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

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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.

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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.

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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)
Fg	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

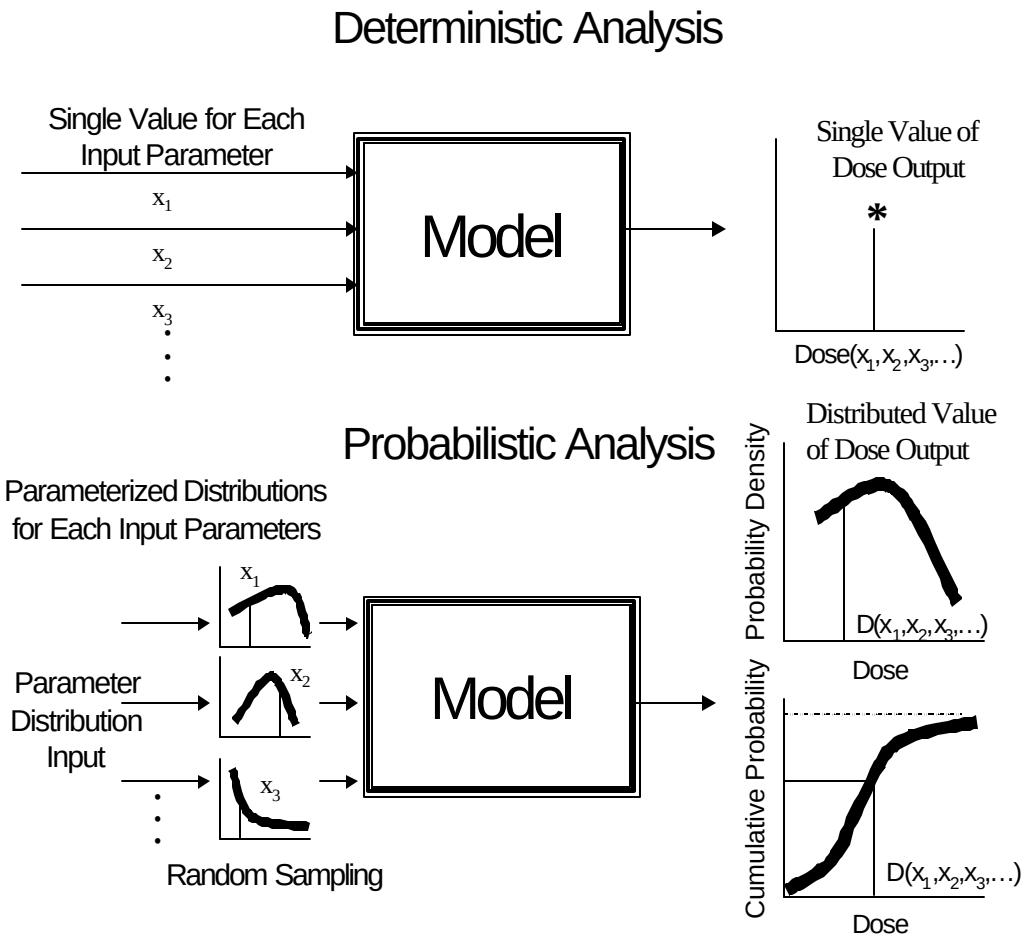

Figure 2.1 Concepts of Deterministic and Probabilistic Analyses

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 effective porosity and total porosity. Care was taken to ensure that consistent minimum and maximum distribution values were assigned in such cases. Such relationships were identified for 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.

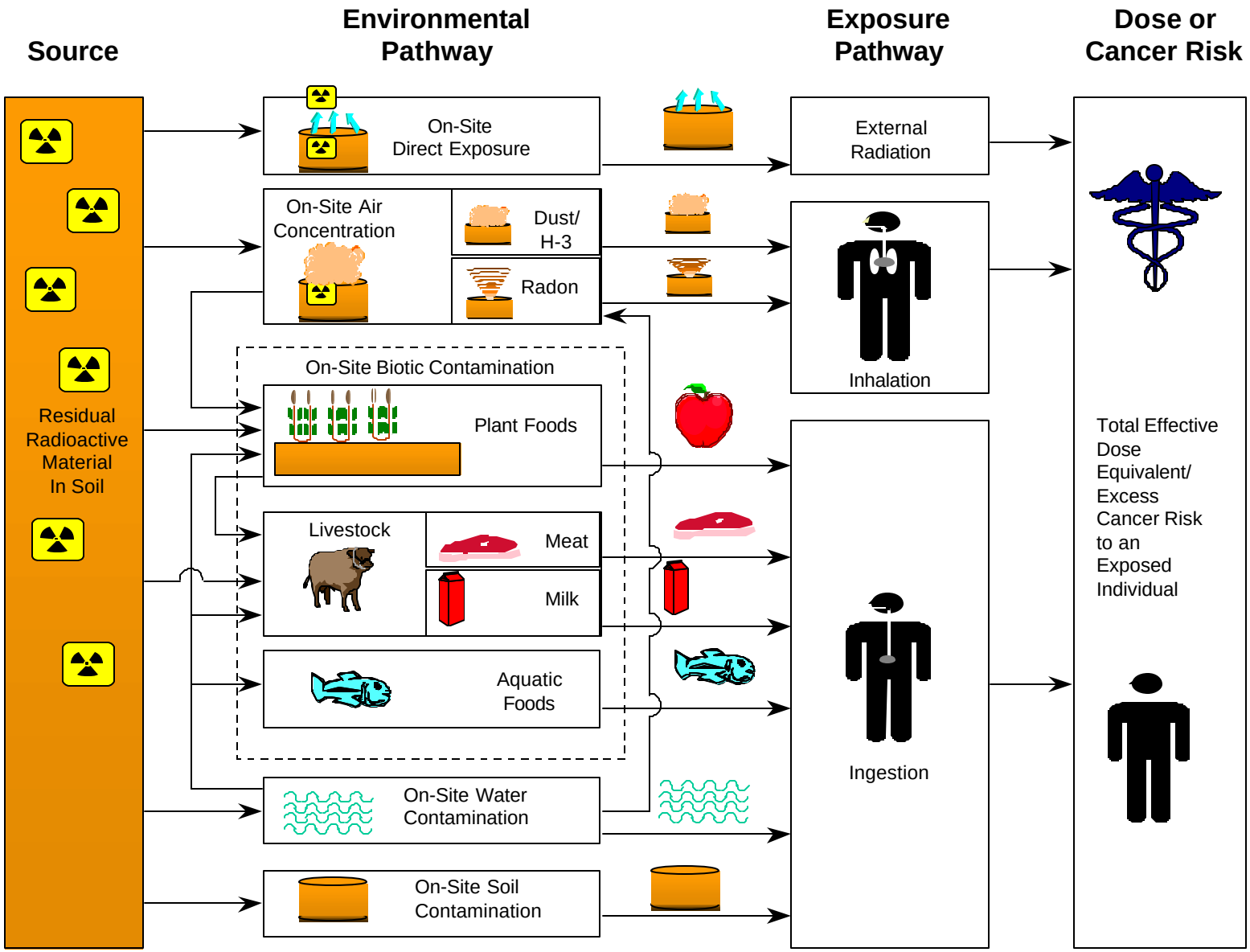

Figure 3.1 Graphical Representation of Pathways Considered in RESRAD

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).

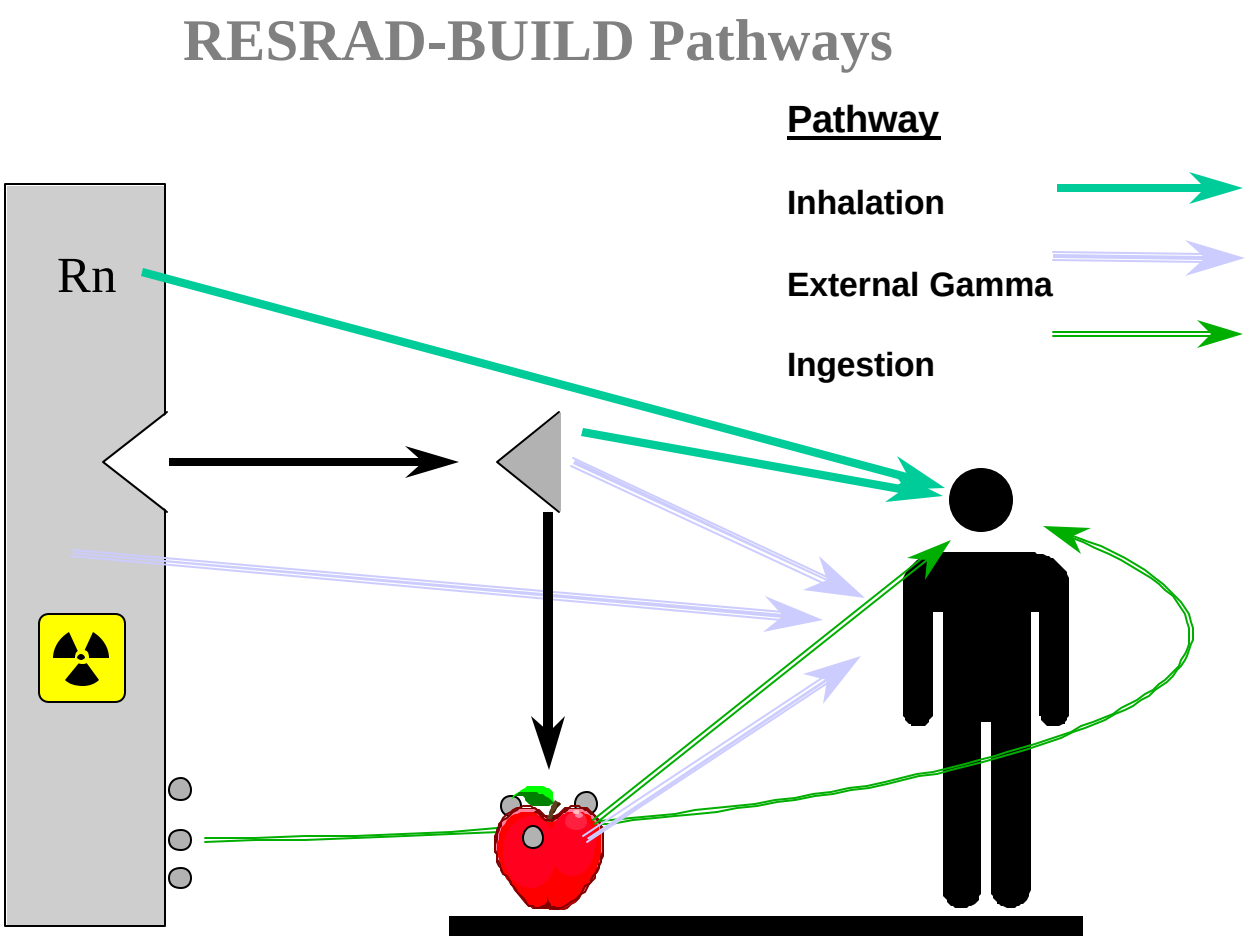

Figure 3.2 Graphical Representation of Pathways Considered in RESRAD-BUILD

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.

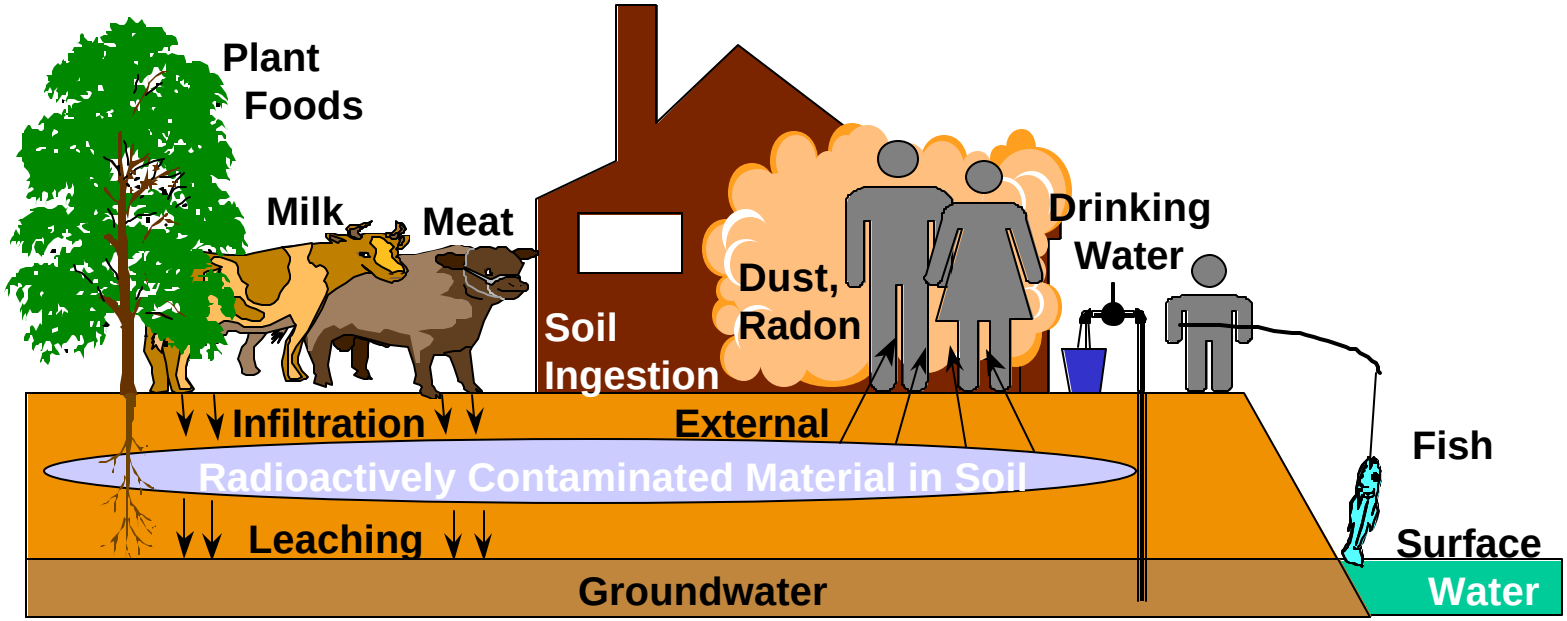

Figure 4.1 Schematic Representation of Exposure Pathways in a Typical Residential Scenario

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 (µg/m^3)	P, B	Empirical
Milk consumption (L/yr)	M, B	Triangular
Runoff coefficient	P	Uniform
Saturated zone b parameter	P	Lognormal
Saturated zone hydraulic gradient	P	Lognormal
Soil ingestion rate (g/yr)	M, B	Triangular
Transfer factors for meat [(pCi/kg)/(pCi/d)]	P	Lognormal
Transfer factors for milk [(pCi/L)/(pCi/d)]	P	Lognormal
Unsaturated zone density (g/cm^3)	P	Normal
Unsaturated zone effective porosity	P	Normal
Unsaturated zone hydraulic conductivity (m/yr)	P	Lognormal
Unsaturated zone, soil-b parameter	P	Lognormal
Unsaturated zone total porosity	P	Normal
Weathering removal constant (1/yr)	P	Triangular

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.