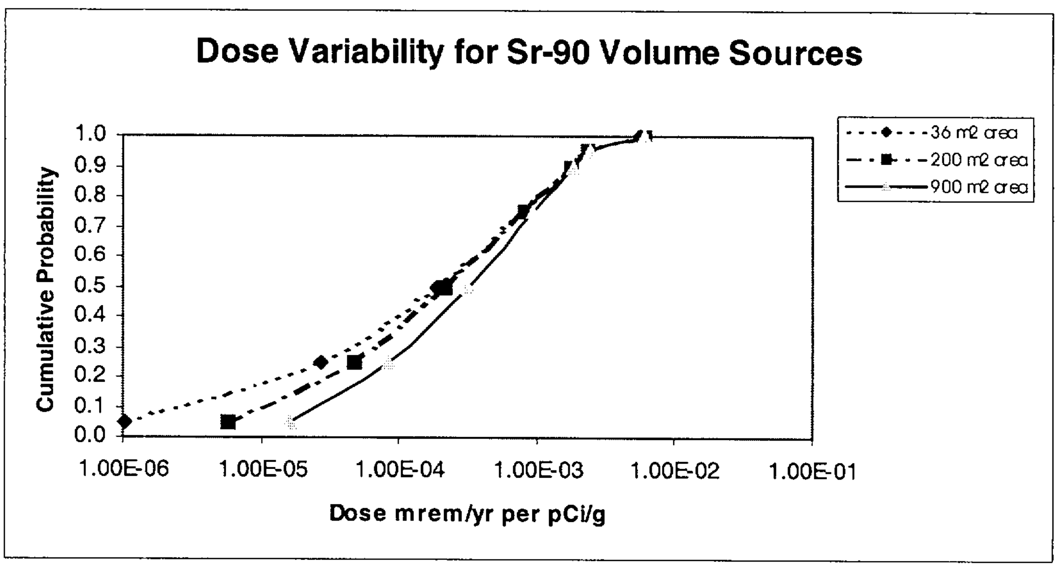

Figure 7.31 Dose Variability of Sr-90 for a Volume Source with Three Source Areas in Building Occupancy Scenario

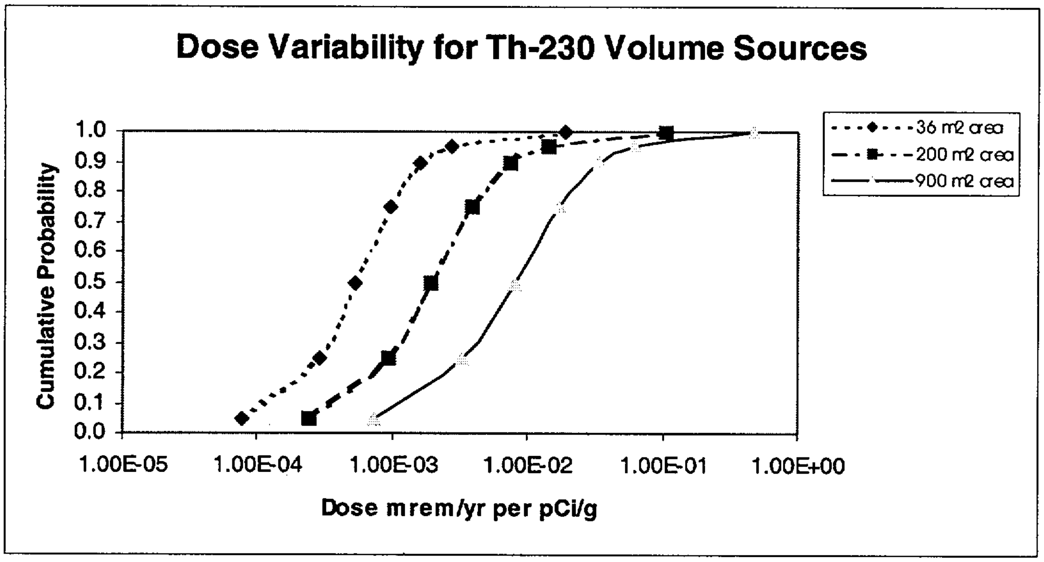

Figure 7.32 Dose Variability of Th-230 for a Volume Source with Three Source Areas in Building Occupancy Scenario

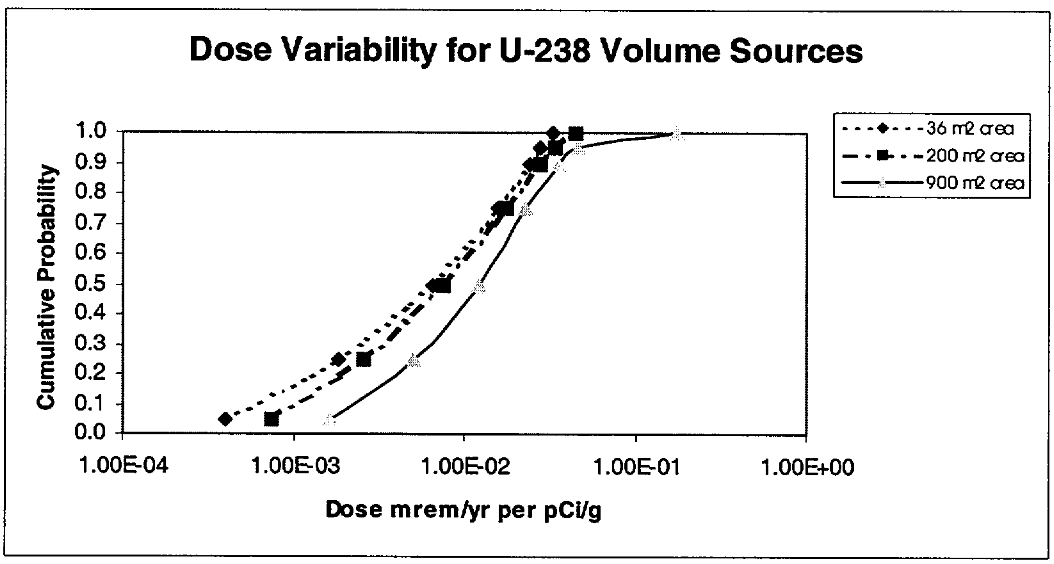

Figure 7.33 Dose Variability of U-238 for a Volume Source with Three Source Areas in Building Occupancy Scenario

Table 7.7. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions (mrem/yr per dpm/cm^2) for Three Source Areas for a Surface Source in the Building Occupancy Scenario

Radionuclide	Source 1: Area = 36 m^2			Source 2: Area = 200 m^2			Source 3: Area = 900 m^2		
	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%
Ac-227	8.96E-02	4.86E-01	1.41E+01	4.77E-01	2.68E+00	1.45E+01	2.11E+00	1.21E+01	1.48E+01
Ag-108	1.71E-02	6.17E-02	3.69E+00	1.76E-02	9.10E-02	5.78E+00	2.08E-02	1.03E-01	6.14E+00
Ag-110	2.11E-02	6.26E-02	3.09E+00	2.18E-02	9.32E-02	4.79E+00	2.21E-02	1.05E-01	5.94E+00
Al-26	3.56E-02	9.19E-02	2.69E+00	3.83E-02	1.37E-01	4.01E+00	4.12E-02	1.59E-01	4.72E+00
Am-241	5.99E-03	3.39E-02	1.57E+01	3.27E-02	1.88E-01	1.58E+01	1.47E-01	8.47E-01	1.59E+01
Am-243	9.37E-03	3.45E-02	1.08E+01	3.56E-02	1.87E-01	1.48E+01	1.51E-01	8.42E-01	1.54E+01
Au-195	1.23E-05	1.14E-03	1.35E+02	1.79E-05	1.25E-03	1.21E+02	2.71E-05	1.26E-03	8.19E+01
Bi-207	1.77E-02	5.50E-02	3.25E+00	1.83E-02	8.11E-02	5.00E+00	1.90E-02	9.10E-02	6.03E+00
C-14	6.94E-08	9.10E-07	4.11E+01	3.05E-07	4.95E-06	5.19E+01	1.31E-06	2.08E-05	5.43E+01
Ca-41	3.17E-08	5.00E-07	5.81E+01	1.76E-07	2.77E-06	5.81E+01	7.93E-07	1.25E-05	5.80E+01
Cd-109	6.35E-06	8.96E-05	1.64E+01	1.78E-05	1.35E-04	1.05E+01	5.18E-05	2.73E-04	1.04E+01
Ce-144	3.77E-04	1.34E-03	3.82E+00	4.55E-04	1.91E-03	4.99E+00	5.59E-04	2.29E-03	5.30E+00
Cf-252	1.73E-03	1.00E-02	1.45E+01	9.59E-03	5.59E-02	1.45E+01	4.33E-02	2.51E-01	1.45E+01
Cl-36	4.82E-06	1.89E-05	5.15E+00	9.01E-06	3.88E-05	7.10E+00	1.96E-05	1.04E-04	1.09E+01
Cm-243	6.22E-03	2.35E-02	1.07E+01	2.33E-02	1.28E-01	1.49E+01	1.00E-01	5.77E-01	1.55E+01
Cm-244	3.11E-03	1.82E-02	1.58E+01	1.73E-02	1.01E-01	1.57E+01	7.75E-02	4.55E-01	1.58E+01
Cm-248	2.19E-02	1.26E-01	1.59E+01	1.22E-01	7.03E-01	1.59E+01	5.50E-01	3.15E+00	1.58E+01
Co-57	1.80E-04	3.11E-03	1.88E+01	1.85E-04	4.02E-03	2.80E+01	2.11E-04	4.10E-03	2.86E+01
Co-60	3.15E-02	7.93E-02	2.66E+00	3.32E-02	1.18E-01	4.04E+00	3.58E-02	1.36E-01	4.74E+00
Cs-134	1.49E-02	4.95E-02	3.42E+00	1.52E-02	7.34E-02	5.40E+00	1.54E-02	8.15E-02	6.70E+00
Cs-135	2.06E-07	2.59E-06	4.00E+01	8.15E-07	1.40E-05	5.58E+01	3.28E-06	6.31E-05	6.27E+01
Cs-137	6.13E-03	2.11E-02	3.54E+00	6.49E-03	3.13E-02	5.38E+00	6.98E-03	3.60E-02	6.28E+00
Eu-152	1.35E-02	3.86E-02	3.12E+00	1.41E-02	5.68E-02	4.71E+00	1.60E-02	6.49E-02	5.20E+00
Eu-154	1.45E-02	4.11E-02	3.21E+00	1.53E-02	6.04E-02	4.87E+00	1.66E-02	6.98E-02	5.63E+00
Eu-155	4.19E-05	1.61E-03	5.33E+01	5.86E-05	1.85E-03	5.16E+01	9.32E-05	1.85E-03	3.39E+01
Fe-55	3.47E-08	1.84E-07	1.64E+01	1.93E-07	1.02E-06	1.63E+01	8.65E-07	4.59E-06	1.64E+01
Gd-152	3.19E-03	1.85E-02	1.54E+01	1.77E-02	1.03E-01	1.54E+01	7.97E-02	4.64E-01	1.54E+01
Gd-153	2.22E-05	1.32E-03	8.98E+01	3.17E-05	1.39E-03	7.60E+01	4.82E-05	1.40E-03	5.05E+01
Ge-68	6.49E-03	2.45E-02	3.85E+00	6.58E-03	3.61E-02	6.16E+00	6.76E-03	4.00E-02	7.53E+00
H-3	1.86E-09	1.92E-08	1.82E+01	1.04E-08	1.07E-07	1.81E+01	4.64E-08	4.82E-07	1.82E+01
I-129	6.08E-06	2.37E-04	1.22E+02	3.20E-05	7.12E-04	6.97E+01	1.33E-04	2.51E-03	6.08E+01
K-40	2.19E-03	5.32E-03	2.55E+00	2.47E-03	8.06E-03	3.65E+00	2.71E-03	9.82E-03	4.50E+00
Mn-54	6.76E-03	2.06E-02	3.27E+00	6.98E-03	3.05E-02	5.06E+00	6.98E-03	3.43E-02	6.37E+00

Table 7.7. Quantile Values (at 50 percentile and 90 percentile) of Unit-Source Dose Distributions ($mrem/yr$ per dpm/cm^2) for Three Source Areas for a Surface Source in the Building Occupancy Scenario (Continued)

	Source 1: Area = 36 m^2			Source 2: Area = 200 m^2			Source 3: Area = 900m^2		
Radionuclide	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%	Dose @ 50%	Dose @ 90%	Dose @ 95%/ Dose @ 50%
Na-22	2.36E-02	6.98E-02	3.08E+00	2.42E-02	1.04E-01	4.82E+00	2.45E-02	1.16E-01	5.98E+00
Nb-94	1.82E-02	5.81E-02	3.29E+00	1.95E-02	8.65E-02	4.94E+00	2.27E-02	9.95E-02	5.35E+00
Ni-59	4.25E-08	3.89E-07	1.86E+01	2.36E-07	2.16E-06	1.86E+01	1.06E-06	9.73E-06	1.86E+01
Ni-63	9.86E-08	8.92E-07	1.62E+01	5.50E-07	4.95E-06	1.61E+01	2.47E-06	2.23E-05	1.62E+01
Np-237	1.13E-02	4.23E-02	1.08E+01	4.41E-02	2.30E-01	1.46E+01	1.86E-01	1.03E+00	1.53E+01
Pa-231	1.91E-02	1.05E-01	1.52E+01	1.02E-01	5.81E-01	1.58E+01	4.55E-01	2.61E+00	1.58E+01
Pb-210	4.19E-04	4.09E-03	1.69E+01	2.22E-03	2.27E-02	1.76E+01	1.00E-02	1.02E-01	1.75E+01
Pm-147	3.96E-07	1.75E-06	1.08E+01	1.73E-06	9.23E-06	1.38E+01	7.34E-06	4.16E-05	1.46E+01
Pu-238	5.18E-03	2.98E-02	1.59E+01	2.87E-02	1.65E-01	1.58E+01	1.29E-01	7.43E-01	1.59E+01
Pu-239	5.68E-03	3.28E-02	1.60E+01	3.16E-02	1.82E-01	1.58E+01	1.42E-01	8.20E-01	1.59E+01
Pu-240	5.68E-03	3.28E-02	1.60E+01	3.16E-02	1.82E-01	1.58E+01	1.42E-01	8.20E-01	1.59E+01
Pu-241	1.05E-04	6.08E-04	1.59E+01	5.81E-04	3.48E-03	1.60E+01	2.66E-03	1.56E-02	1.57E+01
Pu-242	5.45E-03	3.14E-02	1.59E+01	3.03E-02	1.74E-01	1.59E+01	1.36E-01	7.84E-01	1.59E+01
Pu-244	2.97E-02	6.71E-02	3.69E+00	6.58E-02	2.05E-01	8.15E+00	1.64E-01	7.75E-01	1.35E+01
Ra-226	2.61E-02	6.26E-02	2.59E+00	3.02E-02	9.77E-02	3.76E+00	3.90E-02	1.27E-01	4.54E+00
Ra-228	1.70E-02	4.17E-02	2.72E+00	2.61E-02	7.43E-02	3.34E+00	4.68E-02	1.39E-01	6.10E+00
Ru-106	1.75E-03	5.95E-03	3.47E+00	1.91E-03	8.92E-03	5.19E+00	2.34E-03	1.01E-02	5.63E+00
Sb-125	3.68E-03	1.45E-02	3.97E+00	3.71E-03	2.12E-02	6.38E+00	3.78E-03	2.33E-02	7.84E+00
Sm-147	9.82E-04	5.68E-03	1.55E+01	5.45E-03	3.16E-02	1.55E+01	2.46E-02	1.42E-01	1.55E+01
Sm-151	3.98E-07	2.28E-06	1.58E+01	2.21E-06	1.27E-05	1.58E+01	9.95E-06	5.72E-05	1.58E+01
Sr-90	5.09E-05	2.12E-04	8.19E+00	1.57E-04	9.10E-04	1.21E+01	5.45E-04	4.04E-03	1.56E+01
Tc-99	3.78E-07	2.22E-06	1.09E+01	1.24E-06	9.23E-06	1.44E+01	4.04E-06	3.99E-05	1.90E+01
Th-228	2.74E-02	5.54E-02	2.91E+00	5.45E-02	1.45E-01	5.93E+00	1.22E-01	5.50E-01	1.10E+01
Th-229	3.21E-02	1.65E-01	1.40E+01	1.61E-01	9.14E-01	1.52E+01	7.16E-01	4.11E+00	1.53E+01
Th-230	4.30E-03	2.48E-02	1.54E+01	2.38E-02	1.38E-01	1.54E+01	1.07E-01	6.22E-01	1.54E+01
Th-232	2.26E-02	1.25E-01	1.48E+01	1.22E-01	6.94E-01	1.52E+01	5.41E-01	3.12E+00	1.54E+01
Tl-204	1.02E-06	3.67E-05	4.91E+01	2.00E-06	4.11E-05	3.35E+01	4.43E-06	5.59E-05	1.91E+01
U-232	1.29E-02	5.59E-02	1.13E+01	5.50E-02	2.95E-01	1.43E+01	2.32E-01	1.32E+00	1.52E+01
U-233	1.78E-03	1.03E-02	1.54E+01	9.86E-03	5.72E-02	1.55E+01	4.45E-02	2.57E-01	1.54E+01
U-234	1.74E-03	1.00E-02	1.54E+01	9.64E-03	5.59E-02	1.55E+01	4.34E-02	2.51E-01	1.55E+01
U-235	4.15E-03	1.28E-02	6.83E+00	1.20E-02	5.23E-02	1.23E+01	4.28E-02	2.34E-01	1.48E+01
U-236	1.64E-03	9.50E-03	1.55E+01	9.14E-03	5.27E-02	1.54E+01	4.11E-02	2.38E-01	1.54E+01
U-238	1.88E-03	9.10E-03	1.32E+01	9.01E-03	5.00E-02	1.49E+01	3.93E-02	2.25E-01	1.52E+01
Zn-65	4.59E-03	1.28E-02	2.91E+00	4.77E-03	1.91E-02	4.48E+00	4.86E-03	2.17E-02	5.54E+00

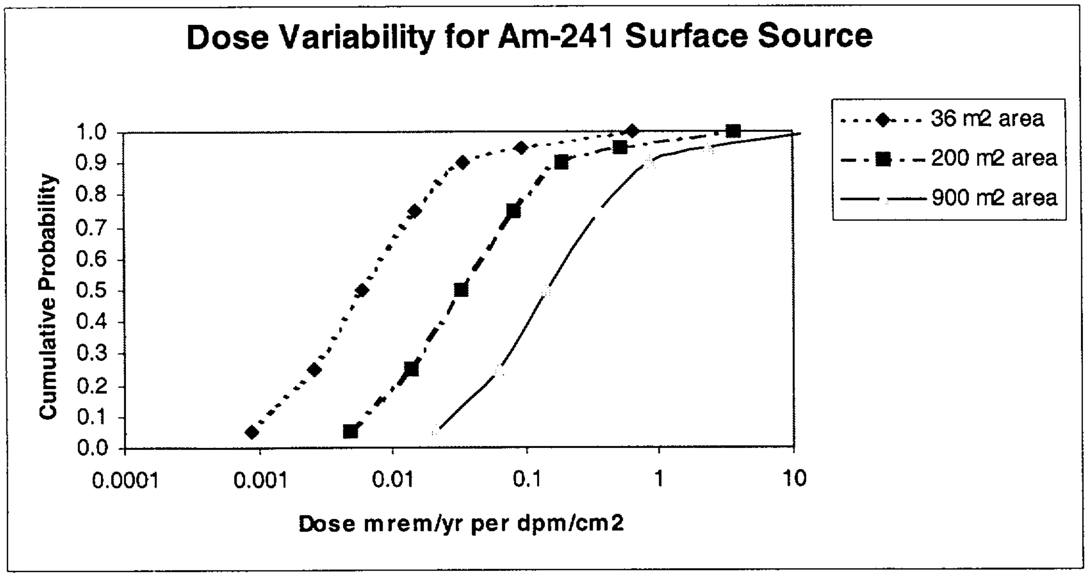

Figure 7.34 Dose Variability of Am-241 for a Surface Source with Three Source Areas in Building Occupancy Scenario

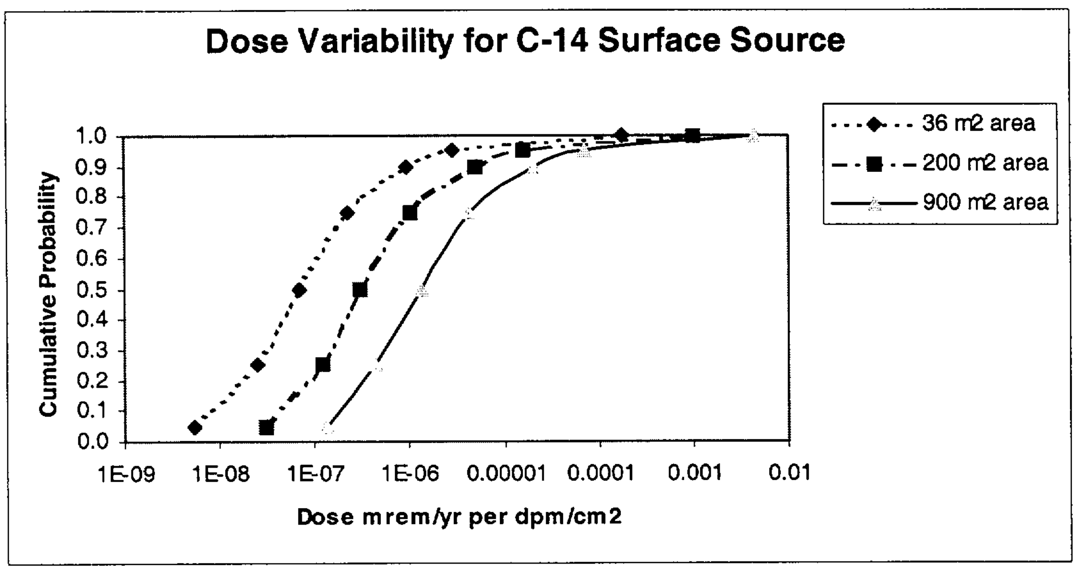

Figure 7.35 Dose Variability of C-14 for a Surface Source with Three Source Areas in Building Occupancy Scenario

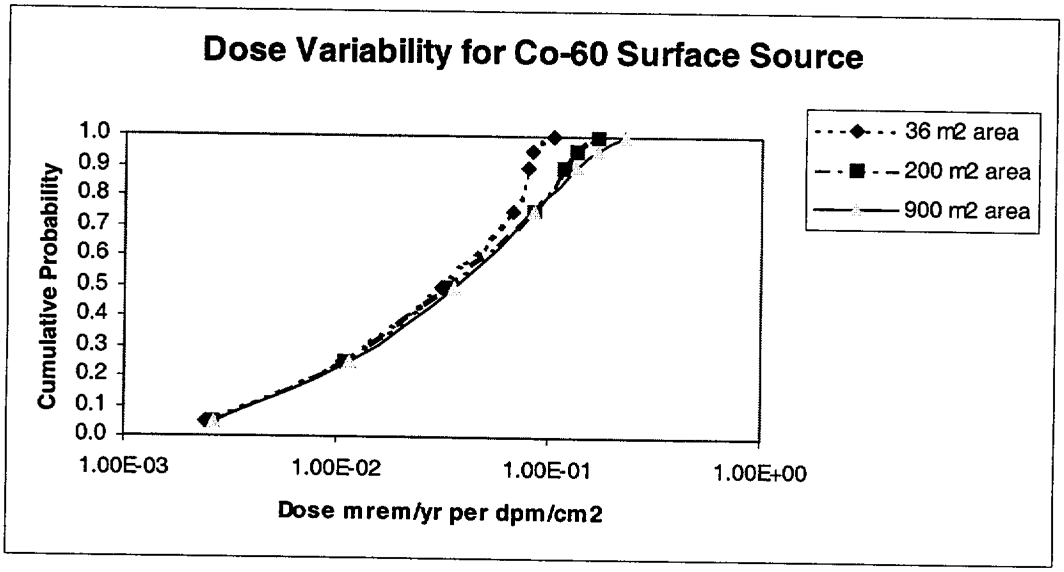

Figure 7.36 Dose Variability of Co-60 for a Surface Source with Three Source Areas in Building Occupancy Scenario

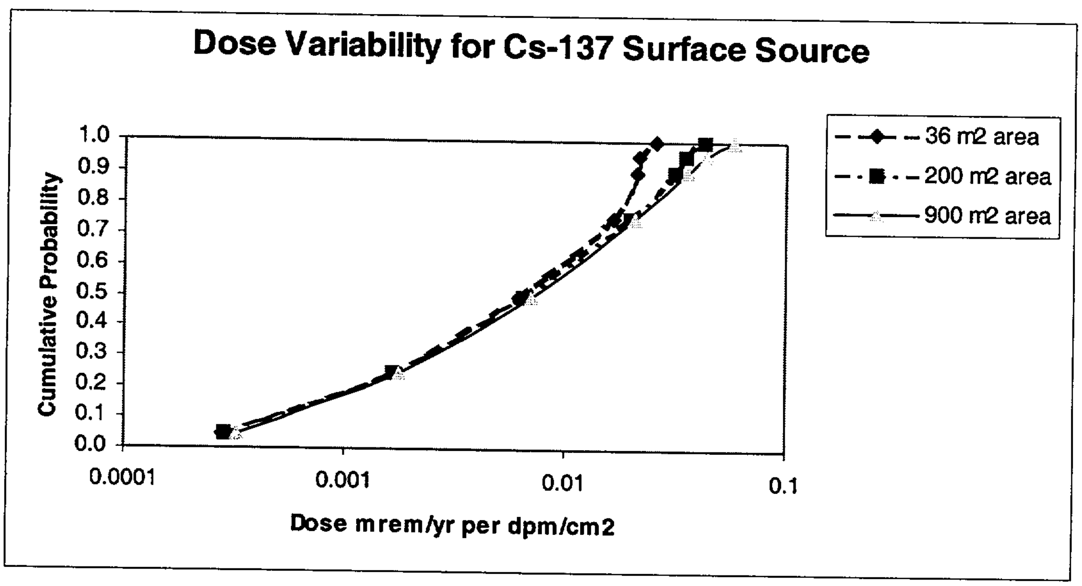

Figure 7.37 Dose Variability of Cs-137 for a Surface Source with Three Source Areas in Building Occupancy Scenario

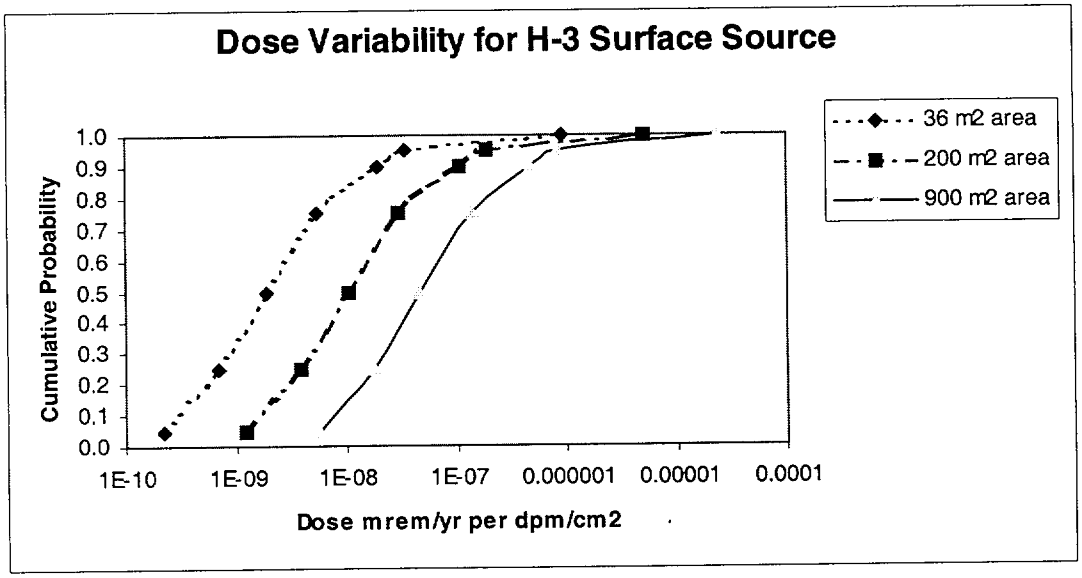

Figure 7.38 Dose Variability of H-3 for a Surface Source with Three Source Areas in Building Occupancy Scenario

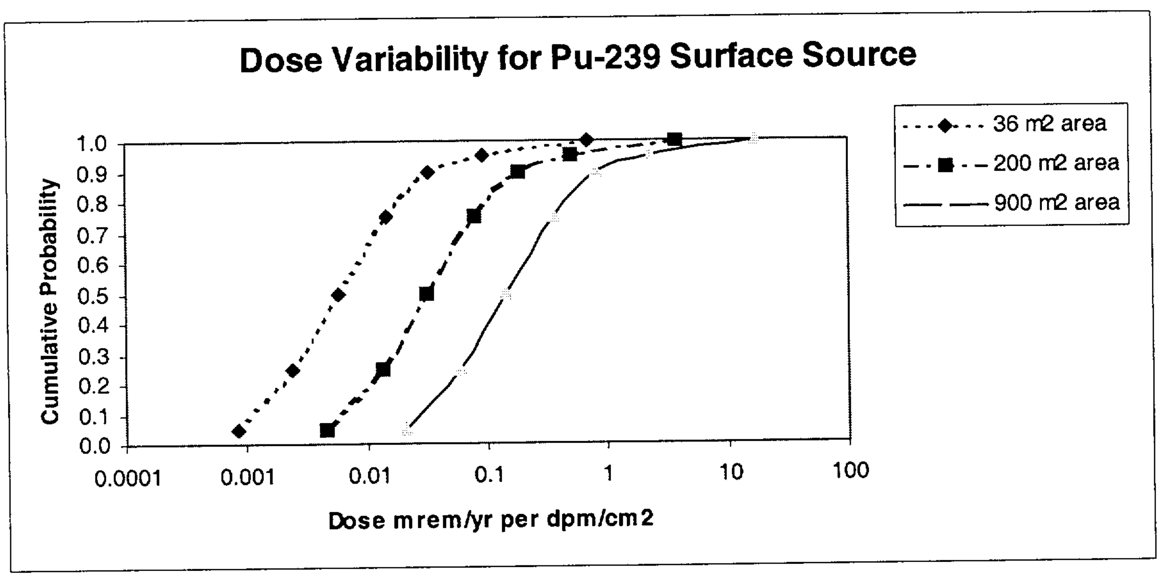

Figure 7.39 Dose Variability of Pu-239 for a Surface Source with Three Source Areas in Building Occupancy Scenario

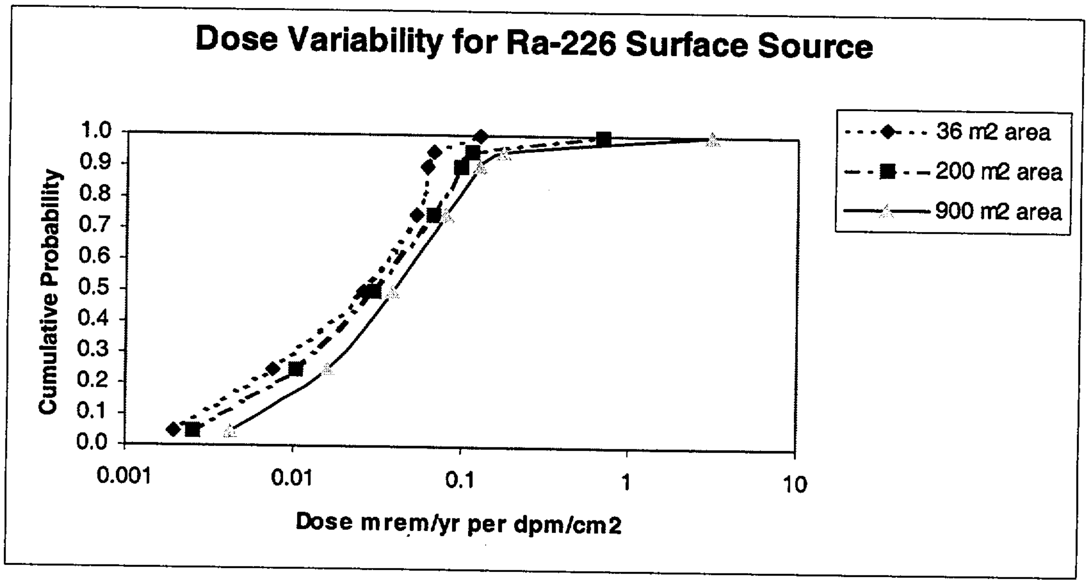

Figure 7.40 Dose Variability of Ra-226 for a Surface Source with Three Source Areas in Building Occupancy Scenario

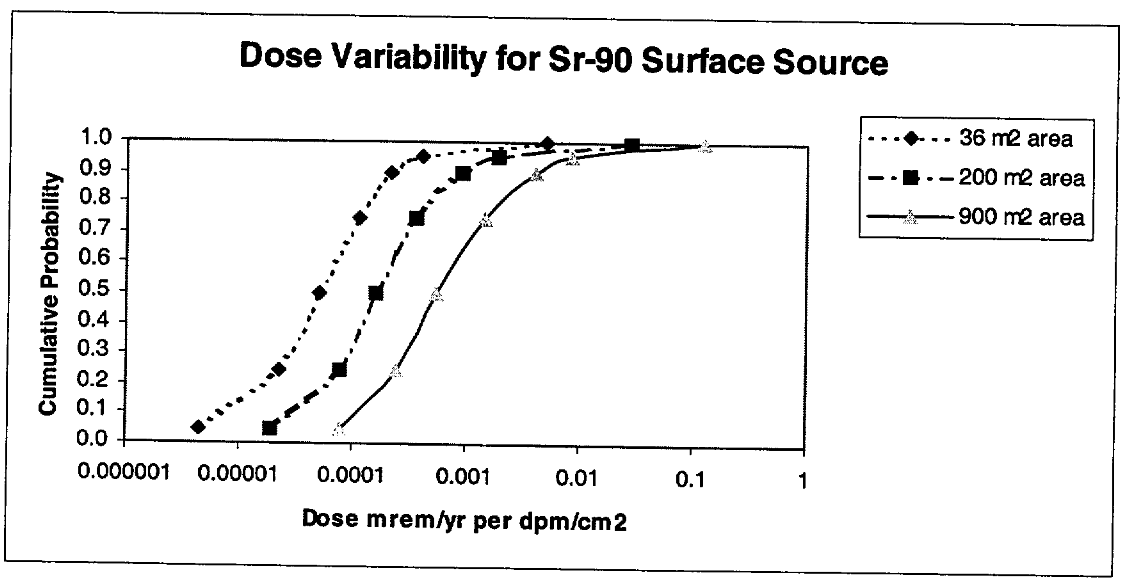

Figure 7.41 Dose Variability of Sr-90 for a Surface Source with Three Source Areas in Building Occupancy Scenario

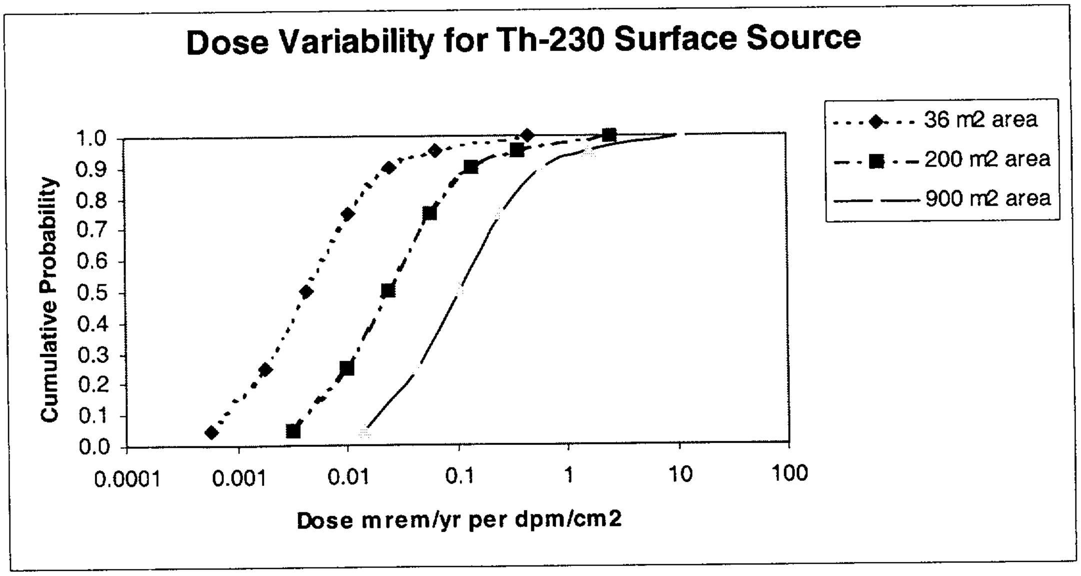

Figure 7.42 Dose Variability of Th-230 for a Surface Source with Three Source Areas in Building Occupancy Scenario

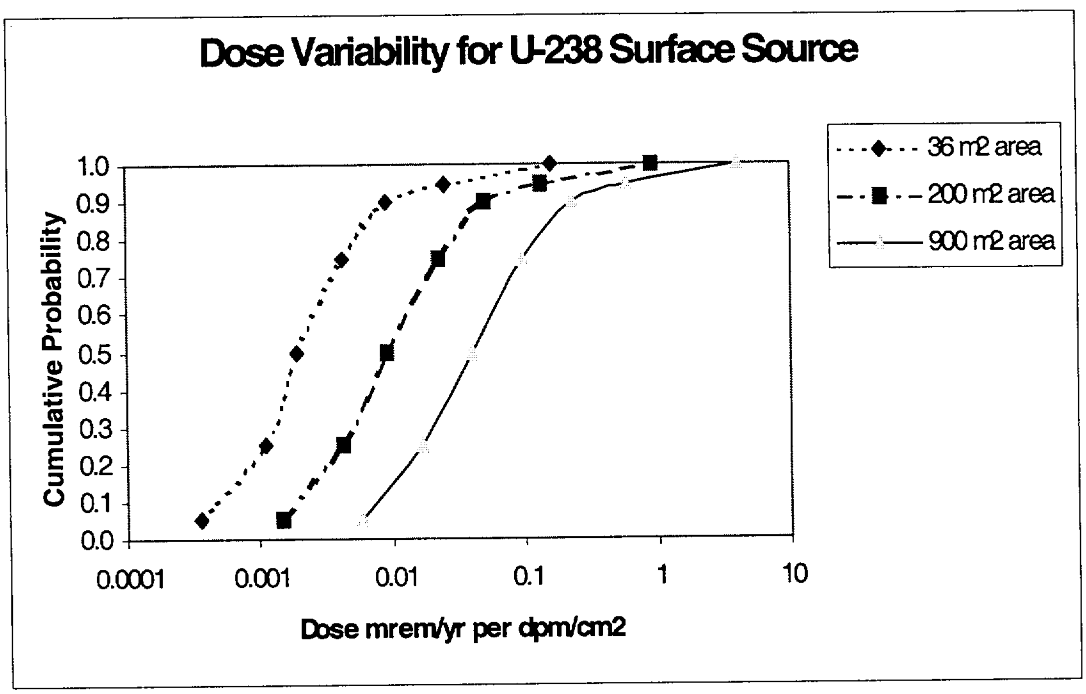

Figure 7.43 Dose Variability of U-238 for a Surface Source with Three Source Areas in Building Occupancy Scenario

Table 7.8. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 36-m² Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	ext	DSTH	EROS0	AREA	
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH	THICK0		
Am-241	inh + ext	EROS0	DSTH	AREA	H
Am-243+D	ext	DSTH			
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	UD
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH			
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH			
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	DKSUS
Co-57	ext	DSTH			
Co-60	ext	DSTH	THICK0		
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	UD
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	ext	DSTH	EROS0	DKSUS	UD
K-40	ext	DSTH	THICK0		
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH			
Pa-231	ext	DSTH	AREA	EROS0	

Table 7.8. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 36-m² Area in a Building Occupancy Scenario (Continued)					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pb-210+D	ext	DSTH	EROS0	AREA	DKSUS
Pm-147	ext	DSTH	EROS0	AREA	
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	DSTH
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	UD	DSDEN	
Tc-99	ext	DSTH	EROS0		
Th-228+D	ext	DSTH	THICK0		
Th-229+D	ext	DSTH			
Th-230+D	inh	AREA	EROS0	DSTH	H
Th-232	ext	DSTH	AREA	EROS0	
Tl-204	ext	DSTH	DSDEN		
U-232	ext	DSTH	THICK0		
U-233	inh	EROS0	AREA	DSTH	H
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH			
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH			
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.9. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 200-m^2 Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	ext	DSTH	AREA	EROS0	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	EROS0	AREA	DSTH	H
Am-243+D	ext	DSTH	EROS0	AREA	
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	AREA
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH			
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH	EROS0	AREA	
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	UD
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	DENSI0
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	ext	EROS0	DSTH	DKSUS	AREA
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH	AREA	EROS0	
Pa-231	ext	DSTH	AREA	EROS0	H

Table 7.9. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 200-m^2 Area in a Building Occupancy Scenario (Continued)					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pb-210+D	ext	DSTH	EROS0	AREA	DKSUS
Pm-147	ext	DSTH	EROS0	AREA	
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	AREA	DSDEN	UD
Tc-99	ext	DSTH	EROS0	AREA	DKSUS
Th-228+D	ext	DSTH			
Th-229+D	ext	DSTH	AREA	EROS0	
Th-230+D	inh	EROS0	AREA	H	DSTH
Th-232	ext	DSTH	AREA	EROS0	
Tl-204	ext	DSTH			
U-232	ext	DSTH			
U-233	inh	EROS0	AREA	H	DSTH
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH	AREA		
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH	AREA	EROS0	
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.10. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 900-m^2 Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	ext	DSTH	EROS0	AREA	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	EROS0	AREA	H	
Am-243+D	ext	DSTH	EROS0	AREA	
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	ext	DSTH	EROS0	DKSUS	AREA
Ca-41	inh + ing	EROS0	AREA	DKSUS	UD
Cd-109	ext	DSTH	EROS0	AREA	
Ce-144+D	ext	DSTH			
Cf-252	inh	EROS0	AREA	H	
Cl-36	ext	DSTH			
Cm-243	ext	DSTH	EROS0	AREA	
Cm-244	inh	EROS0	AREA	H	
Cm-248	inh	EROS0	AREA	H	
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ext	DSTH	DKSUS	EROS0	
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	EROS0	AREA	H	UD
Gd-152	inh	EROS0	AREA	H	
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	DKSUS	UD	H
I-129	inh + ing	EROS0	DKSUS	AREA	UD
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	EROS0	AREA	DKSUS	H
Ni-63	inh	EROS0	AREA	DKSUS	H
Np-237+D	ext	DSTH	AREA	EROS0	
Pa-231	inh	EROS0	AREA	DSTH	H

Table 7.10. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for a Volume Source of 900-m^2 Area in a Building Occupancy Scenario (Continued)					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pb-210+D	inh	EROS0	AREA	DKSUS	UD
Pm-147	ext	DSTH	EROS0	AREA	H
Pu-238	inh	EROS0	AREA	H	
Pu-239	inh	EROS0	AREA	H	
Pu-240	inh	EROS0	AREA	H	
Pu241+D	inh	EROS0	AREA	H	
Pu-242	inh	EROS0	AREA	H	
Pu-244+D	ext	DSTH			
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH			
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	EROS0	AREA	H	
Sm-151	inh	EROS0	AREA	H	
Sr-90+D	ext	DSTH	AREA	EROS0	DSDEN
Tc-99	ext	DSTH	EROS0	AREA	DKSUS
Th-228+D	ext	DSTH			
Th-229+D	ext	DSTH	AREA	EROS0	H
Th-230+D	inh	EROS0	AREA	H	
Th-232	inh + ext	AREA	EROS0	DSTH	H
Tl-204	ext	DSTH			
U-232	ext	DSTH	AREA	EROS0	
U-233	inh	EROS0	AREA	H	
U-234	inh	EROS0	AREA	H	
U-235+D	ext	DSTH	EROS0	AREA	
U-236	inh	EROS0	AREA	H	
U-238+D	ext	DSTH	AREA	EROS0	
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

and without the uncertainty on shielding thickness is shown in Figure 7.44.

For radionuclides for which inhalation was the dominant pathway, room area and source erosion rate were two dominant parameters that contributed to large dose variability. Three radionuclides (Am-241, Cm-244, and Pu-238) were selected to study the effect of room area and erosion rate on the dose variability. Figures 7.45 and 7.46 show the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty on room area and source erosion rate.

7.2.3.2 Dominant Pathways and Sensitive Parameters in Area Source

Tables 7.11 through 7.13 list the four most sensitive parameters based on SRRC along with the dominant pathway for the three sources. Tables C.7 through C.9 in Appendix C present detailed information, including SRRC values. Only sensitive parameters with SRRC values of ≥0.1 are only listed in these tables. An SRRC value of 0.1 means that one standard deviation change in the parameter value will change the resultant dose by 0.1 times the standard deviation of the dose.

For radionuclides for which external exposure was the dominant pathway, shielding thickness was found to be the dominant contributor to the dose variability. Three radionuclides (Co-60, Al-26, and Eu-152) were selected to study the effect of shielding thickness. It was observed that after removing the shielding thickness from uncertainty analysis, dose variability was significantly reduced. Figure 7.47 shows the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty on shielding thickness.

For radionuclides for which inhalation was the dominant pathway, many parameters (e.g., room area, removable fraction, source lifetime) contributed to the dose variability. Figures 7.48 through 7.50 show the dose ratio (95th percentile dose to 50th percentile dose) with and without the uncertainty for room area, removable fraction, and source lifetime, respectively, for Am-241, Pu-239, and U-238.

For radionuclides with the ingestion pathway as the dominant contributor to the dose, apart from three parameters (room area, removable fraction, source life-time) that contributed to dose variability in the inhalation pathway, deposition velocity and resuspension rate also showed high sensitivity. Figures 7.51 and 7.52 show the effect of deposition velocity and resuspension rate on the dose variability for C-14, I-129, and Cs-135.

7.2.4 Parameter Correlation Results

The results showed that resuspension rate and deposition velocity were sensitive parameters for some radionuclides (e.g., C-14, Ca-41, Cs-135, and I-129) in the case of volume sources. A positive rank correlation of 0.9 was used between deposition velocity and resuspension rate. Four radionuclides (Ca-41, I-129, C-14, and Cs-135) were selected to study the effect of correlation. Figure 7.53 shows the difference in dose variability with and without correlation between deposition velocity and resuspension rate. Dose variability was considerably reduced by the use of correlation. In the absence of knowledge of real correlation between deposition velocity and resuspension rate, rank correlation was not used in the analysis.

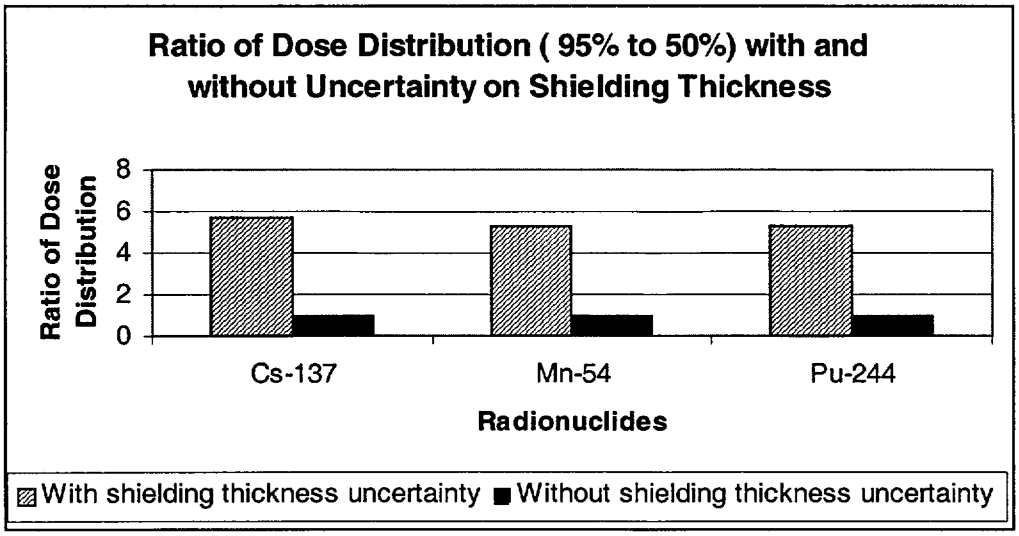

Figure 7.44 Ratio of Dose Distribution with and without Uncertainty on Shielding Thickness for a Volume Source in Building Occupancy Scenario

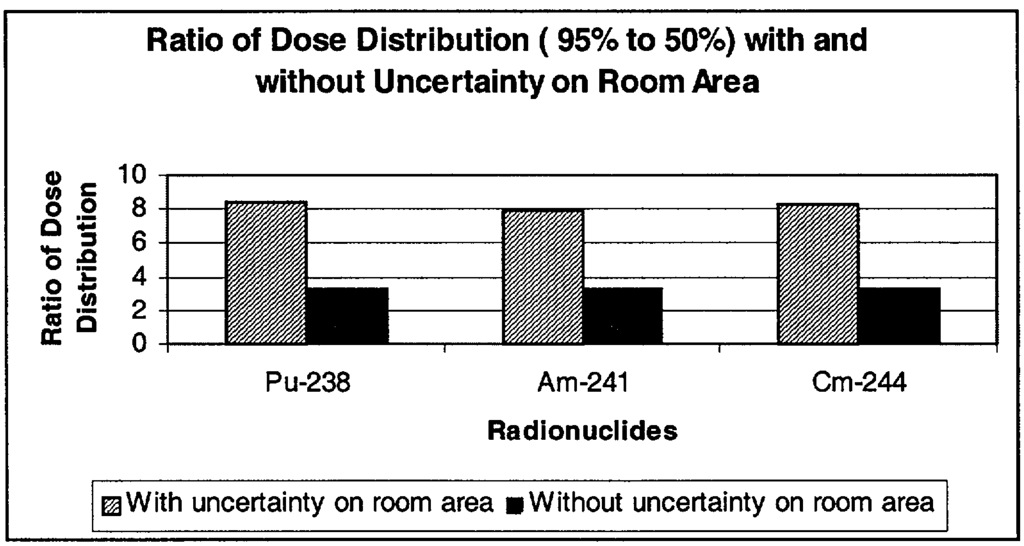

Figure 7.45 Ratio of Dose Distribution with and without Uncertainty on Room Area for a Volume Source in Building Occupancy Scenario

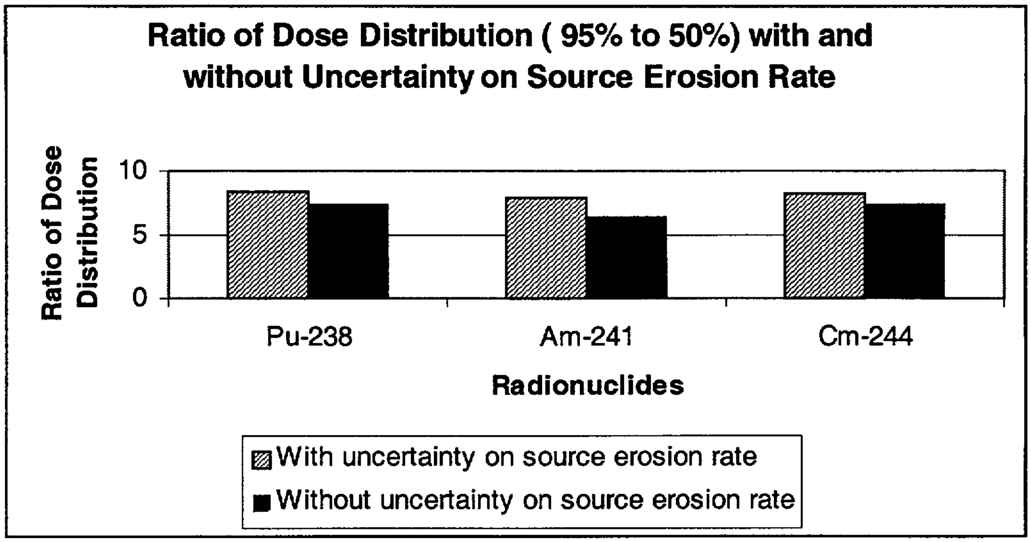

Figure 7.46 Ratio of Dose Distribution with and without Uncertainty on Source Erosion Rate for a Volume Source in Building Occupancy Scenario

Table 7.11. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 36-m^2 Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	DSTH
Au-195	ext	DSTH			
Bi-207	ext	DSTH			
C-14	inh + ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	ext	DSTH	AREA	RF0	RMVFR
Ce-144+D	ext	DSTH			
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	ext	DSTH	AREA	RF0	UD
Cm-243	inh	AREA	RF0	RMVFR	DSTH
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	inh + ing	DKSUS	AREA	RF0	DSTH
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH			
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH			
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	DSTH
Pa-231	inh	AREA	RF0	RMVFR	H

Table 7.11. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 36-m^2 Area in a Building Occupancy Scenario (Continued)					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pb-210+D	inh	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	DSTH
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	ext	DSTH	AREA	RF0	RMVFR
Ra-226+D	ext	DSTH			
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	DSTH	RMVFR
Tc-99	inh + ext	DSTH	AREA	RF0	RMVFR
Th-228+D	ext	DSTH	AREA	RF0	RMVFR
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	DSTH
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh + ext	DSTH	AREA	RF0	RMVFR
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.12. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 200-m^2 Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	H
Au-195	ext	DSTH	AREA	RF0	RMVFR
Bi-207	ext	DSTH			
C-14	inh + ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	ext	DSTH	AREA	RF0	RMVFR
Ce-144+D	ext	DSTH			
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	ext	DSTH	AREA	RF0	RMVFR
Cm-243	inh	AREA	RF0	RMVFR	H
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	inh + ing	DKSUS	AREA	RF0	RMVFR
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH	AREA	RF0	RMVFR
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH	AREA	RF0	RMVFR
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	inh + ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H

Table 7.12. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 200-m² Area in a Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	H
Pa-231	inh	AREA	RF0	RMVFR	H
Pb-210+D	inh + ing	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	H
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	inh	AREA	DSTH	RF0	RMVFR
Ra-226+D	ext	DSTH	AREA	RF0	
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH			
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	RMVFR	UD
Tc-99	inh	AREA	RF0	RMVFR	DSTH
Th-228+D	ext	DSTH	AREA	RF0	RMVFR
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	H
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh	AREA	RF0	RMVFR	DSTH
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

Table 7.13. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 900-m² Area in a Building Occupancy Scenario					
Radionuclide	Dominant Pathway[a]	Four Most Sensitive Parameters[b] Based on SRRC Analysis			
		1	2	3	4
Ac-227+D[c]	inh	AREA	RF0	RMVFR	H
Ag-108m+D	ext	DSTH			
Ag-110+D	ext	DSTH			
Al-26	ext	DSTH			
Am-241	inh	AREA	RF0	RMVFR	H
Am-243+D	inh	AREA	RF0	RMVFR	H
Au-195	ext	DSTH	AREA	RF0	RMVFR
Bi-207	ext	DSTH			
C-14	inh +ing	AREA	DKSUS	RF0	RMVFR
Ca-41	inh + ing	AREA	DKSUS	RF0	RMVFR
Cd-109	inh	AREA	DSTH	RF0	RMVFR
Ce-144+D	ext	DSTH	AREA	RF0	RMVFR
Cf-252	inh	AREA	RF0	RMVFR	H
Cl-36	inh	AREA	DSTH	RF0	RMVFR
Cm-243	inh	AREA	RF0	RMVFR	H
Cm-244	inh	AREA	RF0	RMVFR	H
Cm-248	inh	AREA	RF0	RMVFR	H
Co-57	ext	DSTH			
Co-60	ext	DSTH			
Cs-134	ext	DSTH			
Cs-135	ing	DKSUS	AREA	RF0	RMVFR
Cs-137+D	ext	DSTH			
Eu-152	ext	DSTH			
Eu-154	ext	DSTH			
Eu-155	ext	DSTH	AREA	RF0	RMVFR
Fe-55	inh	AREA	RF0	RMVFR	H
Gd-152	inh	AREA	RF0	RMVFR	H
Gd-153	ext	DSTH	AREA	RF0	RMVFR
Ge-68+D	ext	DSTH			
H-3	inh + ing	AREA	RF0	RMVFR	DKSUS
I-129	inh + ing	DKSUS	AREA	RF0	RMVFR
K-40	ext	DSTH			
Mn-54	ext	DSTH			
Na-22	ext	DSTH			
Nb-94	ext	DSTH			
Ni-59	inh	AREA	RF0	RMVFR	H
Ni-63	inh	AREA	RF0	RMVFR	H
Np-237+D	inh	AREA	RF0	RMVFR	H

Table 7.13. Four Most Sensitive Parameters Based on SRRC Analysis and Dominant Pathways for an Area Source of 900-m² Area in a Building Occupancy Scenario (Continued)					
		Four Most Sensitive Parameters[b] Based on SRRC Analysis			
Radionuclide	Dominant Pathway[a]	1	2	3	4
Pa-231	inh	AREA	RF0	RMVFR	H
Pb-210+D	inh + ing	AREA	RF0	RMVFR	DKSUS
Pm-147	inh	AREA	RF0	RMVFR	H
Pu-238	inh	AREA	RF0	RMVFR	H
Pu-239	inh	AREA	RF0	RMVFR	H
Pu-240	inh	AREA	RF0	RMVFR	H
Pu241+D	inh	AREA	RF0	RMVFR	H
Pu-242	inh	AREA	RF0	RMVFR	H
Pu-244+D	inh	AREA	RF0	RMVFR	H
Ra-226+D	ext	DSTH	AREA	RF0	UD
Ra-228+D	ext	DSTH	AREA	RF0	RMVFR
Ru-106+D	ext	DSTH	AREA	RF0	
Sb-125	ext	DSTH			
Sm-147	inh	AREA	RF0	RMVFR	H
Sm-151	inh	AREA	RF0	RMVFR	H
Sr-90+D	inh	AREA	RF0	RMVFR	H
Tc-99	inh + ing	AREA	RF0	RMVFR	DKSUS
Th-228+D	inh	AREA	RF0	RMVFR	DSTH
Th-229+D	inh	AREA	RF0	RMVFR	H
Th-230+D	inh	AREA	RF0	RMVFR	H
Th-232	inh	AREA	RF0	RMVFR	H
Tl-204	ext	DSTH	AREA	RF0	UD
U-232	inh	AREA	RF0	RMVFR	H
U-233	inh	AREA	RF0	RMVFR	H
U-234	inh	AREA	RF0	RMVFR	H
U-235+D	inh	AREA	RF0	RMVFR	H
U-236	inh	AREA	RF0	RMVFR	H
U-238+D	inh	AREA	RF0	RMVFR	H
ZN-65	ext	DSTH			

[a] Pathways: ext = external, inh = inhalation, ing = ingestion.

[b] Parameters are only listed if SRRC was greater than 0.1. Descriptive name of the parameter is given in Table B.1.

[c] +D indicates that associated radionuclides with half-lives less than 6 months are in secular equilibrium with the principal radionuclides.

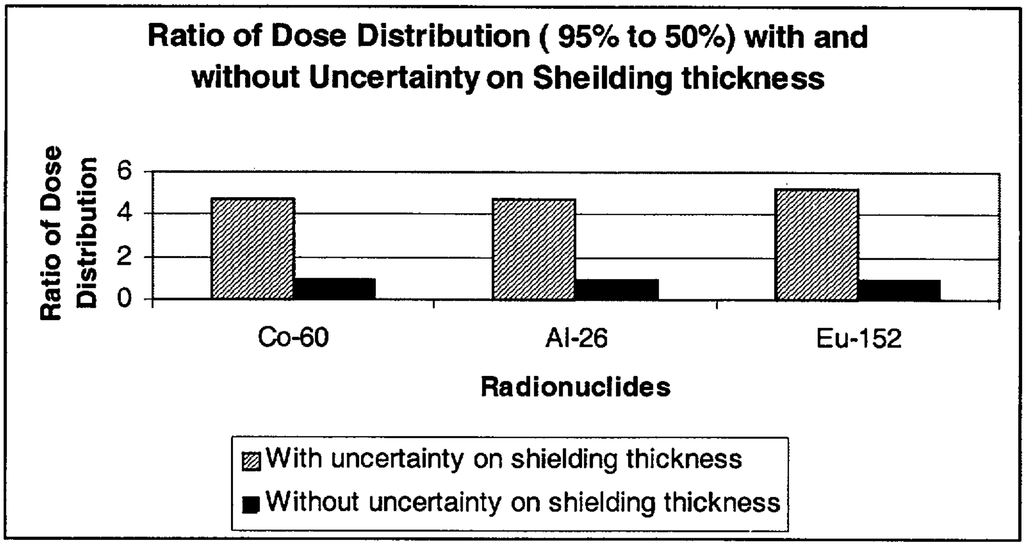

Figure 7.47 Ratio of Dose Distribution with and without Uncertainty on Shielding Thickness for a Surface Source in Building Occupancy Scenario

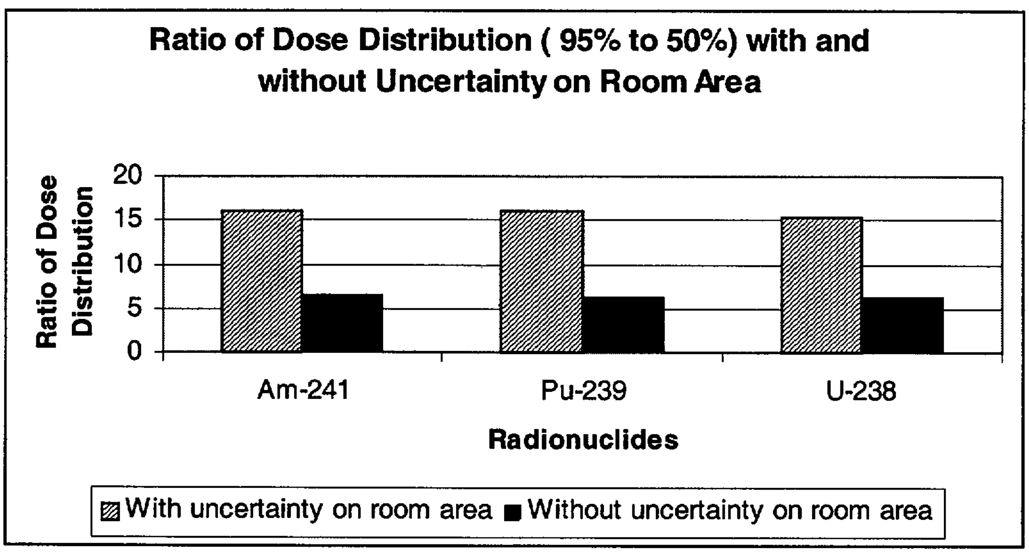

Figure 7.48 Ratio of Dose Distribution with and without Uncertainty on Room Area for a Surface Source in Building Occupancy Scenario

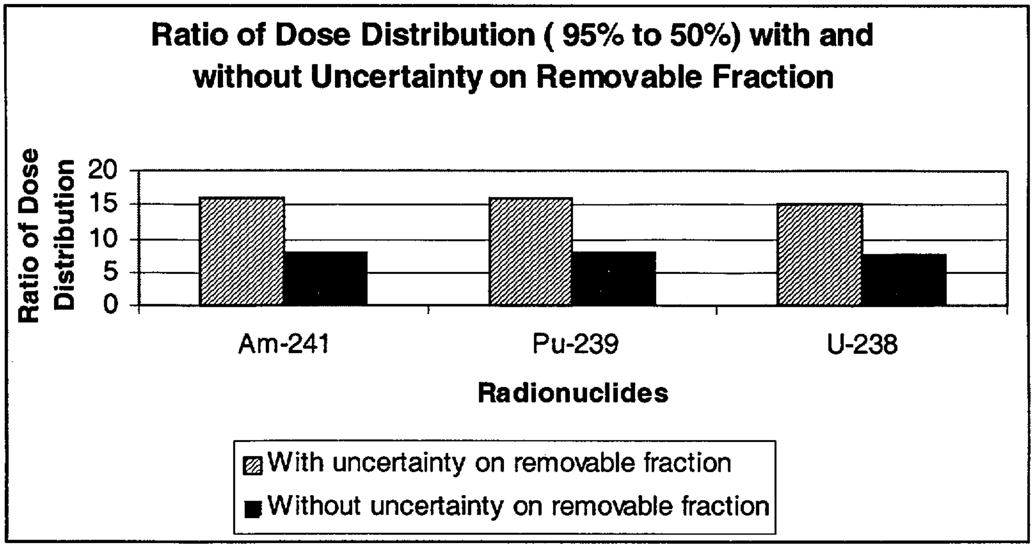

Figure 7.49 Ratio of Dose Distribution with and without Uncertainty on Removable Fraction for a Surface Source in Building Occupancy Scenario

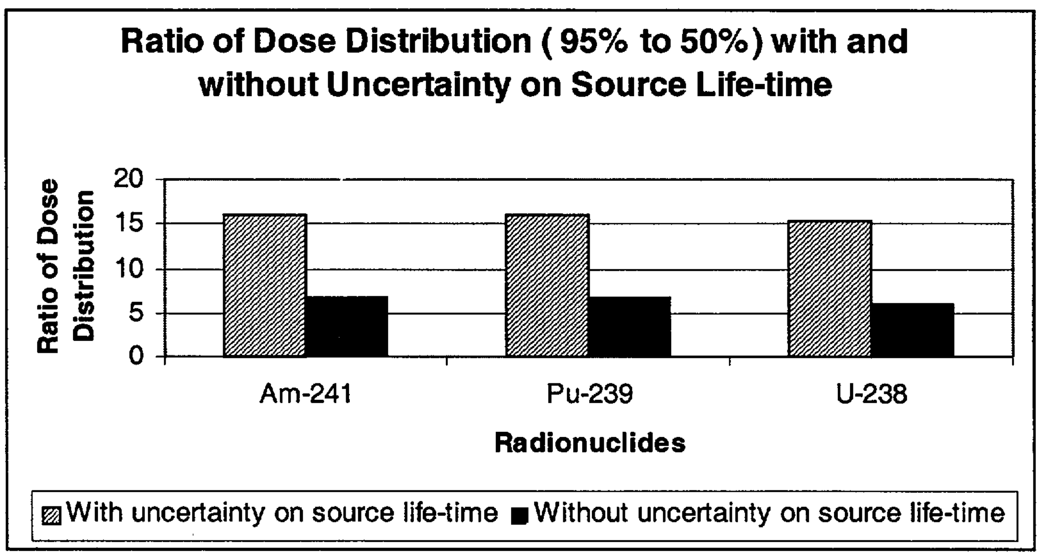

Figure 7.50 Ratio of Dose Distribution with and without Uncertainty on Source Lifetime for a Surface Source in Building Occupancy Scenario

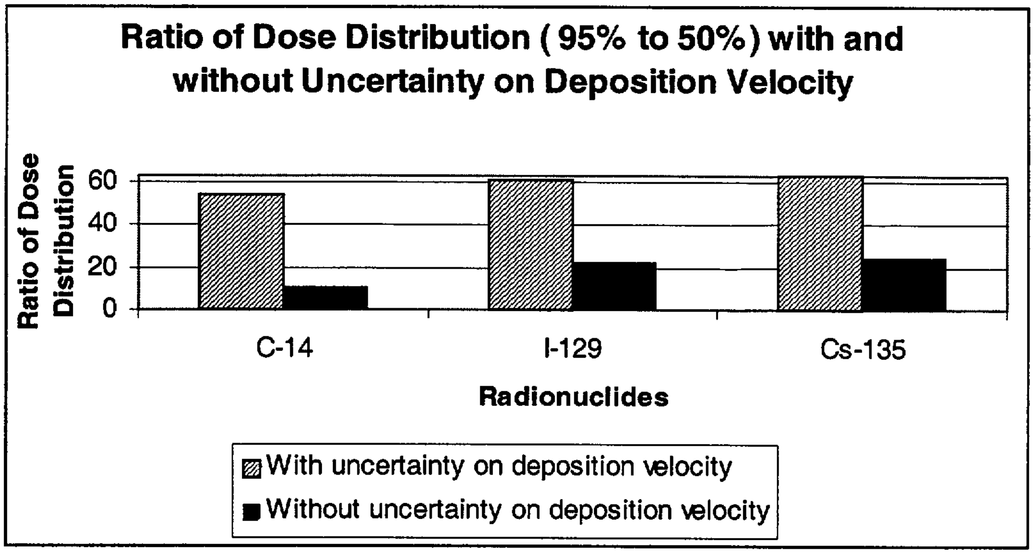

Figure 7.51 Ratio of Dose Distribution with and without Uncertainty on Deposition Velocity for a Surface Source in Building Occupancy Scenario

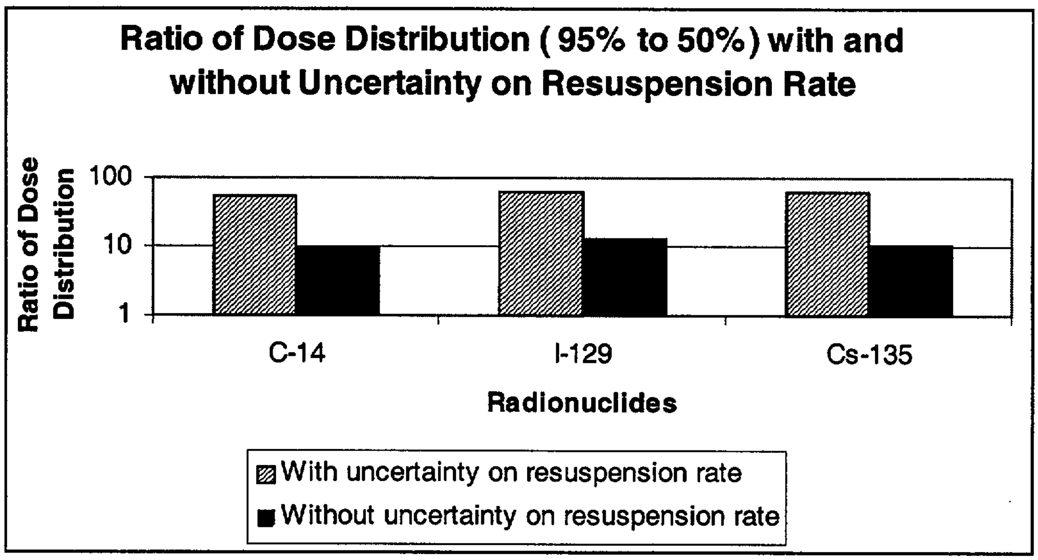

Figure 7.52 Ratio of Dose Distribution with and without Uncertainty on Resuspension Rate for a Surface Source in Building Occupancy Scenario

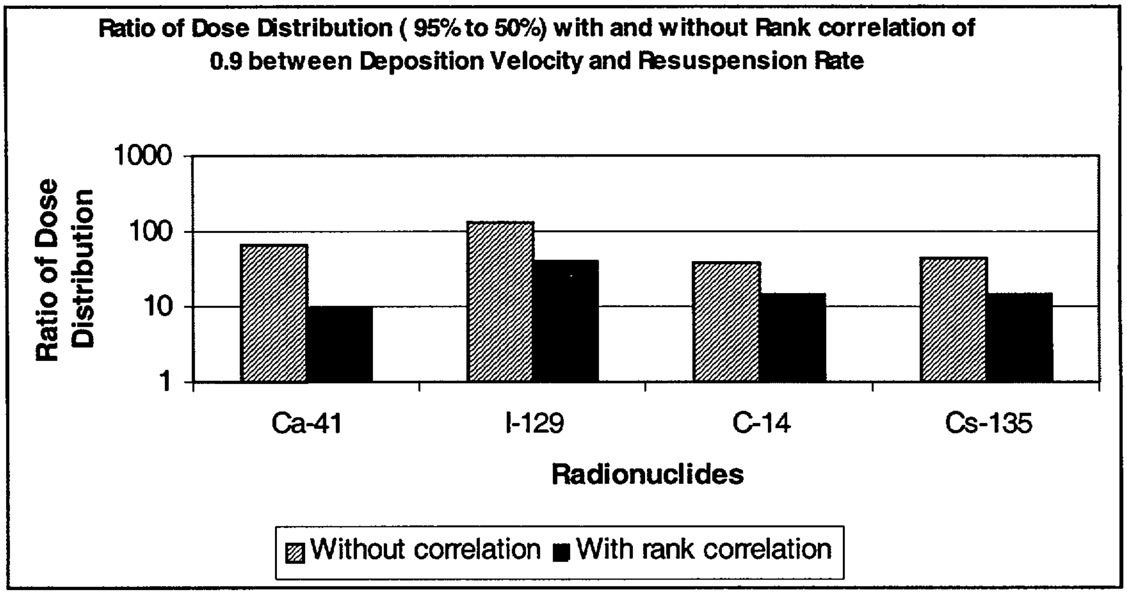

Figure 7.53 Ratio of Dose Distribution with and without Rank Correlation between Deposition Velocity and Resuspension Rate for a Surface Source in Building Occupancy Scenario

8 SUMMARY AND DISCUSSION

The probabilistic dose analysis discussed in this report was conducted to assess the effects of parameter distributions on estimated doses for residual radionuclides as calculated with the RESRAD and RESRAD-BUILD codes for the residential and building occupancy scenarios, respectively. Parameter distributions developed by Biwer et al. (2000) were successfully incorporated into the RESRAD and RESRAD-BUILD codes, and the capability of the two codes to conduct site-specific analyses was tested.

The probabilistic dose analysis was performed by using the stratified sampling of the Latin hypercube sampling (LHS) method to obtain a collection of input distributions. This method provides a rather efficient process for multiparameter sampling. In the analysis, the total effective dose equivalent (TEDE) was estimated for an average member of the critical group under the two scenarios used to assess compliance with the U.S. Nuclear Regulatory Commission's (NRC's) decommissioning and license termination criteria. For RESRAD, the peak dose within a time frame of 1,000 years was captured; for RESRAD-BUILD, the dose at time 0 was computed.

The dose distribution analysis conducted for this report used the generic distributions developed in the Parameter Distribution Report (Biwer et al., 2000) to test the distribution data and to demonstrate the capability of RESRAD and RESRAD-BUILD to perform a site-specific analysis. The specific strategy used to select input values depended on the parameter categories (physical, behavioral, or metabolic). The effect of correlation of input parameter distribution was studied. In cases when a clear relationship was identified (such as bulk density and total porosity and total porosity and effective porosity), strong rank correlations were used.

Some parameters previously identified to be important to dose values (Cheng et al., 1999) were confirmed in the analysis. For RESRAD, such parameters include radionuclide concentrations, source area, and source thickness. For RESRAD-BUILD, these parameters include radionuclide concentrations and source area. To illustrate the sensitivity of the parameters, three source configurations were analyzed for RESRAD: (1) area of 100 m^2 and thickness of 15 cm; (2) area of 2,400 m^2 and thickness of 15 cm; (3) area of 10,000 m^2 and thickness of 2 m. For RESRAD-BUILD, three different areas (36 m^2, 200 m^2, and 900 m^2) were analyzed for area sources, and the same three areas (36 m^2, 200 m^2, and 900 m^2) along with the probability distribution on source thickness were used for volume sources.

Results for the residential scenario indicate that for a change from the baseline configuration (source configuration 1) to an increased area (source configuration 2), a 19-fold increase in the estimated dose could occur, while a change from the baseline case to an extended thickness and area (source configuration 3) could lead a 100-fold increase in the estimated dose. Similarly for the building occupancy scenario, a change in source area could lead to a 25-fold increase in the estimated dose.

Quantile values (at 50th percentile and 90th percentile) of the dose distributions were generated. Dose spread for different radionuclides was identified by the ratio of dose at the 99th percentile to that at the 50th percentile for the residential scenario and by the ratio of dose at the 95th percentile to that at the 50th percentile for the building occupancy scenario. Regression analysis was used to identify sensitive parameters. The partial rank correlation coefficients and standardized rank regression coefficients were used as illustrative examples in the residential and building occupancy scenarios, respectively. The effects of sensitive parameters on distribution were studied for selected radionuclides.

Results demonstrate the successful integration of the parameter distributions developed for the residential and building occupancy scenarios with the probabilistic module developed for the RESRAD and RESRAD-BUILD codes to support NRC's license termination effort. The results demonstrate that the codes and the developed input parameter distributions can be used to accomplish a probabilistic analysis. Application of the process is therefore shown to be feasible for site-specific modeling and analysis in the future when data pertinent to a specific site can be developed.

In a site-specific application, however, some general aspects must be taken into account to ensure accurate modeling and analysis:

- Parameter sensitivity depends on the contamination configuration, and, therefore, it is site specific. It is important that ranking of key parameters be assessed for each individual site.

- Potential correlation between a parameter and the estimated dose varies from radionuclide to radionuclide. Special considerations, experience, and judgment would be needed in obtaining an accurate assessment.

- Site-specific data collection may be needed for parameters consistently identified to be important to the dose analysis in this report.

8.1 HIGHLIGHTS OF RESIDENTIAL SCENARIO RESULTS

- Probabilistic dose analyses for 90 principal radionuclides in three source configurations were performed with distributions for 33 radionuclide-independent parameters and many radionuclide-dependent parameters for the residential scenario.

- Results indicate that the doses calculated appear reasonable and show a consistent pattern. The ratio between the 99th percentile dose and 50th percentile dose ranges from 2.0 to 79 for all radionuclides. Such variations depend on the source configurations and on the type of radionuclide. For radionuclides with a dominant external pathway, the ratio between the 99th percentile dose and 50th percentile dose was close to 2.3 (Ag-108m and Eu-152). For radionuclides with other dominant pathways, dose variabilities were higher. However, site-specific distributions should be used whenever available, especially for sensitive parameters such as the external shielding factor and the plant transfer factor.

- Input rank correlations between total porosity and effective porosity and between bulk density and total porosity were studied, and the results were used in the probabilistic dose analysis to ensure proper pairing between the parameters.

- Significant changes in dose values were observed among the three source configurations (i.e., changes in source thickness or source area resulted in significant changes in dose). For some radionuclides (e.g., Ca-145 and H-3), dose values changed by an order of magnitude. The dose at 90th percentile increased by 12% to 2,900% when the source area changed from 100 m^2 to 2,400 m^2 with a constant source thickness of 15 cm. When the source thickness was changed to 2 m and the source area to 10,000 m^2 from a source thickness of 15 cm and an area of 2,400 m^2, dose at 90th percentile increased by 5% to 2,600%.

- For about 30 radionuclides, the upper 10% of the peak doses occurred at times other than time 0. For these radionuclides, sensitive parameters would change with the dose percentile selected.

- The external shielding factor was the most sensitive parameter in many cases when external exposure was the dominant pathway (this factor accounts for the shielding provided by the structure of the house when the receptor is inside), and the total dose variability could be explained with just the variability in the external shielding factor.

- The plant transfer factor was the most sensitive parameter in many cases when plant ingestion was the dominant pathway (such as for Ca-45 and Cs-135).

- It was observed that no single correlation or regression coefficient (e.g., PRCC, SRRC) can be used alone to identify sensitive parameters in all the cases. The coefficients are useful guides, but they have to be used in conjunction with other aids, such as scatter plots, and must undergo further analysis.

8.2 HIGHLIGHTS OF BUILDING OCCUPANCY SCENARIO RESULTS

- Probabilistic dose analyses were performed for 67 principal radionuclides for two source types (volume and area), with three source areas, with distributions for 15 parameters.

- Results indicate 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.

- Dose variability in the RESRAD-BUILD results for the building occupancy scenario for both volume and area sources was much more than the dose variability observed in RESRAD results for the residential scenario.

- Significant changes (by as much as 25-fold) in dose values were observed with change in source area (from 36 m^2 to 900 m^2) for many radionuclides (such as Cm-244 and Ni-63). For radionuclides with a dominant external pathway (e.g., Co-60, Cs-137), dose changes with source area occurred only at high dose percentile values. Because of shielding between the source and receptor, dose values did not change at low dose percentile values.

- For radionuclides with a dominant external exposure pathway (e.g., Co-60, Cs-137), shielding thickness between the source and receptor was the dominant contributor to the dose variability (ratio between the 95th percentile dose and 50th percentile dose) for volume as well as area sources.

- For radionuclides such as Am-241 and Pu-238 with a dominant inhalation pathway, room area and source erosion rate were the two most sensitive parameters for volume sources. For area sources, the parameters room area, removable fraction, and source lifetime all contributed to the dose variability.

- For a volume source, the ingestion pathway was dominant only for two radionuclides (Ca-41 and H-3). For surface sources, the ingestion pathway was dominant for a few more radionuclides (C-14, Cs-135, I-129).

- For radionuclides with a dominant ingestion pathway (such as C-14 and Cs-135), in addition to the sensitive parameters identified for the inhalation pathway, deposition velocity and resuspension rate also contributed to dose variability.

- When a rank correlation coefficient of 0.9 between deposition velocity and resuspension rate was used, the dose variability was significantly reduced (by a factor of 7).

9 REFERENCES

Beyeler, W.E., et al. NUREG/CR-5512, SAND99-2148, Vol. 3, "Residual Radioactive Contamination from Decommissioning: Parameter Analysis." Prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission. October 1999.

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, IL, for U.S. Nuclear Regulatory Commission. 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, IL, for U.S. Nuclear Regulatory Commission. October 1999.

Cullen, A.C. and H.C. Frey. *Probabilistic Techniques in Exposure Assessment.* Plenum Press: New York, N.Y. 1999.

Haaker, R., et al. NUREG/CR-5512, Vol. 4, "Comparison of Models and Assumptions Used in the DandD 1.0, RESRAD 5.61 and RESRAD-BUILD 1.50 Computer Codes with Respect to the Residential Farmer and Industrial Occupant Scenario Provided in NUREG/CR-5512." Prepared by Sandia National Laboratories, Albuquerque N.M., for U.S. Nuclear Regulatory Commission. October 1999.

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, N.M., for the U.S. Nuclear Regulatory Commission. 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, N.M., for U.S. Nuclear Regulatory Commission. 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, N.M., for U.S. Nuclear Regulatory Commission. June 1985.

International Atomic Energy Agency. "Evaluating Reliability of Predictions Made Using Environmental Transfer Models." Report No. 100. IAEA: Vienna. 1989.

International Commission on Radiological Protection. "Principles of Monitoring for the Protection of the Population." ICRP Publication 43. Pergamon Press: New York, N.Y. 1984.

Kamboj, S., et al. "Parameters and Parameter Types in RESRAD and RESRAD-BUILD Codes." Letter report prepared by Argonne National Laboratory, Argonne, IL, for U.S. Nuclear Regulatory Commission. September 1999.

Kennedy, W.E. and Strenge, D.L. 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. October 1992.

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,* Vol. 21, pp. 239-245. 1979.

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

Nuclear Regulatory Commission (U.S.) (NRC). Draft Regulatory Guide, DG 4006, "Demonstrating Compliance with the Radiological Criteria for License Termination." Office of Nuclear Regulatory Research, NRC: Washington, D.C. August 1998b.

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 1998c.

Wernig, M.A., et al. NUREG/CR-5512, Vol. 2, "Residual Radioactive Contamination from Decommissioning." Office of Nuclear Regulatory Research, NRC: Washington, D.C. May 1999.

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, WI. 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, IL. 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, IL. November 1994.

APPENDIX A

DESCRIPTION OF PROBABILISTIC MODULE USED TO EVALUATE DOSE DISTRIBUTION

APPENDIX A

DESCRIPTION OF PROBABILISTIC MODULE USED TO EVALUATE DOSE DISTRIBUTION

This appendix discusses the details of the probabilistic module used to evaluate dose distribution. The details presented include integration of the module with the RESRAD and RESRAD-BUILD codes, general navigation, and input forms.

A.1 INTEGRATION WITH RESRAD CODES

The probabilistic module is integrated into both the RESRAD and RESRAD-BUILD software packages. The system has been designed so that the details of file, data, and calculational modules are hidden from the user. The high-level details of this system are shown in Figure A.1. The user can start the programs, specify cases, and run the codes in a manner similar to the previous versions. The probabilistic module input is displayed through either the toolbar or by pressing the "F8" key when the windows focus is on a specific parameter. The output module is displayed through the menu. (See Figure A.2 for a diagram of this process.)

A.2 NAVIGATION

The procedures for using the probabilistic analysis module are as follows:

- Users run the standard software interface (RESRAD or RESRAD-BUILD) to set deterministic values for parameters not involved with probabilistic analysis.

- Probabilistic analysis is set by finding parameters in the standard interface and pressing the "F8" key. The probabilistic input window with four tab screens will appear.

- The parameter will be automatically added, with its default distribution, to the list of parameters for probabilistic analysis.

- If the probabilistic analysis is activated, after running the standard software, the probabilistic runs will begin.

- After the calculations are completed, the interactive output window will appear so tables and graphics can be created to display results. Access is available to both the textual report and the detailed data dump files.

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

The input window (see Section A.3) takes information from the default distribution database and from the user's commands to construct the list of parameters, their distributions and correlations, and general sampling options. At run time, the LHS code is activated to perform the sampling. The code is then run on these samplings, and the results are stored for incorporation into textual reports.

A.3 INPUT WINDOWS

A.3.1 Sample Specifications

The user is allowed to specify details of the sample generation (Figure A.3). Included in this

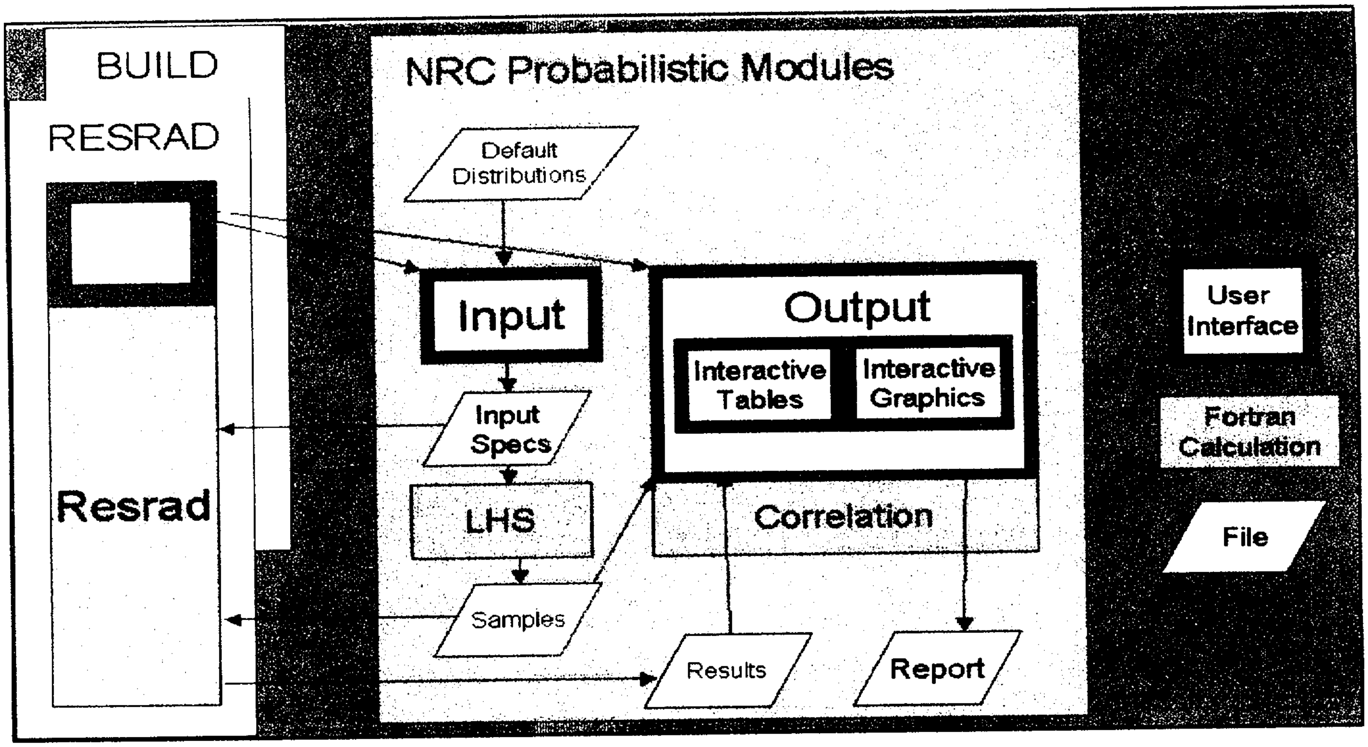

Figure A.1 Integration of Probabilistic Modules with RESRAD/RESRAD-BUILD Codes

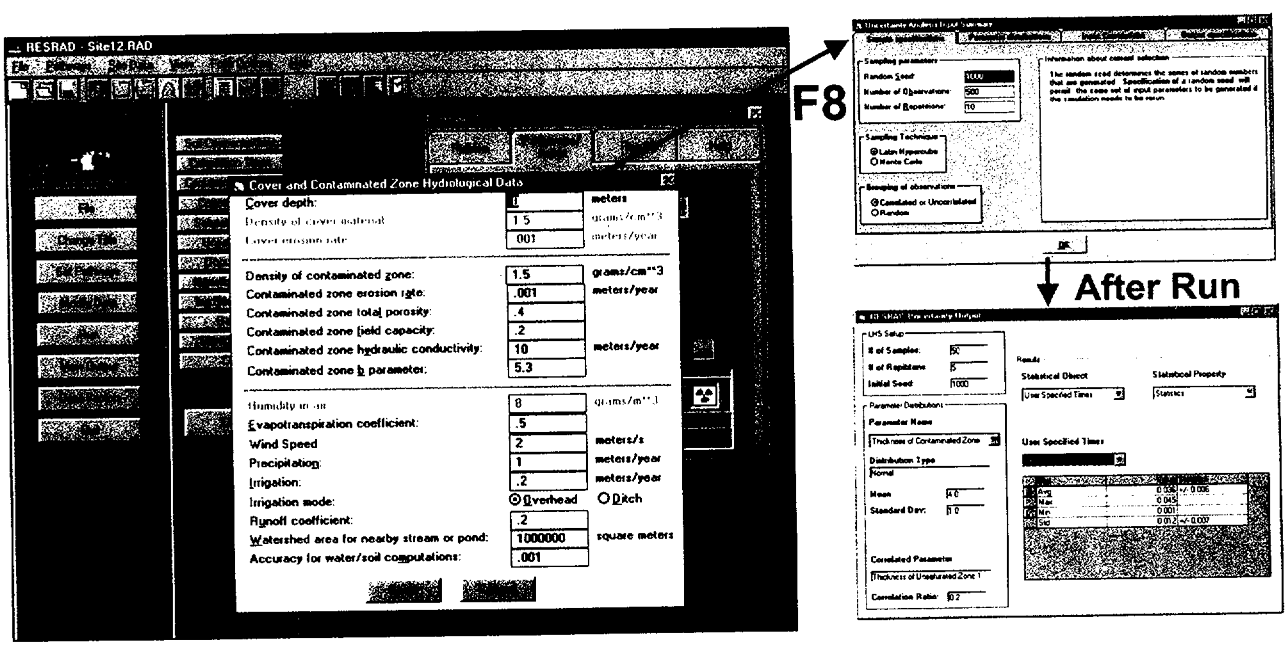

Figure A.2 Diagram Showing User's Access from RESRAD Interface (left) to Probabilistic Input Window (upper right) and Probabilistic Output Window (lower right).

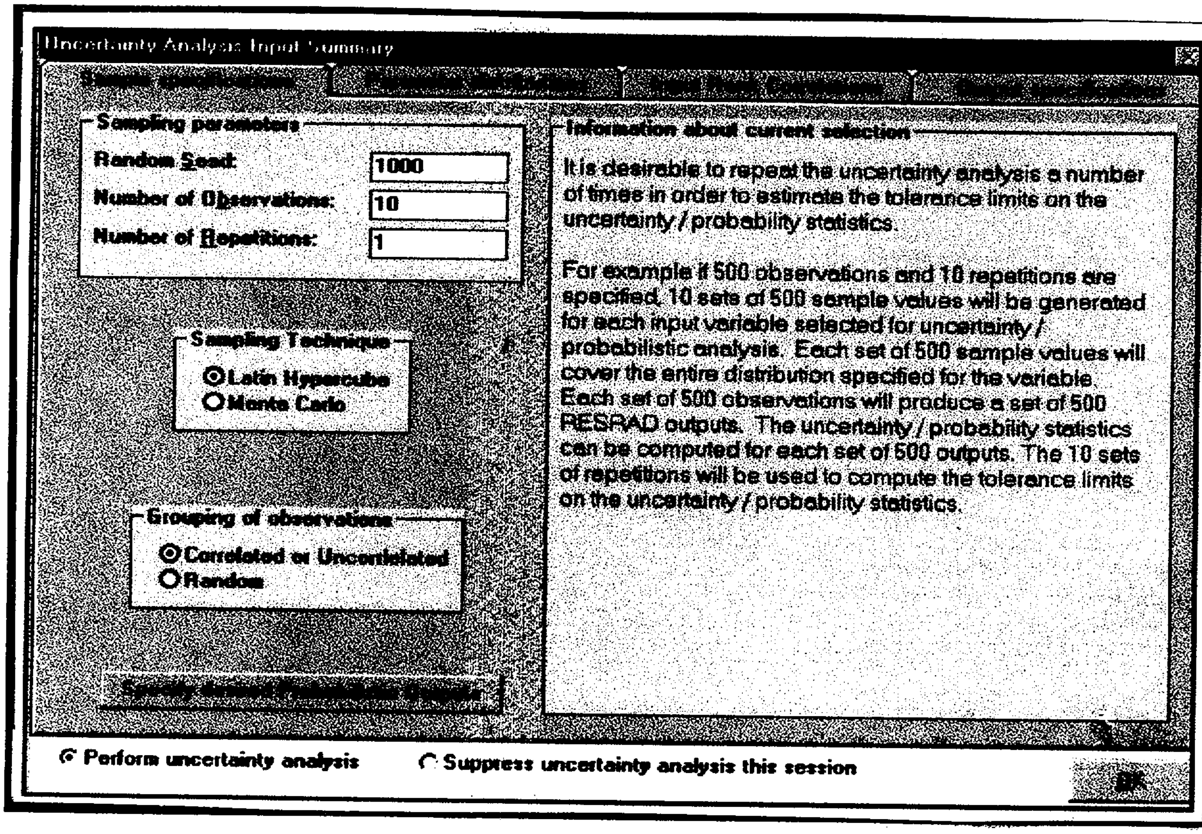

Figure A.3 Probabilistic Analysis Sample Specification

specification are the beginning random seed, the number of observations and repetitions, the sampling technique, and the grouping of observations. Detailed information about these options is displayed on the right-hand side of this window as the user navigates through the options. Usually the user will be concerned with the number of observations and repetitions.

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

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

A.3.2 Parameter Distributions

The parameter distribution tab screen allows the user to view and edit all currently specified parameter distributions for probabilistic analysis (Figure A.4). The parameters are listed in the left frame. The detailed distribution properties are shown in the right frame.

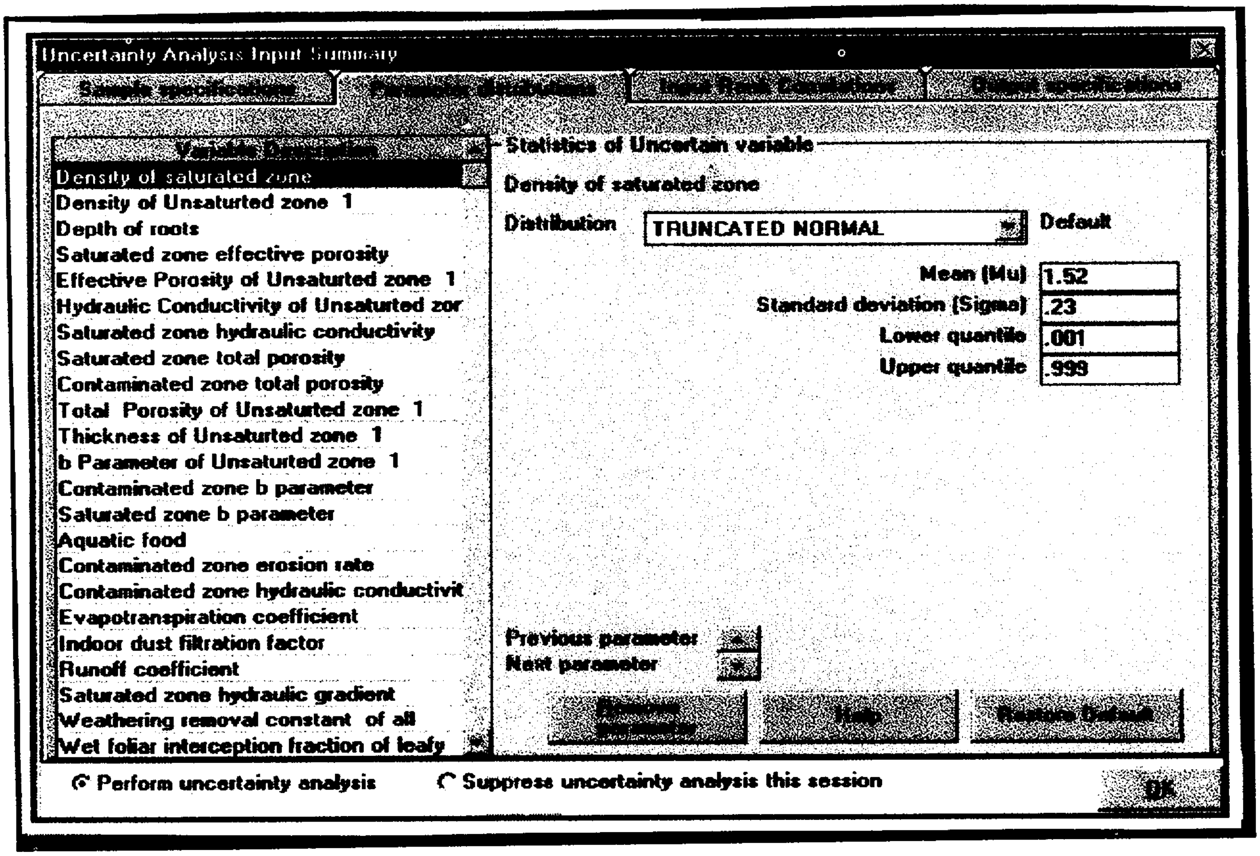

Figure A.4 Specified Parameter Distributions for Probabilistic Analysis

Navigation: Navigation to other parameter distributions is achieved by either clicking on the parameter on the left side or using the "Up-Down" arrow control on the left side.

Parameter List for Probabilistic Analysis: The list of the currently chosen parameters is shown on the left in a three-column table displaying the variable description, variable name in the code, and the distribution type. If the user clicks on any element in the row, complete distribution properties for the variable will appear for review and edit on the right.

Statistics of Uncertain Variable: The properties involved are the distribution type, shape parameters concerning the specific distribution type, and upper and lower truncation bounds. In the particular example shown in Figure A.4, the shape parameters are for the normal distribution, that is, the mean and standard deviation. If the user wishes to accept the default distribution for this parameter, the "Default for assumptions" can be selected. These assumptions also include those specified on the "Sample Specification" tab that are beyond the input specifications of the deterministic RESRAD codes. The user can also remove the parameter from further probabilistic consideration by clicking the "Remove Parameter" button.

A.3.3 Input Rank Correlations

The input correlations tab screen allows the user to view and edit all correlations between input parameters for probabilistic analysis (Figure A.5). The paired parameters with non-zero correlations are listed in the left frame. Correlations can be modified, added, or deleted in the right frame.

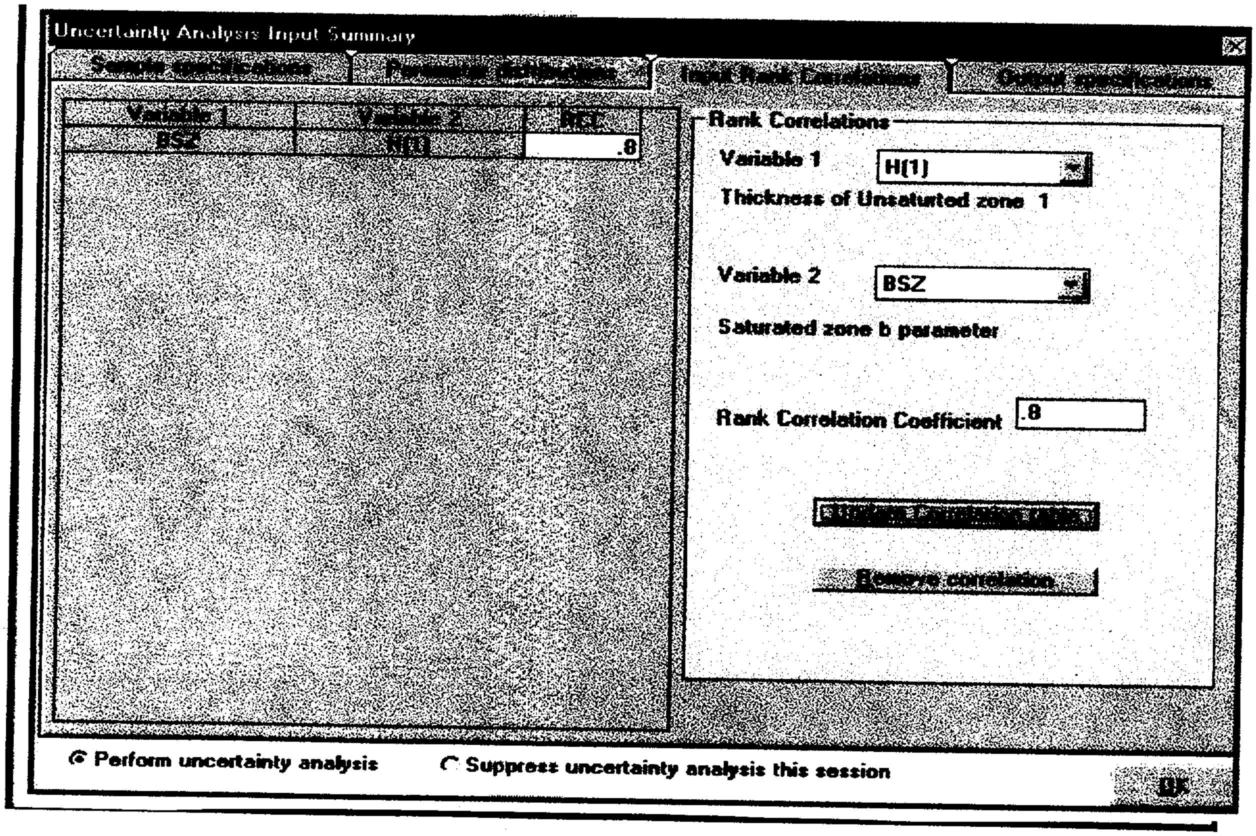

Figure A.5 Specified Input Rank Correlation for Probabilistic Analysis

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

Parameter List for Correlation: The currently chosen pairs of parameters are listed in the left frame in a three-column table that shows the variable names in the code and the correlation coefficient. If the user clicks on any element in any row of the table, the correlation can be modified or deleted in the right frame. The range of correlation coefficient is –1.00 to 1.00. The correlation for all pairs not specified here is assumed to be 0.0. The user can check the results of the sampling correlation after the run has been completed. Full descriptions of the variables can be seen in the right frame. If more parameters are chosen for correlation than fit in the window, the left side becomes a scrolling table.

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

APPENDIX B

PARAMETER DISTRIBUTIONS USED IN PROBABILISTIC DOSE ANALYSES

APPENDIX B

PARAMETER DISTRIBUTIONS USED IN PROBABILISTIC DOSE ANALYSES

This appendix contains data tables and figures for parameter distribution and probabilistic dose analyses. Table B.1 provides the assigned distribution types and each distribution's statistical parameters for the RESRAD and RESRAD-BUILD codes on the basis of the Parameter Distribution Report (Biwer et al., 2000). Tables B.2 and B.3 list the parameter values, type, and distribution types used in the probabilistic dose analysis for the RESRAD and RESRAD-BUILD codes, respectively.
Figures B.1 through B.48 provide the sampling frequency or the cumulative probability of the physical parameter values based on Latin hypercube sampling and the probability density or the cumulative distribution function of the parameter for the residential and building occupancy scenarios.

Table B.1. Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD and RESRAD-BUILD Parameters						
Parameter	Name[a]	Assigned Distribution Type	Distribution's Statistical Parameters[b]			
			1	2	3	4
RESRAD						
Density of contaminated zone (g/cm^3)	DENSCZ	Normal (truncated)	1.52	0.23	0.001	0.999
Density of cover material (g/cm^3)	DENSCV	Normal (truncated)	1.52	0.23	0.001	0.999
Density of saturated zone (g/m^3)	DENSAQ	Normal (truncated)	1.52	0.23	0.001	0.999
Depth of roots (m)	DROOT	Uniform	0.3	4.0		
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone)(cm^3/g)	DCACTC, DCACTU, DCACTS	Lognormal-n (truncated)	Radionuclide specific (Table 3.9-1, Biwer et al., 2000)			
Saturated zone effective porosity	EPSZ	Normal (truncated)	0.355	0.0906	0.001	0.999
Saturated zone hydraulic conductivity (m/yr)	HCSZ	Lognormal-n (bounded)	2.3	2.11	0.004	9250
Saturated zone total porosity	TPSZ	Normal (truncated)	0.425	0.0867	0.001	0.999
Transfer factors for plants	BRTF(1)	Lognormal-n (truncated)	Element specific (Table 6.2-1, Biwer et al., 2000)			
Unsaturated zone thickness (m)	H	Lognormal-n (bounded)	2.296	1.276	0.18	320
Aquatic food contaminated fraction	FR9	Triangular	0	1	0.39	
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	BBIO(1)	Lognormal-n	Element specific (Table 6.8-1, Biwer et al., 2000)			
C-14 evasion layer thickness in soil (m)	DMC	Triangular	0.2	0.6	0.3	
Contaminated zone b parameter	BCZ	Lognormal-n (bounded)	1.06	0.66	0.5	30
Inhalation rate (m^3/yr)	INHALAR	Triangular	4380	13100	8400	

Table B.1. Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD and RESRAD-BUILD Parameters (Continued)						
Parameter	Name[a]	Assigned Distribution Type	Distribution's Statistical Parameters[b] 1	2	3	4
Contaminated zone erosion rate (m/yr)	VCZ	Empirical	Defined by cumulative probability (Table 3.8-1, Biwer et al., 2000)			
Contaminated zone hydraulic conductivity (m/yr)	HCCZ	Lognormal-n (bounded)	2.3	2.11	0.004	9250
Contaminated zone total porosity	TPCZ	Normal (truncated)	0.425	0.0867	0.001	0.999
Cover depth (m)	COVER0	None recommended				
Cover erosion rate (m/yr)	VCV	Empirical	Defined by cumulative probability (Table 3.8-1, Biwer et al., 2000)			
Depth of soil mixing layer (m)	DM	Triangular	0	0.6	0.15	
Drinking water intake (L/yr)	DWI	Lognormal-n (truncated)	6.015	0.489	0.001	0.999
Evapotranspiration coefficient	EVAPTR	Uniform	0.5	0.75		
External gamma shielding factor	SHF1	Lognormal-n (bounded)	-1.3	0.59	0.044	1.0
Fruit, vegetables, and grain consumption (kg/yr)	DIET(1)	Triangular	135	318	178	
Indoor dust filtration factor	SHF3	Uniform	0.15	0.95		
Mass loading for inhalation ($\mu g/m^3$)	MLINH	Empirical	Defined by cumulative probability (Table 4.6-1, Biwer et al., 2000)			
Milk consumption (L/yr)	DIET(3)	Triangular	60	200	102	
Runoff coefficient	RUNOFF	Uniform	0.1	0.8		
Saturated zone b parameter	BSZ	Lognormal-n (bounded)	1.06	0.66	0.5	30
Saturated zone hydraulic gradient	HGWT	Lognormal-n (bounded)	-5.11	1.77	7E-5	0.5

Table B.1. Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD and RESRAD-BUILD Parameters (Continued)

Parameter	Name[a]	Assigned Distribution Type	Distribution's Statistical Parameters[b]			
			1	2	3	4
Soil ingestion rate (g/yr)	SOIL	Triangular	0	36.5	18.3	
Transfer factors for meat [(pCi/kg)/(pCi/d)]	BRTF(2)	Lognormal-n (truncated)	Element specific (Table 6.3-1, Biwer et al., 2000)			
Transfer factors for milk [(pCi/L)/(pCi/d)]	BRTF(3)	Lognormal-n (truncated)	Element specific (Table 6.4-1, Biwer et al., 2000)			
Unsaturated zone density (g/cm^3)	DENSUZ	Normal (truncated)	1.52	0.23	0.001	0.999
Unsaturated zone effective porosity	EPUZ	Normal (truncated)	0.355	0.0906	0.001	0.999
Unsaturated zone hydraulic conductivity (m/yr)	HCUZ	Lognormal-n (bounded)	2.3	2.11	0.004	9250
Unsaturated zone, soil-b parameter	BUZ	Lognormal-n (bounded)	1.06	0.66	0.5	30
Unsaturated zone total porosity	TPUZ	Normal (truncated)	0.425	0.0867	0.001	0.999
Weathering removal constant (1/yr)	WLAM	Triangular	5.1	84	18	
Well pumping rate (m^3/yr)	UW	None recommended				
Well pump intake depth (below water table) (m)	DWIBWT	Triangular	6	30	10	
Wet foliar interception fraction for leafy vegetables	RWET(2)	Triangular	0.06	0.95	0.67	
Wet-weight crop yields for non-leafy vegetables (kg/m^2)	YU(1)	Lognormal-n (truncated)	0.56	0.48	0.001	0.999
Wind speed (m/s)	WIND	Lognormal-n (bounded)	1.445	0.2419	1	16
Humidity	HUMIDITY	Lognormal-n (truncated)	1.98	0.334	0.001	0.999

Table B.1. Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD and RESRAD-BUILD Parameters (Continued)						
Parameter	Name[a]	Assigned Distribution Type	Distribution's Statistical Parameters[b]			
			1	2	3	4
Indoor fraction	FTIN	Empirical	Defined by cumulative probability (Table 7.6-1, Biwer et al., 2000)			
RESRAD-BUILD						
Removable fraction	RMVFR	Triangular	0.0	1.0	0.2	
Resuspension rate (1/s)	DKSUS	Loguniform	2.8E-10	1.4E-5		
Shielding density (g/cm^3)	DSDEN	Uniform	2.2	2.6		
Source density, volume source (g/cm^3)	DENSI0	Uniform	2.2	2.6		
Air exchange rate for building and room (1/h)	LAMBDAT	Lognormal-n (truncated)	0.4187	0.88	0.001	0.999
Air release fraction	AIRFR	Triangular	1E-6	1	0.07	
Deposition velocity (m/s)	UD	Loguniform	2.7E-6	2.7E-3		
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	INGE1	None recommended				
Humidity (g/m^3)	HUMIDITY	Uniform	6.5	13.1		
Indoor fraction	FTIN	Empirical	Defined by cumulative probability (Table 7.6-1, Biwer et al., 2000)			
Receptor indirect ingestion rate (m^2/h)	INGE2	Loguniform	2.8E-5	2.9E-4		
Receptor inhalation rate (m^3/d)	BRTRATE	Triangular	12	46	33.6	
Room area (m^2)	AREA	Triangular	3	900	36	
Room height (m)	H	Triangular	2.4	9.1	3.7	
Shielding thickness (cm)	DSTH	Triangular	0.0	30	0.0	
Source erosion rate, volume source (cm/d)	EROS0	Triangular	0.0	5.6E-7	0.0	
Source porosity	H3POROSITY	Uniform	0.04	0.25		
Source thickness, volume source (cm)	THICK	Triangular	2.5	30	15	

Table B.1. Assigned Distribution Types and Distribution's Statistical Parameters for RESRAD and RESRAD-BUILD Parameters (Continued)

Parameter	Name[a]	Assigned Distribution Type	Distribution's Statistical Parameters[b]			
			1	2	3	4
Time for source removal or source lifetime (d)	RF0	Triangular	1,000	100,000	10,000	
Volumetric water content	H3VOLFRACT	Uniform	0.04	0.25		
Water fraction available for evaporation	H3RMFR	Triangular	0.5	1.0	0.75	
Wet + dry zone thickness (cm)	H3THICK	Uniform	5	30		

[a] Name of the parameter by which parameters are identified in sensitivity tables.

[b] For normal and lognormal distribution, statistical parameter 1 is the mean, 2 is the standard deviation, 3 is the lower quantile value, and 4 is the upper quantile. For the bounded lognormal distribution, parameters 3 and 4 are the actual lower and upper bounds. Parameters for element specific or distribution defined by cumulative probability distributions are not provided in this table (see Parameter Distribution Report [Biwer et al., 2000]). For uniform distribution, statistical parameter 1 is the minimum and parameter 2 is the maximum of the distribution. For triangular distribution, parameter 1 is the minimum value, parameter 2 is the maximum value, and parameter 3 is the most likely value of the distribution.

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Nuclide concentration	pCi/g	P	1		NR[c]	NR	NR	NR
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zones)	cm^3/g	P	Lognormal-n (truncated)	Biwer et al., 2000	Element specific	Element specific	Element specific	Element specific
Number of unsaturated zones	-[d]	P	1	RESRAD	NR	NR	NR	NR
Time since placement of material	yr	P	0	RESRAD	NR	NR	NR	NR
Groundwater concentration	pCi/L	P	0	RESRAD	NR	NR	NR	NR
Leach rate	1/yr	P	0	RESRAD	NR	NR	NR	NR
Solubility limit	mol/L	P	0	RESRAD	NR	NR	NR	NR
Use plant/soil ratio	check box	NA[e]	NA	RESRAD	NR	NR	NR	NR
Basic radiation dose limit	mrem/yr	NA	25	DandD	NR	NR	NR	NR
Times for calculations	yr	P	1, 3, 10, 30, 100, 300, 1000	RESRAD	NR	NR	NR	NR
Area of contaminated zone	m^2	P	100, 2400, 10,000	RESRAD	NR	NR	NR	NR
Thickness of contaminated zone	m	P	0.15, 0.15, 2.0	RESRAD	NR	NR	NR	NR
Length parallel to aquifer flow	m	P	10, 49, 100	RESRAD	NR	NR	NR	NR
Cover depth	m	P	0	RESRAD	NR	NR	NR	NR
Density of cover material	g/cm^3	P	Normal (truncated)	Biwer et al., 2000	1.52	0.23	0.001	0.999
Cover erosion rate	m/yr	P, B	NA	Biwer et al., 2000	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Density of contaminated zone	g/cm^3	P	Normal (truncated)	Biwer et al., 2000	1.52	0.23	0.001	0.999
Contaminated zone total porosity	-	P	Normal (truncated)	Biwer et al., 2000	0.425	0.0867	0.001	0.999
Contaminated zone field capacity	-	P	0.2	RESRAD	NR	NR	NR	NR
Contaminated zone erosion rate	m/yr	P, B	Defined by cumulative probability	Biwer et al., 2000				
Contaminated zone hydraulic conductivity	m/yr	P	Lognormal-n (bounded)	Biwer et al., 2000	2.3	2.11	0.004	9250
Contaminated zone b parameter	-	P	Lognormal-n (bounded)	Biwer et al., 2000	1.06	0.66	0.5	30
Humidity in air	g/m^3	P	Lognormal-n (truncated)	Biwer et al., 2000	1.98	0.334	0.001	0.999
Evapotranspiration coefficient	-	P	Uniform	Biwer et al., 2000	0.5	0.75		
Wind speed	m/s	P	Lognormal-n (bounded)	Biwer et al., 2000	1.445	0.2419	1	16
Precipitation rate	m/yr	P	1.0	RESRAD	NR	NR	NR	NR
Irrigation rate	m/yr	B	0.1125	Calculated based on DandD default	NR	NR	NR	NR
Irrigation mode	-	B	Overhead	RESRAD	NR	NR	NR	NR
Runoff coefficient	-	P	Uniform	Biwer et al., 2000	0.1	0.8		
Watershed area for nearby stream or pond	m^2	P	1,000,000	RESRAD	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Accuracy for water soil computation	-	NA	0.001	RESRAD	NR	NR	NR	NR
Density of saturated zone	g/cm^3	P	Normal (truncated)	Biwer et al., 2000	1.52	0.23	0.001	0.999
Saturated zone total porosity	-	P	Normal (truncated)	Biwer et al., 2000	0.425	0.0867	0.001	0.999
Saturated zone effective porosity	-	P	Normal (truncated)	Biwer et al., 2000	0.355	0.0906	0.001	0.999
Saturated zone field capacity	-	P	0.2	RESRAD	NR	NR	NR	NR
Saturated zone hydraulic conductivity	m/yr	P	Lognormal-n (bounded)	Biwer et al., 2000	2.3	2.11	0.004	9250
Saturated zone hydraulic gradient	-	P	Lognormal-n (bounded)	Biwer et al., 2000	-5.11	1.77	7E-5	0.5
Saturated zone b parameter	-	P	Lognormal-n (bounded)	Biwer et al., 2000	1.06	0.66	0.5	30
Water table drop rate	m/yr	P	0.001	RESRAD	NR	NR	NR	NR
Well pump intake depth (below water table)	m	P	Triangular	Biwer et al., 2000	6	30	10	
Model: nondispersion (ND) or mass-balance (MB)	-	NA	ND	RESRAD	NR	NR	NR	NR
Well pumping rate	m^3/yr	B, P	409.3, 668, 1523	Biwer et al., 2000				
Unsaturated zone thickness	m	P	Defined by cumulative probability	Biwer et al., 2000				
Unsaturated zone density	g/cm^3	P	Normal (truncated)	Biwer et al., 2000	1.52	0.23	0.001	0.999
Unsaturated zone total porosity	-	P	Normal (truncated)	Biwer et al., 2000	0.425	0.0867	0.001	0.999

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Unsaturated zone effective porosity	-	P	Normal (truncated)	Biwer et al., 2000	0.355	0.0906	0.001	0.999
Unsaturated zone field capacity	-	P	0.2	RESRAD	NR	NR	NR	NR
Unsaturated zone, soil-specific b parameter		P	Lognormal-n (bounded)	Biwer et al., 2000	1.06	0.66	0.5	30
Unsaturated zone hydraulic conductivity	m/yr	P	Lognormal-n (bounded)	Biwer et al., 2000	2.3	2.11	0.004	9250
Inhalation rate	m^3/yr	M, B	8400	Biwer et al., 2000	NR	NR	NR	NR
Mass loading for inhalation	μ/m^3	P, B	Defined by cumulative probability	Biwer et al., 2000				
Exposure duration	yr	B	30	RESRAD	NR	NR	NR	NR
Indoor dust filtration factor	-	P, B	Uniform	Biwer et al., 2000	0.15	0.95		
External gamma shielding factor	-	P	Lognormal-n (bounded)	Biwer et al., 2000	-1.4	0.84	0	1
Indoor time fraction	-	B	0.65	Beyeler et al., 1999	NR	NR	NR	NR
Outdoor time fraction	-	B	0.12	Beyeler et al., 1999	NR	NR	NR	NR
Shape of the contaminated zone (shape factor flag)	-	P	Circular	RESRAD	NR	NR	NR	NR
Fruit, vegetables, and grain consumption	kg/yr	M, B	178	Biwer et al., 2000	NR	NR	NR	NR
Leafy vegetable consumption	kg/yr	M, B	21.4	DandD	NR	NR	NR	NR
Milk consumption	L/yr	M, B	102	Biwer et al., 2000	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Meat and poultry consumption	kg/yr	M, B	65.1	DandD	NR	NR	NR	NR
Fish consumption	kg/yr	M, B	20.6	DandD	NR	NR	NR	NR
Other seafood consumption	kg/yr	M, B	0.9	RESRAD	NR	NR	NR	NR
Soil ingestion rate	g/yr	M, B	18.3	Biwer et al., 2000	NR	NR	NR	NR
Drinking water intake	L/yr	M, B	461.5	Biwer et al., 2000	NR	NR	NR	NR
Drinking water contaminated fraction	-	B, P	1	RESRAD	NR	NR	NR	NR
Household water contaminated fraction	-	B, P	1	RESRAD	NR	NR	NR	NR
Livestock water contaminated fraction	-	B, P	1	RESRAD	NR	NR	NR	NR
Irrigation water contaminated fraction	-	B, P	1	RESRAD	NR	NR	NR	NR
Aquatic food contaminated fraction	-	B, P	Triangular	Biwer et al., 2000	0	1	0.39	
Plant food contaminated fraction	-	B, P	-1	RESRAD	NR	NR	NR	NR
Meat contaminated fraction	-	B, P	-1	RESRAD	NR	NR	NR	NR
Milk contaminated fraction	-	B, P	-1	RESRAD	NR	NR	NR	NR
Livestock fodder intake for meat	kg/d	M	68	RESRAD	NR	NR	NR	NR
Livestock fodder intake for milk	kg/d	M	55	RESRAD	NR	NR	NR	NR
Livestock water intake for meat	L/d	M	50	RESRAD	NR	NR	NR	NR
Livestock water intake for milk	L/d	M	160	RESRAD	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Livestock intake of soil	kg/d	M	0.5	RESRAD	NR	NR	NR	NR
Mass loading for foliar deposition	g/m^3	P	4E-4	DandD	NR	NR	NR	NR
Depth of soil mixing layer	m	P	Triangular	Biwer et al., 2000	0	0.6	0.15	
Depth of roots	m	P	Uniform	Biwer et al., 2000	0.3	4.0		
Groundwater fractional usage for drinking water	-	B, P	1	RESRAD	NR	NR	NR	NR
Groundwater fractional usage for household water	-	B, P	1	RESRAD	NR	NR	NR	NR
Groundwater fractional usage for livestock water	-	B, P	1	RESRAD	NR	NR	NR	NR
Groundwater fractional usage for irrigation water	-	B, P	1	RESRAD	NR	NR	NR	NR
Wet-weight crop yields for non-leafy vegetables	kg/m^2	P	Lognormal-n (truncated)	Biwer et al., 2000	0.56	0.48	0.001	0.999
Wet-weight crop yields for leafy vegetables	kg/m^2	P	2.9	Beyeler et al., 1999	NR	NR	NR	NR
Wet-weight crop yields for fodder	kg/m^2	P	1.8868	Beyeler et al., 1999	NR	NR	NR	NR
Length of growing season for non-leafy vegetables	yr	P	0.2466	Beyeler et al., 1999	NR	NR	NR	NR
Length of growing season for leafy vegetables	yr	P	0.123	Beyeler et al., 1999	NR	NR	NR	NR
Length of growing season for fodder	yr	P	0.082	Beyeler et al., 1999	NR	NR	NR	NR
Translocation factor for non-leafy vegetables	-	P	0.1	DandD	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Translocation factor for leafy vegetables	-	P	1	DandD	NR	NR	NR	NR
Translocation factor for fodder	-	P	1	DandD	NR	NR	NR	NR
Weathering removal constant	1/yr	P	Triangular	Biwer et al., 2000	5.1	84	18	
Wet foliar interception fraction for non-leafy vegetables	-	P	0.35	Beyeler et al., 1999	NR	NR	NR	NR
Wet foliar interception fraction for leafy vegetables	-	P	Triangular	Biwer et al., 2000	0.06	0.95	0.67	
Wet foliar interception fraction for fodder	-	P	0.35	Beyeler et al., 1999	NR	NR	NR	NR
Dry foliar interception fraction for non-leafy vegetables	-	P	0.35	Beyeler et al., 1999	NR	NR	NR	NR
Dry foliar interception fraction for leafy vegetables	-	P	0.35	Beyeler et al., 1999	NR	NR	NR	NR
Dry foliar interception fraction for fodder	-	P	0.35	Beyeler et al., 1999	NR	NR	NR	NR
Cover total porosity	-	P	NA	RESRAD	NR	NR	NR	NR
Cover volumetric water content	-	P	NA	RESRAD	NR	NR	NR	NR
Cover radon diffusion coefficient	m^2/s	P	NA	RESRAD	NR	NR	NR	NR
Building foundation thickness	m	P	0.15	RESRAD	NR	NR	NR	NR
Building foundation density	g/cm^3	P	2.4	RESRAD	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)

RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Building foundation total porosity	-	P	0.1	RESRAD	NR	NR	NR	NR
Building foundation volumetric water content	-	P	0.03	RESRAD	NR	NR	NR	NR
Building foundation radon diffusion coefficient	m^2/s	P	3.0E-7	RESRAD	NR	NR	NR	NR
Contamination radon diffusion coefficient	m^2/s	P	2.0E-6	RESRAD	NR	NR	NR	NR
Radon vertical dimension of mixing	m	P	2	RESRAD	NR	NR	NR	NR
Building air exchange rate	1/h	P, B	0.5	RESRAD	NR	NR	NR	NR
Building height	m	P	2.5	RESRAD	NR	NR	NR	NR
Building indoor area factor	-	P	0	RESRAD	NR	NR	NR	NR
Foundation depth below ground surface	m	P	-1	RESRAD	NR	NR	NR	NR
Radon-222 emanation coefficient	-	P	0.25	RESRAD	NR	NR	NR	NR
Radon-220 emanation coefficient	-	P	0.15	RESRAD	NR	NR	NR	NR
Storage times for fruits, non-leafy vegetables, and grain	d	B	14	RESRAD	NR	NR	NR	NR
Storage times for leafy vegetables	d	B	1	RESRAD	NR	NR	NR	NR
Storage times for milk	d	B	1	RESRAD	NR	NR	NR	NR
Storage times for meat	d	B	20	RESRAD	NR	NR	NR	NR
Storage times for fish	d	B	7	RESRAD	NR	NR	NR	NR
Storage times for crustacea and mollusks	d	B	7	RESRAD	NR	NR	NR	NR
Storage times for well water	d	B	1	RESRAD	NR	NR	NR	NR

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)								
RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Storage times for surface water	d	B	1	RESRAD	NR	NR	NR	NR
Storage times for livestock fodder	d	B	45	RESRAD	NR	NR	NR	NR
C-12 concentration in local water	g/cm^3	P	2E-5	RESRAD	NR	NR	NR	NR
C-12 concentration in contaminated soil	g/g	P	0.03	RESRAD	NR	NR	NR	NR
Fraction of vegetation carbon absorbed from soil	-	P	0.02	RESRAD	NR	NR	NR	NR
Fraction of vegetation carbon absorbed from air	-	P	0.98	RESRAD	NR	NR	NR	NR
C-14 evasion layer thickness in soil	m	P	Triangular	Biwer et al., 2000	0.2	0.6	0.3	
C-14 evasion flux rate from soil	1/s	P	7E-07	RESRAD	NR	NR	NR	NR
C-12 evasion flux rate from soil	1/s	P	1E-10	RESRAD	NR	NR	NR	NR
Grain fraction in livestock feed	-	B	0.25 (beef cattle) 0.1 (cow)	Beyeler et al., 1999	NR	NR	NR	NR
Inhalation dose conversion factors	mrem/pCi	M	Nuclide specific	RESRAD	NR	NR	NR	NR
Ingestion dose conversion factors	mrem/pCi	M	Nuclide specific	RESRAD	NR	NR	NR	NR
Slope factor - external	(risk/yr)/ (pCi/g)	M	Nuclide specific	RESRAD	NR	NR	NR	NR
Slope factor - inhalation	risk/pCi	M	Nuclide specific	RESRAD	NR	NR	NR	NR
Slope factor - ingestion	risk/pCi	M	Nuclide specific	RESRAD	NR	NR	NR	NR
Plant transfer factor	-	P	Lognormal (truncated)	Biwer et al., 2000	Element specific	Element specific	Element specific	Element specific

Table B.2. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD Code (Continued)

RESRAD Parameter	Unit	Parameter Type[a]	Parameter Value/ Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Meat transfer factor	(pCi/kg)/ (pCi/d)	P	Lognormal (truncated)	Biwer et al., 2000	Element specific	Element specific	Element specific	Element specific
Milk transfer factor	(pCi/L)/ (pCi/d)	P	Lognormal (truncated)	Biwer et al., 2000	Element specific	Element specific	Element specific	Element specific
Bioaccumulation factor for fish	(pCi/kg)/ (pCi/L)	P	Lognormal (truncated)	Biwer et al., 2000	Element specific	Element specific	Element specific	Element specific
Bioaccumulation factor for crustacea and mollusks	(pCi/kg)/ (pCi/L)	P	Element specific	RESRAD	NR	NR	NR	NR

[a] P = physical, B = behavioral, and M = metabolic; when more than one parameter type is listed, the first is primary and next is secondary (Kamboj et al., 1999).

[b] For normal and lognormal distribution, distribution parameter 1 is the mean, 2 is the standard deviation, 3 is the lower quantile value, and 4 is the upper quantile. For bounded lognormal distribution, parameters 3 and 4 are the actual lower and upper bounds. Parameters for element-specific values or distribution defined by cumulative probability distributions are not provided in this table (see the Parameter Distribution Report [Biwer et al., 2000]). For uniform distribution, parameter 1 is the minimum and parameter 2 is the maximum of the distribution. For triangular distribution, parameter 1 is the minimum value, parameter 2 is the maximum value, and parameter 3 is the most likely value of the distribution.

[c] NR = not required (RESRAD parameters for which distributions are not developed and for which statistical parameters are not required).

[d] Hyphen indicates that the parameter is dimensionless.

[e] NA = not applicable.

Table B.3. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD-BUILD Code

Parameter	Units	Parameter Type[a]	Parameter Value/Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
External dose conversion factor	(mrem/yr)/(pCi/g)	M	Nuclide specific	RESRAD-BUILD	NR[c]	NR	NR	NR
Inhalation dose conversion factor	mrem/pCi	M	Nuclide specific	RESRAD-BUILD	NR	NR	NR	NR
Ingestion dose conversion factors	mrem/pCi	M	Nuclide specific	RESRAD-BUILD	NR	NR	NR	NR
Air Submersion dose conversion factors	(mrem/yr)/(pCi/m^3)	M	Nuclide specific	RESRAD-BUILD				
Exposure duration	d	B	365	RESRAD-BUILD	NR	NR	NR	NR
Indoor fraction	-[d]	B	0.365	Biwer et al., 2000	NR	NR	NR	NR
Number of evaluation times	-	P	2	RESRAD-BUILD	NR	NR	NR	NR
Time	yr	P	1	RESRAD-BUILD	NR	NR	NR	NR
Number of rooms	-	P	1	RESRAD-BUILD	NR	NR	NR	NR
Deposition velocity	m/s	P	Loguniform	Biwer et al., 2000	2.7E-6	2.7E-3		
Resuspension rate	1/s	P, B	Loguniform	Biwer et al., 2000	2.8E-10	1.4E-5		
Room height	m	P	Triangular	Biwer et al., 2000	2.4	9.1	3.7	
Room area	m^2	P	Triangular	Biwer et al., 2000	3	900	36	
Air exchange rate for building and room	1/h	B	1.52	Biwer et al., 2000	NR	NR	NR	NR
Net flow	m^3/h	B	0	RESRAD-BUILD	NR	NR	NR	NR
Outdoor inflow	m^3/h	B, P	60	RESRAD-BUILD	NR	NR	NR	NR

Table B.3. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD-BUILD Code (Continued)

Parameter	Units	Parameter Type[a]	Parameter Value/Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Number of receptors	-	B	1	RESRAD-BUILD	NR	NR	NR	NR
Receptor room	-	B	1	RESRAD-BUILD	NR	NR	NR	NR
Receptor location	m	B	1,1,1 (Cartesian coordinates)	RESRAD-BUILD	NR	NR	NR	NR
Receptor time fraction	-	B	1	RESRAD-BUILD	NR	NR	NR	NR
Receptor inhalation rate	m^3/d	M, B	33.6	Biwer et al., 2000	NR	NR	NR	NR
Receptor indirect ingestion rate	m^2/h	B	1.1E-4	Biwer et al., 2000	NR	NR	NR	NR
Number of sources	-	P	1	RESRAD-BUILD	NR	NR	NR	NR
Source type	-	P	Area, volume	RESRAD-BUILD	NR	NR	NR	NR
Source room or primary room	-	P	1	RESRAD-BUILD	NR	NR	NR	NR
Source direction	-	P	X	RESRAD-BUILD	NR	NR	NR	NR
Source location	-	P	0,0,0	RESRAD-BUILD	NR	NR	NR	NR
Source length or area	m or m^2	P	36	RESRAD-BUILD	NR	NR	NR	NR
Air release fraction	-	B	0.07	Biwer et al., 2000	NR	NR	NR	NR
Direct ingestion rate	g/h (volume) and 1/h (other)	B	0	Biwer et al., 2000	NR	NR	NR	NR
Removable fraction	-	P, B	Triangular	Biwer et al., 2000	0.0	1.0	0.2	
Time for source removal or source lifetime	d	P, B	Triangular	Biwer et al., 2000	1000	100,000	10,000	
Radon release fraction	-	P, B	0	RESRAD-BUILD	NR	NR	NR	NR

Table B.3. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD-BUILD Code (Continued)								
Parameter	Units	Parameter Type[a]	Parameter Value/Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Radionuclide concentration	pCi/g, dpm/cm^2	P	1 (Co-60)	RESRAD-BUILD	NR	NR	NR	NR
Number of regions in volume source	-	P	1	RESRAD-BUILD	NR	NR	NR	NR
Contaminated region-volume source	-	P	1	RESRAD-BUILD	NR	NR	NR	NR
Source thickness, volume source	cm	P	Triangular	Biwer et al., 2000	2.5	30	15	
Source density, volume source	g/cm^3	P	Uniform	Biwer et al., 2000	2.2	2.6		
Source erosion rate, volume source	cm/d	P, B	Triangular	Biwer et al., 2000	0.0	5.6E-7	0.0	NR
Source porosity	-	P	Uniform	Biwer et al., 2000	0.04	0.25		
Radon effective diffusion coefficient	m^2/s	P	3E-7	RESRAD-BUILD	NR	NR	NR	NR
Radon emanation coefficient	-	P	0	RESRAD-BUILD	NR	NR	NR	NR
Shielding thickness	cm	P, B	Triangular	Biwer et al., 2000	0.0	30	0.0	
Shielding density	g/cm^3	P	Uniform	Biwer et al., 2000	2.2	2.6		
Shielding material	-	P	Concrete	RESRAD-BUILD	NR	NR	NR	NR
Dry zone thickness	cm	P	0	RESRAD-BUILD	NR	NR	NR	NR
Wet + dry zone thickness	cm	P	Uniform	Biwer et al., 2000	5	30		
Volumetric water content	-	P	Uniform	Biwer et al., 2000	0.04	0.25		

Table B.3. Parameter Values and Distribution Types Used in the Probabilistic Dose Analysis for the RESRAD-BUILD Code (Continued)								
Parameter	Units	Parameter Type[a]	Parameter Value/Distribution Type Used	Source	Distribution's Statistical Parameters[b]			
					1	2	3	4
Water fraction available for evaporation	-	P	Triangular	Biwer et al., 2000	0.5	1.0	0.75	
Humidity	g/m^3	P, B	Uniform	Biwer et al., 2000	6.5	13.1		

[a] P = physical, B = behavioral, and M = metabolic; when more than one parameter type is listed, the first is primary and next is secondary (Kamboj et al., 1999).

[b] For normal and lognormal distribution, distribution parameter 1 is the mean, 2 is the standard deviation, 3 is the lower quantile value, and 4 is the upper quantile. For bounded lognormal distribution, parameters 3 and 4 are the actual lower and upper bounds. Parameters for element-specific values or distribution defined by cumulative probability distributions are not provided in this table (see the Parameter Distribution Report [Biwer et al., 2000]). For uniform distribution, parameter 1 is the minimum and parameter 2 is the maximum of the distribution. For triangular distribution, parameter 1 is the minimum value, parameter 2 is the maximum value, and parameter 3 is the most likely value of the distribution.

[c] NR = not required (RESRAD parameters for which distributions are not developed and for which statistical parameters are not required).

[d] A hyphen indicates that the parameter is dimensionless.

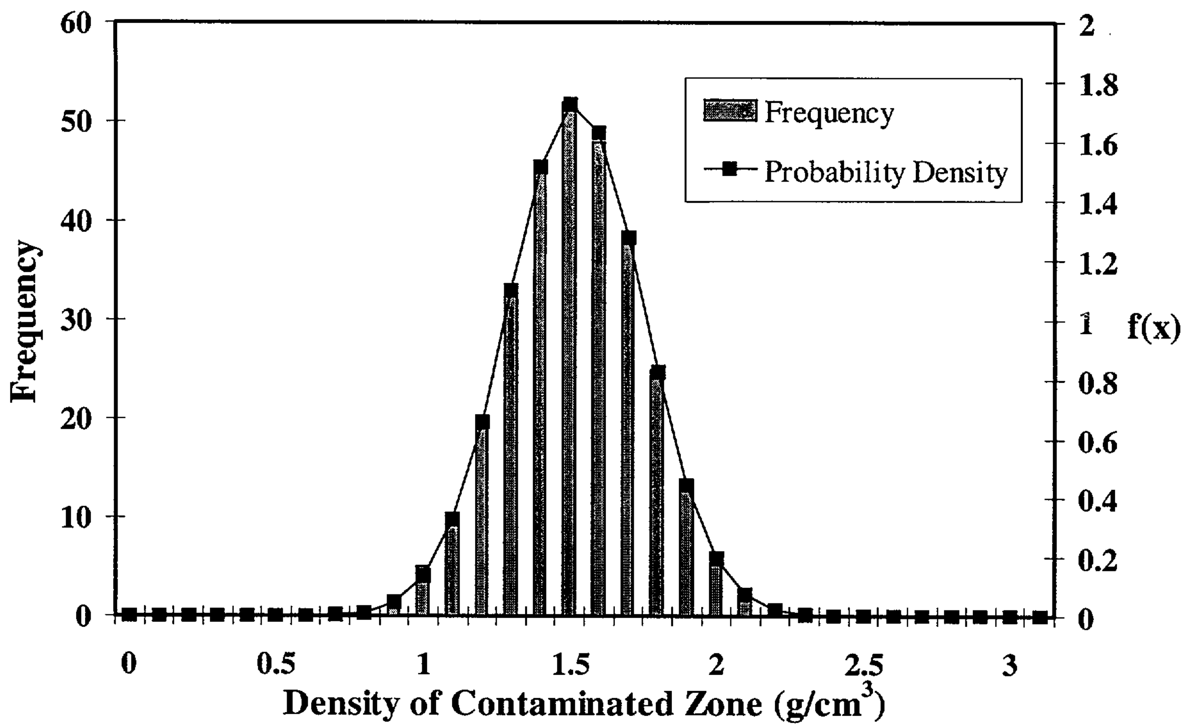

Figure B.1 Sampling Frequency and Probability Density of the Density of Contaminated Zone

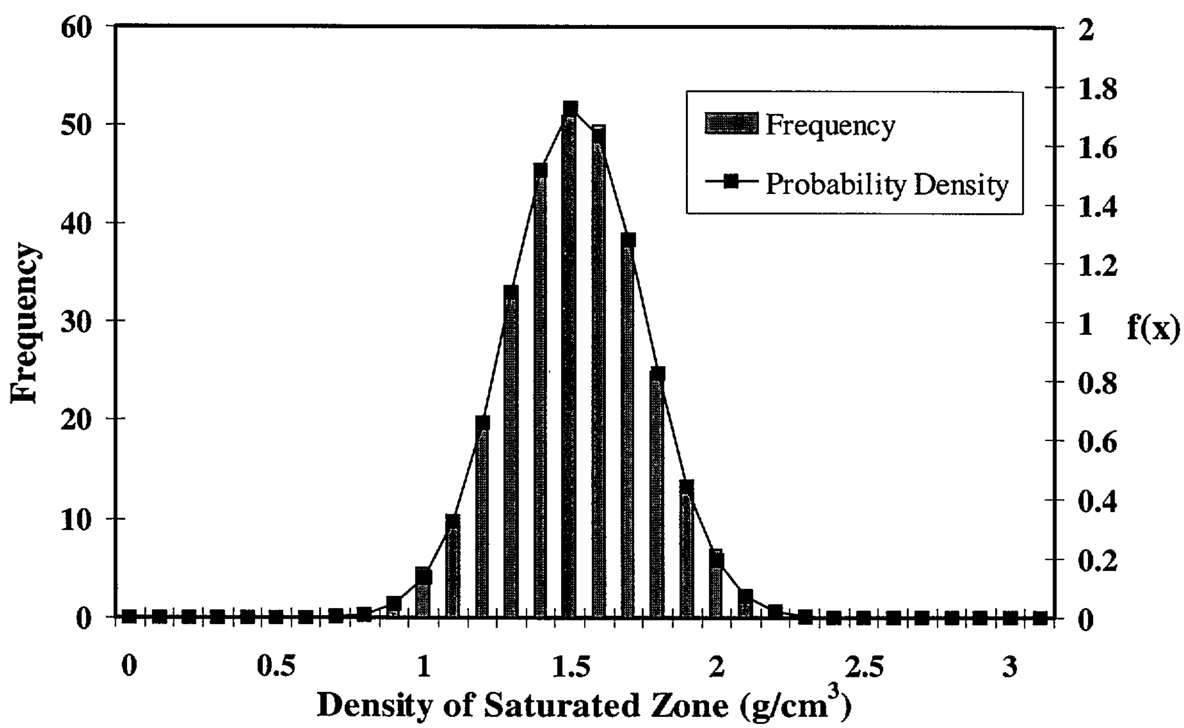

Figure B.2 Sampling Frequency and Probability Density of the Density of Saturated Zone

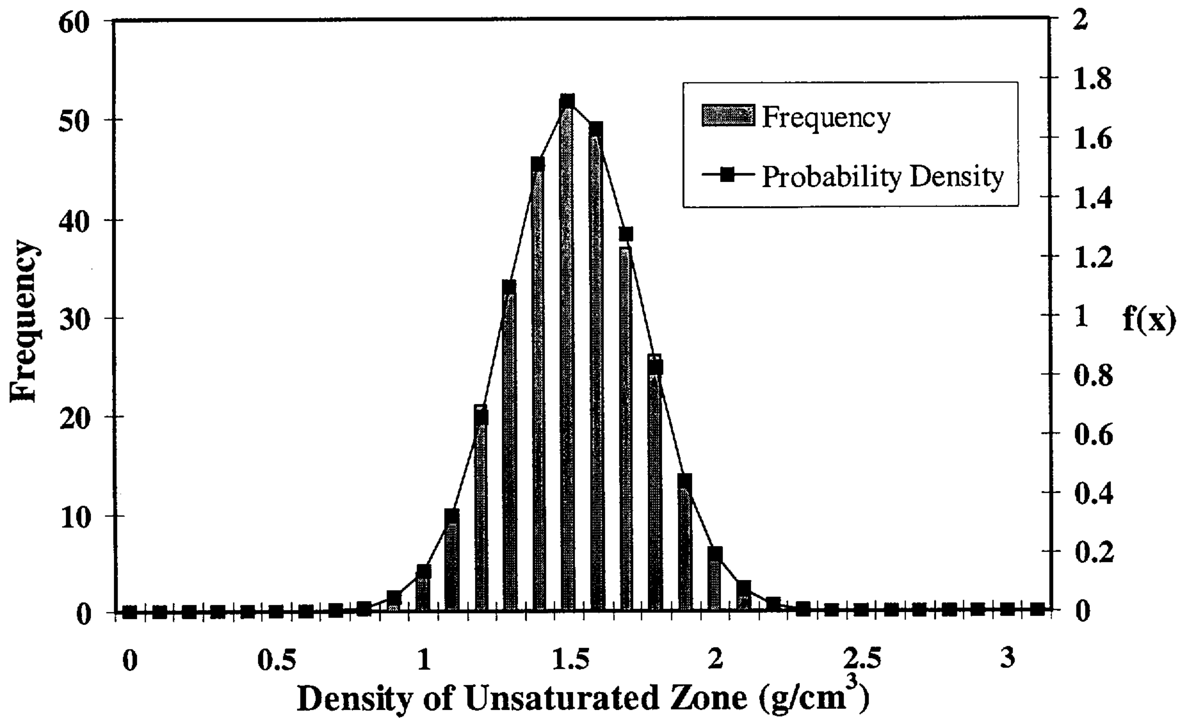

Figure B.3 Sampling Frequency and Probability Density of the Density of Unsaturated Zone

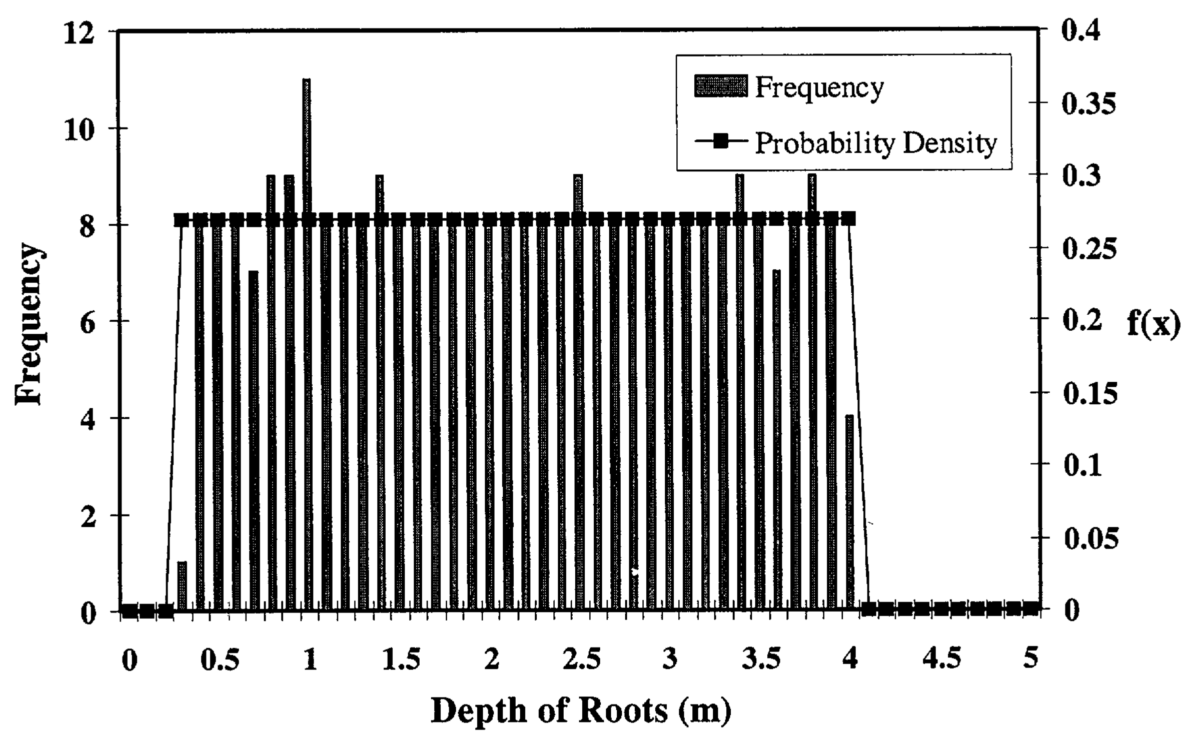

Figure B.4 Sampling Frequency and Probability Density of the Depth of Roots

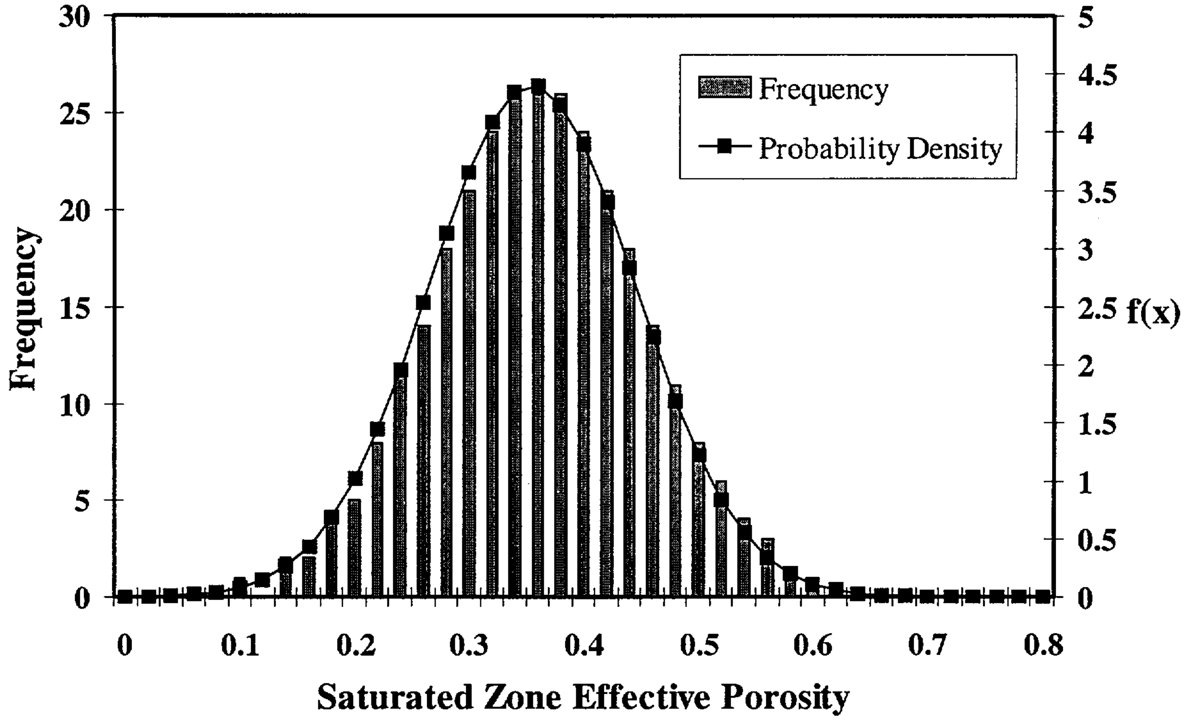

Figure B.5 Sampling Frequency and Probability Density of the Saturated Zone Effective Porosity

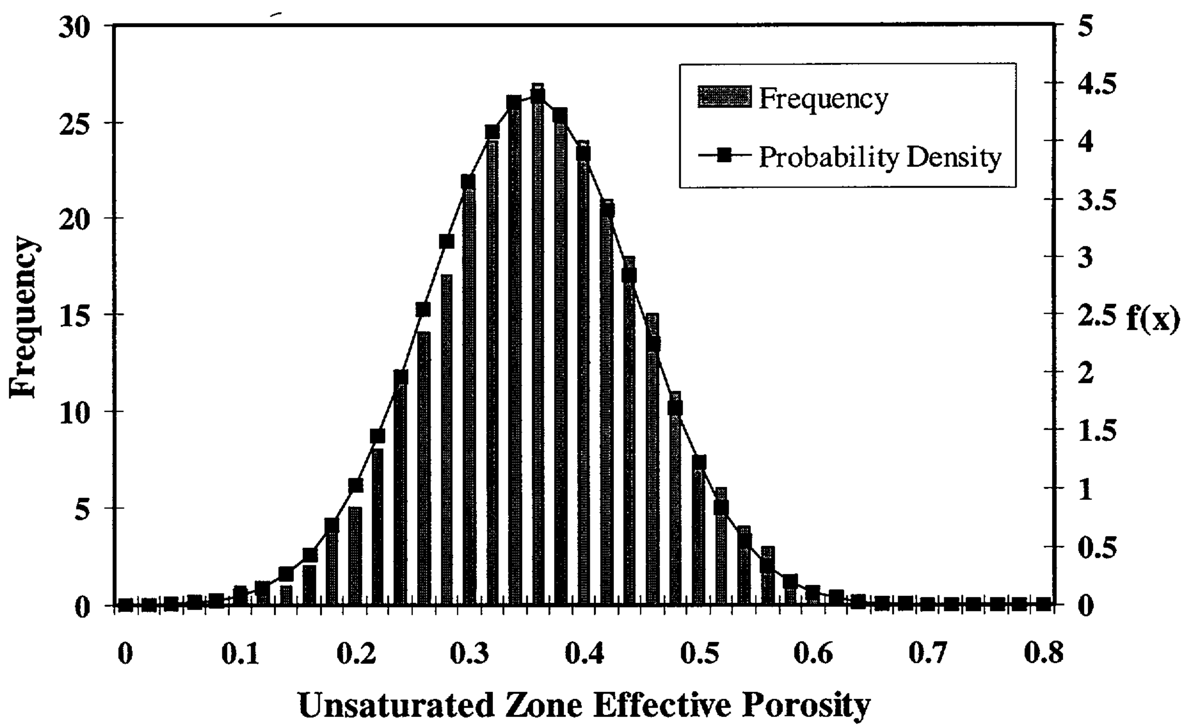

Figure B.6 Sampling Frequency and Probability Density of the Unsaturated Zone Effective Porosity

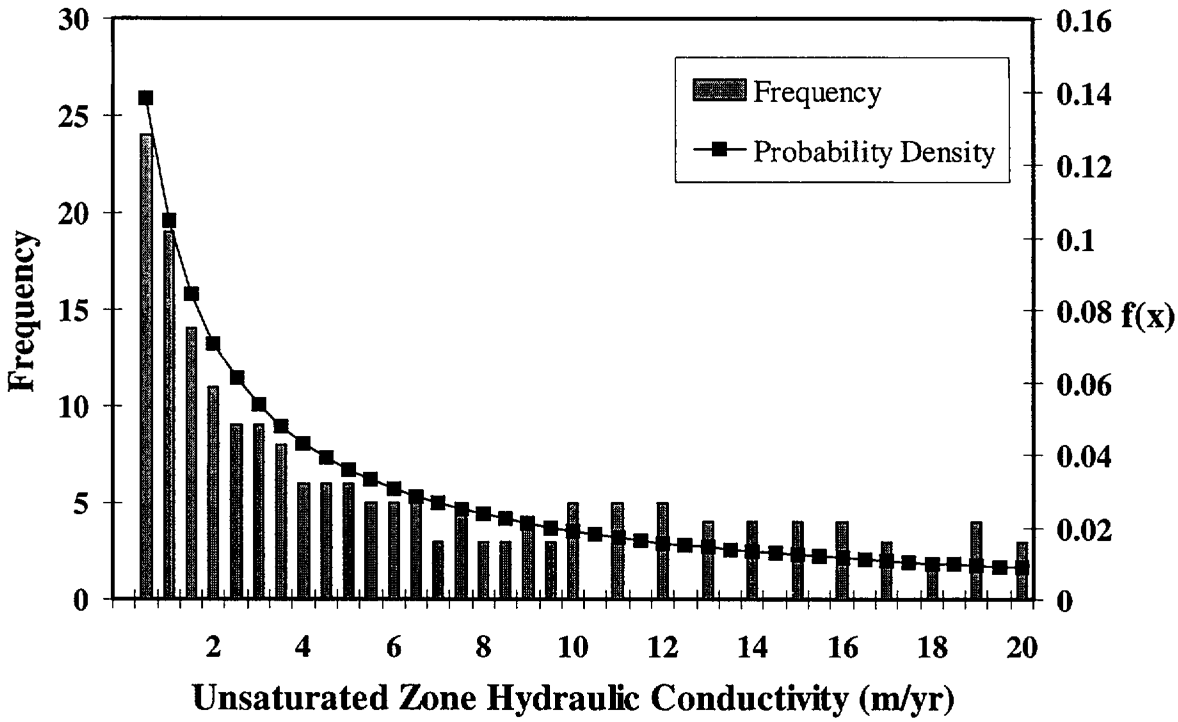

Figure B.7 Sampling Frequency and Probability Density of the Unsaturated Zone Hydraulic Conductivity

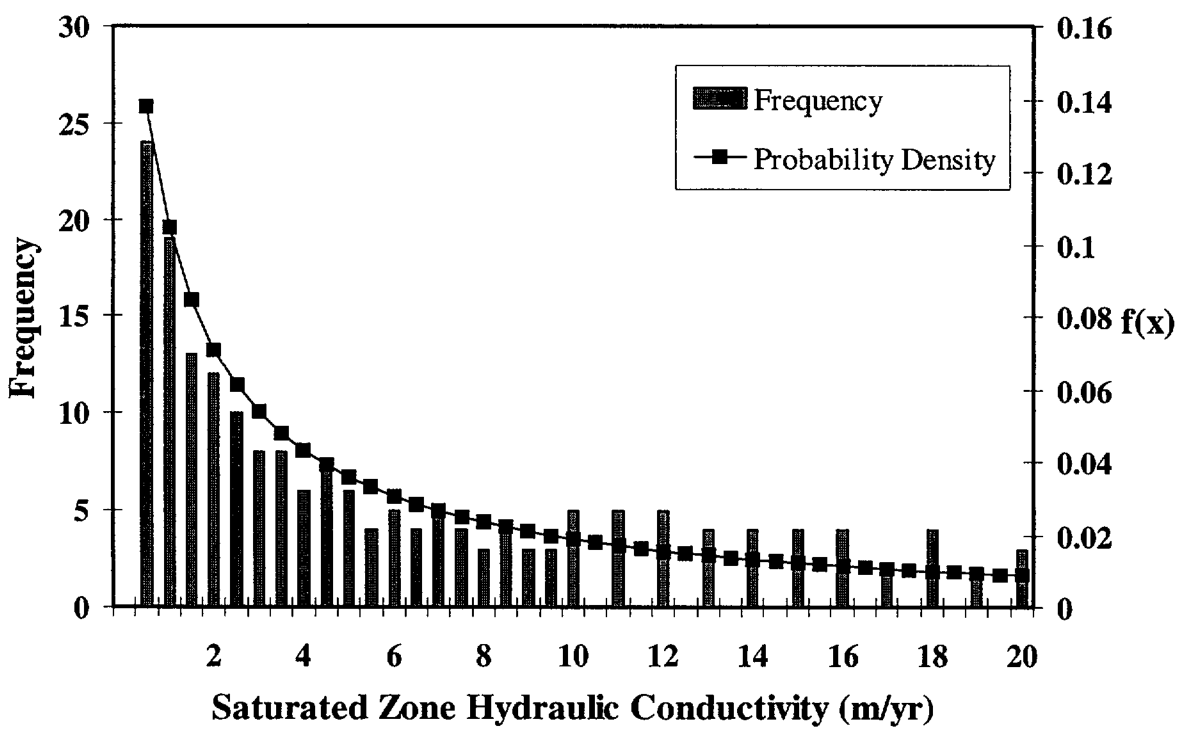

Figure B.8 Sampling Frequency and Probability Density of the Saturated Zone Hydraulic Conductivity

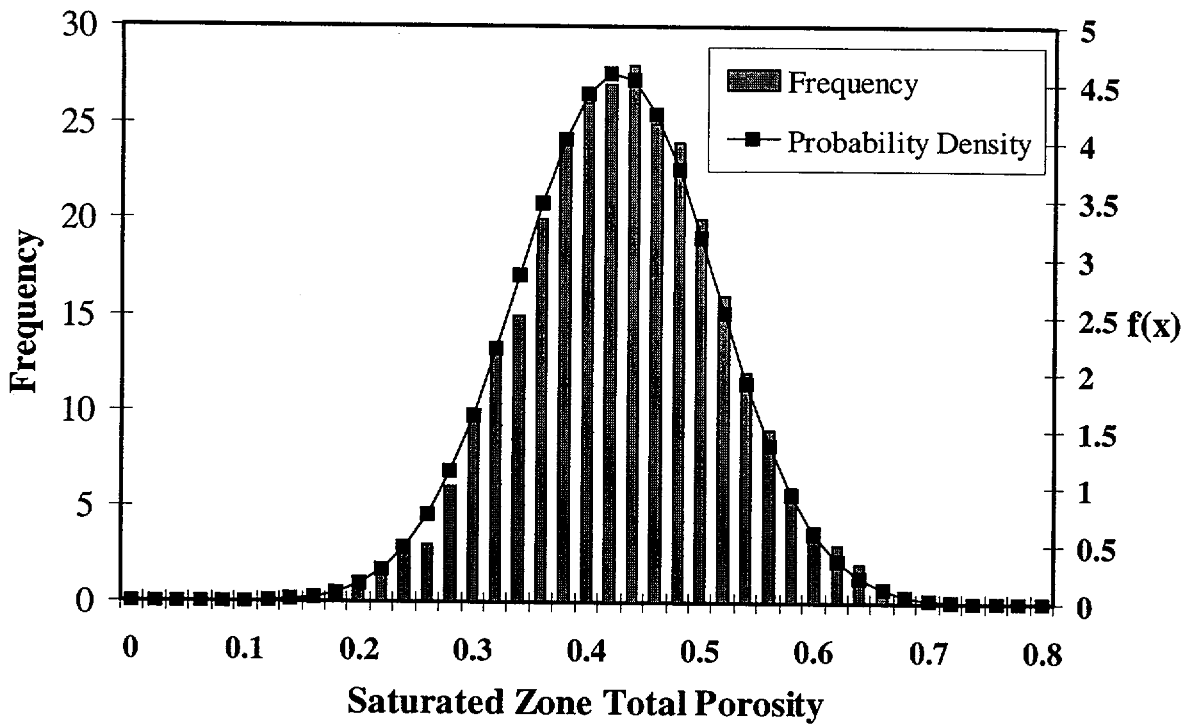

Figure B.9 Sampling Frequency and Probability Density of the Saturated Zone Total Porosity

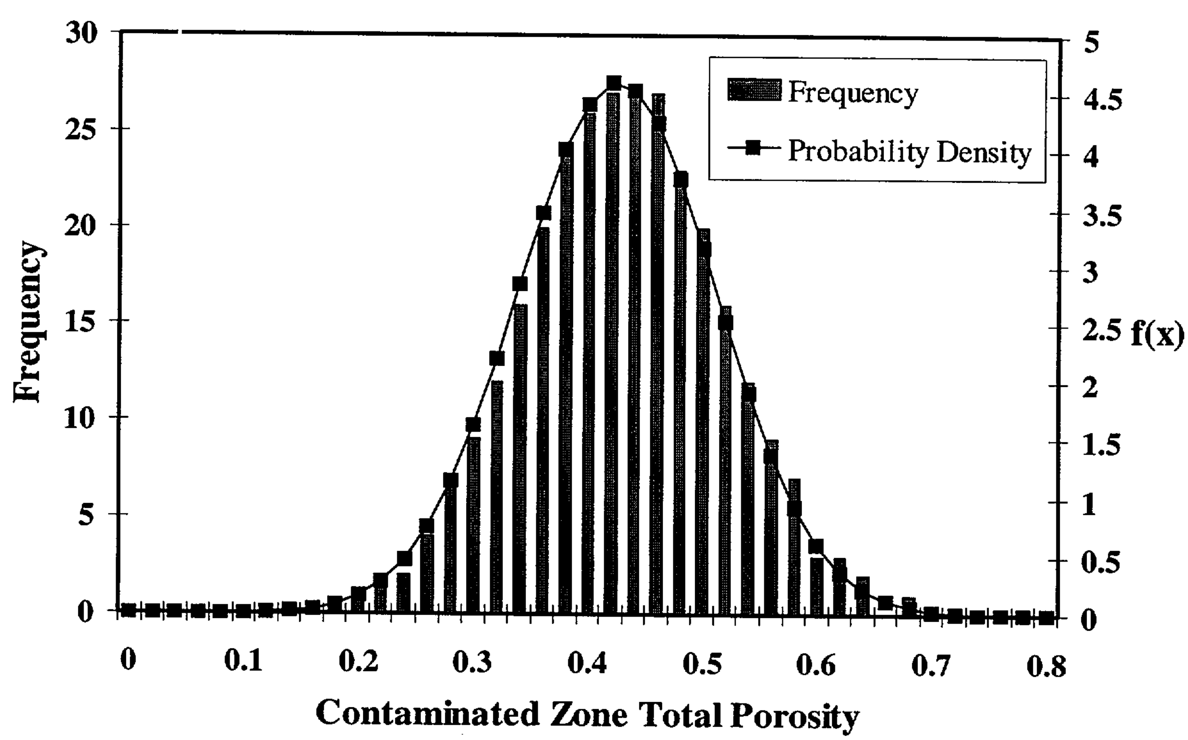

Figure B.10 Sampling Frequency and Probability Density of the Contaminated Zone Total Porosity

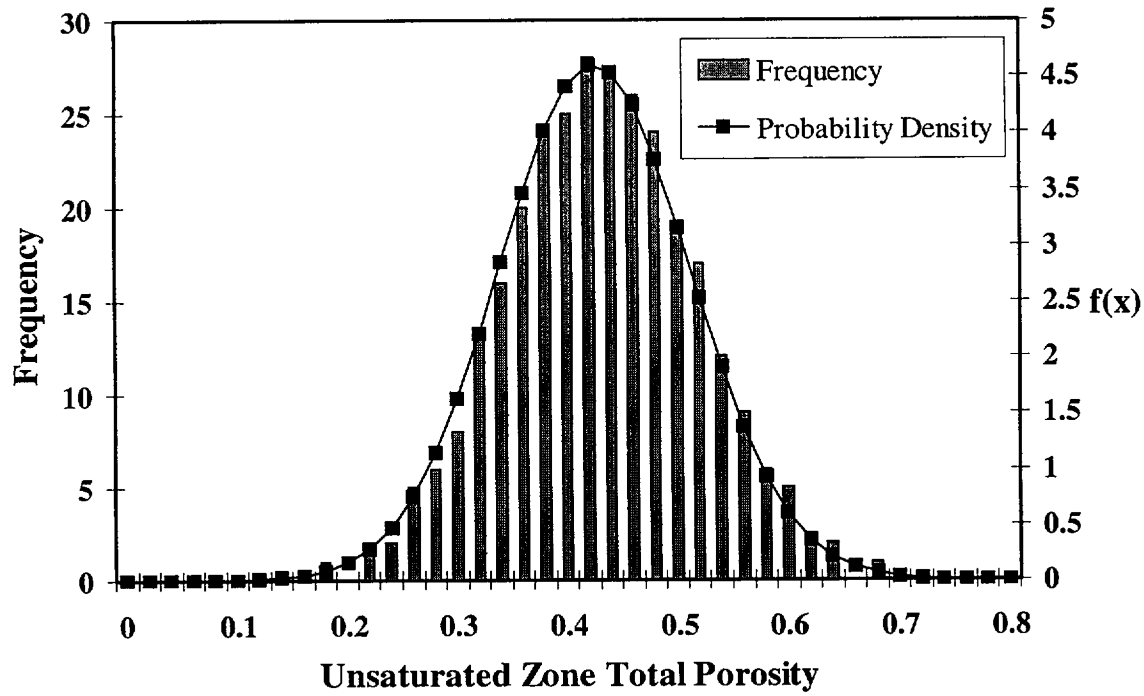

Figure B.11 Sampling Frequency and Probability Density of the Unsaturated Zone Total Porosity

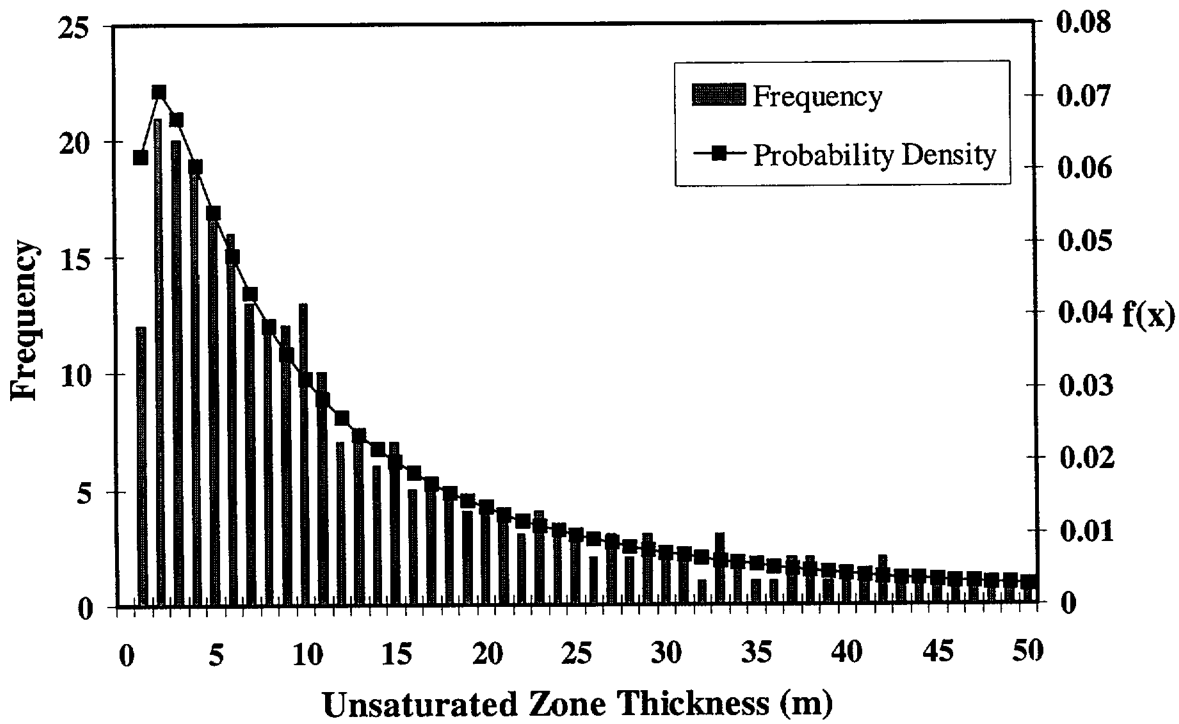

Figure B.12 Sampling Frequency and Probability Density of the Unsaturated Zone Thickness

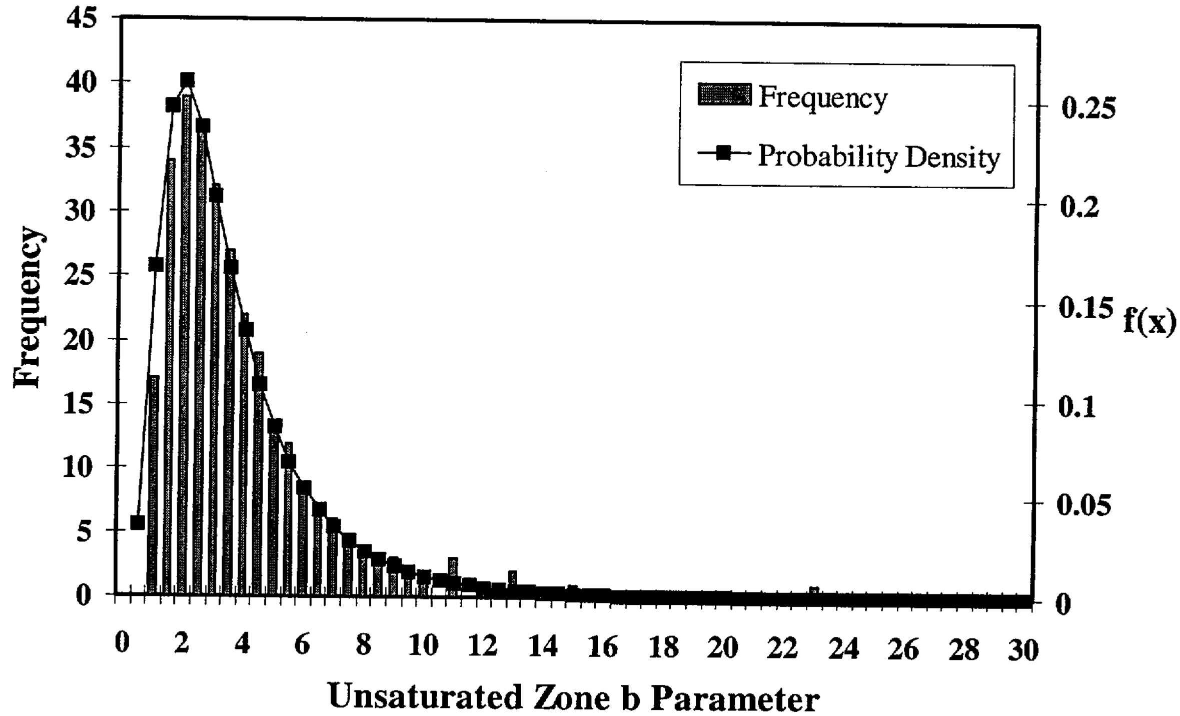

Figure B.13 Sampling Frequency and Probability Density of the Unsaturated Zone b Parameter

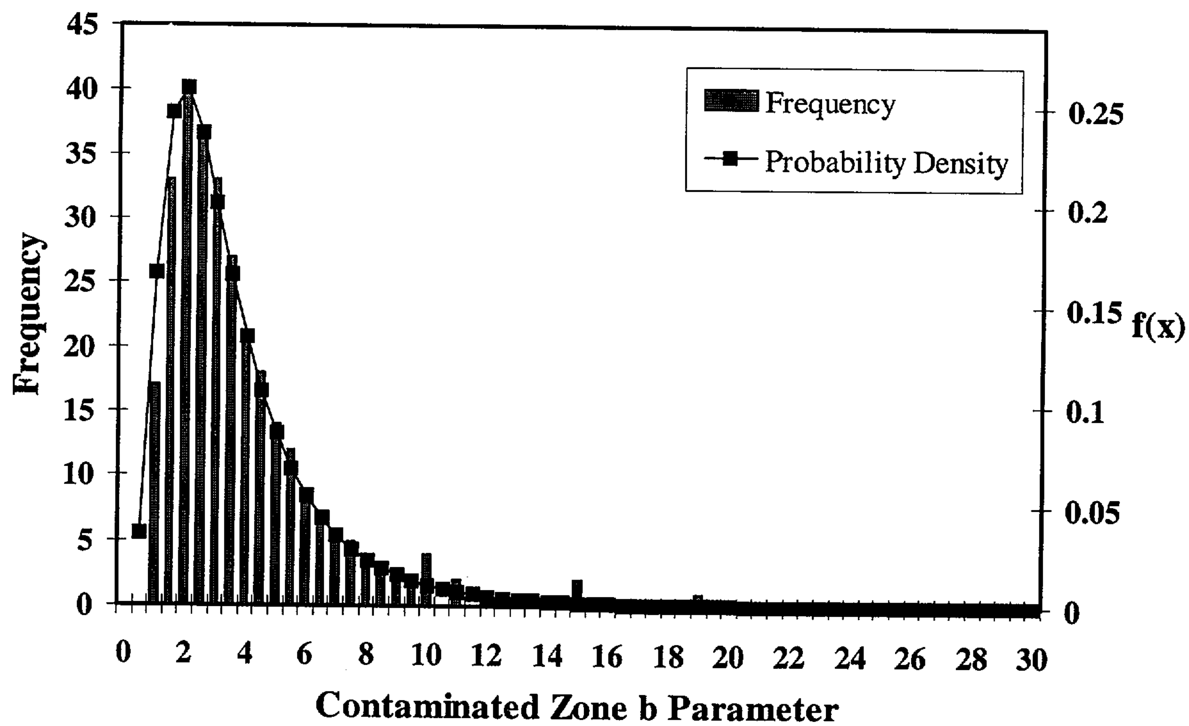

Figure B.14 Sampling Frequency and Probability Density of the Contaminated Zone b Parameter

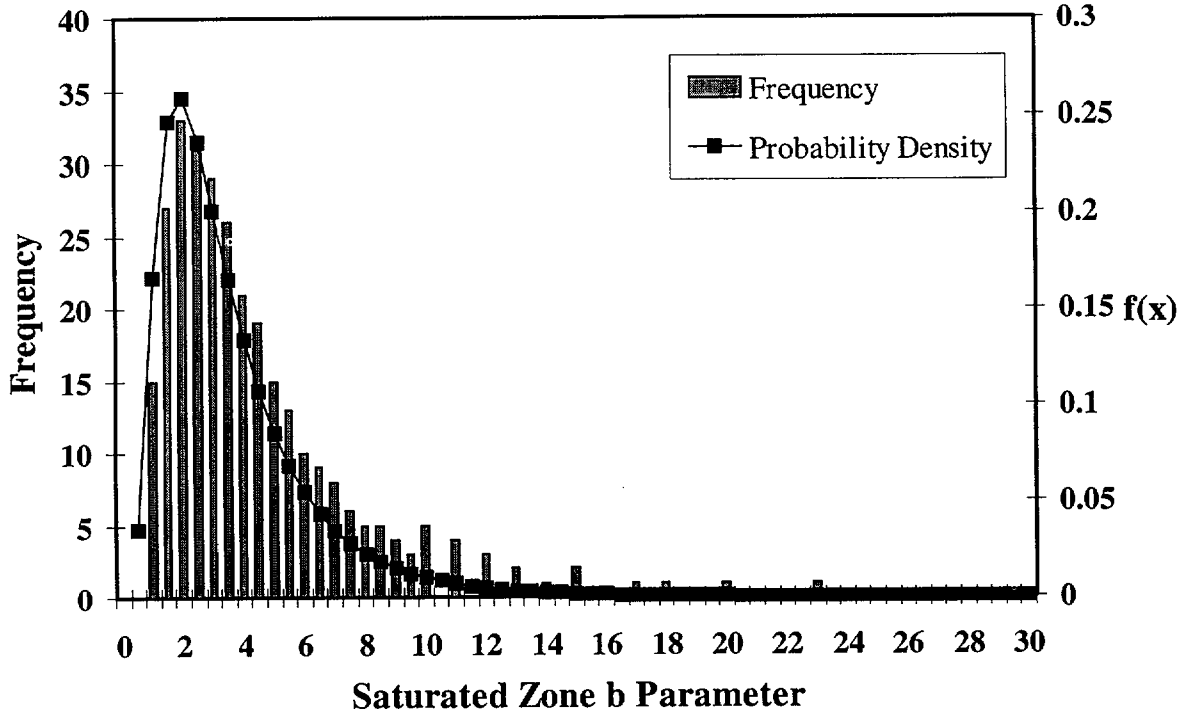

Figure B.15 Sampling Frequency and Probability Density of the Saturated Zone b Parameter

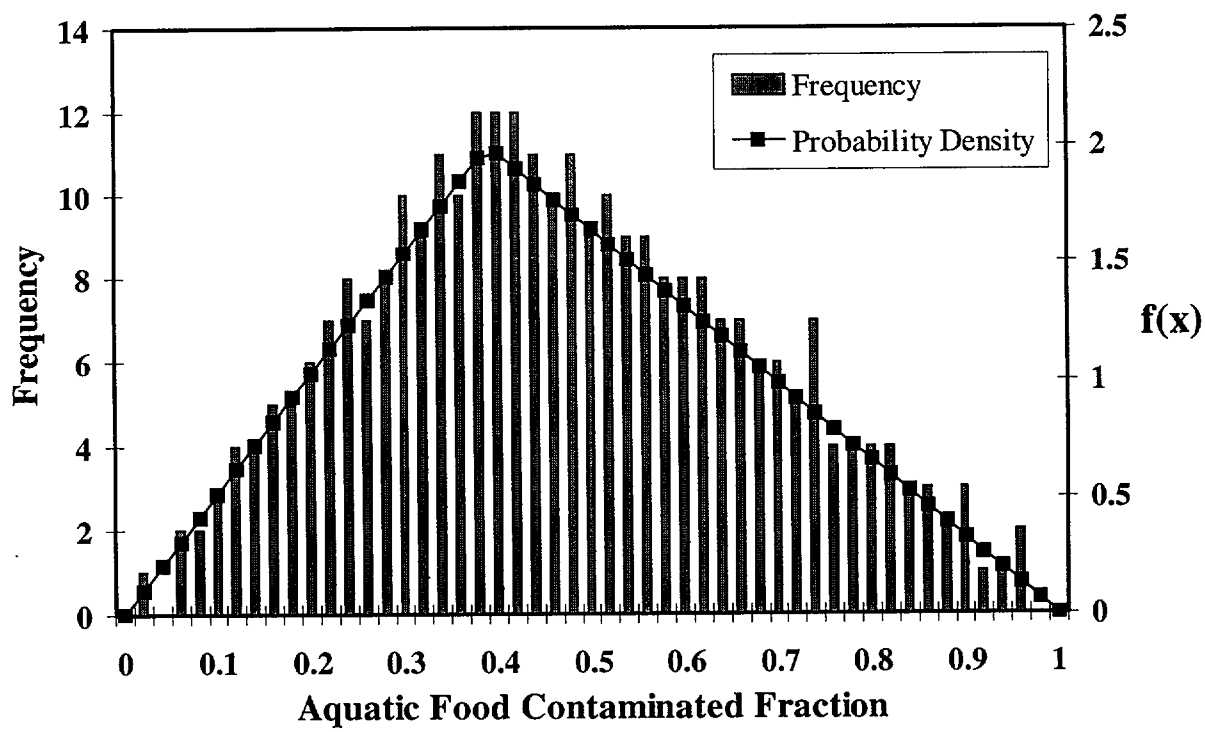

Figure B.16 Sampling Frequency and Probability Density of the Aquatic Food Contaminated Fraction

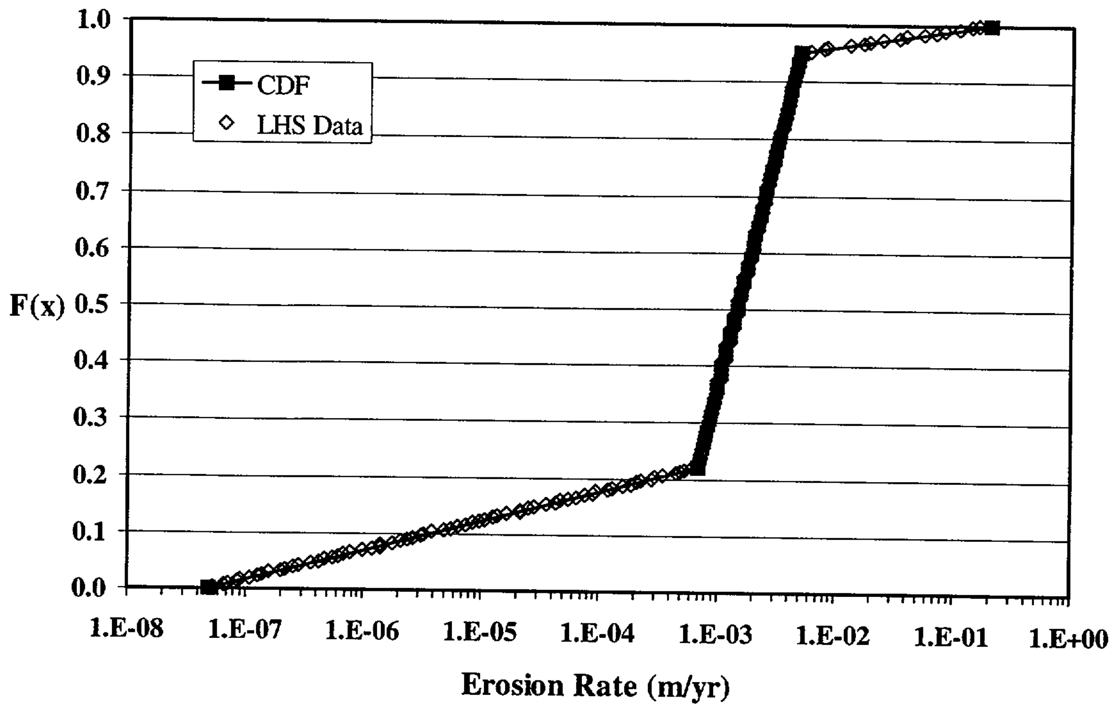

Figure B.17 Sampled Cumulative Probability and the Cumulative Distribution Function of the Erosion Rate

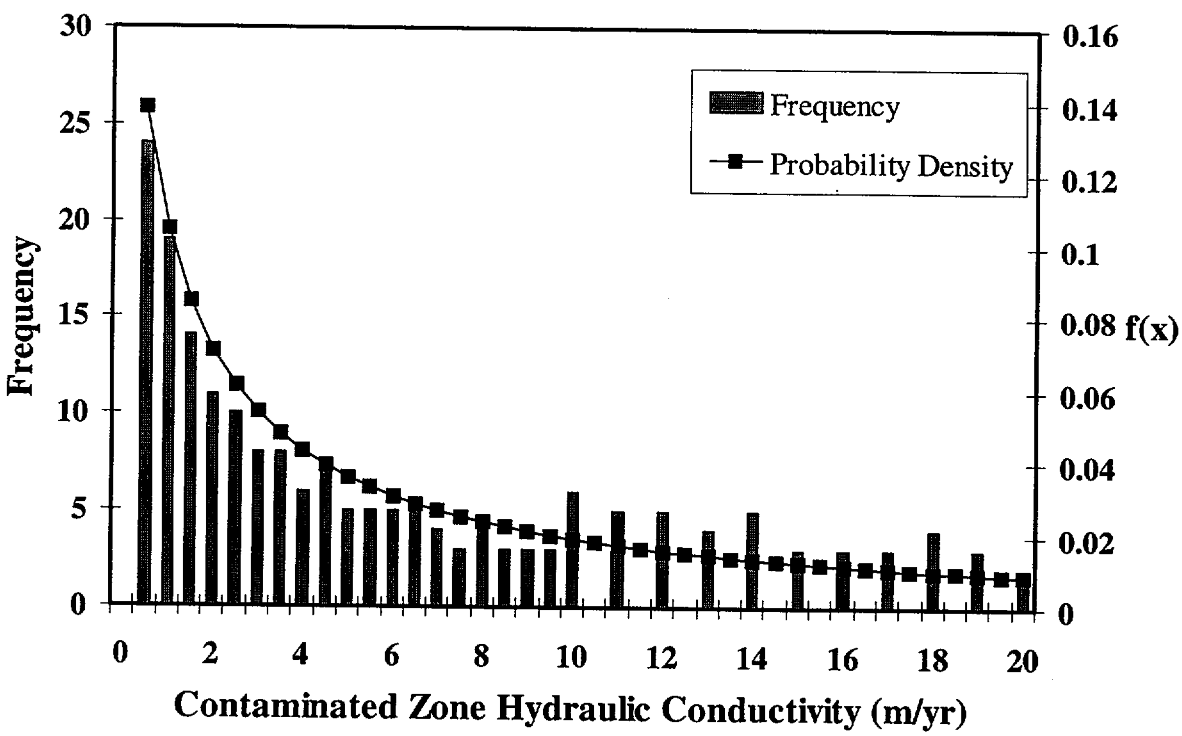

Figure B.18 Sampling Frequency and Probability Density of the Contaminated Zone Hydraulic Conductivity

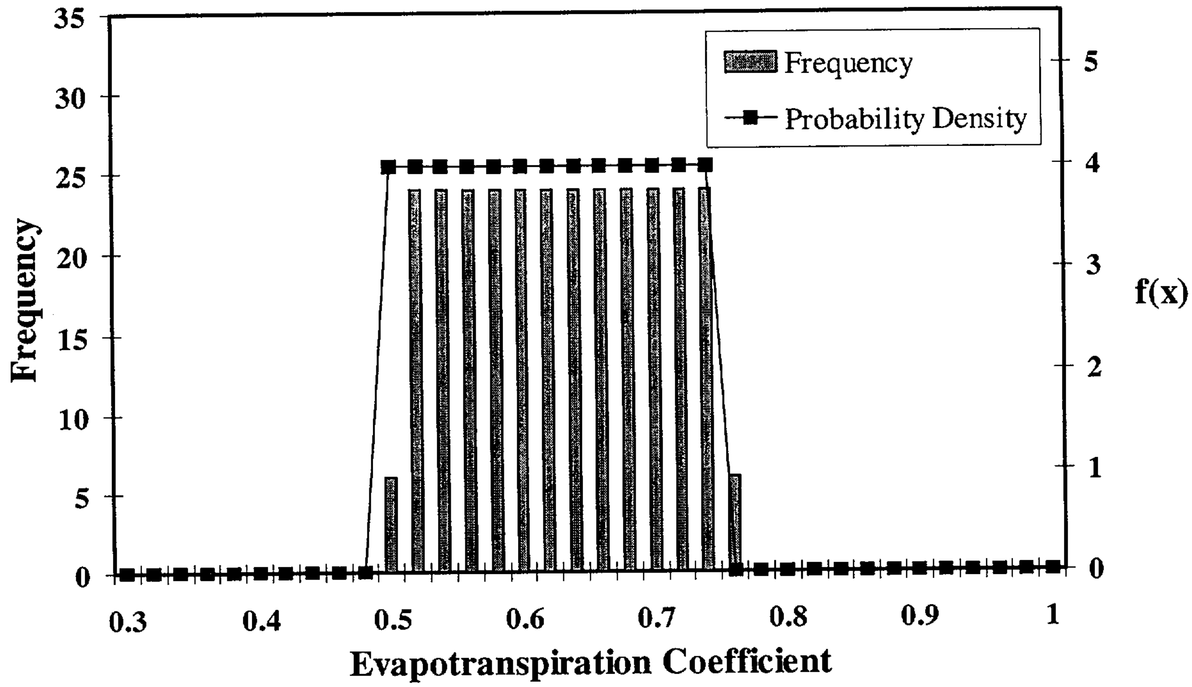

Figure B.19 Sampling Frequency and Probability Density of the Evapotranspiration Coefficient

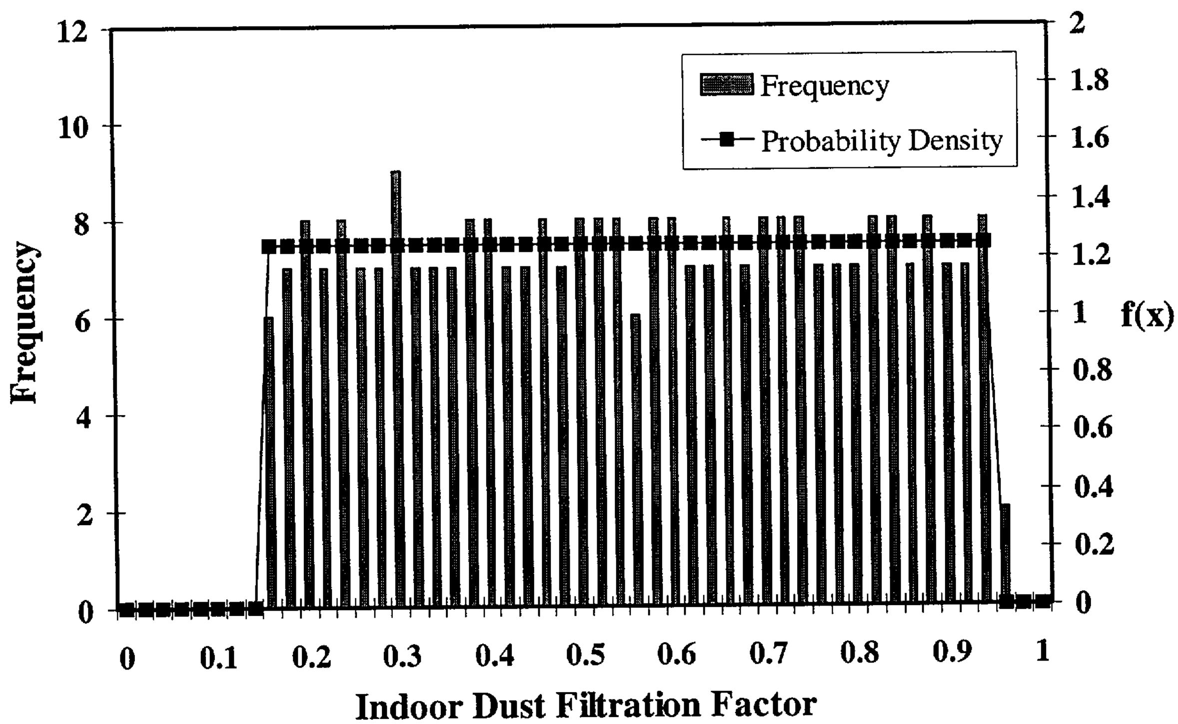

Figure B.20 Sampling Frequency and Probability Density of the Indoor Dust Filtration Factor

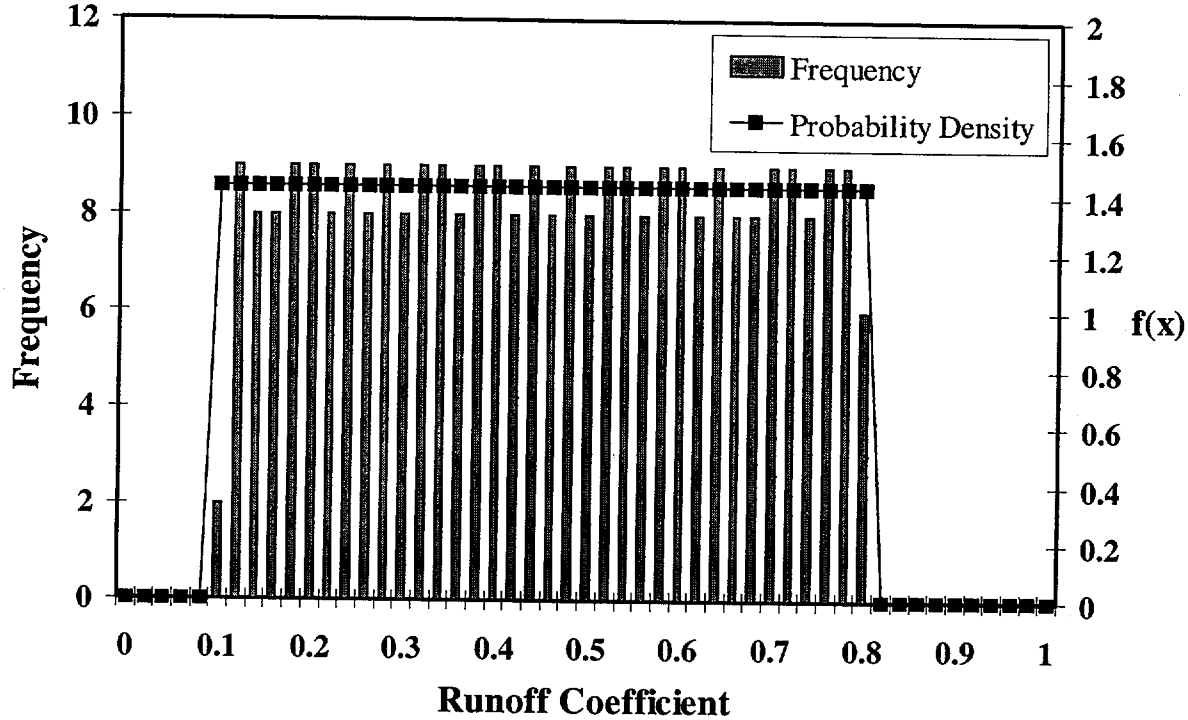

Figure B.21 Sampling Frequency and Probability Density of the Runoff Coefficient

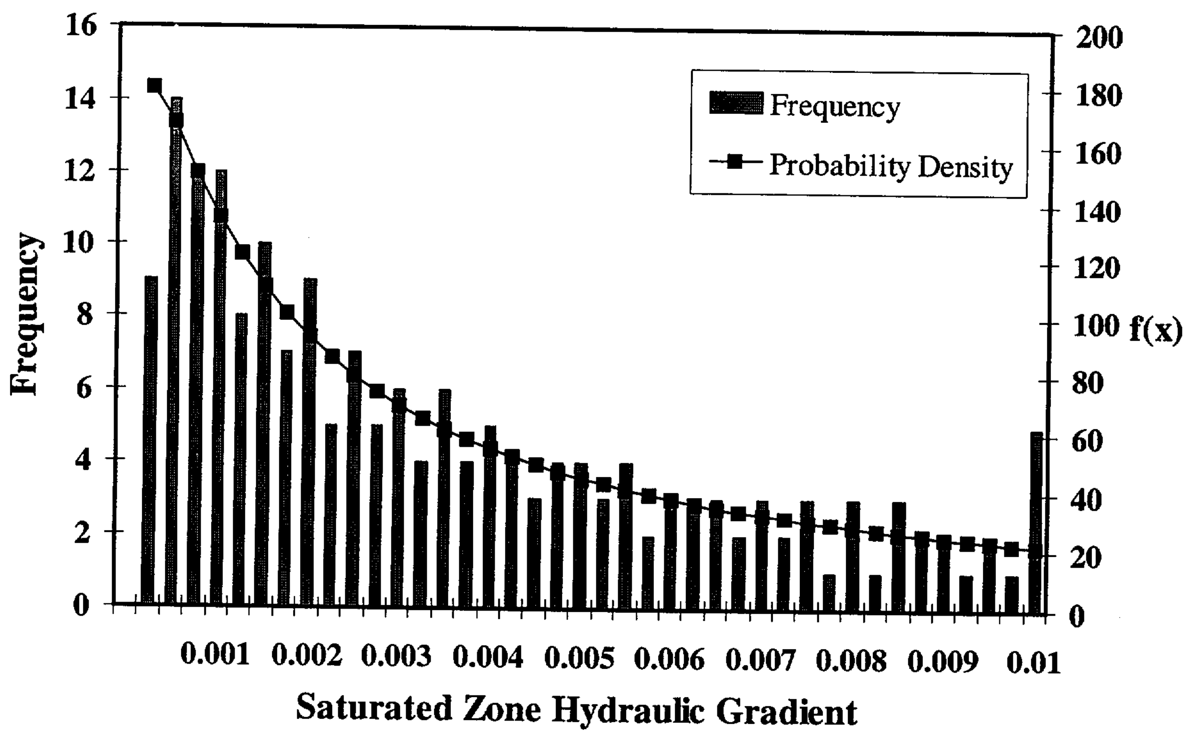

Figure B.22 Sampling Frequency and Probability Density of the Saturated Zone Hydraulic Gradient

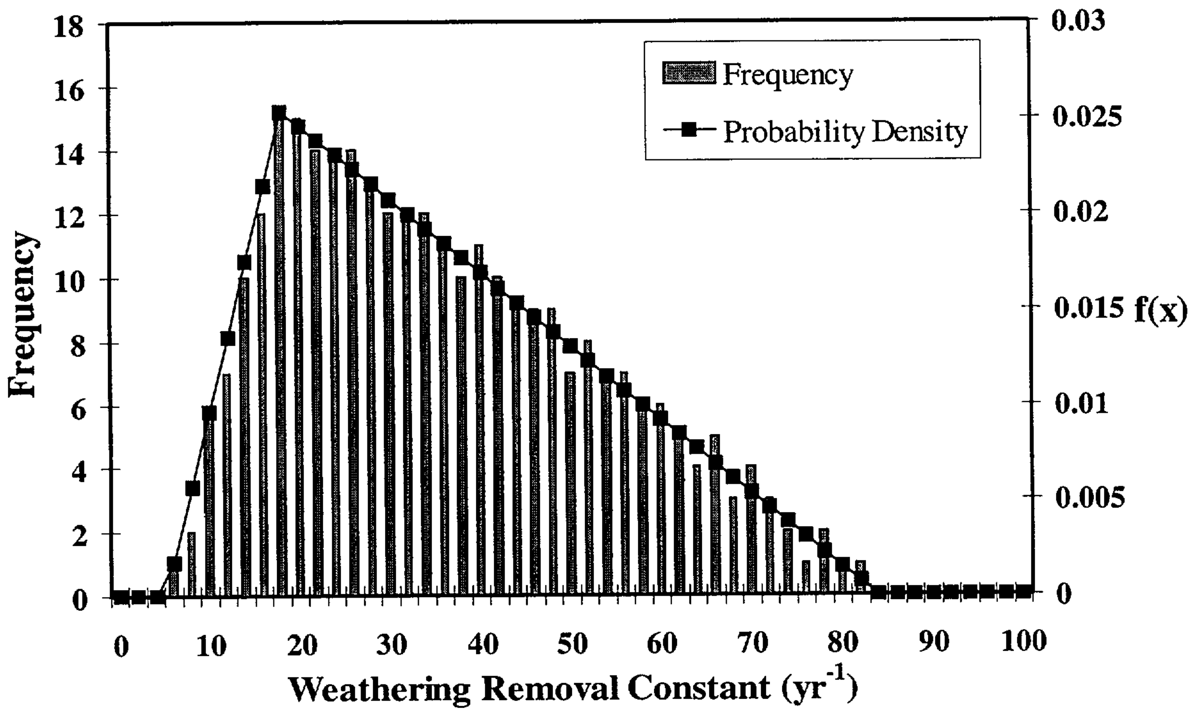

Figure B.23 Sampling Frequency and Probability Density of the Weathering Removal Constant

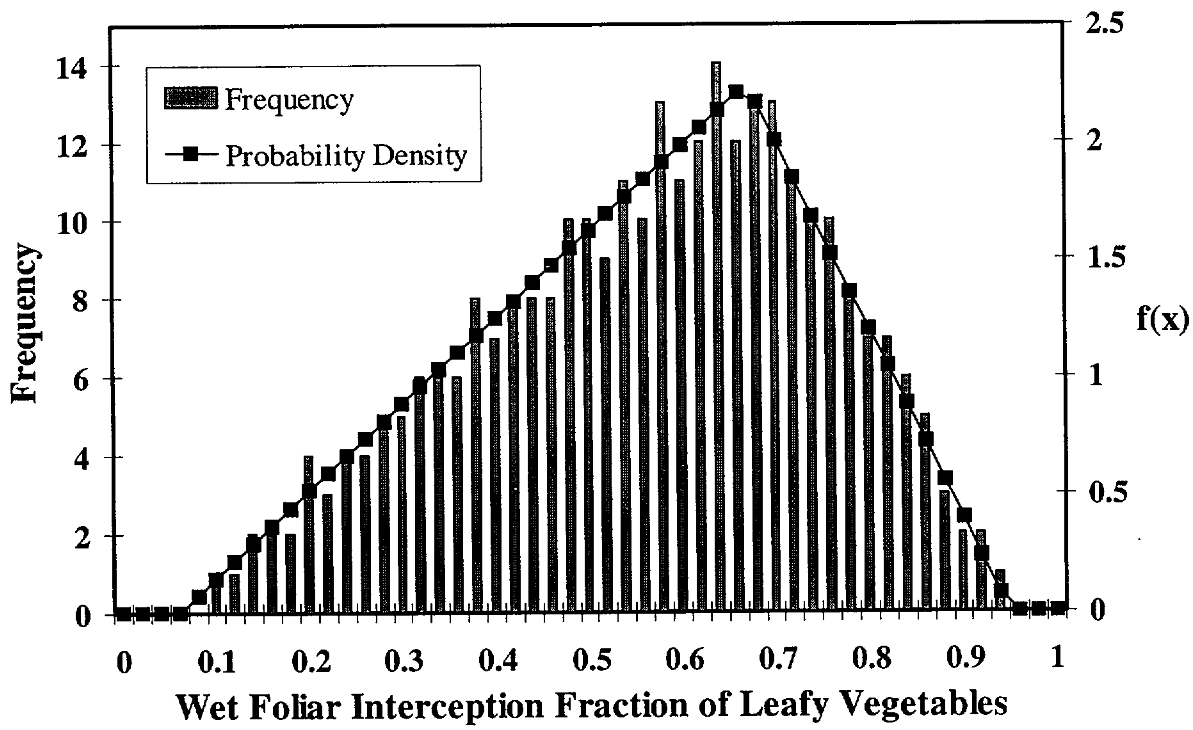

Figure B.24 Sampling Frequency and Probability Density of the Wet Foliar Interception Fraction of Leafy Vegetables

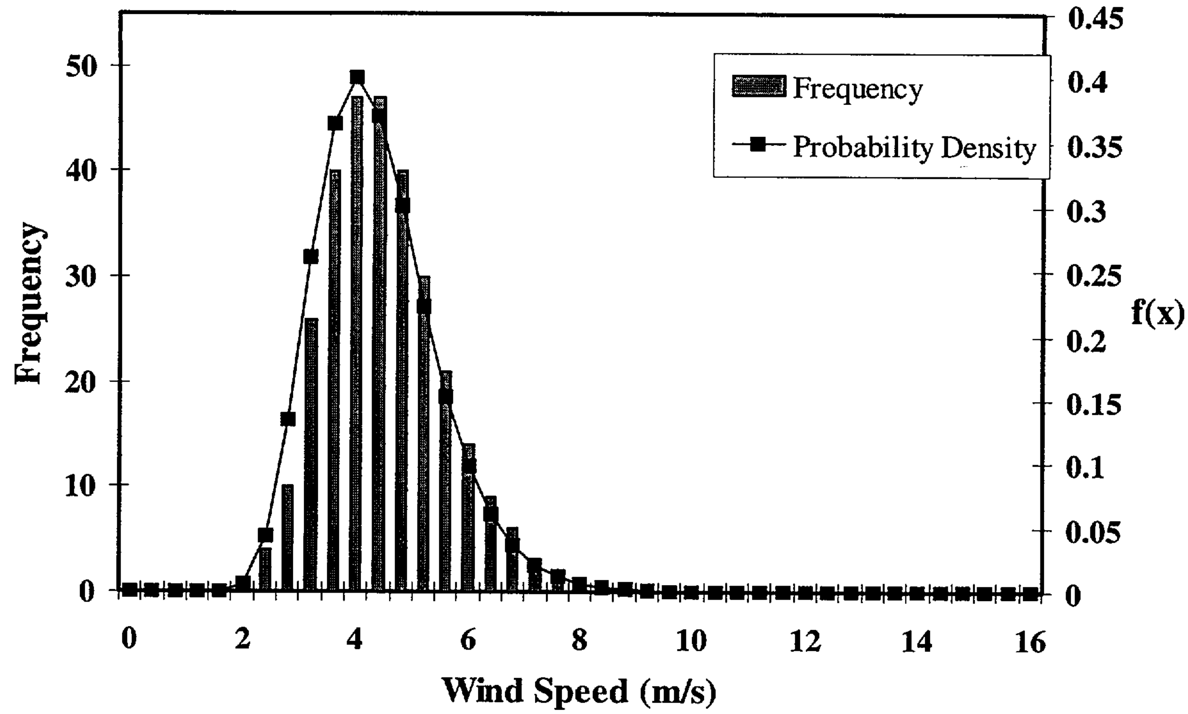

Figure B.25 Sampling Frequency and Probability Density of the Wind Speed

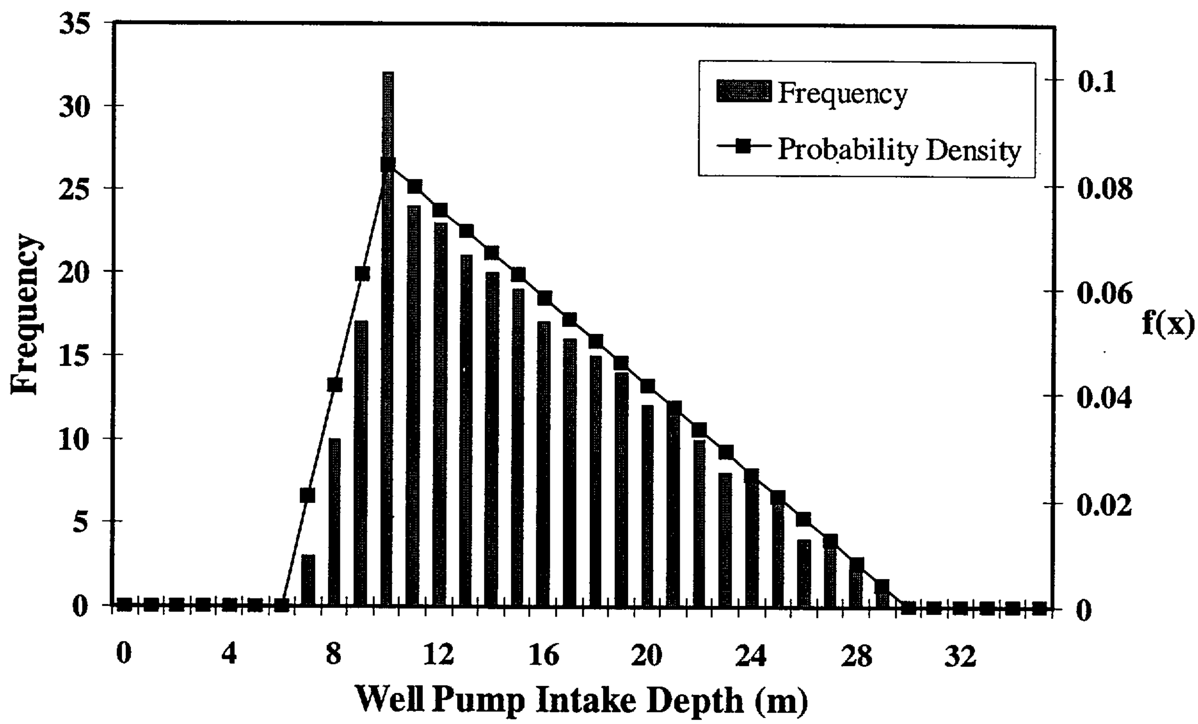

Figure B.26 Sampling Frequency and Probability Density of the Well Pump Intake Depth

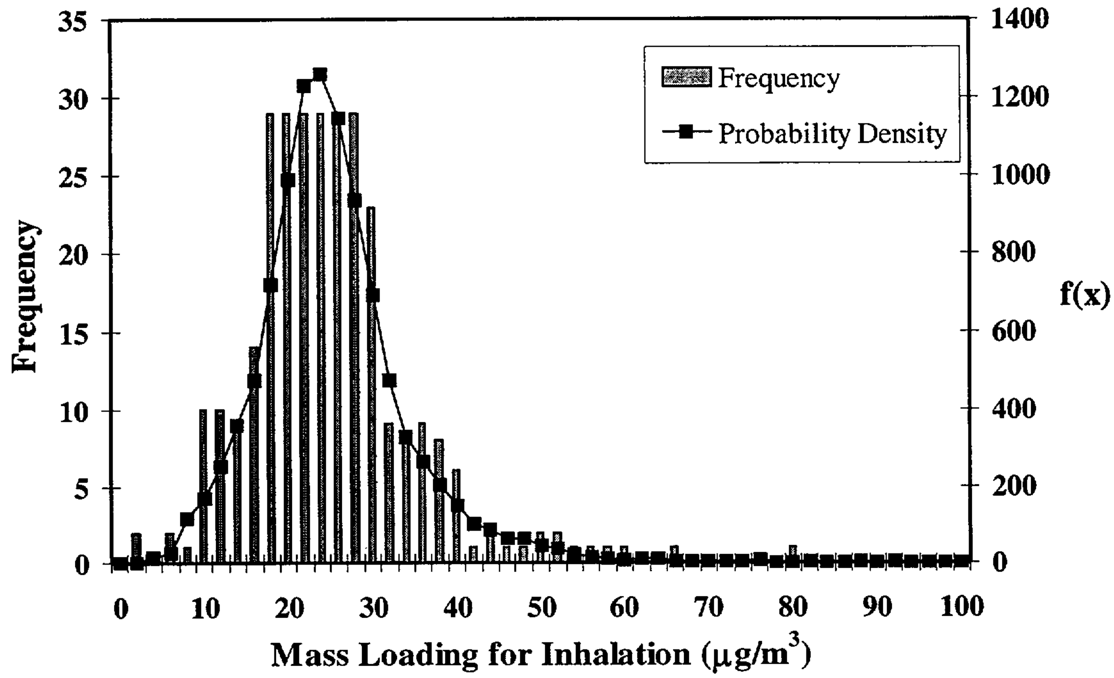

Figure B.27 Sampling Frequency and Probability Density of the Mass Loading for Inhalation

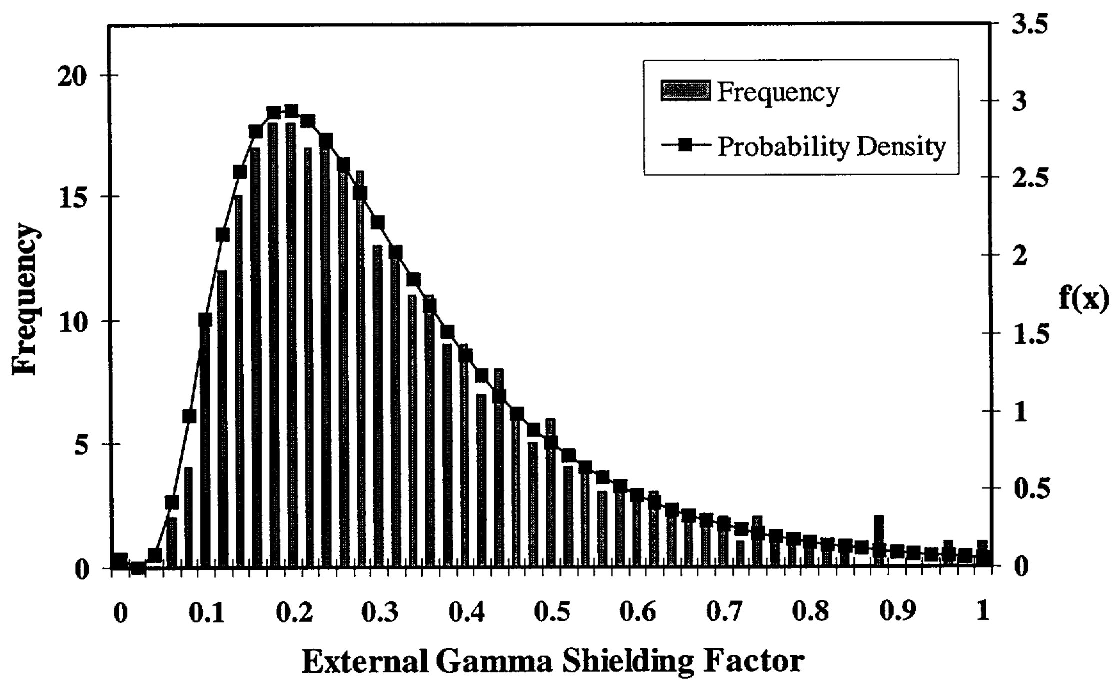

Figure B.28 Sampling Frequency and Probability Density of the External Gamma Shielding Factor

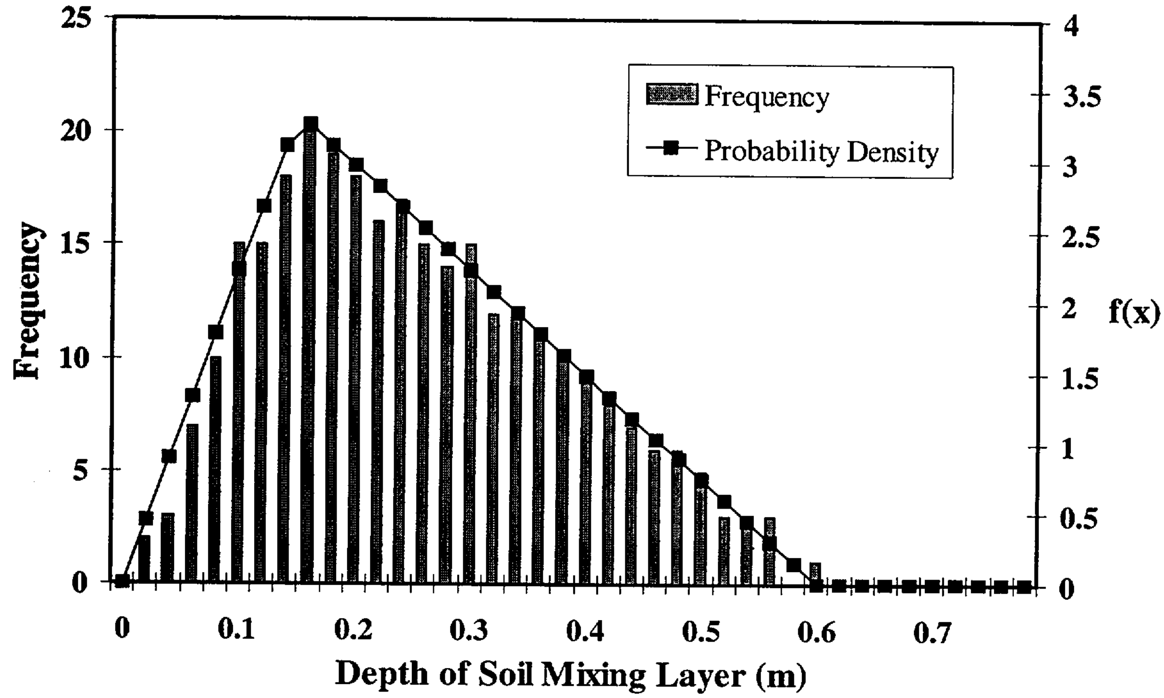

Figure B.29 Sampling Frequency and Probability Density of the Depth of Soil Mixing Layer

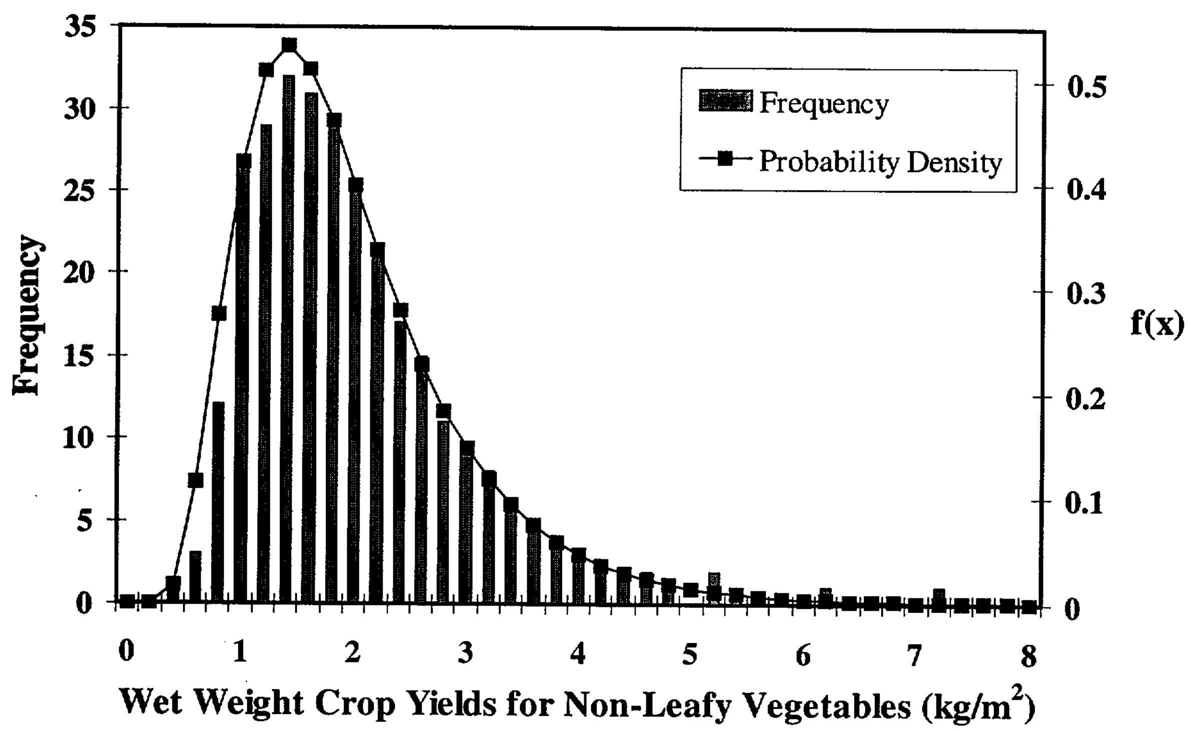

Figure B.30 Sampling Frequency and Probability Density of the Wet Weight Crop Yields for Non-Leafy Vegetables

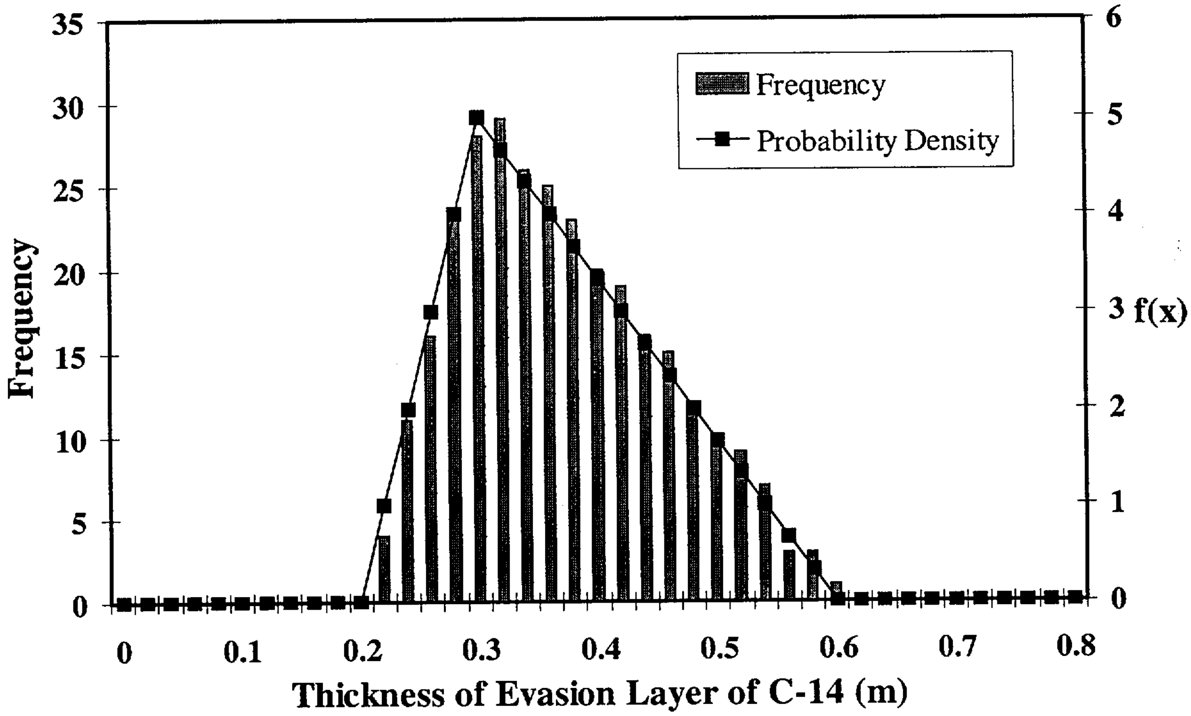

Figure B.31 Sampling Frequency and Probability Density of the Thickness of Evasion Layer of C-14

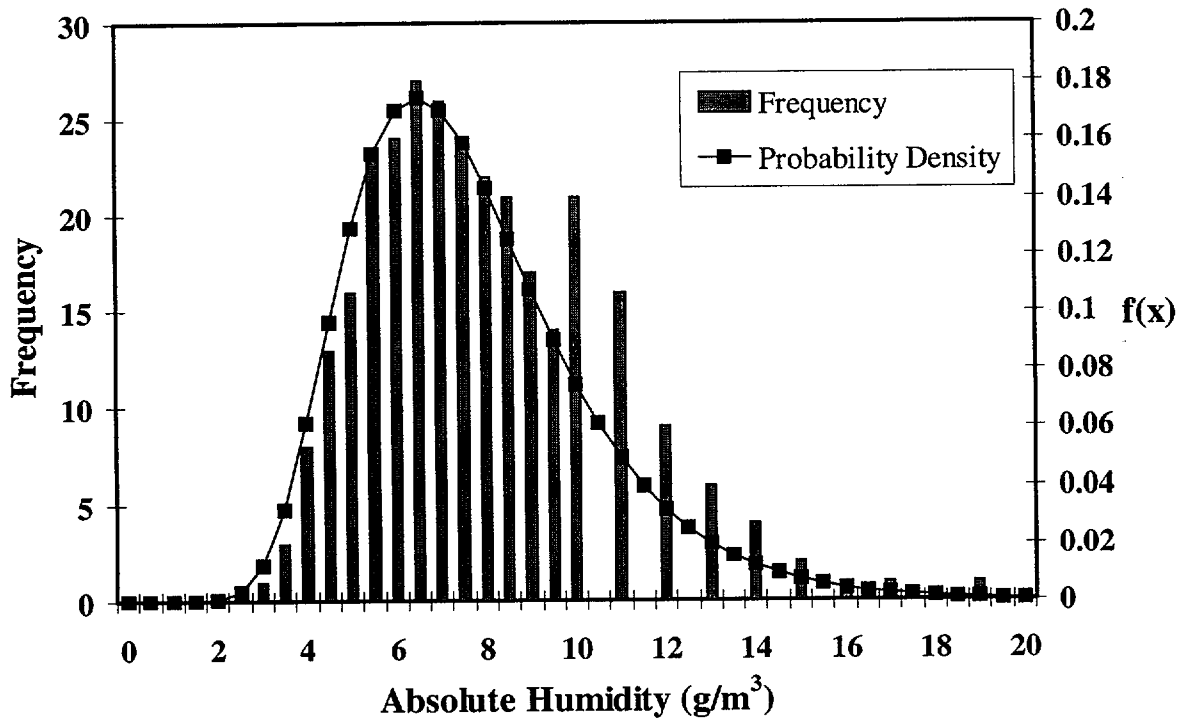

Figure B.32 Sampling Frequency and Probability Density of the Absolute Humidity

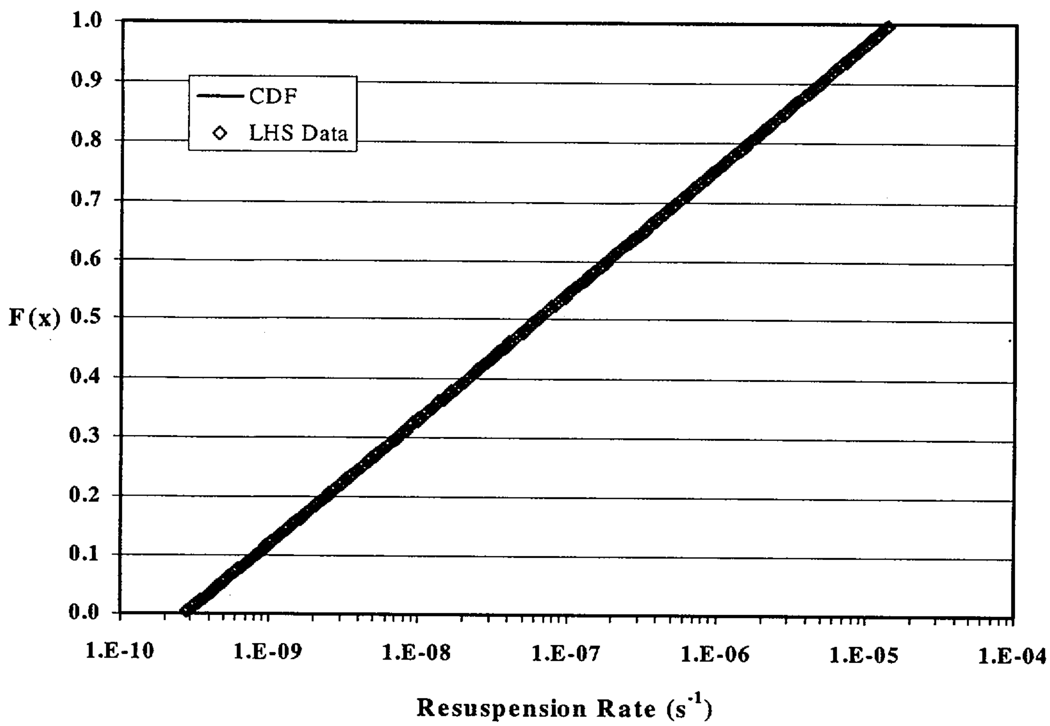

Figure B.33 Sampled Cumulative Probability and the Cumulative Distribution Function of the Resuspension Rate

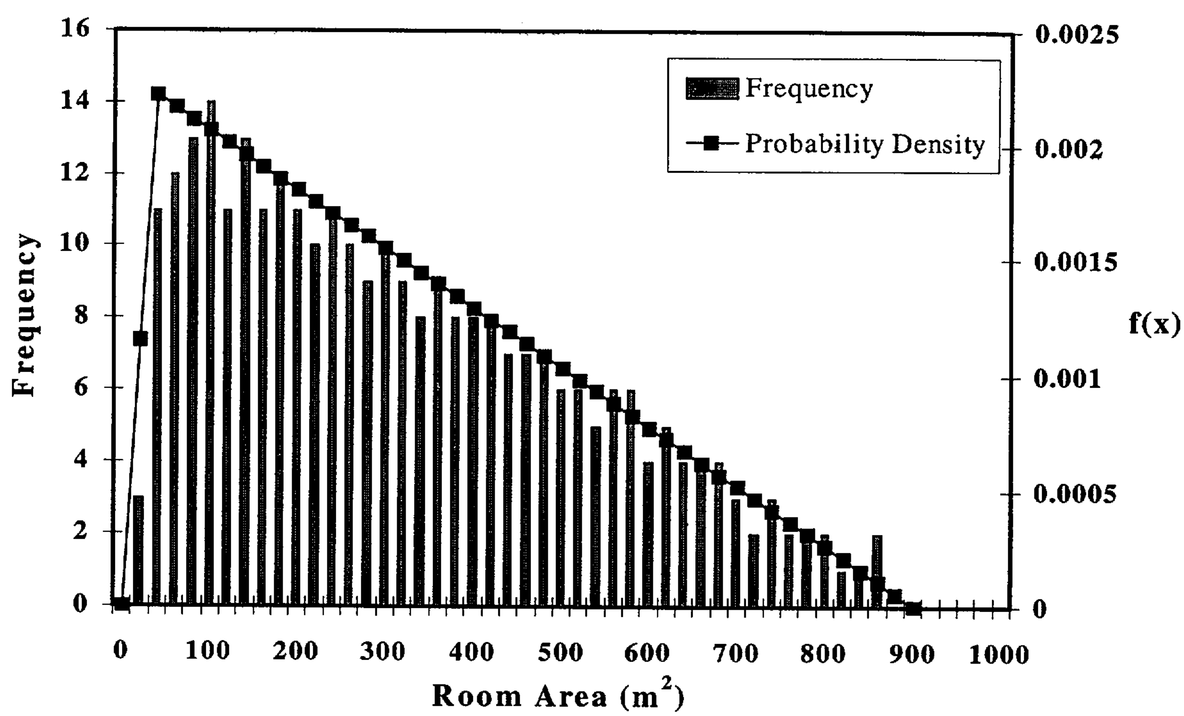

Figure B.34 Sampling Frequency and Probability Density of the Room Area

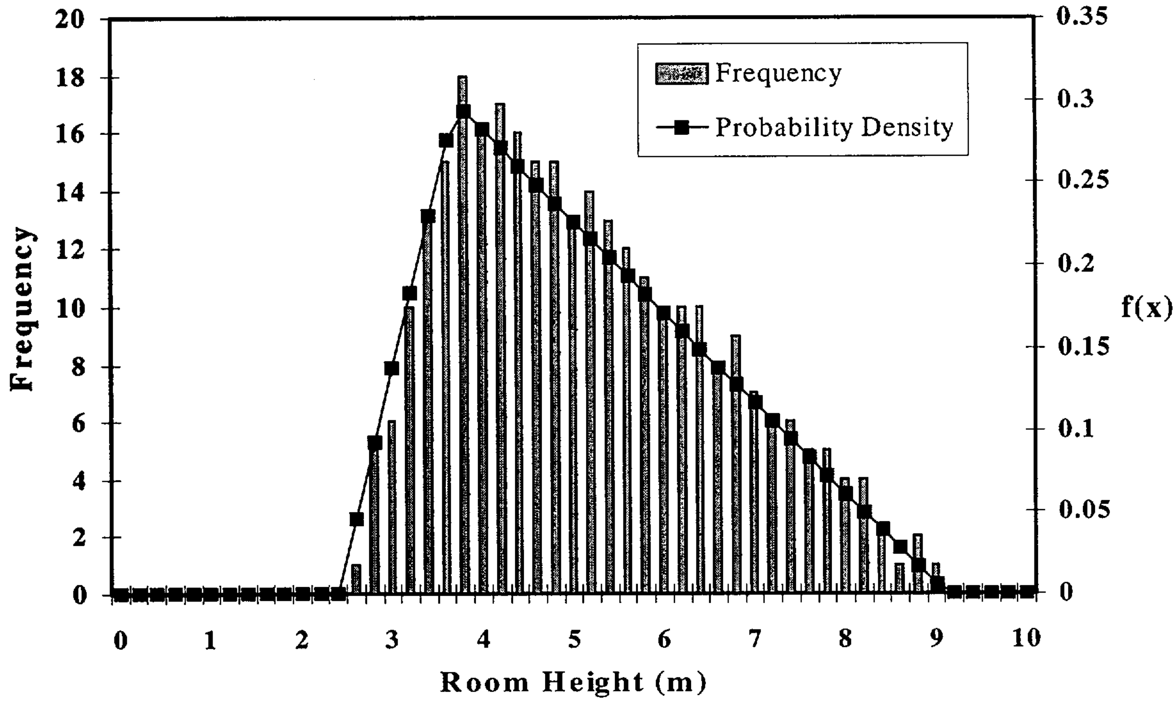

Figure B.35 Sampling Frequency and Probability Density of the Room Height

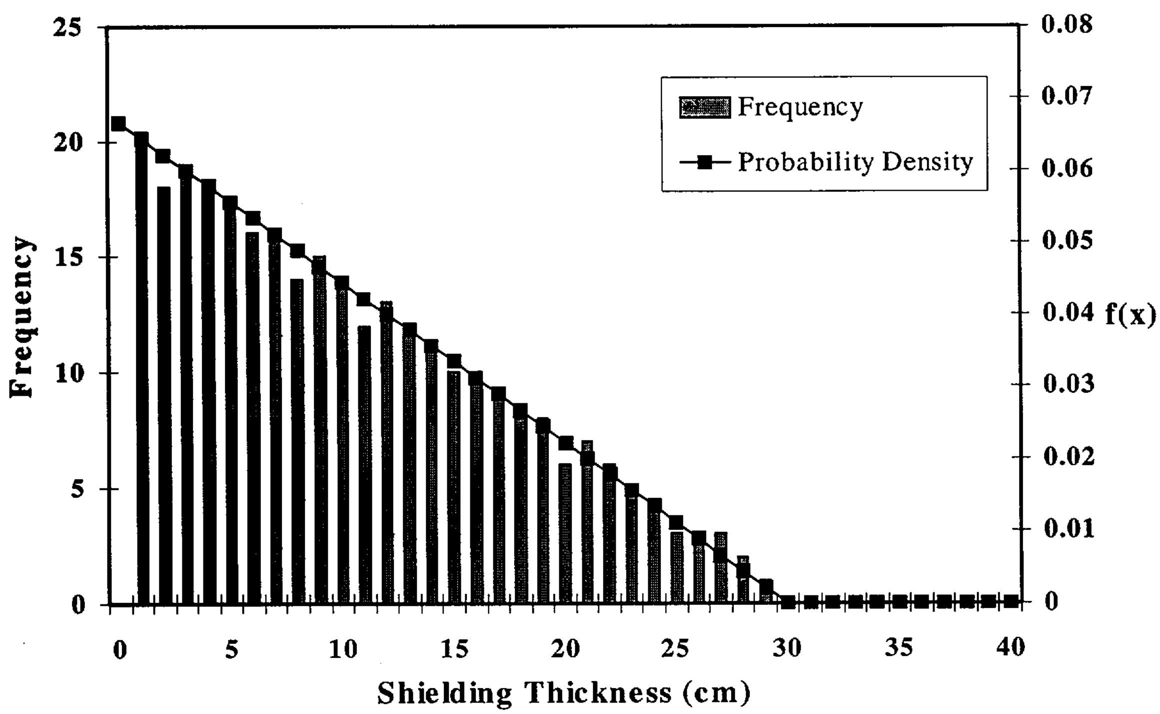

Figure B.36 Sampling Frequency and Probability Density of the Shielding Thickness

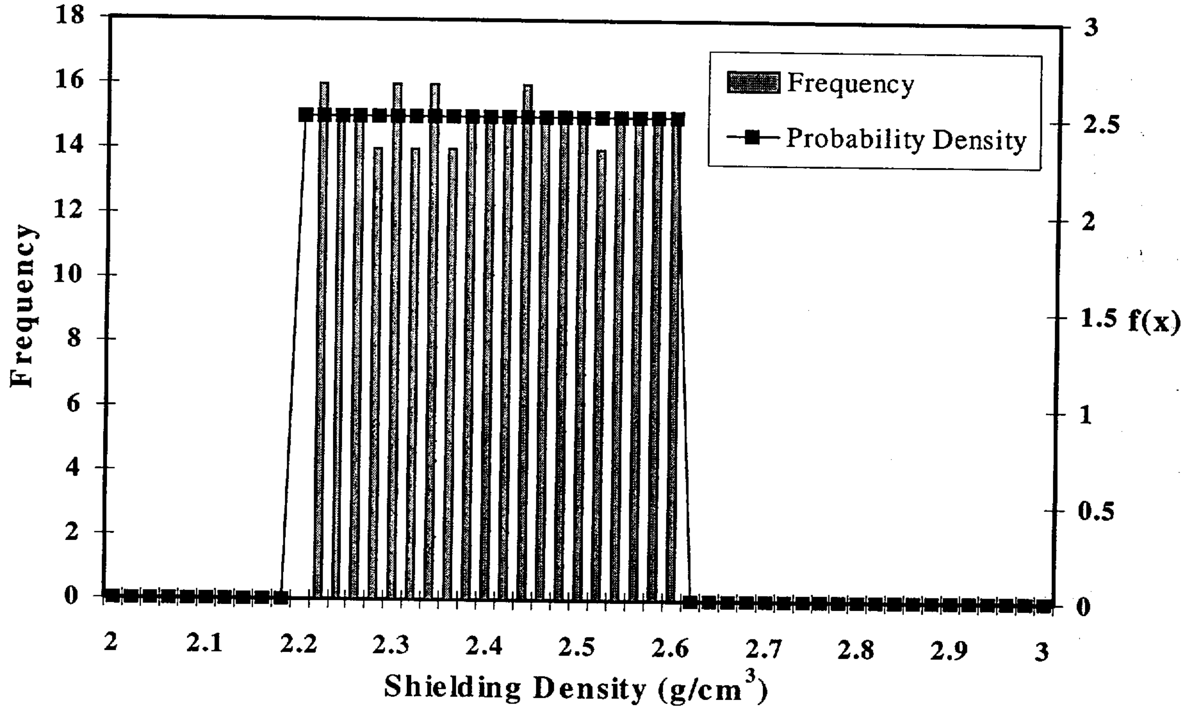

Figure B.37 Sampling Frequency and Probability Density of the Shielding Density

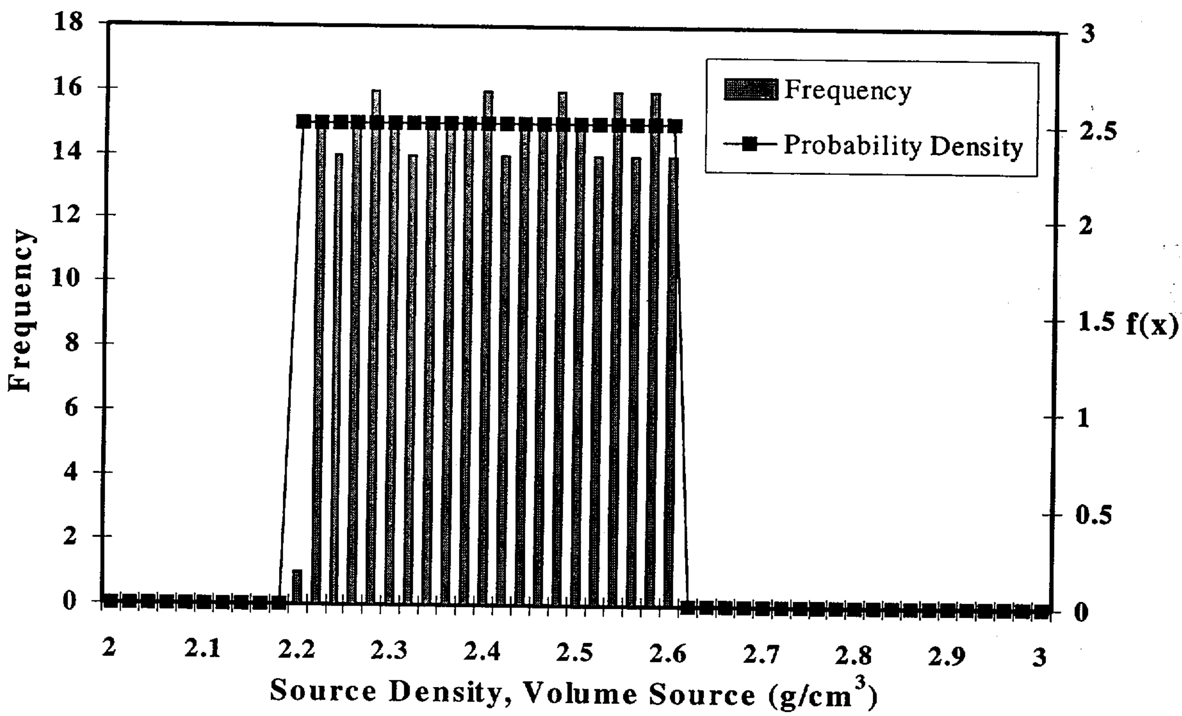

Figure B.38 Sampling Frequency and Probability Density of the Source Density, Volume Source

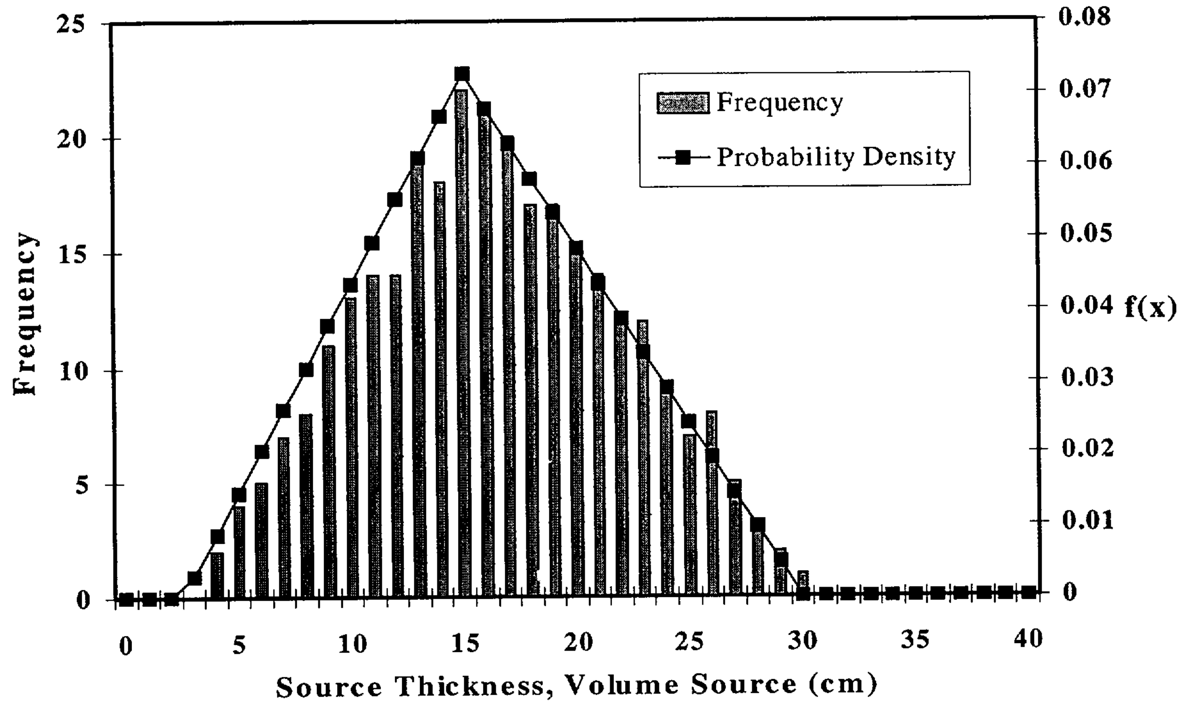

Figure B.39 Sampling Frequency and Probability Density of the Source Thickness, Volume Source

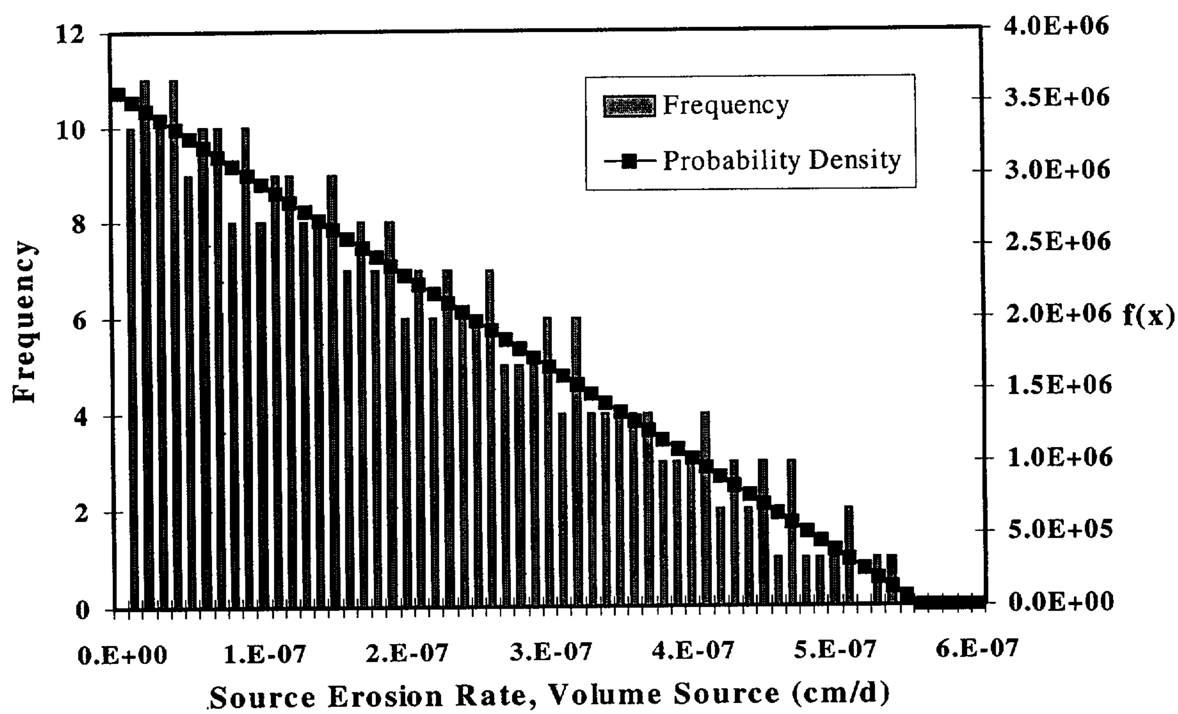

Figure B.40 Sampling Frequency and Probability Density of the Source Erosion Rate, Volume Source

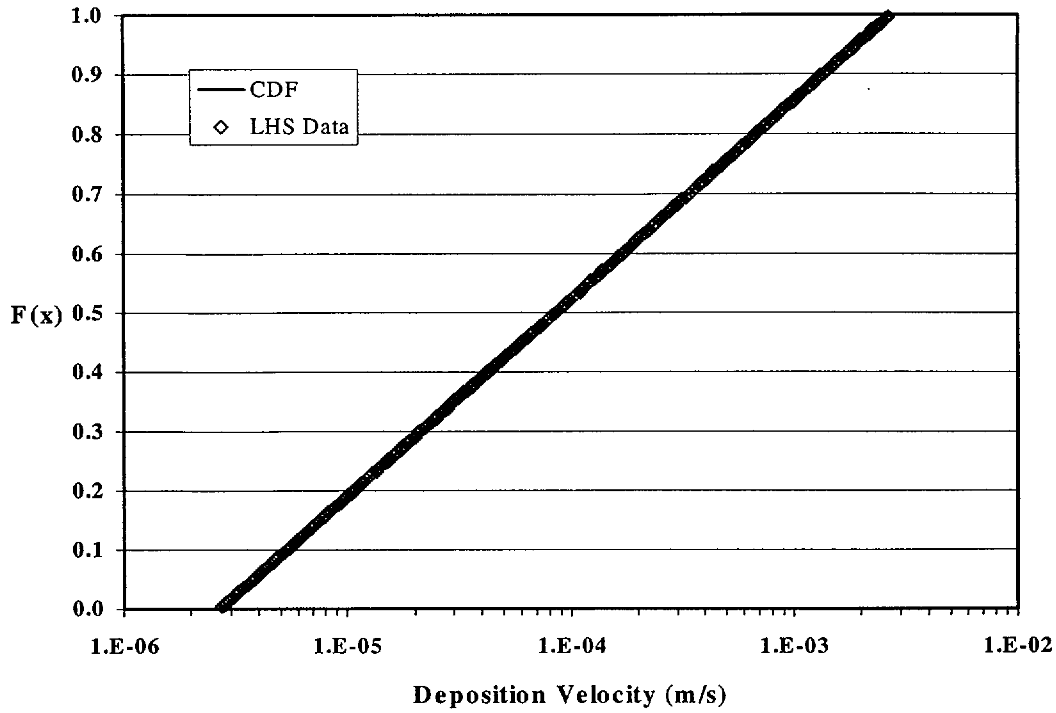

Figure B.41 Sampled Cumulative Probability and the Cumulative Distribution Function of the Deposition Velocity

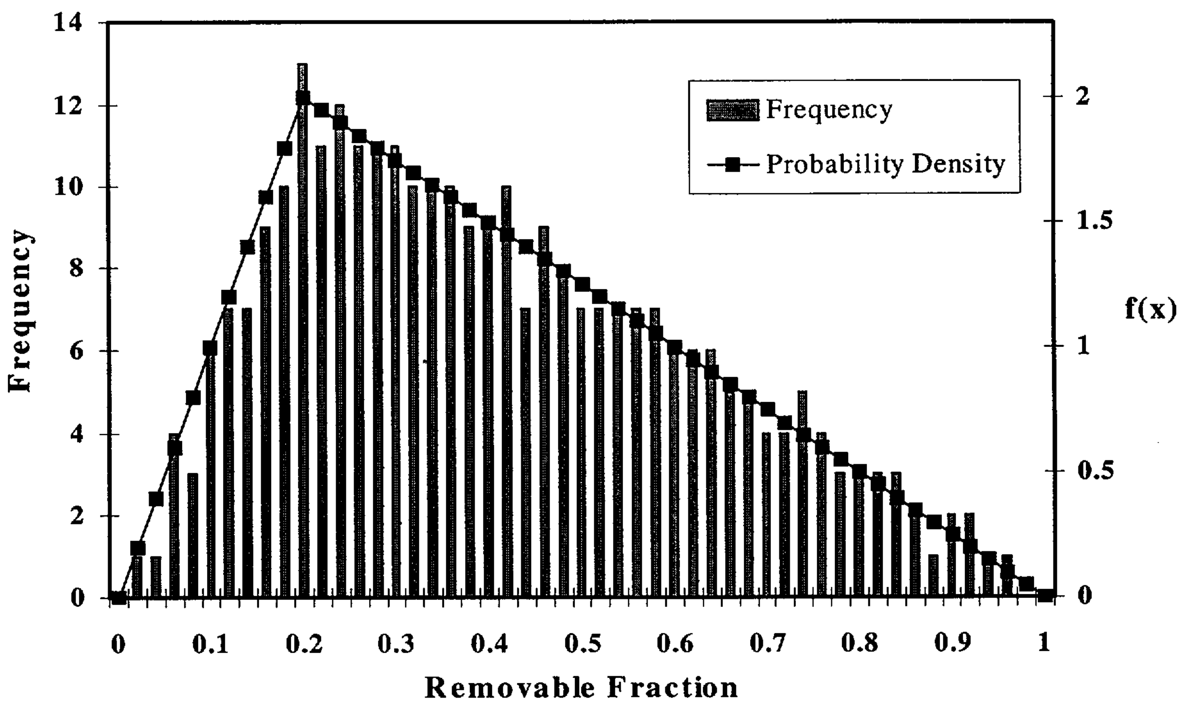

Figure B.42 Sampling Frequency and Probability Density of the Removable Fraction

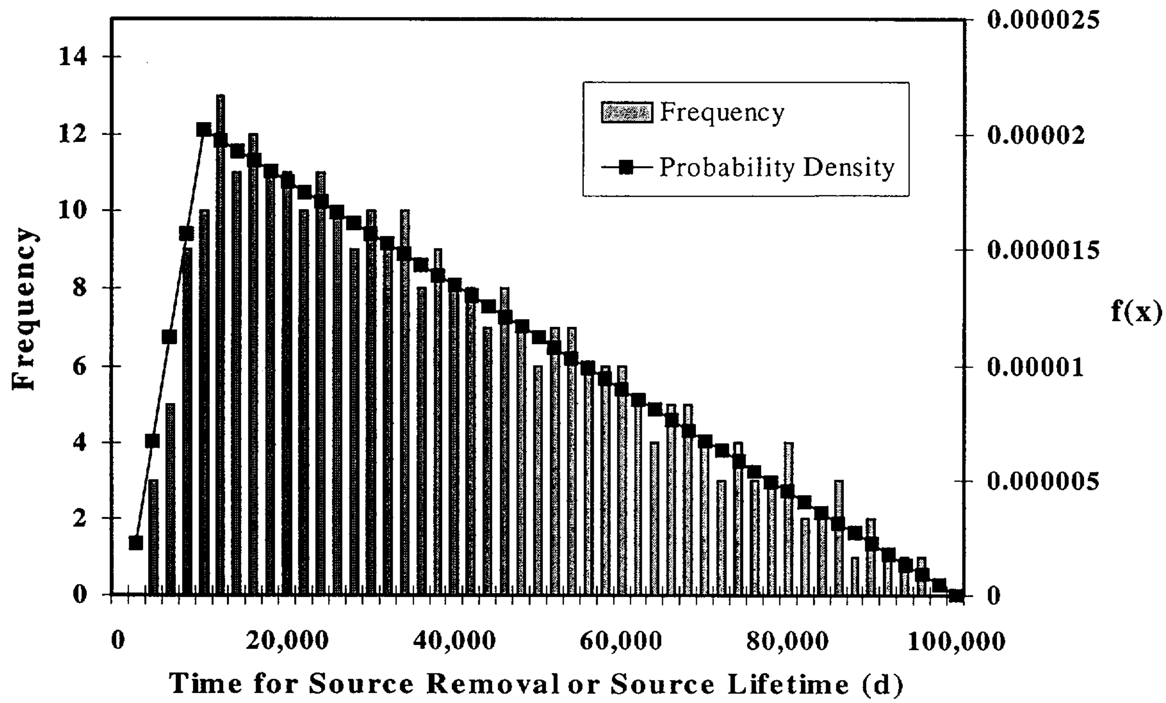

Figure B.43 Sampling Frequency and Probability Density of the Source Lifetime

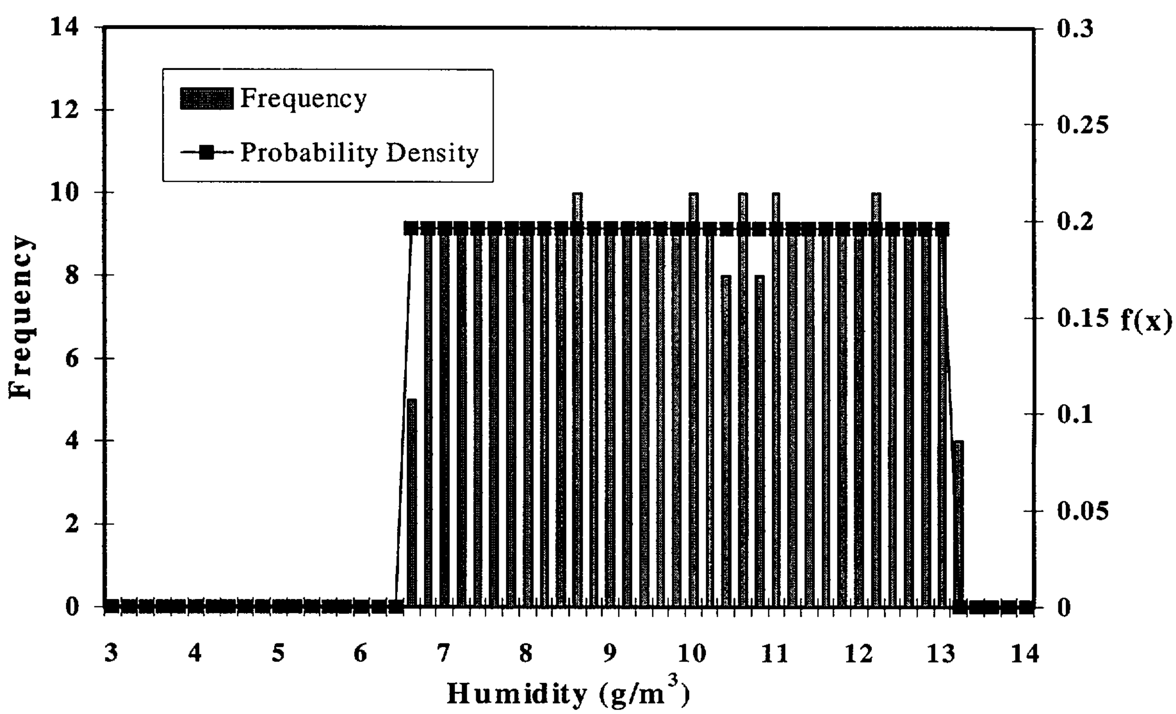

Figure B.44 Sampling Frequency and Probability Density of the Humidity

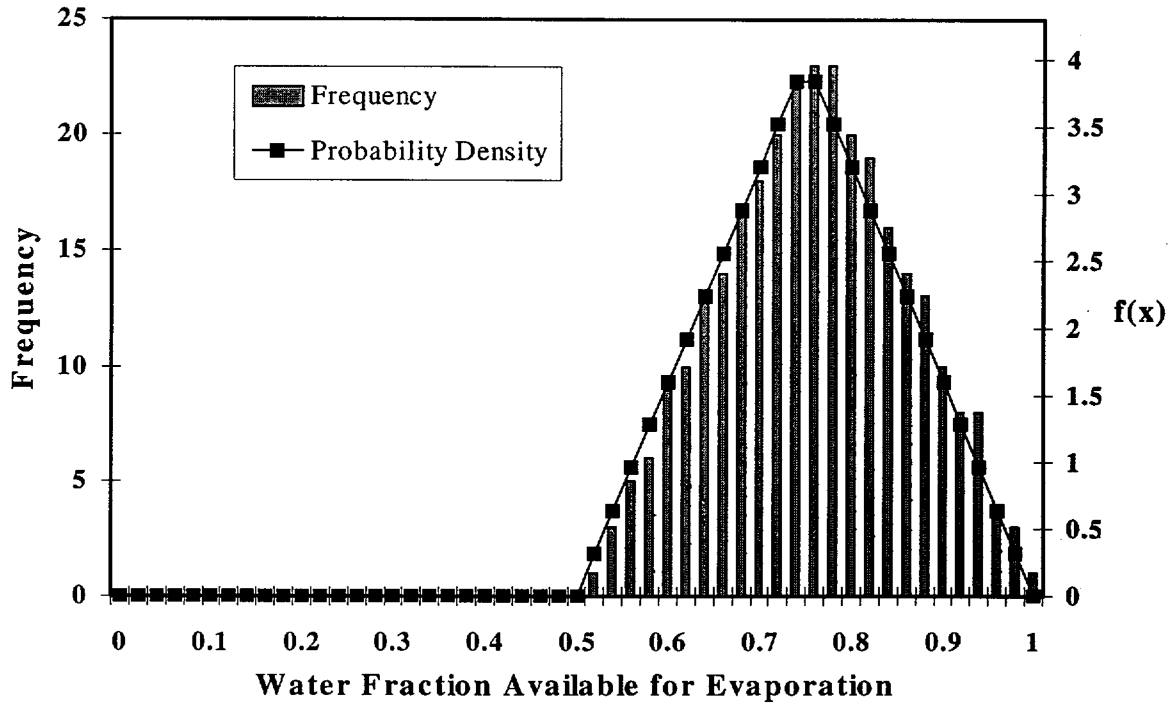

Figure B.45 Sampling Frequency and Probability Density of the Water Fraction Available for Evaporation

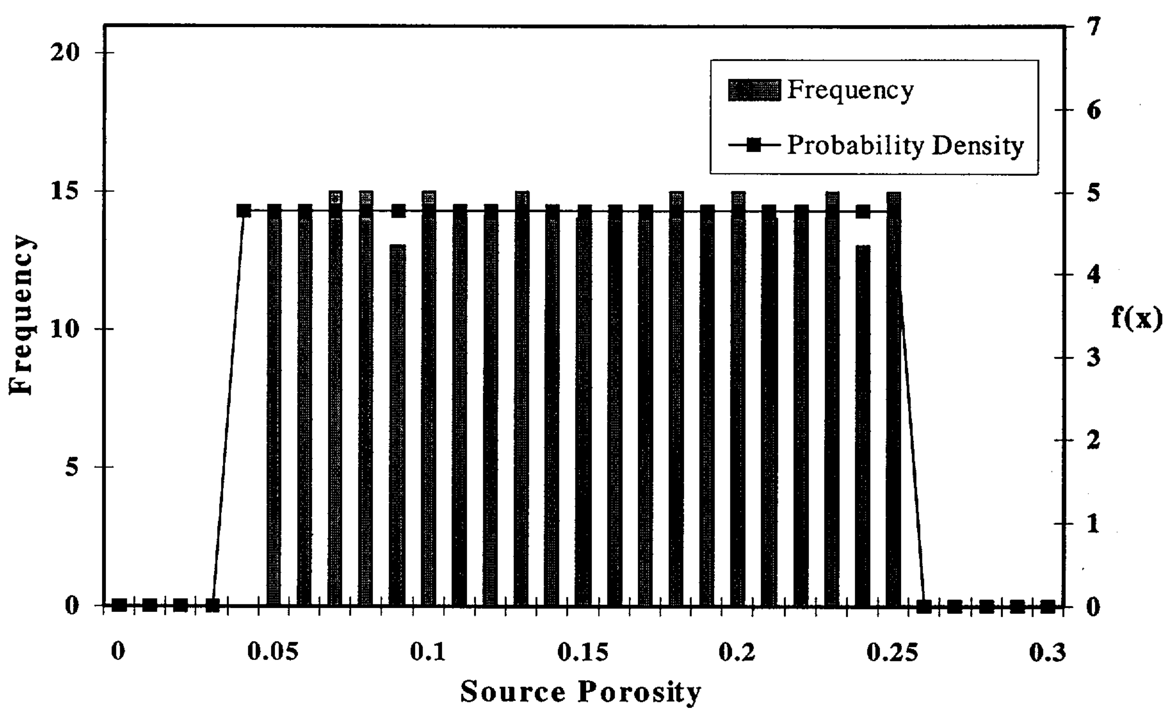

Figure B.46 Sampling Frequency and Probability Density of the Source Porosity

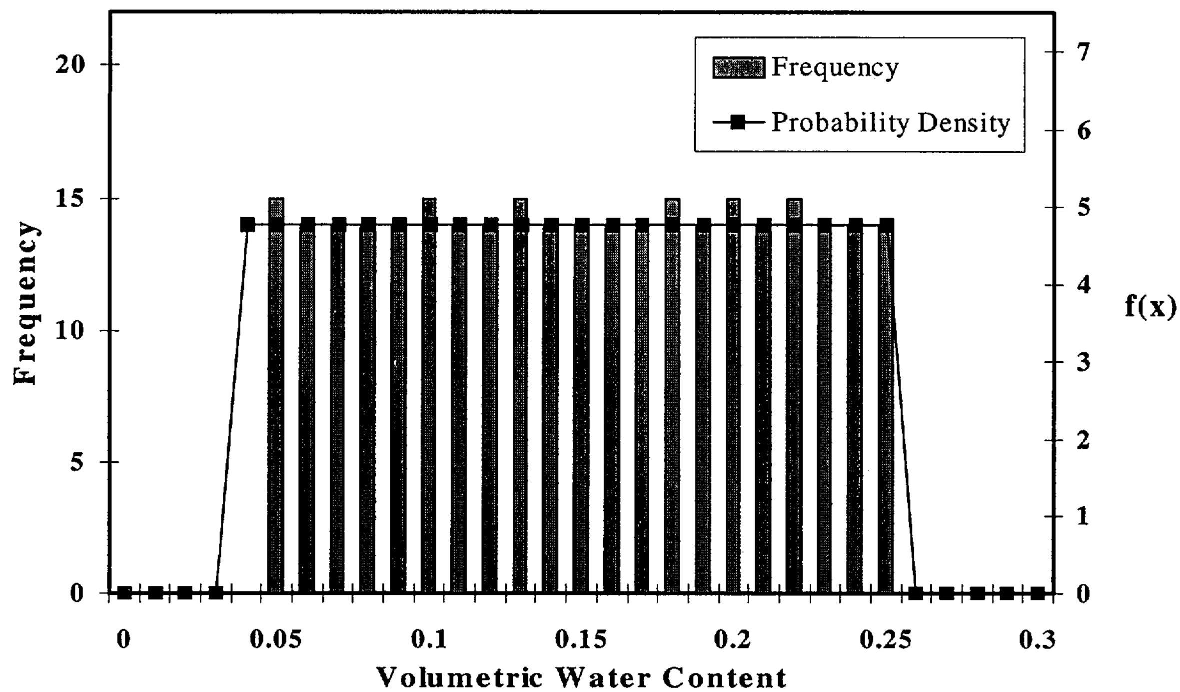

Figure B.47 Sampling Frequency and Probability Density of the Volumetric Water Content

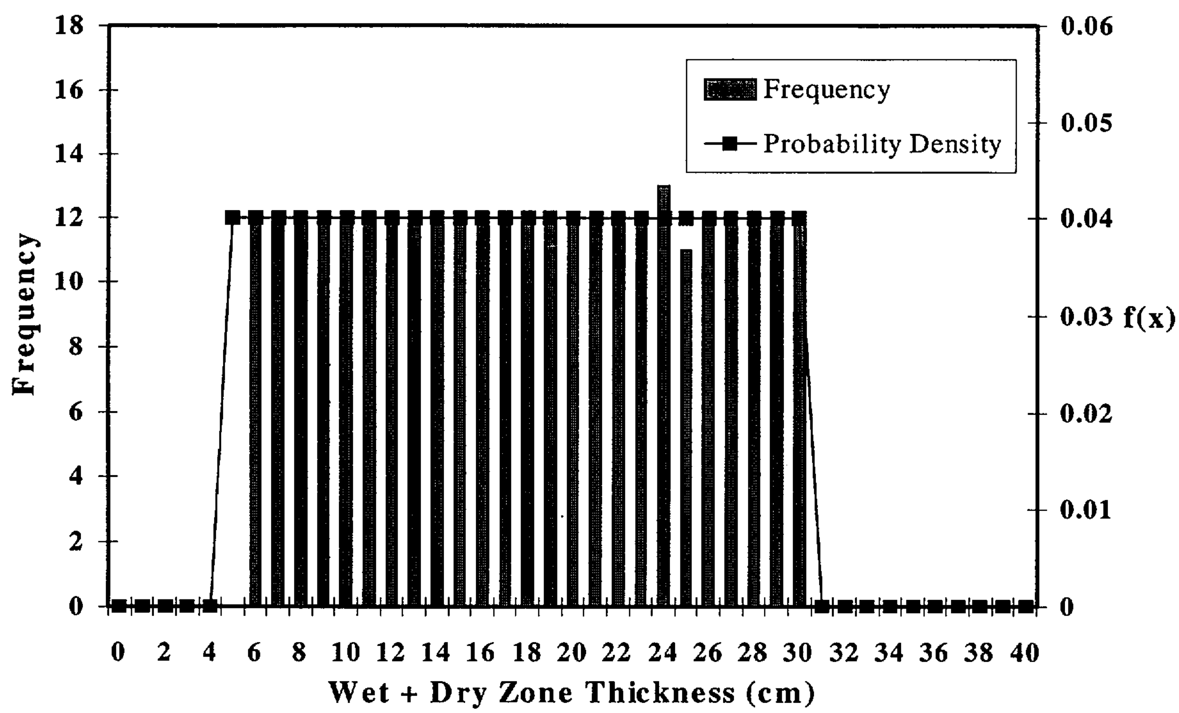

Figure B.48 Sampling Frequency and Probability Density of the Wet + Dry Zone Thickness

REFERENCES FOR APPENDIX B

Beyeler, W.E., et al. NUREG/CR-5512, SAND99-2148, Vol. 3, "Residual Radioactive Contamination from Decommissioning: Parameter Analysis," Prepared by Sandia National Laboratories, Albuquerque, N.M., for U.S. Nuclear Regulatory Commission, Washington, D.C. 1999.

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. 2000.

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. 1999.

APPENDIX C

SENSITIVITY ANALYSIS RESULTS

APPENDIX C

SENSITIVITY ANALYSIS RESULTS

This appendix contains the detailed sensitivity analysis results for both residential and building occupancy scenarios. Tables C.1 through C.3 list the sensitive parameters and most important pathways based on partial rank correlation coefficients for the three source configurations in the residential scenario.

Tables C.4 through C.9 list sensitive parameters for three source areas and most important pathways based on standardized rank regression coefficients in the building occupancy scenario for volume and area sources.

Table C.1 Four Most Sensitive Parameters Based on PRCC for a Source of 100-m^2 Area and 15-cm Thickness in the Residential Scenario

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Ac-227	ext	SHF1	0.94	DCACTC(1)	0.41	BRTF(89,1)	0.4	DM	-0.28
Ag-108	ext	SHF1	0.98	DCACTC(1)	0.42				
Ag-110	ext	SHF1	0.98	DCACTC(1)	0.4				
Al-26	ext	SHF1	0.96	DCACTC(1)	0.45				
Am-241	plant + ext	SHF1	0.82	BRTF(95,1)	0.79	DROOT	-0.69	DM	-0.62
Am-243	ext	SHF1	0.98	DROOT	-0.29				
Au-195	ext	SHF1	0.93	DCACTC(1)	0.6				
Ba-133	ext	SHF1	0.96	DCACTC(1)	0.47				
BI-207	ext	SHF1	0.9	DCACTC(1)	0.62				
C-14	plant	DROOT	-0.73	DMC	0.38	DCACTS(1)	-0.35	DCACTU1(1)	-0.33
Ca-41	plant	BRTF(20,1)	0.91	DROOT	-0.78	HCSZ	0.32		
Ca-45	plant	BRTF(20,1)	0.97	DROOT	-0.91				
Cd-109	plant	BRTF(48,1)	0.9	DROOT	-0.73	DCACTC(1)	0.55	SHF1	0.5
Ce-141	ext	SHF1	1						
Ce-144	ext	SHF1	0.99						
Cf-252	plant	BRTF(98,1)	0.87	DM	-0.78	DROOT	-0.74	MLINH	0.39
Cl-36	plant	BRTF(17,1)	0.95	DROOT	-0.82	DCACTC(1)	0.74	RUNOFF	0.28
Cm-243	ext	SHF1	0.99	BRTF(96,1)	0.45	DROOT	-0.39	DM	-0.27
Cm-244	plant	BRTF(96,1)	0.87	DM	-0.8	DROOT	-0.78	SHF3	0.4
Cm-246	plant	BRTF(96,1)	0.88	DROOT	-0.79	DM	-0.78	WIND	-0.36
Cm-247	ext	SHF1	0.99	BRTF(96,1)	0.32	VCZ	-0.31		
Cm-248	plant	BRTF(96,1)	0.89	DROOT	-0.82	DM	-0.81	MLINH	0.35
Co-57	ext	SHF1	0.98	DCACTC(1)	0.47				
Co-60	ext	SHF1	0.97	DCACTC(1)	0.46				
Cs-134	ext	SHF1	0.98	DCACTC(1)	0.37				

Table C.1 Four Most Sensitive Parameters Based on PRCC for a Source of 100-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Cs-135	plant	BRTF(55,1)	0.96	DROOT	-0.88	BRTF(55,2)	0.4	DM	-0.36
Cs-137	ext	SHF1	0.98	DCACTC(1)	0.38				
Eu-152	ext	SHF1	0.95	DCACTC(2)	0.31				
Eu-154	ext	SHF1	0.96	DCACTC(1)	0.44				
Eu-155	ext	SHF1	0.97	DCACTC(1)	0.45				
Fe-55	meat + plant	DM	-0.85	BRTF(26,2)	0.78	BRTF(26,1)	0.75	DROOT	-0.53
Fe-59	ext	SHF1	0.99	DCACTC(1)	0.4				
Gd-152	plant + inh	BRTF(64,1)	0.7	DM	-0.67	MLINH	0.59	DROOT	-0.49
Gd-153	ext	SHF1	0.97	DCACTC(1)	0.43				
Ge-68	ext	SHF1	0.9	DCACTC(1)	0.68				
H-3	water + plant	DROOT	-0.73	HCSZ	0.46	HGWT	0.43	H(1)	-0.42
I-125	ext	SHF1	0.85	BRTF(53,1)	0.69	DCACTC(1)	0.67	DROOT	-0.55
I-129	water + plant	BRTF(53,1)	0.6	DROOT	-0.45	DCACTC(1)	0.41	HCSZ	0.36
Ir-192	ext	SHF1	0.96	DCACTC(1)	0.5				
K-40	ext	SHF1	0.97	DCACTC(1)	0.6	BRTF(19,1)	0.5	RUNOFF	0.46
Mn-54	ext	SHF1	0.97	DCACTC(1)	0.47				
Na-22	ext	SHF1	0.92	DCACTC(1)	0.57				
Nb-93	ext + plant	SHF1	0.86	BRTF(41,1)	0.69	DROOT	-0.54	DCACTC(1)	0.4
Nb-94	ext	SHF1	0.94	DCACTC(1)	0.49				
Nb-95	ext	SHF1	0.99	DCACTC(1)	0.39				
Ni-59	plant	BRTF(28,1)	0.96	DROOT	-0.9	BRTF(28,3)	0.39		
Ni-63	plant	BRTF(28,1)	0.96	DROOT	-0.9	BRTF(28,3)	0.39		
Np-237	plant + ext	BRTF(93,1)	0.72	SHF1	0.68	DROOT	-0.55	DCACTC(1)	0.51
Pa-231	plant	BRTF(91,1)	0.58	DCACTC(2)	0.57	VCZ	-0.52	DROOT	-0.49
Pb-210	plant	DROOT	-0.88	BRTF(82,1)	0.82	BRTF(84,1)	0.76	DM	-0.27
Pm-147	ext + plant	SHF1	0.86	BRTF(61,1)	0.68	DROOT	-0.61	BCZ	-0.27
Po-210	plant	BRTF(84,1)	0.96	DROOT	-0.9	DM	-0.36	BRTF(84,2)	0.3
Pu-238	plant	BRTF(94,1)	0.88	DM	-0.78	DROOT	-0.77	MLINH	0.47

Table C.1 Four Most Sensitive Parameters Based on PRCC for a Source of 100-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Pu-239	plant	BRTF(94,1)	0.88	DM	-0.79	DROOT	-0.77	MLINH	0.37
Pu-240	plant	BRTF(94,1)	0.87	DM	-0.79	DROOT	-0.79	MLINH	0.41
Pu-241	plant	VCZ	-0.6	SHF1	0.59	DCACTC(1)	0.51	DROOT	-0.5
Pu-242	plant	BRTF(94,1)	0.88	DM	-0.82	DROOT	-0.77	MLINH	0.38
Pu-244	ext	SHF1	0.99	VCZ	-0.28				
Ra-226	ext	SHF1	0.98	BRTF(88,1)	0.43	DROOT	-0.42	VCZ	-0.3
Ra-228	ext	SHF1	0.96	VCZ	-0.47	DROOT	-0.31	BRTF(88,1)	0.25
Ru-106	ext	SHF1	0.98	DCACTC(1)	0.36				
S-35	plant + meat	BRTF(16,1)	0.96	DROOT	-0.85	BRTF(16,2)	0.75	DCACTC(1)	0.31
Sb-124	ext	SHF1	0.97	DCACTC(1)	0.44				
Sb-125	ext	SHF1	0.95	DCACTC(2)	0.39				
Sc-46	ext	SHF1	0.98	DCACTC(1)	0.38				
Se-75	ext	SHF1	1						
Se-79	plant	BRTF(34,1)	0.96	DROOT	-0.85	BRTF(34,2)	0.7		
Sm-147	plant	BRTF(62,1)	0.83	DROOT	-0.64	DM	-0.61	MLINH	0.41
Sm-151	plant	BRTF(62,1)	0.89	DROOT	-0.71	DM	-0.55	BRTF(62,2)	0.33
Sn-113	ext	SHF1	0.98	DCACTC(1)	0.42				
Sr-85	ext	SHF1	0.97	DCACTC(1)	0.58				
Sr-89	plant	BRTF(38,1)	0.93	DROOT	-0.83	SHF1	0.68	DCACTC(1)	0.25
Sr-90	plant	BRTF(38,1)	0.95	DROOT	-0.87	DCACTC(1)	0.35	SHF1	0.25
Ta-182	ext	SHF1	0.95	DCACTC(1)	0.5				
Tc-99	plant	BRTF(43,1)	0.9	DROOT	-0.8	DCACTC(1)	0.77	RUNOFF	0.38
Te-125	ext	SHF1	0.89	BRTF(52,1)	0.58	DCACTC(1)	0.57	DROOT	-0.4
Th-228	ext	SHF1	0.98	DCACTC(1)	0.31				
Th-229	ext	SHF1	0.98	DCACTC(1)	0.33				
Th-230	ext	VCZ	-0.9	DCACTC(4)	0.57	SHF1	0.56		
Th-232	ext	SHF1	0.83	VCZ	-0.72	DCACTC(3)	0.5		
Tl-204	plant	BRTF(81,1)	0.85	SHF1	0.67	DROOT	-0.67	DCACTC(1)	0.46

Table C.1 Four Most Sensitive Parameters Based on PRCC for a Source of 100-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
U-232	ext	SHF1	0.72	DCACTC(2)	0.72	VCZ	-0.37		
U-233	ext + plant	DCACTC(2)	0.48	VCZ	-0.46	BRTF(92,1)	0.4	DROOT	-0.35
U-234	plant	BRTF(92,1)	0.61	DROOT	-0.59	DM	-0.48	VCZ	-0.31
U-235	ext	SHF1	0.95	DCACTC(3)	0.57				
U-236	plant	BRTF(92,1)	0.65	DROOT	-0.49	DM	-0.44	MLINH	0.36
U-238	ext	SHF1	0.9	DCACTC(6)	0.48				
Zn-65	ext	SHF1	0.92	DCACTC(1)	0.52				
Zr-93	water	HCSZ	0.71	HGWT	0.66	H(1)	-0.61		
Zr-95	ext	SHF1	0.99						

[a] ext = external, fish = fish ingestion, inh = inhalation, meat = meat ingestion, plant = plant ingestion, water = water ingestion.

Table C.2 Four Most Sensitive Parameters Based on PRCC for a Source of 2,400-m^2 Area and 15-cm Thickness in the Residential Scenario

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Ac-227	plant	SHF1	0.79	BRTF(89,1)	0.76	DROOT	-0.58	DM	-0.41
Ag-108	ext	SHF1	0.98	DCACTC(1)	0.43				
Ag-110	ext	SHF1	0.98	DCACTC(1)	0.4				
Al-26	ext	SHF1	0.96	DCACTC(1)	0.46				
Am-241	plant	BRTF(95,1)	0.9	DROOT	-0.79	DM	-0.76	SHF1	0.35
Am-243	ext	SHF1	0.92	BRTF(95,1)	0.66	DROOT	-0.58	DM	-0.36
Au-195	ext	SHF1	0.92	DCACTC(1)	0.6				
Ba-133	ext	SHF1	0.96	DCACTC(1)	0.48				
BI-207	ext	SHF1	0.91	DCACTC(1)	0.62				
C-14	plant	DROOT	-0.83	DMC	0.48	WIND	-0.46	DCACTU1(1)	-0.3
Ca-41	plant	BRTF(20,1)	0.96	DROOT	-0.86	DCACTC(1)	0.25		
Ca-45	plant	BRTF(20,1)	0.97	DROOT	-0.91				
Cd-109	plant	BRTF(48,1)	0.95	DROOT	-0.84	DCACTC(1)	0.48		
Ce-141	ext	SHF1	1						
Ce-144	ext	SHF1	0.99						
Cf-252	plant	BRTF(98,1)	0.92	DROOT	-0.8	DM	-0.77		
Cl-36	plant	BRTF(17,1)	0.95	DROOT	-0.83	DCACTC(1)	0.73	BRTF(17,2)	0.38
Cm-243	ext	SHF1	0.91	BRTF(96,1)	0.72	DROOT	-0.62	DM	-0.35
Cm-244	plant	BRTF(96,1)	0.9	DROOT	-0.83	DM	-0.78		
Cm-246	plant	BRTF(96,1)	0.91	DROOT	-0.84	DM	-0.78		
Cm-247	ext	SHF1	0.95	BRTF(96,1)	0.61	DROOT	-0.53	DM	-0.27
Cm-248	plant	BRTF(96,1)	0.92	DROOT	-0.87	DM	-0.81		
Co-57	ext	SHF1	0.98	DCACTC(1)	0.48				
Co-60	ext	SHF1	0.97	DCACTC(1)	0.48				
Cs-134	ext	SHF1	0.98	DCACTC(1)	0.39	BRTF(55,1)	0.36		

Table C.2 Four Most Sensitive Parameters Based on PRCC for a Source of 2,400-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Cs-135	plant	BRTF(55,1)	0.95	DROOT	-0.85	BRTF(55,2)	0.57	DM	-0.5
Cs-137	ext	SHF1	0.97	BRTF(55,1)	0.49	DCACTC(1)	0.36	DROOT	-0.35
Eu-152	ext	SHF1	0.96	DCACTC(2)	0.32				
Eu-154	ext	SHF1	0.96	DCACTC(1)	0.44				
Eu-155	ext	SHF1	0.97	DCACTC(1)	0.45				
Fe-55	meat	DM	-0.89	BRTF(26,2)	0.86	BRTF(26,1)	0.66	DROOT	-0.39
Fe-59	ext	SHF1	0.99	DCACTC(1)	0.39				
Gd-152	plant	BRTF(64,1)	0.85	DROOT	-0.64	DM	-0.61	BRTF(64,2)	0.52
Gd-153	ext	SHF1	0.98	DCACTC(1)	0.44				
Ge-68	ext	SHF1	0.89	DCACTC(1)	0.67				
H-3	plant	DROOT	-0.88	RUNOFF	0.6	HCSZ	0.35	H(1)	-0.29
I-125	plant	BRTF(53,1)	0.88	DROOT	-0.74	DCACTC(1)	0.54	DM	-0.53
I-129	water + plant	BRTF(53,1)	0.7	DROOT	-0.51	DCACTC(1)	0.47	HCSZ	0.31
Ir-192	ext	SHF1	0.96	DCACTC(1)	0.51				
K-40	ext + plant	SHF1	0.86	BRTF(19,1)	0.82	DROOT	-0.67	DCACTC(1)	0.37
Mn-54	ext	SHF1	0.97	DCACTC(1)	0.48				
Na-22	ext	SHF1	0.92	DCACTC(1)	0.58				
Nb-93	plant	BRTF(41,1)	0.91	DROOT	-0.78	SHF1	0.56	DCACTC(1)	0.29
Nb-94	ext	SHF1	0.94	DCACTC(1)	0.5				
Nb-95	ext	SHF1	0.99	DCACTC(1)	0.39				
Ni-59	plant	BRTF(28,1)	0.95	DROOT	-0.87	BRTF(28,3)	0.6	DM	-0.36
Ni-63	plant	BRTF(28,1)	0.95	DROOT	-0.87	BRTF(28,3)	0.6	DM	-0.36
Np-237	plant	BRTF(93,1)	0.86	DROOT	-0.74	DCACTC(1)	0.39	SHF1	0.31
Pa-231	plant	BRTF(91,1)	0.89	DROOT	-0.79	VCZ	-0.39	DCACTC(2)	0.34
Pb-210	plant	DROOT	-0.88	BRTF(82,1)	0.8	BRTF(84,1)	0.75	DM	-0.33
Pm-147	plant	BRTF(61,1)	0.85	DROOT	-0.72	DM	-0.55	BRTF(61,2)	0.53
Po-210	plant	BRTF(84,1)	0.95	DROOT	-0.87	BRTF(84,2)	0.49	DM	-0.43
Pu-238	plant	BRTF(94,1)	0.91	DROOT	-0.82	DM	-0.76		

Table C.2 Four Most Sensitive Parameters Based on PRCC for a Source of 2,400-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)									
	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
Radionuclide		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Pu-239	plant	BRTF(94,1)	0.9	DROOT	-0.8	DM	-0.78		
Pu-240	plant	BRTF(94,1)	0.9	DROOT	-0.83	DM	-0.77		
Pu-241	plant	DROOT	-0.77	DM	-0.66	BRTF(94,1)	0.63	BRTF(95,1)	0.62
Pu-242	plant	BRTF(94,1)	0.92	DROOT	-0.83	DM	-0.82		
Pu-244	ext	SHF1	0.98	BRTF(94,1)	0.36	DROOT	-0.34		
Ra-226	ext + plant	SHF1	0.86	BRTF(88,1)	0.73	DROOT	-0.67	VCZ	-0.33
Ra-228	ext + plant	SHF1	0.89	BRTF(88,1)	0.71	DROOT	-0.68	VCZ	-0.32
Ru-106	ext	SHF1	0.97	BRTF(44,1)	0.4	DCACTC(1)	0.36	DROOT	-0.3
S-35	meat	BRTF(16,1)	0.95	BRTF(16,2)	0.84	DROOT	-0.84	DCACTC(1)	0.28
Sb-124	ext	SHF1	0.98	DCACTC(1)	0.44				
Sb-125	ext	SHF1	0.96	DCACTC(2)	0.41				
Sc-46	ext	SHF1	0.98	DCACTC(1)	0.38				
Se-75	ext	SHF1	0.98	BRTF(34,1)	0.62	DROOT	-0.46	BRTF(34,2)	0.31
Se-79	meat	BRTF(34,1)	0.94	DROOT	-0.81	BRTF(34,2)	0.81	DM	-0.29
Sm-147	plant	BRTF(62,1)	0.88	DROOT	-0.67	DM	-0.58	BRTF(62,2)	0.58
Sm-151	plant	BRTF(62,1)	0.88	DROOT	-0.68	BRTF(62,2)	0.59	DM	-0.56
Sn-113	ext	SHF1	0.96	BRTF(50,1)	0.47	DCACTC(1)	0.38	DROOT	-0.31
Sr-85	ext	SHF1	0.97	DCACTC(1)	0.58	RUNOFF	0.26		
Sr-89	plant	BRTF(38,1)	0.97	DROOT	-0.91				
Sr-90	plant	BRTF(38,1)	0.96	DROOT	-0.89	DCACTC(1)	0.33		
Ta-182	ext	SHF1	0.95	DCACTC(1)	0.5				
Tc-99	plant	BRTF(43,1)	0.94	DCACTC(1)	0.87	DROOT	-0.86	RUNOFF	0.44
Te-125	plant	BRTF(52,1)	0.88	DROOT	-0.73	SHF1	0.69	DCACTC(1)	0.44
Th-228	ext	SHF1	0.98	DCACTC(1)	0.32				
Th-229	ext	SHF1	0.94	BRTF(90,1)	0.63	DROOT	-0.53	DM	-0.36
Th-230	ext	VCZ	-0.89	DCACTC(4)	0.51	SHF1	0.44	DROOT	-0.33
Th-232	ext	SHF1	0.77	VCZ	-0.64	DCACTC(3)	0.47	BRTF(88,1)	0.44
Tl-204	plant	BRTF(81,1)	0.94	DROOT	-0.81	DCACTC(1)	0.45	BRTF(81,2)	0.39

Table C.2 Four Most Sensitive Parameters Based on PRCC for a Source of 2,400-m^2 Area and 15-cm Thickness in the Residential Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
U-232	ext	DCACTC(2)	0.72	SHF1	0.72	VCZ	-0.33		
U-233	plant	BRTF(92,1)	0.67	DROOT	-0.58	DM	-0.45	DCACTC(2)	0.29
U-234	plant	BRTF(92,1)	0.79	DROOT	-0.73	DM	-0.53		
U-235	ext	SHF1	0.94	DCACTC(3)	0.59	BRTF(92,1)	0.31		
U-236	plant	BRTF(92,1)	0.76	DROOT	-0.63	DM	-0.45	DCACTC(4)	0.28
U-238	ext + plant	SHF1	0.81	BRTF(92,1)	0.52	DROOT	-0.4	DCACTC(6)	0.38
Zn-65	ext	SHF1	0.87	BRTF(30,1)	0.52	DCACTC(1)	0.48	DROOT	-0.42
Zr-93	water	HCSZ	0.71	HGWT	0.64	H(1)	-0.64	VCZ	-0.25
Zr-95	ext	SHF1	0.99						

[a] ext = external, fish = fish ingestion, inh = inhalation, meat = meat ingestion, plant = plant ingestion, water = water ingestion.

Table C.3 Four Most Sensitive Parameters Based on PRCC for a Source of 10,000-m^2 Area and 2-m Thickness in the Residential Scenario

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Ac-227	plant	BRTF(89,1)	0.99	SHF1	0.77	DROOT	-0.75		
Ag-108	ext	SHF1	1	DCACTC(1)	0.25				
Ag-110	ext	SHF1	1						
Al-26	ext	SHF1	1	DCACTC(1)	0.3				
Am-241	plant	BRTF(95,1)	0.99	DROOT	-0.88				
Am-243	plant	BRTF(95,1)	0.96	SHF1	0.79	DROOT	-0.61		
Au-195	ext + plant	SHF1	0.92	BRTF(79,1)	0.85	DROOT	-0.28		
Ba-133	ext	SHF1	1	BRTF(56,1)	0.38	DCACTC(1)	0.32		
BI-207	ext	SHF1	0.99	BRTF(83,1)	0.57	DCACTC(1)	0.38		
C-14	plant	WIND	-0.71	DROOT	-0.69	DMC	0.35	DCACTS(1)	-0.25
Ca-41	plant	BRTF(20,1)	0.97	DROOT	-0.61	BBIO(20,1)	0.29	HCSZ	0.28
Ca-45	plant	BRTF(20,1)	0.99	DROOT	-0.86	BRTF(20,3)	0.29		
Cd-109	plant	BRTF(48,1)	0.99	DROOT	-0.83	BRTF(48,3)	0.4		
Ce-141	ext	SHF1	1	BRTF(58,1)	0.6				
Ce-144	ext	SHF1	0.99	BRTF(58,1)	0.75				
Cf-252	plant	BRTF(98,1)	0.99	DROOT	-0.9				
Cl-36	meat	BRTF(17,1)	0.99	BRTF(17,2)	0.78	DROOT	-0.71	BRTF(17,3)	0.42
Cm-243	plant	BRTF(96,1)	0.97	SHF1	0.8	DROOT	-0.71	BRTF(95,3)	-0.18
Cm-244	plant	BRTF(96,1)	0.99	DROOT	-0.88				
Cm-246	plant	BRTF(96,1)	0.99	DROOT	-0.89				
Cm-247	plant	BRTF(96,1)	0.93	SHF1	0.87	DROOT	-0.58		
Cm-248	plant	BRTF(96,1)	0.99	DROOT	-0.89				
Co-57	ext	SHF1	0.96	BRTF(27,1)	0.77	BRTF(27,2)	0.5	DROOT	-0.25
Co-60	ext	SHF1	0.97	BRTF(27,1)	0.74	BRTF(27,2)	0.47		

Table C.3 Four Most Sensitive Parameters Based on PRCC for a Source of 10,000-m^2 Area and 2-m Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Cs-134	ext	SHF1	0.92	BRTF(55,1)	0.87	DROOT	-0.35	BRTF(55,2)	0.3
Cs-135	meat	BRTF(55,1)	0.99	BRTF(55,2)	0.8	DROOT	-0.77	BRTF(55,3)	0.37
Cs-137	plant + ext	BRTF(55,1)	0.91	SHF1	0.88	DROOT	-0.44	BRTF(55,2)	0.38
Eu-152	ext	SHF1	1	DCACTC(2)	0.33				
Eu-154	ext	SHF1	1	DCACTC(1)	0.26				
Eu-155	ext	SHF1	1	BRTF(63,1)	0.43	DCACTC(1)	0.26		
Fe-55	meat	BRTF(26,2)	0.93	BRTF(26,1)	0.88	DROOT	-0.34		
Fe-59	ext	SHF1	1						
Gd-152	plant	BRTF(64,1)	0.97	BRTF(64,2)	0.74	DROOT	-0.54		
Gd-153	ext	SHF1	1	BRTF(64,1)	0.33	DCACTC(1)	0.27		
Ge-68	ext + meat	SHF1	0.88	BRTF(32,1)	0.8	BRTF(32,2)	0.66	DROOT	-0.26
H-3	plant	DROOT	-0.87	RUNOFF	0.67	HCCZ	0.57	DCACTC(1)	-0.57
I-125	plant + meat	BRTF(53,1)	0.98	BRTF(53,2)	0.8	DROOT	-0.75	BRTF(53,3)	0.47
I-129	meat + water	BRTF(53,1)	0.85	BRTF(53,2)	0.4	DROOT	-0.38	HCSZ	0.34
Ir-192	ext	SHF1	1	BRTF(77,1)	0.61	DCACTC(1)	0.26		
K-40	plant	BRTF(19,1)	0.98	DROOT	-0.67	SHF1	0.62	BRTF(19,3)	0.25
Mn-54	ext	SHF1	0.99	BRTF(25,1)	0.77	DROOT	-0.27		
Na-22	ext	SHF1	0.98	BRTF(11,1)	0.74	DCACTC(1)	0.28		
Nb-93	plant	BRTF(41,1)	0.99	DROOT	-0.86	SHF1	0.32		
Nb-94	ext	SHF1	1	DCACTC(1)	0.33				
Nb-95	ext	SHF1	1	BRTF(41,1)	0.31	DCACTC(1)	0.28		
Ni-59	plant	BRTF(28,1)	0.97	BRTF(28,3)	0.8	DROOT	-0.69	BRTF(28,2)	0.36
Ni-63	plant	BRTF(28,1)	0.97	BRTF(28,3)	0.8	DROOT	-0.69	BRTF(28,2)	0.36
Np-237	plant	BRTF(93,1)	0.92	DROOT	-0.46	HCSZ	0.31		
Pa-231	plant	BRTF(91,1)	0.96	DROOT	-0.66	BRTF(89,1)	0.53		
Pb-210	plant	BRTF(82,1)	0.88	BRTF(84,1)	0.85	DROOT	-0.67	BRTF(84,2)	0.26
Pm-147	plant	BRTF(61,1)	0.96	BRTF(61,2)	0.75	DROOT	-0.58		
Po-210	plant	BRTF(84,1)	0.99	DROOT	-0.8	BRTF(84,2)	0.68		

Table C.3 Four Most Sensitive Parameters Based on PRCC for a Source of 10,000-m^2 Area and 2-m Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Pu-238	plant	BRTF(94,1)	0.99	DROOT	-0.88				
Pu-239	plant	BRTF(94,1)	0.99	DROOT	-0.89				
Pu-240	plant	BRTF(94,1)	0.99	DROOT	-0.88				
Pu-241	plant	BRTF(95,1)	0.85	BRTF(94,1)	0.69	DROOT	-0.56		
Pu-242	plant	BRTF(94,1)	0.99	DROOT	-0.87				
Pu-244	ext	SHF1	0.97	BRTF(94,1)	0.85	DROOT	-0.42		
Ra-226	plant	BRTF(88,1)	0.89	DROOT	-0.67	BRTF(82,1)	0.61	BRTF(84,1)	0.6
Ra-228	plant	BRTF(88,1)	0.97	DROOT	-0.74	SHF1	0.74		
Ru-106	ext + plant	SHF1	0.94	BRTF(44,1)	0.86	DROOT	-0.38		
S-35	meat	BRTF(16,1)	0.97	BRTF(16,2)	0.93	DROOT	-0.57		
Sb-124	ext	SHF1	1	BRTF(51,1)	0.32	DCACTC(1)	0.31		
Sb-125	ext	SHF1	1	BRTF(52,1)	0.45	DCACTC(2)	0.29		
Sc-46	ext	SHF1	1						
Se-75	meat	BRTF(34,1)	0.9	SHF1	0.8	BRTF(34,2)	0.72	DROOT	-0.35
Se-79	meat	BRTF(34,1)	0.97	BRTF(34,2)	0.91	DROOT	-0.58	BRTF(34,3)	0.33
Sm-147	plant	BRTF(62,1)	0.97	BRTF(62,2)	0.75	DROOT	-0.53		
Sm-151	plant	BRTF(62,1)	0.97	BRTF(62,2)	0.76	DROOT	-0.54		
Sn-113	ext + plant	SHF1	0.89	BRTF(50,1)	0.88	DROOT	-0.33	BRTF(50,2)	0.28
Sr-85	ext	SHF1	0.97	BRTF(38,1)	0.8	DROOT	-0.28		
Sr-89	plant	BRTF(38,1)	0.99	DROOT	-0.84	BRTF(38,2)	0.43		
Sr-90	plant	BRTF(38,1)	0.99	DROOT	-0.84	BRTF(38,2)	0.43		
Ta-182	ext	SHF1	1	DCACTC(1)	0.34				
Tc-99	plant	BRTF(43,1)	0.99	DROOT	-0.84	DCACTC(1)	0.4	EVAPTR	0.25
Te-125	plant	BRTF(52,1)	0.99	DROOT	-0.78	BRTF(52,2)	0.65	SHF1	0.37
Th-228	ext	SHF1	1	BRTF(90,1)	0.7				
Th-229	plant	BRTF(90,1)	0.95	SHF1	0.86	DROOT	-0.57		
Th-230	plant	VCZ	-0.79	DROOT	-0.53	DCACTC(4)	0.49	BRTF(88,1)	0.47
Th-232	plant	BRTF(88,1)	0.93	SHF1	0.66	DROOT	-0.6	BRTF(90,1)	0.26

Table C.3 Four Most Sensitive Parameters Based on PRCC for a Source of 10,000-m^2 Area and 2-m Thickness in the Residential Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	PRCC	Parameter	PRCC	Parameter	PRCC	Parameter	PRCC
Tl-204	plant + meat	BRTF(81,1)	0.98	BRTF(81,2)	0.82	DROOT	-0.67		
U-232	ext	SHF1	0.92	DCACTC(2)	0.54	BRTF(92,1)	0.48	DROOT	-0.32
U-233	plant	BRTF(92,1)	0.78	DROOT	-0.4	DCACTC(2)	0.38	VCZ	-0.32
U-234	water + plant	BRTF(92,1)	0.91	DROOT	-0.58	DCACTU1(5)	-0.29		
U-235	plant	SHF1	0.73	BRTF(92,1)	0.65	BRTF(91,1)	0.46	DCACTC(3)	0.42
U-236	plant	BRTF(92,1)	0.93	DROOT	-0.5				
U-238	plant	BRTF(92,1)	0.92	SHF1	0.65	DROOT	-0.43		
Zn-65	meat	BRTF(30,1)	0.97	SHF1	0.75	DROOT	-0.64	BRTF(30,2)	0.63
Zr-93	water	H(1)	-0.74	HCSZ	0.7	HGWT	0.63	FR9	0.47
Zr-95	ext	SHF1	1						

[a] ext = external, fish = fish ingestion, meat = meat ingestion, plant = plant ingestion, water = water ingestion.

Table C.4 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Volume Source in the Building Occupancy Scenario									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	ext	DSTH	-0.94	EROS0	0.14	AREA	-0.14		
Ag-108	ext	DSTH	-0.99						
Ag-110	ext	DSTH	-0.99						
Al-26	ext	DSTH	-0.98	THICK0	0.1				
Am-241	inh + ext	EROS0	0.5	DSTH	-0.48	AREA	-0.45	H	-0.16
Am-243	ext	DSTH	-0.97						
Au-195	ext	DSTH	-1						
Bl-207	ext	DSTH	-0.99						
C-14	ext	DSTH	-0.72	EROS0	0.26	DKSUS	-0.25	UD	0.21
Ca-41	inh + ing	EROS0	0.54	AREA	-0.47	DKSUS	-0.42	UD	0.29
Cd-109	ext	DSTH	-0.99						
Ce-144	ext	DSTH	-0.99						
Cf-252	inh	EROS0	0.69	AREA	-0.61	H	-0.19		
Cl-36	ext	DSTH	-1						
Cm-243	ext	DSTH	-0.98						
Cm-244	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Cm-248	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Co-57	ext	DSTH	-1						
Co-60	ext	DSTH	-0.98	THICK0	0.1				
Cs-134	ext	DSTH	-0.99						
Cs-135	ext	DSTH	-0.79	DKSUS	-0.23	EROS0	0.2	UD	0.18
Cs-137	ext	DSTH	-0.99						
Eu-152	ext	DSTH	-0.99						
Eu-154	ext	DSTH	-0.99						

Table C.4 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Volume Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Eu-155	ext	DSTH	-1						
Fe-55	inh	EROS0	0.67	AREA	-0.61	H	-0.18	UD	0.11
Gd-152	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Gd-153	ext	DSTH	-1						
Ge-68	ext	DSTH	-0.99						
H-3	inh + ing	AREA	-0.71	DKSUS	-0.33	UD	0.25	H	-0.22
I-129	ext	DSTH	-0.49	EROS0	0.37	DKSUS	-0.35	UD	0.29
K-40	ext	DSTH	-0.98	THICK0	0.1				
Mn-54	ext	DSTH	-0.99						
Na-22	ext	DSTH	-0.99						
Nb-94	ext	DSTH	-0.99						
Ni-59	inh	EROS0	0.63	AREA	-0.57	DKSUS	-0.22	H	-0.18
Ni-63	inh	EROS0	0.64	AREA	-0.58	DKSUS	-0.2	H	-0.18
Np-237	ext	DSTH	-0.99						
Pa-231	ext	DSTH	-0.9	AREA	-0.2	EROS0	0.2		
Pb-210	ext	DSTH	-0.74	EROS0	0.29	AREA	-0.28	DKSUS	-0.18
Pm-147	ext	DSTH	-0.91	EROS0	0.18	AREA	-0.16		
Pu-238	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Pu-239	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-240	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-241	inh	EROS0	0.66	AREA	-0.6	H	-0.18	DSTH	-0.17
Pu-242	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-244	ext	DSTH	-0.99						
Ra-226	ext	DSTH	-0.99						
Ra-228	ext	DSTH	-0.99						
Ru-106	ext	DSTH	-0.99						
Sb-125	ext	DSTH	-0.99						
Sm-147	inh	EROS0	0.68	AREA	-0.62	H	-0.19		

Table C.4 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Volume Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Sm-151	inh	EROS0	0.67	AREA	-0.61	H	-0.2		
Sr-90	ext	DSTH	-0.27	UD	-0.14	DSDEN	-0.13		
Tc-99	ext	DSTH	-0.95	EROS0	0.1				
Th-228	ext	DSTH	-0.98	THICK0	0.11				
Th-229	ext	DSTH	-0.97						
Th-230	inh	AREA	-0.55	EROS0	0.55	DSTH	-0.43	H	-0.17
Th-232	ext	DSTH	-0.95	AREA	-0.12	EROS0	0.12		
Tl-204	ext	DSTH	-0.99						
U-232	ext	DSTH	-0.98	THICK0	0.11				
U-233	inh	EROS0	0.56	AREA	-0.55	DSTH	-0.4	H	-0.17
U-234	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
U-235	ext	DSTH	-0.99						
U-236	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-238	ext	DSTH	-0.98						
Zn-65	ext	DSTH	-0.99						

[a] ext = external, ing = ingestion, inh = inhalation.

Table C.5 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Volume Source in the Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	ext	DSTH	-0.8	AREA	-0.31	EROS0	0.31		
Ag-108	ext	DSTH	-0.99						
Ag-110	ext	DSTH	-0.99						
Al-26	ext	DSTH	-0.99						
Am-241	inh	EROS0	0.62	AREA	-0.56	DSTH	-0.24	H	-0.19
Am-243	ext	DSTH	-0.9	EROS0	0.19	AREA	-0.18		
Au-195	ext	DSTH	-1						
Bi-207	ext	DSTH	-0.99						
C-14	ext	DSTH	-0.57	EROS0	0.34	DKSUS	-0.32	AREA	-0.28
Ca-41	inh + ing	EROS0	0.54	AREA	-0.47	DKSUS	-0.42	UD	0.29
Cd-109	ext	DSTH	-0.97						
Ce-144	ext	DSTH	-0.99						
Cf-252	inh	EROS0	0.68	AREA	-0.62	H	-0.18		
Cl-36	ext	DSTH	-0.99						
Cm-243	ext	DSTH	-0.93	EROS0	0.16	AREA	-0.16		
Cm-244	inh	EROS0	0.68	AREA	-0.62	H	-0.18		
Cm-248	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Co-57	ext	DSTH	-1						
Co-60	ext	DSTH	-0.99						
Cs-134	ext	DSTH	-0.99						
Cs-135	ext	DSTH	-0.65	DKSUS	-0.32	EROS0	0.28	UD	0.26
Cs-137	ext	DSTH	-0.99						
Eu-152	ext	DSTH	-0.99						
Eu-154	ext	DSTH	-0.99						

Table C.5 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Volume Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Eu-155	ext	DSTH	-1						
Fe-55	inh	EROS0	0.67	AREA	-0.61	H	-0.18	UD	0.11
Gd-152	inh	EROS0	0.68	AREA	-0.62	H	-0.19	DENSI0	0.03
Gd-153	ext	DSTH	-1						
Ge-68	ext	DSTH	-0.99						
H-3	inh + ing	AREA	-0.71	DKSUS	-0.33	UD	0.25	H	-0.22
I-129	ext	EROS0	0.41	DSTH	-0.39	DKSUS	-0.39	AREA	-0.33
K-40	ext	DSTH	-0.99						
Mn-54	ext	DSTH	-0.99						
Na-22	ext	DSTH	-0.99						
Nb-94	ext	DSTH	-0.99						
Ni-59	inh	EROS0	0.63	AREA	-0.57	DKSUS	-0.22	H	-0.18
Ni-63	inh	EROS0	0.64	AREA	-0.58	DKSUS	-0.2	H	-0.18
Np-237	ext	DSTH	-0.94	AREA	-0.14	EROS0	0.13		
Pa-231	ext	DSTH	-0.68	AREA	-0.4	EROS0	0.39	H	-0.12
Pb-210	ext	DSTH	-0.47	EROS0	0.46	AREA	-0.43	DKSUS	-0.24
Pm-147	ext	DSTH	-0.8	EROS0	0.29	AREA	-0.26		
Pu-238	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Pu-239	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-240	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-241	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Pu-242	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-244	ext	DSTH	-0.99						
Ra-226	ext	DSTH	-0.99						
Ra-228	ext	DSTH	-0.99						
Ru-106	ext	DSTH	-0.99						
Sb-125	ext	DSTH	-0.99						
Sm-147	inh	EROS0	0.68	AREA	-0.62	H	-0.19		

Table C.5 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Volume Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Sm-151	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Sr-90	ext	DSTH	-0.3	AREA	-0.14	DSDEN	-0.13	UD	-0.12
Tc-99	ext	DSTH	-0.88	EROS0	0.17	AREA	-0.15	DKSUS	-0.11
Th-228	ext	DSTH	-0.99						
Th-229	ext	DSTH	-0.89	AREA	-0.21	EROS0	0.21		
Th-230	inh	EROS0	0.67	AREA	-0.61	H	-0.19	DSTH	-0.13
Th-232	ext	DSTH	-0.81	AREA	-0.31	EROS0	0.29		
Tl-204	ext	DSTH	-0.99						
U-232	ext	DSTH	-0.97						
U-233	inh	EROS0	0.67	AREA	-0.61	H	-0.19	DSTH	-0.12
U-234	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-235	ext	DSTH	-0.97	AREA	-0.1				
U-236	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-238	ext	DSTH	-0.94	AREA	-0.15	EROS0	0.14		
Zn-65	ext	DSTH	-0.99						

[a] ext = external, ing = ingestion, inh = inhalation.

Table C.6 First Four Most Sensitive Parameters Based on SRRC for a 900-m^2 Volume Source in the Building Occupancy Scenario									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	ext+inh	DSTH	-0.51	EROS0	0.51	AREA	-0.51	H	-0.15
Ag-108	ext	DSTH	-0.99						
Ag-110	ext	DSTH	-0.99						
Al-26	ext	DSTH	-0.99						
Am-241	inh	EROS0	0.67	AREA	-0.61	H	-0.19		
Am-243	ext	DSTH	-0.76	EROS0	0.33	AREA	-0.32		
Au-195	ext	DSTH	-0.99						
Bi-207	ext	DSTH	-0.99						
C-14	ext	DSTH	-0.42	EROS0	0.41	DKSUS	-0.38	AREA	-0.35
Ca-41	inh + ing	EROS0	0.54	AREA	-0.47	DKSUS	-0.42	UD	0.29
Cd-109	ext	DSTH	-0.94	EROS0	0.14	AREA	-0.13		
Ce-144	ext	DSTH	-0.99						
Cf-252	inh	EROS0	0.68	AREA	-0.62	H	-0.18		
Cl-36	ext	DSTH	-0.98						
Cm-243	ext	DSTH	-0.8	EROS0	0.31	AREA	-0.3		
Cm-244	inh	EROS0	0.68	AREA	-0.62	H	-0.18		
Cm-248	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Co-57	ext	DSTH	-1						
Co-60	ext	DSTH	-0.99						
Cs-134	ext	DSTH	-0.99						
Cs-135	ext	DSTH	-0.51	DKSUS	-0.38	EROS0	0.35	UD	0.31
Cs-137	ext	DSTH	-0.99						
Eu-152	ext	DSTH	-0.99						
Eu-154	ext	DSTH	-0.99						

Table C.6 First Four Most Sensitive Parameters Based on SRRC for a 900-m^2 Volume Source in the Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Eu-155	ext	DSTH	-0.99						
Fe-55	inh	EROS0	0.67	AREA	-0.61	H	-0.18	UD	0.11
Gd-152	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Gd-153	ext	DSTH	-0.99						
Ge-68	ext	DSTH	-0.99						
H-3	inh + ing	AREA	-0.71	DKSUS	-0.33	UD	0.25	H	-0.22
I-129	inh + ing	EROS0	0.45	DKSUS	-0.42	AREA	-0.36	UD	0.32
K-40	ext	DSTH	-0.99						
Mn-54	ext	DSTH	-0.99						
Na-22	ext	DSTH	-0.99						
Nb-94	ext	DSTH	-0.99						
Ni-59	inh	EROS0	0.63	AREA	-0.57	DKSUS	-0.22	H	-0.18
Ni-63	inh	EROS0	0.64	AREA	-0.58	DKSUS	-0.2	H	-0.18
Np-237	ext	DSTH	-0.83	AREA	-0.27	EROS0	0.27		
Pa-231	inh	EROS0	0.58	AREA	-0.57	DSTH	-0.34	H	-0.18
Pb-210	inh	EROS0	0.58	AREA	-0.52	DKSUS	-0.26	UD	0.24
Pm-147	ext	DSTH	-0.62	EROS0	0.43	AREA	-0.4	H	-0.12
Pu-238	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Pu-239	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-240	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-241	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Pu-242	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Pu-244	ext	DSTH	-0.98						
Ra-226	ext	DSTH	-0.99						
Ra-228	ext	DSTH	-0.99						
Ru-106	ext	DSTH	-0.99						
Sb-125	ext	DSTH	-0.99						
Sm-147	inh	EROS0	0.68	AREA	-0.62	H	-0.19		

Table C.6 First Four Most Sensitive Parameters Based on SRRC for a 900-m² Volume Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Sm-151	inh	EROS0	0.67	AREA	-0.62	H	-0.19		
Sr-90	ext	DSTH	-0.32	AREA	-0.24	EROS0	0.19	DSDEN	-0.13
Tc-99	ext	DSTH	-0.77	EROS0	0.26	AREA	-0.23	DKSUS	-0.17
Th-228	ext	DSTH	-0.98						
Th-229	ext	DSTH	-0.69	AREA	-0.4	EROS0	0.39	H	-0.11
Th-230	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
Th-232	inh + ext	AREA	-0.52	EROS0	0.51	DSTH	-0.5	H	-0.16
Tl-204	ext	DSTH	-0.97						
U-232	ext	DSTH	-0.9	AREA	-0.2	EROS0	0.19		
U-233	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-234	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-235	ext	DSTH	-0.9	EROS0	0.2	AREA	-0.19		
U-236	inh	EROS0	0.68	AREA	-0.62	H	-0.19		
U-238	ext	DSTH	-0.79	AREA	-0.32	EROS0	0.31		
Zn-65	ext	DSTH	-0.99						

[a] ext = external, ing = ingestion, inh = inhalation.

Table C.7 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Area Source in the Building Occupancy Scenario									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	inh	AREA	-0.6	RF0	-0.53	RMVFR	0.47	H	-0.21
Ag-108	ext	DSTH	-1						
Ag-110	ext	DSTH	-1						
Al-26	ext	DSTH	-1						
Am-241	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.22
Am-243	inh	AREA	-0.55	RF0	-0.47	RMVFR	0.4	DSTH	-0.3
Au-195	ext	DSTH	-0.98						
Bi-207	ext	DSTH	-1						
C-14	inh + ing	AREA	-0.42	DKSUS	-0.4	RF0	-0.35	RMVFR	0.28
Ca-41	inh + ing	AREA	-0.47	DKSUS	-0.43	RF0	-0.41	RMVFR	0.35
Cd-109	ext	DSTH	-0.83	AREA	-0.26	RF0	-0.2	RMVFR	0.17
Ce-144	ext	DSTH	-1						
Cf-252	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.2
Cl-36	ext	DSTH	-0.88	AREA	-0.19	RF0	-0.17	UD	0.1
Cm-243	inh	AREA	-0.57	RF0	-0.47	RMVFR	0.41	DSTH	-0.31
Cm-244	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Cm-248	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Co-57	ext	DSTH	-1						
Co-60	ext	DSTH	-1						
Cs-134	ext	DSTH	-1						
Cs-135	inh + ing	DKSUS	-0.43	AREA	-0.39	RF0	-0.32	DSTH	-0.3
Cs-137	ext	DSTH	-1						
Eu-152	ext	DSTH	-1						
Eu-154	ext	DSTH	-1						
Eu-155	ext	DSTH	-0.98						
Fe-55	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.46	H	-0.21
Gd-152	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21

Table C.7 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Area Source in the Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Gd-153	ext	DSTH	-0.98						
Ge-68	ext	DSTH	-1						
H-3	inh + ing	AREA	-0.53	RF0	-0.47	RMVFR	0.39	DKSUS	-0.29
I-129	inh + ing	DKSUS	-0.42	AREA	-0.39	RF0	-0.31	RMVFR	0.27
K-40	ext	DSTH	-1						
Mn-54	ext	DSTH	-1						
Na-22	ext	DSTH	-1						
Nb-94	ext	DSTH	-1						
Ni-59	inh	AREA	-0.55	RF0	-0.51	RMVFR	0.42	H	-0.2
Ni-63	inh	AREA	-0.55	RF0	-0.52	RMVFR	0.43	H	-0.2
Np-237	inh	AREA	-0.56	RF0	-0.48	RMVFR	0.4	DSTH	-0.3
Pa-231	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.22
Pb-210	inh	AREA	-0.54	RF0	-0.48	RMVFR	0.4	DKSUS	-0.24
Pm-147	inh	AREA	-0.57	RF0	-0.46	RMVFR	0.42	DSTH	-0.29
Pu-238	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-239	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-240	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-241	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-242	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-244	ext	DSTH	-0.75	AREA	-0.35	RF0	-0.3	RMVFR	0.21
Ra-226	ext	DSTH	-0.98						
Ra-228	ext	DSTH	-0.94	AREA	-0.14	RF0	-0.13		
Ru-106	ext	DSTH	-1						
Sb-125	ext	DSTH	-1						
Sm-147	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Sm-151	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.22
Sr-90	inh	AREA	-0.42	RF0	-0.38	DSTH	-0.26	RMVFR	0.23
Tc-99	inh + ext	DSTH	-0.53	AREA	-0.4	RF0	-0.34	RMVFR	0.24
Th-228	ext	DSTH	-0.81	AREA	-0.3	RF0	-0.26	RMVFR	0.17
Th-229	inh	AREA	-0.59	RF0	-0.52	RMVFR	0.46	H	-0.22
Th-230	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22

Table C.7 First Four Most Sensitive Parameters Based on SRRC for a 36-m^2 Area Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Th-232	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Tl-204	ext	DSTH	-0.93	AREA	-0.13	RF0	-0.1		
U-232	inh	AREA	-0.59	RF0	-0.49	RMVFR	0.42	DSTH	-0.28
U-233	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-234	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-235	inh + ext	DSTH	-0.56	AREA	-0.47	RF0	-0.38	RMVFR	0.33
U-236	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-238	inh	AREA	-0.59	RF0	-0.51	RMVFR	0.44	H	-0.22
Zn-65	ext	DSTH	-1						

[a] ext = external, ing = ingestion, inh = inhalation.

Table C.8 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Area Source in the Building Occupancy Scenario									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Ag-108	ext	DSTH	-1						
Ag-110	ext	DSTH	-1						
Al-26	ext	DSTH	-1						
Am-241	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.22
Am-243	inh	AREA	-0.58	RF0	-0.52	RMVFR	0.45	H	-0.22
Au-195	ext	DSTH	-0.95	AREA	-0.11				
Bi-207	ext	DSTH	-1						
C-14	inh + ing	AREA	-0.46	DKSUS	-0.42	RF0	-0.39	RMVFR	0.32
Ca-41	inh + ing	AREA	-0.47	DKSUS	-0.43	RF0	-0.41	RMVFR	0.35
Cd-109	ext	DSTH	-0.67	AREA	-0.39	RF0	-0.3	RMVFR	0.26
Ce-144	ext	DSTH	-0.98						
Cf-252	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.2
Cl-36	ext	DSTH	-0.69	AREA	-0.33	RF0	-0.29	RMVFR	0.18
Cm-243	inh	AREA	-0.6	RF0	-0.52	RMVFR	0.46	H	-0.21
Cm-244	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Cm-248	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Co-57	ext	DSTH	-1						
Co-60	ext	DSTH	-1						
Cs-134	ext	DSTH	-1						
Cs-135	inh + ing	DKSUS	-0.46	AREA	-0.44	RF0	-0.36	RMVFR	0.3
Cs-137	ext	DSTH	-1						
Eu-152	ext	DSTH	-1						
Eu-154	ext	DSTH	-1						

Table C.8 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Area Source in the Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Eu-155	ext	DSTH	-0.94	AREA	-0.13	RF0	-0.11		
Fe-55	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.46	H	-0.21
Gd-152	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21
Gd-153	ext	DSTH	-0.95	AREA	-0.11	RF0	-0.1		
Ge-68	ext	DSTH	-1						
H-3	inh + ing	AREA	-0.53	RF0	-0.47	RMVFR	0.39	DKSUS	-0.29
I-129	inh + ing	DKSUS	-0.44	AREA	-0.41	RF0	-0.34	RMVFR	0.29
K-40	ext	DSTH	-0.98						
Mn-54	ext	DSTH	-1						
Na-22	ext	DSTH	-1						
Nb-94	ext	DSTH	-1						
Ni-59	inh + ing	AREA	-0.55	RF0	-0.51	RMVFR	0.42	H	-0.2
Ni-63	inh + ing	AREA	-0.55	RF0	-0.52	RMVFR	0.43	H	-0.2
Np-237	inh	AREA	-0.58	RF0	-0.53	RMVFR	0.45	H	-0.22
Pa-231	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pb-210	inh + ing	AREA	-0.54	RF0	-0.49	RMVFR	0.4	DKSUS	-0.25
Pm-147	inh	AREA	-0.6	RF0	-0.52	RMVFR	0.46	H	-0.21
Pu-238	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-239	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-240	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-241	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-242	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-244	inh	AREA	-0.52	DSTH	-0.45	RF0	-0.43	RMVFR	0.36
Ra-226	ext	DSTH	-0.94	AREA	-0.11	RF0	-0.1		
Ra-228	ext	DSTH	-0.81	AREA	-0.3	RF0	-0.25	RMVFR	0.17
Ru-106	ext	DSTH	-0.99						
Sb-125	ext	DSTH	-1						
Sm-147	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22

Table C.8 First Four Most Sensitive Parameters Based on SRRC for a 200-m^2 Area Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Sm-151	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.21
Sr-90	inh	AREA	-0.54	RF0	-0.48	RMVFR	0.36	UD	0.19
Tc-99	inh	AREA	-0.49	RF0	-0.42	RMVFR	0.32	DSTH	-0.28
Th-228	ext	DSTH	-0.54	AREA	-0.49	RF0	-0.39	RMVFR	0.33
Th-229	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.47	H	-0.22
Th-230	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Th-232	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Tl-204	ext	DSTH	-0.85	AREA	-0.23	RF0	-0.17	UD	0.13
U-232	inh	AREA	-0.6	RF0	-0.53	RMVFR	0.46	H	-0.21
U-233	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-234	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-235	inh	AREA	-0.58	RF0	-0.48	RMVFR	0.43	DSTH	-0.26
U-236	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-238	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.47	H	-0.22
Zn-65	ext	DSTH	-1						

[a] ext = external, ing = ingestion, inh = inhalation.

Table C.9 First Four Most Sensitive Parameters Based on SRRC for a 900-m^2 Area Source in the Building Occupancy Scenario

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Ac-227	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Ag-108	ext	DSTH	-0.99						
Ag-110	ext	DSTH	-1						
Al-26	ext	DSTH	-0.99						
Am-241	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Am-243	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Au-195	ext	DSTH	-0.9	AREA	-0.18	RF0	-0.14	RMVFR	0.13
Bi-207	ext	DSTH	-0.99						
C-14	inh + ing	AREA	-0.46	DKSUS	-0.43	RF0	-0.4	RMVFR	0.33
Ca-41	inh + ing	AREA	-0.47	DKSUS	-0.43	RF0	-0.41	RMVFR	0.35
Cd-109	inh	AREA	-0.51	DSTH	-0.45	RF0	-0.4	RMVFR	0.36
Ce-144	ext	DSTH	-0.91	AREA	-0.19	RF0	-0.16	RMVFR	0.1
Cf-252	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.2
Cl-36	inh	AREA	-0.46	DSTH	-0.44	RF0	-0.39	RMVFR	0.28
Cm-243	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Cm-244	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Cm-248	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Co-57	ext	DSTH	-0.99						
Co-60	ext	DSTH	-1						
Cs-134	ext	DSTH	-1						
Cs-135	ing	DKSUS	-0.47	AREA	-0.45	RF0	-0.38	RMVFR	0.32
Cs-137	ext	DSTH	-0.98						
Eu-152	ext	DSTH	-1						
Eu-154	ext	DSTH	-0.99						

Table C.9 First Four Most Sensitive Parameters Based on SRRC for a 900-m^2 Area Source in the Building Occupancy Scenario (Continued)

Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Eu-155	ext	DSTH	-0.88	AREA	-0.22	RF0	-0.17	RMVFR	0.14
Fe-55	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.46	H	-0.21
Gd-152	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21
Gd-153	ext	DSTH	-0.9	AREA	-0.19	RF0	-0.15	RMVFR	0.13
Ge-68	ext	DSTH	-1						
H-3	inh + ing	AREA	-0.53	RF0	-0.47	RMVFR	0.39	DKSUS	-0.29
I-129	inh + ing	DKSUS	-0.45	AREA	-0.43	RF0	-0.36	RMVFR	0.3
K-40	ext	DSTH	-0.97						
Mn-54	ext	DSTH	-1						
Na-22	ext	DSTH	-1						
Nb-94	ext	DSTH	-0.98						
Ni-59	inh	AREA	-0.55	RF0	-0.51	RMVFR	0.42	H	-0.2
Ni-63	inh	AREA	-0.55	RF0	-0.52	RMVFR	0.43	H	-0.2
Np-237	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pa-231	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pb-210	inh + ing	AREA	-0.54	RF0	-0.49	RMVFR	0.4	DKSUS	-0.25
Pm-147	inh	AREA	-0.6	RF0	-0.53	RMVFR	0.47	H	-0.2
Pu-238	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-239	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-240	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-241	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
Pu-242	inh	AREA	-0.58	RF0	-0.54	RMVFR	0.46	H	-0.22
Pu-244	inh	AREA	-0.58	RF0	-0.51	RMVFR	0.43	H	-0.22
Ra-226	ext	DSTH	-0.83	AREA	-0.23	RF0	-0.2	UD	0.12
Ra-228	ext	DSTH	-0.56	AREA	-0.48	RF0	-0.38	RMVFR	0.32
Ru-106	ext	DSTH	-0.95	AREA	-0.13	RF0	-0.12		
Sb-125	ext	DSTH	-1						
Sm-147	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22

Table C.9 First Four Most Sensitive Parameters Based on SRRC for a 900-m^2 Area Source in the Building Occupancy Scenario (Continued)									
Radionuclide	Dominant Pathway[a]	Rank 1		Rank 2		Rank 3		Rank 4	
		Parameter	SRRC	Parameter	SRRC	Parameter	SRRC	Parameter	SRRC
Sm-151	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.46	H	-0.21
Sr-90	inh	AREA	-0.56	RF0	-0.51	RMVFR	0.41	H	-0.2
Tc-99	inh + ing	AREA	-0.52	RF0	-0.46	RMVFR	0.37	DKSUS	-0.26
Th-228	inh	AREA	-0.59	RF0	-0.49	RMVFR	0.43	DSTH	-0.26
Th-229	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Th-230	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Th-232	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Tl-204	ext	DSTH	-0.71	AREA	-0.32	RF0	-0.23	UD	0.18
U-232	inh	AREA	-0.6	RF0	-0.54	RMVFR	0.47	H	-0.21
U-233	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-234	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-235	inh	AREA	-0.59	RF0	-0.53	RMVFR	0.46	H	-0.22
U-236	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
U-238	inh	AREA	-0.59	RF0	-0.54	RMVFR	0.47	H	-0.22
Zn-65	ext	DSTH	-1						

[a] ext = external, ing = ingestion, inh = inhalation.

NRC FORM 335
(2-89)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-6676

2. TITLE AND SUBTITLE

Probabilistic Dose Analysis Using Parameter Distributions Developed for RESRAD and RESRAD-BUILD Codes

3. DATE REPORT PUBLISHED

MONTH	YEAR
July	2000

4. FIN OR GRANT NUMBER

Job Code No. Y6112

5. AUTHOR(S)

S. Kamboj, D. LePoire, E. Gnanapragasam, B.M. Biwer, J.Cheng, J. Arnish, C.Yu, and S.Y. Chen

6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION - NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Argonne National Laboratory
Environmental Assessment Division
9700 South Cass Avenue
Argonne, Illinois 60439

9. SPONSORING ORGANIZATION - NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Risk Analysis and Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington D.C. 20555-0001

10. SUPPLEMENTARY NOTES

T. Mo, NRC Project Manager

11. ABSTRACT *(200 words or less)*

The existing RESRAD 6.0 and RESRAD-BUILD 3.0 codes for site-specific radiation dose modeling applications are being developed and adapted for use with the U.S. Nuclear Regulatory Commission's (NR C's) Standard Review Plan for decommissioning and as tools for demonstrating compliance with the license term ination rule in a risk-informed manner. Computer interfaces and software modules have been developed under NRC sponsor ship to perform the probabilistic simulation of dose. RESRAD and RESRAD-BUILD codes are part of the RESRAD fam ily of codes that have been developed by the U.S. Department of Energy (DOE) and for many years have been successfull y applied to cleanup efforts at sites contaminated with radioactive materials. Specifically, the RESRAD code applies to cleanup of soil and RESRAD-BUILD applies to the cleanup of buildings and structures at a site. This report desc ribes the use of these codes to perform probabilistic dose analysis. The dose analysis presented in this report has fu lly demonstrated the process of using the integrated system of RESRAD 6.0 and RESRAD-BUILD 3.0 codes and the probabilist ic modules, together with distributions of input parameters, for dose assessment at a relatively complex site. This demon stration enables site-specifc application of the codes for dose analysis where pertinent parameters and their distributions are available or can be developed. Results of the uncertainty analysis and sensitivity analysis of dose to input parameter values indicated that because the dependence of dose on the input parameters is complex, no single correlation or regression coeffi cient can be used alone to identify sensitive parameters in all cases. However, the results could give an indication of the degree of sensitivity of the calculated dose to changes in input parameter values for each exposure situation. Therefore, the coefficients are useful guides, but they have to be used in conjunction with other aids, such as scatter plots and further analy sis, to accurately identify the sensitive parameters.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

RESRAD and RESRAD-BUILD computer codes, Standard Review Plan for decommissionin g and license termination, risk informed regulation, probabilistic and site-specific radiation dose analysis, parameter distributions, uncertainty analysis of calculated dose and sensitivit y analysis of the dose to input parameters, regression analysis, correlation coefficients, scatter plots, U.S. Nuclear Regulatory Commission, U.S. Department of Energy

13. AVAILABILITY STATEMENT

unlimited

14. SECURITY CLASSIFICATION

(This Page)
unclassified

(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

Printed on recycled paper

Federal Recycling Program

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

1975 25 2000
years