NUREG/CR-6697
ANL/EAD/TM-98

Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes

Argonne National Laboratory

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

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ABSTRACT

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

This report is the third in a series documenting the procedures used to enhance the deterministic RESRAD and RESRAD-BUILD codes for probabilistic dose analysis. A six-step procedure was used in developing default parameter distributions and the probabilistic analysis modules. These six steps include (1) listing and categorizing parameters, (2) ranking parameters, (3) developing parameter distributions, (4) testing parameter distributions for probabilistic analysis, (5) developing probabilistic modules, and (6) testing probabilistic modules and integrated codes. These six steps are discussed and summarized in this report. Steps 4 and 5 are documented in separate NUREG/CR reports (NUREG/CR-6676 [Kamboj et al., 2000] and NUREG/CR-6692 [LePoire et al., 2000]). The reports for steps 1, 2, 3, and 6 are included in this report as attachments.

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

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EXECUTIVE SUMMARY

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

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

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

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

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

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

The results indicated that all parameter distributions are reasonable and consistent for all cases and radionuclides analyzed. However, site-specific distributions should be used whenever available, especially for sensitive parameters such as shielding thickness and room area. RESRAD-BUILD dose variability for the building occupancy scenario for both volume and area sources was much greater than the variability observed in RESRAD results for the residential scenario.

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

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

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

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

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

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

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

Overall, 14 parameters were ranked as high priority, 59 were ranked as medium priority, and the remaining 122 were ranked as low priority for RESRAD and RESRAD-BUILD combined.

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

FOREWORD

This contractor technical report, NUREG/CR-6697, was prepared by Argonne National Laboratory[1] staff under their U.S. Department of Energy (DOE) Interagency Work Order (JCN Y6112) with the Radiation Protection, Environmental Risk and Waste Management Branch, Division of Risk Analysis and Applications, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission. This report is the third in a series documenting the procedures used to enhance the deterministic RESRAD and RESRAD-BUILD computer codes (developed by DOE) for probabilistic dose analysis. The procedures for listing, categorizing, ranking of input parameters, and testing the integrated system of the probabilistic modules and the codes are included in this report as attachments. The procedures for testing of the parameter distributions for probabilistic analysis and for developing the probabilistic modules are documented in two other NUREG/CR reports (NUREG/CR- 6676 and NUREG/CR-6692).

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

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ABBREVIATIONS

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

1 INTRODUCTION

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

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

As part of the development of site-specific implementation guidance supporting the License Termination Rule and development of a Standard Review Plan (SRP) on Decommissioning (NRC, 2000), the NRC recognized the need to perform probabilistic analysis with codes that could be used for site-specific modeling. Such modeling capabilities exist with the RESRAD (Yu et al., 1993b) and RESRAD-BUILD (Yu et al., 1994) codes. These two codes were developed at Argonne National Laboratory (Argonne) under sponsorship of the U.S. Department of Energy (DOE). These DOE codes possess the following attributes: (1) the software has been widely accepted and there is already a large user base, (2) the models in the software were designed for and have been successfully applied at sites with relatively complex physical and contamination conditions, and (3) verification and validation of the codes are well documented (Camus et al., 1999; Cheng et al., 1995; Yu, 1999; Yu and Gnanapragasam, 1995; Halliburton NUS Corp., 1994; Faillace et al., 1994; IAEA, 1996; Laniak et al., 1997; Mills et al., 1997; Seitz et al., 1992; Seitz et al., 1994; Whelan et al., 1999a, 1999b; Gnanapragasam and Yu, 1997a, 1997b; BIOMOVS II, 1996; Regens, 1998; Yu et al., 1993a, 1993b, 1994; NUREG/CP-0163 [NRC, 1998]). The RESRAD codes have been used primarily to derive site-specific cleanup guidance levels (e.g., the derived concentration guideline levels, or DCGLs) with the deterministic method.

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

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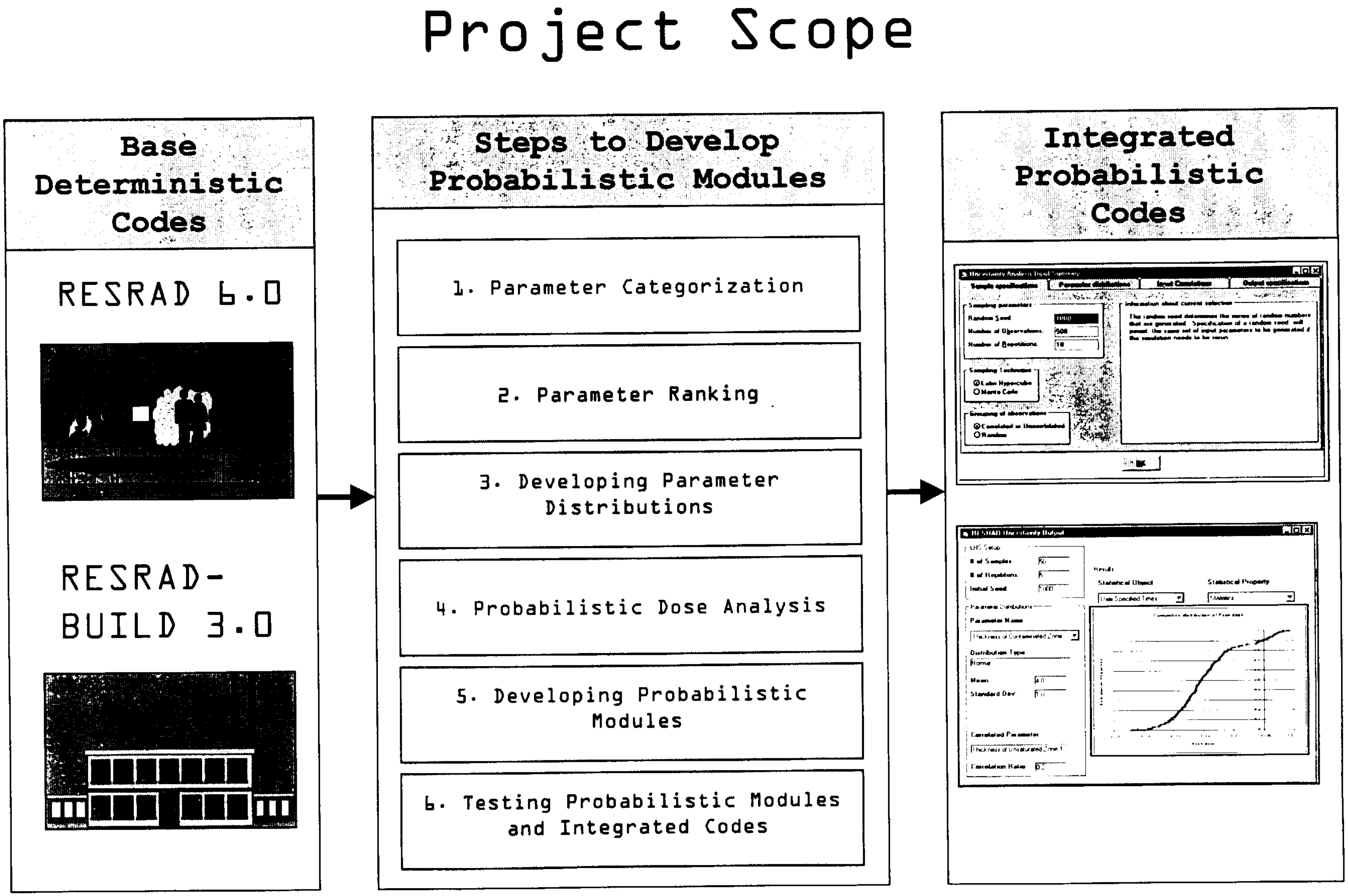
[2] The *critical group* is defined as an individual or relatively homogenous group of individuals expected to receive the highest exposure under the assumptions of the particular scenario considered (NUREG/CR-5512 [Kennedy and Strenge, 1992]). The average member of the critical group is an individual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

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

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

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



Project Scope

Base Deterministic Codes

RESRAD 6.0

RESRAD-BUILD 3.0

Steps to Develop Probabilistic Modules

1. Parameter Categorization
2. Parameter Ranking
3. Developing Parameter Distributions
4. Probabilistic Dose Analysis
5. Developing Probabilistic Modules
6. Testing Probabilistic Modules and Integrated Codes

Integrated Probabilistic Codes

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

2 OVERVIEW OF THE DETERMINISTIC RESRAD AND RESRAD-BUILD CODES

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

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

2.1 RESRAD

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

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

The code uses a pathway analysis method in which the relation between radionuclide concentrations in soil and the dose to a member of a critical group is expressed as a pathway sum, which is the sum of products of "pathway factors." Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or from which radiation can be emitted.

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

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

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

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

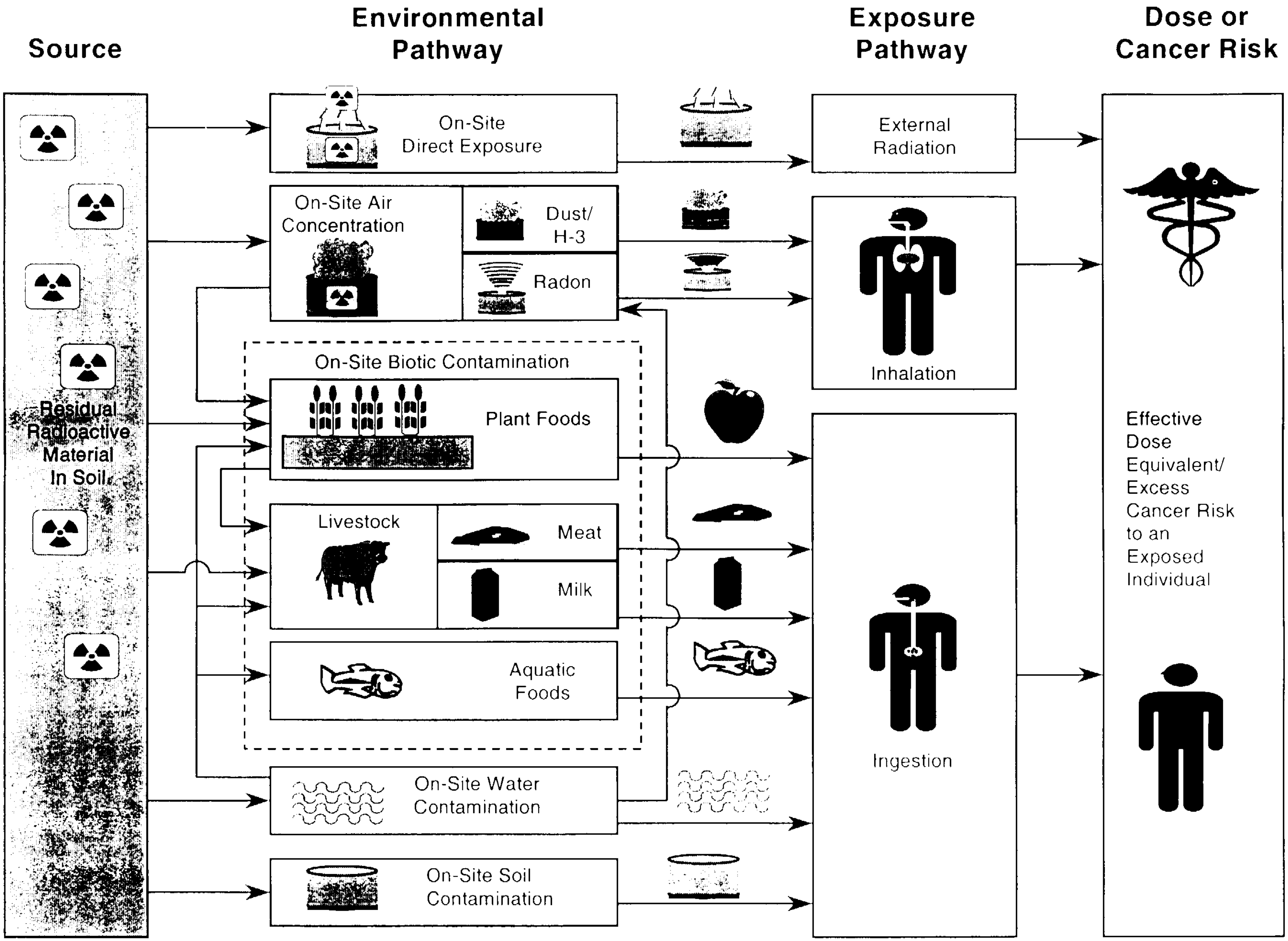


Figure 2.1 Graphical Representation of Pathways Considered in RESRAD

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

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

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

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

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

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

2.2 RESRAD-BUILD

The RESRAD-BUILD code (Yu et al., 1994) is a pathway analysis model designed to evaluate the potential radiological dose to an individual who works or lives in a building contaminated with radioactive material. It considers the releases of radionuclides into the indoor air by diffusion, mechanical removal, or erosion. The transport of radioactive material inside the building from one room or compartment to another is calculated with an indoor air quality model. A single run of the RESRAD-BUILD code can model a building with up to 3 rooms or compartments, 10 distinct source locations, 4 source geometries, 10 receptor locations, and 8 shielding materials. A shielding material can be specified between each source-receptor pair for external gamma dose calculations. It should be noted that certain default parameters and

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

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

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

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

[c] Radionuclide is not in RESRAD-BUILD database.

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

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

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

Seven exposure pathways are considered in RESRAD-BUILD: (1) external exposure directly from the source; (2) external exposure to materials deposited on the floor; (3) external exposure due to air submersion; (4) inhalation of airborne radioactive particulates; (5) inhalation of aerosol indoor radon progeny; (6) inadvertent ingestion of radioactive material directly from the sources; and (7) inadvertent ingestion of materials deposited on the surfaces of the building rooms or compartments. It should be noted that pathways 3, 5, and 7 are not included in the NUREG/CR-5512 building occupancy scenario. Figure 2.2 conceptually illustrates the exposure pathways considered in RESRAD-BUILD.

The air quality model in RESRAD-BUILD evaluates the transport of radioactive dust particulates, tritium, and radon progeny due to (1) air exchange between rooms and with outdoor air, (2) the deposition and resuspension of particulates, and (3) radioactive decay and ingrowth. With RESRAD-BUILD, the user can construct the exposure scenario by adjusting the input parameters. Typical building exposure scenarios include long-term occupancy (resident and office worker) and short-term occupancy (remediation worker and visitor). It should be noted that the building occupancy scenario specified in NUREG/CR-5512 assumes occupancy by a typical light-industry worker.

RESRAD-BUILD can take into account the attenuation afforded by the shielding material between each source-receptor combination when calculating the external dose. The user can select the shielding material from eight material types and input the thickness and density of the material. The user can define the source as point, line, area, or volume source. (Note that NRC's building occupancy scenario assumes an area source only.) The volume source can consist of five layers of different materials, with each layer being porous, homogeneous, and isotropic. Currently, 67 radionuclides are included in the RESRAD-BUILD database. All 67 radionuclides have half-lives of 6 months or greater and are referred to as principal radionuclides. It is assumed that the short-lived decay products with half-lives of 6 months or less, referred to as the associated radionuclides, are in secular equilibrium with their parent. Table 2.1 lists radionuclides in both the RESRAD-BUILD and RESRAD databases. RESRAD-BUILD has a graphic (3-D display) interface to show the relative positions and shapes of sources and receptors. A text report is provided that contains the deterministic analysis results.

RESRAD-BUILD Pathways

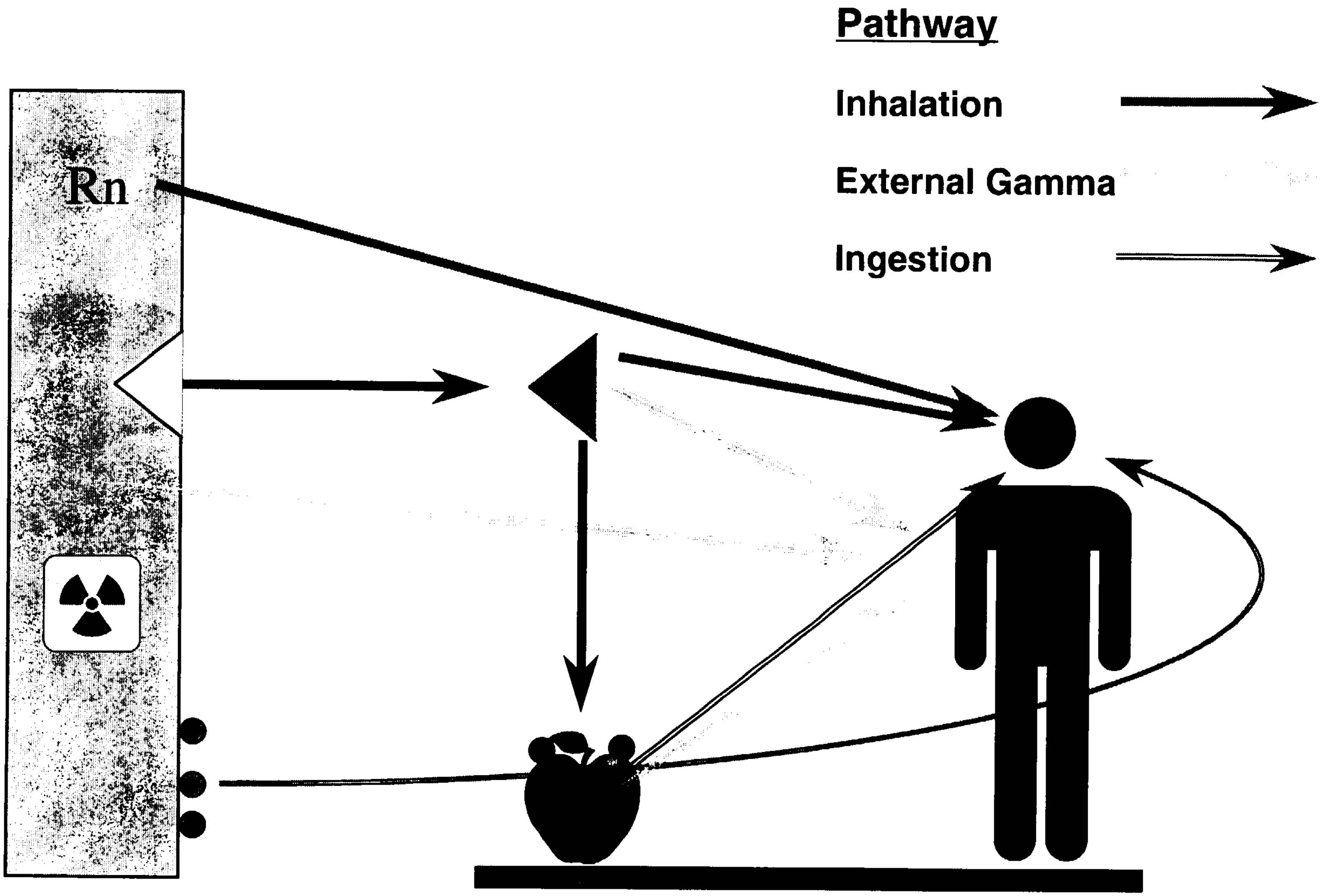


Figure 2.2 Graphical Representation of Pathways Considered in RESRAD-BUILD

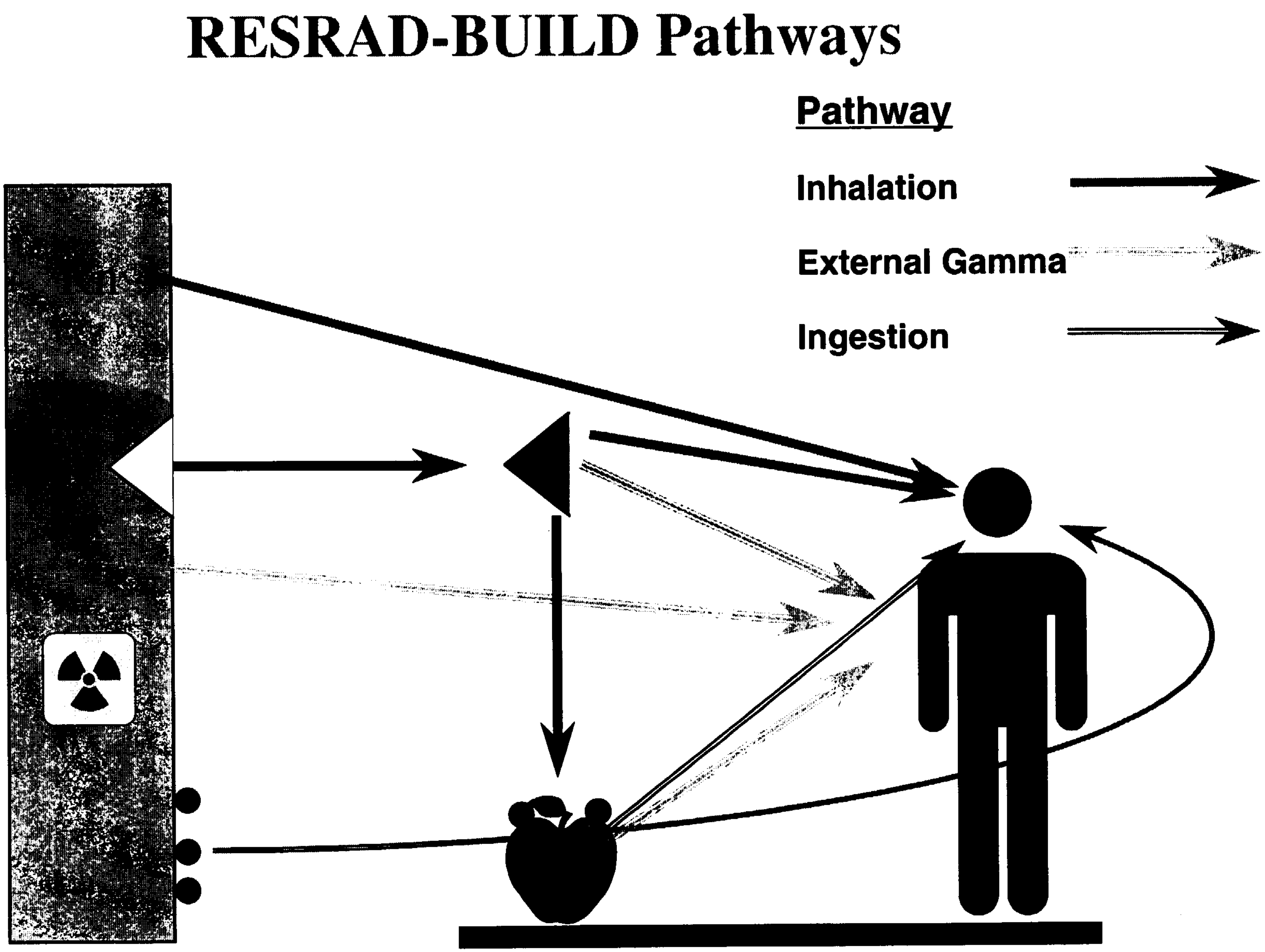


Figure 2.2 Graphical Representation of Pathways Considered in RESRAD-BUILD

3 PROCEDURES TO DEVELOP PROBABILISTIC RESRAD AND RESRAD-BUILD CODES

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

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

3.1 LISTING AND CATEGORIZING INPUT PARAMETERS

The first step in developing parameter distributions was listing all the input parameters used in the RESRAD and RESRAD-BUILD codes. RESRAD has 130 radionuclide-independent parameters, 10 radionuclide-dependent parameters, and 5 element-dependent parameters. RESRAD-BUILD has 45 radionuclide-independent and 5 radionuclide-dependent parameters. For the radionuclide-dependent parameters, the distribution characteristics have to be generated for each radionuclide. A list of parameters and their definitions are included in Attachment A. Also included in the list is the classification of the parameters. The parameters are classified into three types: physical, behavioral, and metabolic. Some parameters may belong to more than one of these types. Additionally, if a parameter does not fit the definition of either physical or metabolic, it is classified as a behavioral parameter. Three RESRAD parameters are not classified because of their function in the code: "Basic radiation dose limit," "Use plant/soil ratio," check box, and "Accuracy for water soil computation."

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

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

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

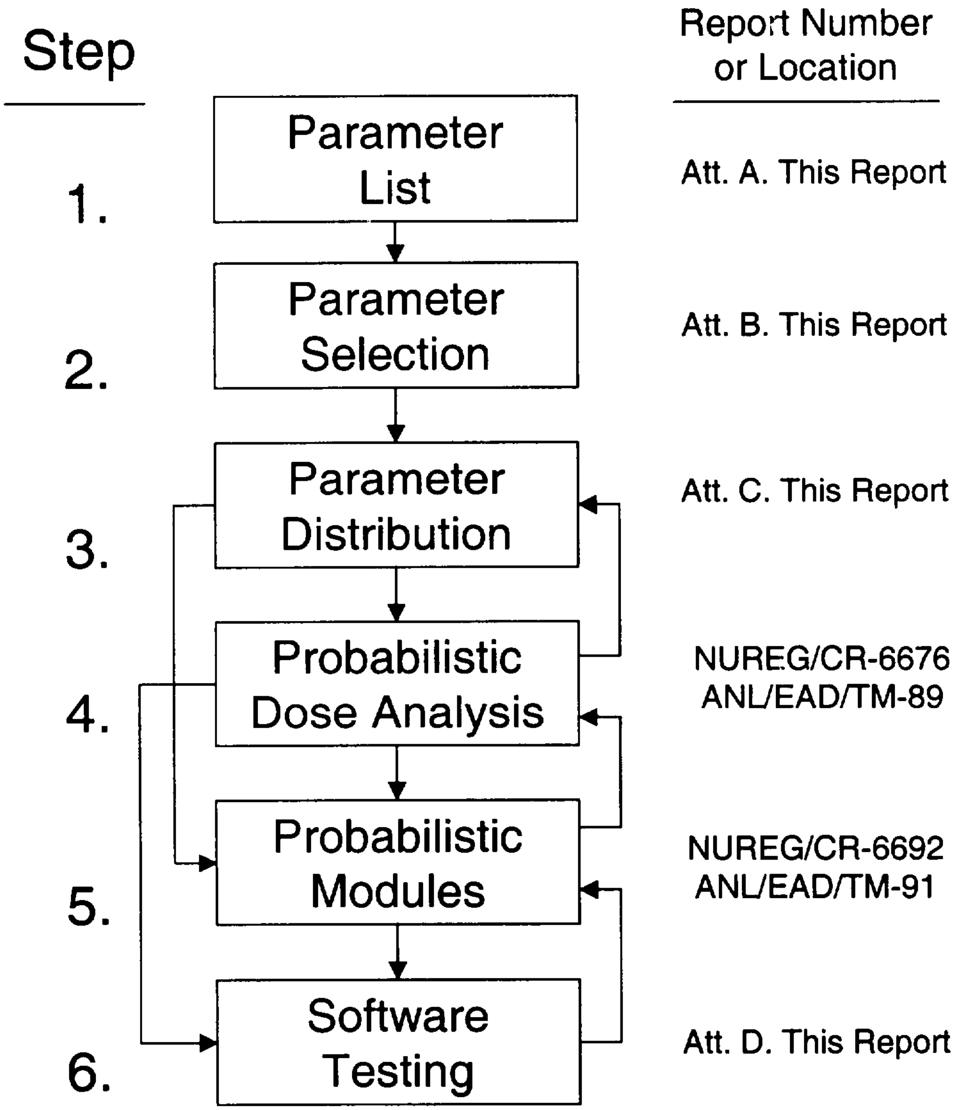


Figure 3.1 Flow Diagram of Steps in Developing Probabilistic RESRAD and RESRAD-BUILD Codes and the Report Locations for Each Step

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

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

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

3.2 SELECTING PARAMETERS FOR DISTRIBUTION ANALYSIS

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

3.2.1 Attribute 1: Relevance in Dose Calculations

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

3.2.2 Attribute 2: Influence on Dose Variability

The influence of the parameter on dose is gauged by using a sensitivity analysis approach. A quantity — normalized dose difference (NDD) — is calculated as $NDD = (D_{high} - D_{low}) / D_{base} \times 100\%$, where $(D_{high} - D_{low})$ is the potential range of the peak radiation dose and D_{base} is the peak dose calculated by setting the studied parameter to its base value. D_{base} is used as a normalization factor. D_{high} and D_{low} are the peak doses obtained by setting the parameter to its high and low values, respectively. The base case used was a subsistence farmer scenario for RESRAD and a building occupancy scenario for RESRAD-BUILD. The parameter values used for the base cases are presented in Attachment B. The representative radionuclides considered in this study are Co-60, Sr-90, Cs-137, Ra-226, Th-230, U-238, Pu-239, and Am-241. The largest NDD among those calculated for the representative radionuclides was selected to represent each parameter's influence, and a numeric score of 1 to 7 was assigned to each parameter on the basis of the largest NDD.

3.2.3 Attribute 3: Parameter Type

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

3.2.4 Attribute 4: Data Availability

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

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

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

3.3 DEVELOPING DEFAULT PARAMETER DISTRIBUTIONS

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

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

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

Sufficient relevant statistical data (data sets/matching function and parameter characteristics) were available for some parameters to clearly show a distribution type. If the use of an empirical distribution was not appropriate, the data were fit to the identified distribution. In certain cases, probability plots or other graphical representations were used to determine goodness of fit.

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

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

3.4 TESTING PARAMETER DISTRIBUTIONS

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

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

Table 3.1. Parameters Assigned Probability Density Functions

Parameter	Parameter Type[a]	Assigned Distribution Type
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 erosion rate (m/yr)	P, B	Empirical
Depth of soil mixing layer (m)	P	Triangular
Drinking water intake (L/yr)	M, B	Lognormal
Evapotranspiration coefficient	P	Uniform
External gamma shielding factor	P	Lognormal
Fruit, vegetables, and grain consumption (kg/yr)	M, B	Triangular
Indoor dust filtration factor	P, B	Uniform
Mass loading for inhalation (μg/m^3)	P, B	Empirical
Milk consumption (L/yr)	M, B	Triangular
Runoff coefficient	P	Uniform
Saturated zone b parameter	P	Lognormal
Saturated zone hydraulic gradient	P	Lognormal
Soil ingestion rate (g/yr)	M, B	Triangular
Transfer factors for meat [(pCi/kg)/(pCi/d)]	P	Lognormal
Transfer factors for milk [(pCi/L)/(pCi/d)]	P	Lognormal
Unsaturated zone density (g/cm^3)	P	Normal
Unsaturated zone effective porosity	P	Normal
Unsaturated zone hydraulic conductivity (m/yr)	P	Lognormal
Unsaturated zone, soil-b parameter	P	Lognormal
Unsaturated zone total porosity	P	Normal
Weathering removal constant (1/yr)	P	Triangular
Well pump intake depth (below water table) (m)	P	Triangular
Wet foliar interception fraction for leafy vegetables	P	Triangular
Wet-weight crop yields for nonleafy vegetables (kg/m^2)	P	Lognormal

Table 3.1. Parameters Assigned Probability Density Functions (Continued)

Parameter	Parameter Type[a]	Assigned Distribution Type
Wind speed (m/s)	P	Lognormal
Humidity in air (g/m^3)	P	Lognormal
Indoor fraction	B	Empirical
Inhalation rate (m^3/yr)	M, P	Triangular
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
Humidity (g/m^3)	P, B	Uniform
Indoor fraction	B	Empirical
Receptor indirect ingestion rate (m^2/h)	B	Loguniform
Receptor inhalation rate (m^3/d)	M, B	Triangular
Room area (m^2)	P	Triangular
Room height (m)	P	Triangular
Shielding thickness (cm)	P, B	Triangular
Source erosion rate, volume source (cm/d)	P, B	Triangular
Source porosity	P	Uniform
Source thickness, volume source (cm)	P	Triangular
Time for source removal or source lifetime (d)	P, B	Triangular
Volumetric water content	P	Uniform
Water fraction available for evaporation	P	Triangular
Wet + dry zone thickness (cm)	P	Uniform

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

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

3.5 DEVELOPING PROBABILISTIC MODULES

The next step was to develop probabilistic modules for the RESRAD and RESRAD-BUILD codes. The requirements of the probabilistic modules were as follows: the deterministic results should not be changed; the parameter distributions identified in Step 3 should be used; the Latin hypercube sampling (LHS) method should be supported; the modules should have a robust, user-friendly interface; they should provide graphical, interactive, and complete output; they should support "peak of the mean" as well as "mean of the peak" statistical dose analysis; they should be compatible with Windows (especially NT) operating systems; and they should be integrated into the RESRAD and RESRAD-BUILD codes.

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

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

3.6 TESTING PROBABILISTIC CODES

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

The post-processor program PCCSRC for correlation and regression analysis was also improved with double precision to get more accurate results. The program was previously tested and verified.

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

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

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

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

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

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

4 OVERVIEW OF THE PROBABILISTIC RESRAD AND RESRAD-BUILD CODES

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

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

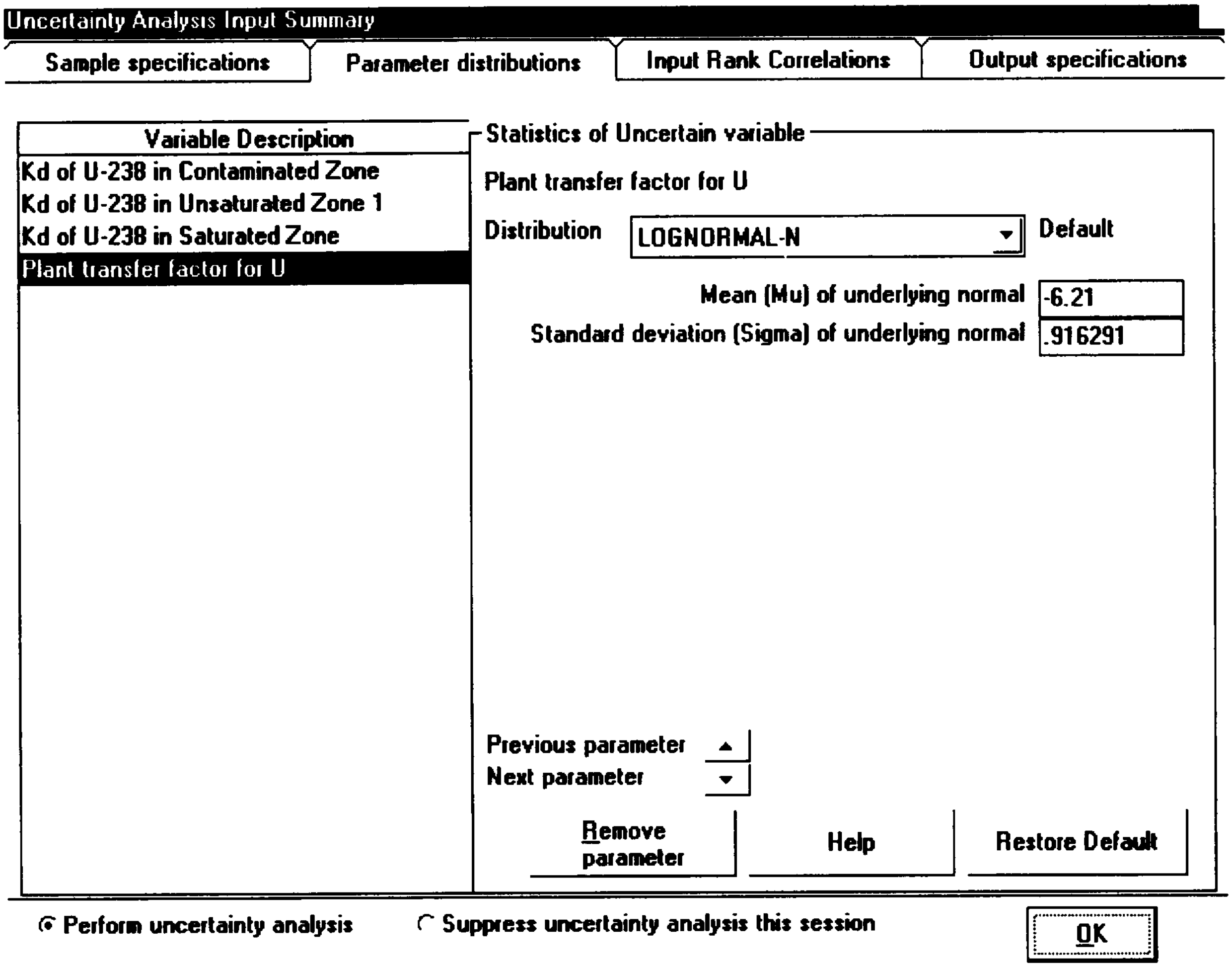
4.1 SAMPLING METHOD

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

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

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

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



Variable Description
Kd of U-238 in Contaminated Zone
Kd of U-238 in Unsaturated Zone 1
Kd of U-238 in Saturated Zone
Plant transfer factor for U

Statistics of Uncertain variable
Plant transfer factor for U
Distribution: LOGNORMAL-N (Default)
Mean (Mu) of underlying normal: -6.21
Standard deviation (Sigma) of underlying normal: .916291

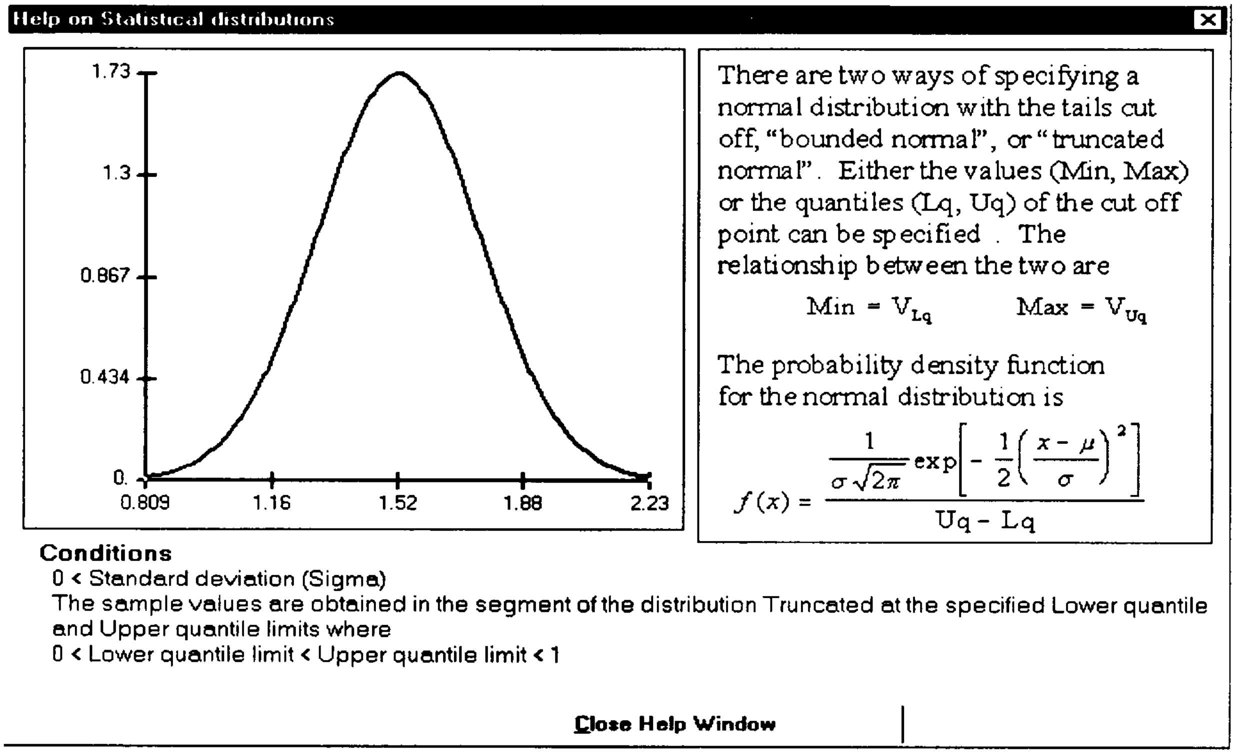
● Perform uncertainty analysis
○ Suppress uncertainty analysis this session

Figure 4.1 Parameter Distribution Input Screen

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

The N_{obs} samples generated for each probabilistic/uncertain parameter must be combined to produce N_{obs} sets of input parameters. Two methods of grouping (or combining) are available — random grouping or correlated/uncorrelated grouping. Under random grouping, the N_{obs} samples generated for each of the parameters are combined randomly to produce (N_{obs}) sets of inputs. For N_{var} probabilistic/uncertain parameters, there are $(N_{obs}!)^{N_{var}}$ ways of combining the samples. It is possible that some pairs of parameters may be correlated to some degree in the randomly selected grouping, especially if N_{obs} is not sufficiently larger than N_{var}.

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



There are two ways of specifying a normal distribution with the tails cut off, "bounded normal", or "truncated normal". Either the values (Min, Max) or the quantiles (Lq, Uq) of the cut off point can be specified . The relationship between the two are

$$\text{Min} = V_{Lq} \qquad \text{Max} = V_{Uq}$$

The probability density function for the normal distribution is

$$f(x) = \frac{\dfrac{1}{\sigma\sqrt{2\pi}}\exp\left[-\dfrac{1}{2}\left(\dfrac{x-\mu}{\sigma}\right)^2\right]}{Uq - Lq}$$

Conditions

0 < Standard deviation (Sigma)

The sample values are obtained in the segment of the distribution Truncated at the specified Lower quantile and Upper quantile limits where

0 < Lower quantile limit < Upper quantile limit < 1

Figure 4.2 An Example of a Help Screen Displaying Parameter Distribution

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

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

4.2 DISTRIBUTION OF PARAMETERS

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

4.3 PROBABILISTIC RESULTS

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

Table 4.1. Listing of Input Data and Information Needed for Sample Generation

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

RESRAD and RESBMC.RPT in RESRAD-BUILD.

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

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

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

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

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

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

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

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

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

Table 4.2. Comparison of Approaches for Correlating the Uncertainty in the Distribution of Doses to the Uncertainty in the Input Parameter

Approach	Advantages	Disadvantages
PCC	Measures linear relationship and gives the unique contribution of an input parameter to the resultant dose.	Large variations in scale distort PCC values, and PCC not of much use when the relationships are nonlinear.
SRC	Measures linear relationship without influence of scale between input parameter and resultant dose. It provides "shared" contribution of an input parameter to the resultant dose.	Less useful when the relationship between input parameter and resultant dose is nonlinear and the input parameters are highly correlated.
PRCC	Estimates nonlinear monotonic relationship and gives the unique contribution of an input parameter to the resultant dose.	Not useful when the relationship between input parameter and resultant dose is nonmonotonic.
SRRC	Estimates nonlinear monotonic relationship and provides "shared" contribution of an input parameter to the resultant dose.	Less useful when input parameters are highly correlated.

Source: Based in part on information from Cullen and Frey (1999).

5 SUMMARY AND DISCUSSION

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

- **Step 1: Listing and Categorizing Parameters**
  All the input parameters used in the RESRAD and RESRAD-BUILD codes (totaling about 200 parameters) were listed, categorized, and defined. The parameters were classified relative to physical, behavioral, or metabolic attributes. Any parameter that would not change if a different group of receptors was considered was classified as a physical parameter. Any parameter that would depend on the receptor's behavior and the scenario definition was classified as a behavioral parameter. Any parameter representing the metabolic characteristics of the potential receptor and that would be independent of the scenario being considered was classified as a metabolic parameter.

- **Step 2: Ranking Parameters**
  A strategy was developed to rank the input parameters and identify them according to their importance in meeting the objective of the analysis. The parameter rankings were divided into three levels: 1 (high priority), 2 (medium priority), and 3 (low priority). The parameters were ranked on the basis of four criteria: (1) relevance of the parameter in dose calculations; (2) variability of the radiation dose as a result of changes in the parameter value; (3) parameter type (physical, behavioral, or metabolic); and (4) availability of data on the parameter in the literature. A composite scoring system was developed to rank the parameters. Overall, 14 parameters were ranked as high priority, 59 were ranked as medium priority, and the remaining 122 were ranked as low priority for RESRAD and RESRAD-BUILD combined.

- **Step 3: Developing Parameter Distributions**
  Parameter distributions were developed for a total of 66 parameters identified in Step 2 as high or medium priority. The data were obtained from a variety of published sources representative of a national distribution. Because they are based on national average data, many of these distributions may not be appropriate for a site-specific assessment. However, their development was necessary for testing of the probabilistic modules in Step 4. Potential correlation among parameters was also studied and discussed.

- **Step 4: Testing Parameter Distributions for Probabilistic Analysis**
  The analysis fully demonstrated the process of using the integrated RESRAD and RESRAD-BUILD codes and the probabilistic modules, together with the parameter distributions, for dose assessment at a relatively complex site. This analysis indicated that a site-specific application could be implemented in cases where pertinent site data could be developed.

- **Step 5: Developing Probabilistic Modules**
  A preprocessor and a post-processor were developed for the RESRAD and RESRAD-BUILD codes for probabilistic dose and risk analysis. The parameter distributions developed in Step 3 were incorporated into the codes as default distributions. Both conventional Monte Carlo sampling and LHS methods are used in both codes. Text reports, interactive output, and graphic output are provided for viewing the results of analysis. A user's guide for the probabilistic code is available as a NUREG/CR document (LePoire et al., 2000).

- **Step 6: Testing Probabilistic Modules and Integrated Codes**
  Testing of the probabilistic codes was the sixth step. It was initiated early in the process when the probabilistic modules were being developed. All components of software modules (such as LHS sampling routine, input interface, output interface, graphic viewer, interactive output viewer) were tested when developed. Finally the integrated code system was tested extensively by Argonne, NRC, and others.

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

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

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

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

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

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ATTACHMENT A

PARAMETERS AND PARAMETER TYPES IN RESRAD AND RESRAD-BUILD CODES

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CONTENTS

TABLES

TABLES (Cont.)

NOTATION

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

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

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

UNITS OF MEASURE

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

PARAMETERS AND PARAMETER TYPES IN RESRAD AND RESRAD-BUILD CODES

1 INTRODUCTION

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

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

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

The RESRAD (Yu et al. 1993a) and RESRAD-BUILD (Yu et al. 1994) codes are currently designed to address Level 2 and Level 3 objectives entailing site-specific analysis. (RESRAD can also be used for Level 1 screening calculations provided a default dataset is developed.) The RESRAD and RESRAD-BUILD codes permit user input of site-specific data to model doses for various exposure scenarios. They have been developed by Argonne National Laboratory and approved by the U.S. Department of Energy (DOE) for evaluation of radioactively contaminated sites and buildings, respectively. These two codes are widely used in the United States and abroad to estimate doses from residual radioactive material and to set site-specific cleanup levels for radioactive contaminants. The RESRAD codes complement NRC's licensing efforts in developing methods for demonstrating compliance with decontamination and decommissioning rules.

1.1 PURPOSE AND SCOPE

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

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

1.2 MODEL DESCRIPTIONS

1.2.1 RESRAD

The RESRAD computer code (Yu et al. 1993a) implements the methodology described in DOE's manual for developing residual radioactive material guidelines for remediation sites. It calculates radiation dose and excess lifetime cancer risk to a chronically exposed on-site resident for different land use and exposure scenarios. The RESRAD code focuses on radioactive contaminants in soil and their transport in air, water, and biological media to a single receptor. Nine exposure pathways are considered in RESRAD: direct exposure, inhalation of particulates and radon, and ingestion of plant foods, meat, milk, aquatic foods, water, and soil. RESRAD uses a pathway analysis approach in which the relation between radionuclide concentrations in soil and the dose to a member of a critical population group is expressed as a pathway sum (the sum of products of "pathway factors"). Pathway factors correspond to pathway segments connecting compartments in the environment between which radionuclides can be transported or from which radiation can be emitted. Radiation doses, health risks, soil guidelines, and media concentrations of radionuclides are calculated for user-specified time intervals. The source is adjusted over time to account for radioactive decay and ingrowth, leaching, erosion, and mixing. RESRAD uses a one-dimensional groundwater model that accounts for differential transport of parent radionuclides and progeny with different distribution coefficients. (A three-dimensional groundwater model has been implemented in RESRAD-OFFSITE, which is currently being developed by Argonne National Laboratory.)

1.2.2 RESRAD-BUILD

The RESRAD-BUILD code (Yu et al. 1994) is a pathway analysis model designed to evaluate the potential radiological dose to an individual who works or lives in a building contaminated with radioactive material. It considers the releases of radionuclides into the indoor air by diffusion, mechanical removal, or erosion. The transport of radioactive material inside the building from one room or compartment to another is calculated with an indoor air quality model. A single run of the RESRAD-BUILD code can model a building with up to 3 rooms or compartments, 10 distinct source geometries, 10 receptor locations, and 8 shielding materials. A shielding material can be specified between each source-receptor pair for external gamma dose calculations. Seven exposure pathways are considered in RESRAD-BUILD: (1) external exposure directly from the source; (2) external exposure to materials deposited on the floor; (3) external exposure due to air submersion; (4) inhalation of airborne radioactive particulates; (5) inhalation of aerosol indoor radon progeny; (6) inadvertent ingestion of radioactive material directly from the sources; and (7) inadvertent ingestion of materials deposited on the surfaces of the building rooms.

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

1.3 PARAMETER CLASSIFICATION

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

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

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

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

2 MODEL PARAMETERS IN RESRAD AND RESRAD-BUILD

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

2.1 RESRAD PARAMETERS

Table 2.1[1] lists user changeable parameters in the RESRAD code. Additional information about these parameters can be obtained from the RESRAD User's Manual (Yu et. al. 1993a). Parameters are arranged according to the input window in which they appear. The number of parameters that a user can change will depend on the pathways and radionuclides selected. In RESRAD, a pathway can be turned on or off. Parameters pertaining to suppressed pathways are blanked out in the data entry screens because they would not be used in the calculations. Radon parameters can only be changed if radon precursor is selected in the radionuclide list and the radon pathway is on. Similarly, a user will have access to carbon-14 parameters only if carbon-14 is selected as a contaminant. Some parameters are nuclide or element specific. Table 2.1 mentions that characteristic of the parameter but does not provide details. Separate tables of nuclide- or element-specific data are also provided for the parameters (Tables 2.2 through 2.6). The code-accepted values are not provided for element- or nuclide-specific parameters. Table 2.1 also identifies the parameter types: physical (P), metabolic (M), and behavioral (B). For some parameters, more than one type is listed; the first one listed is the primary type and the next one is secondary. For example, inhalation rate is identified as M, B, which indicates that it depends primarily on the metabolic characteristics of the potential receptor, but that it also depends on the receptor behavior or exposure scenario.

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

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

2.2 RESRAD-BUILD PARAMETERS

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

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

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

Parameter Name	Unit	Default Value	Code-Accepted Values[a]	Type[b]	References	Description
Carbon-Model Parameters						
C-12 concentration in local water	g/cm^3	2E-5	0–100	P	Yu et al. 1993a	The stable carbon concentration in water.
C-12 concentration in contaminated soil	g/g	0.03	1E-4–1	P	Yu et al. 1993a	The stable carbon concentration in contaminated soil.
Fraction of vegetation carbon absorbed from soil	–	0.02	1E-4–1	P	Yu et al. 1993a	The fraction of total vegetation carbon obtained by direct root uptake from the soil.
Fraction of vegetation carbon absorbed from air	–	0.98	0–1	P	Yu et al. 1993a	The fraction of total vegetation carbon assimilated from the atmosphere through photosynthesis.
C-14 evasion layer thickness in soil	m	0.3	0–10	P	Yu et al. 1993a	The maximum soil thickness layer through which C-14 can escape to the air by conversion to CO_2. C-14 below this depth is assumed to be trapped.
C-14 evasion flux rate from soil	1/s	7E-07	0–1	P	Sheppard et al. 1991	The fraction of the soil inventory of C-14 that is lost to the atmosphere per unit time.
C-12 evasion flux rate from soil	1/s	1E-10	0–1	P	Amiro et al. 1991	The fraction of C-12 in soil that escapes to the atmosphere per unit time.
Grain fraction in livestock feed	–	0.8 (beef cattle) 0.2 (cow)	0–1 0–1	B	Amiro et al. 1991	The fraction of grain (non-leafy) vegetation in the livestock diet. The balance is assumed to be leafy vegetation: hay or fodder.

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

TABLE 2.1 (Cont.)

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

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

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

[c] "–" indicates that the parameter is dimensionless.

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

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

[f] NA = not applicable.

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

Radionuclide[c]	External DCFs (mrem/yr)/ (pCi/g)	Class[d]	Inhalation DCFs (mrem/pCi)	f_1[e]	Ingestion DCF (mrem/pCi)
H-3	0.0	(H2O)	6.40E-08	1	6.40E-08
C-14	1.34E-05	(ORGANIC)	2.09E-06	1	2.09E-06
Na-22	1.37E+01	D	7.66E-06	1	1.15E-05
Al-26	1.74E+01	D	7.96E-05	1.00E-02	1.46E-05
S-35	1.49E-05	W	2.48E-06	8.00E-01	7.33E-06
Cl-36	2.39E-03	W	2.19E-05	1	3.03E-06
K-40	1.04E-00	D	1.24E-05	1	1.86E-05
Ca-41	0.0	W	1.35E-06	3.00E-01	1.27E-06
Ca-45	6.26E-05	W	6.62E-06	3.00E-01	3.16E-06
Sc-46	1.27E+01	Y	2.96E-05	1.00E-04	6.40E-06
Mn-54	5.16E-00	W	6.70E-06	1.00E-01	2.77E-06
Fe-55	0.0	D	2.69E-06	1.00E-01	6.07E-07
Fe-59	7.64E-00	D	1.48E-05	1.00E-01	6.70E-06
Co-57	5.01E-01	Y	9.07E-06	3.00E-01	1.18E-06
Co-60	1.62E+01	Y	2.19E-04	3.00E-01	2.69E-05
Ni-59	0.0	(VAPOR)	2.70E-06	5.00E-02	2.10E-07
Ni-63	0.0	(VAPOR)	6.29E-06	5.00E-02	5.77E-07
Zn-65	3.70E-00	Y	2.04E-05	5.00E-01	1.44E-05
Ge-68+D	5.62E-00	W	5.19E-05	1	1.41E-06
Se-75	1.98E-00	W	8.47E-06	8.00E-01	9.62E-06
Se-79	1.86E-05	W	9.84E-06	8.00E-01	8.70E-06
Sr-85	2.97E-00	Y	5.03E-06	3.00E-01	1.98E-06
Sr-89	9.08E-03	Y	4.14E-05	1.00E-02	9.25E-06
Sr-90+D	2.46E-02	Y	1.31E-03	3.00E-01	1.53E-04
Zr-93	0.0	D	3.21E-04	2.00E-03	1.66E-06
Zr-95+D	4.52E-00	D	2.36E-05	2.00E-03	3.79E-06
Nb-93m	1.04E-04	Y	2.92E-05	1.00E-02	5.21E-07
Nb-94	9.68E-00	Y	4.14E-04	1.00E-02	7.14E-06
Nb-95	4.69E-00	Y	5.81E-06	1.00E-02	2.57E-06
Tc-99	1.26E-04	W	8.33E-06	8.00E-01	1.46E-06
Ru-106+D	1.29E-00	Y	4.77E-04	5.00E-02	2.74E-05
Ag-108m+D	9.65E-00	Y	2.83E-04	5.00E-02	7.62E-06
Ag-110m+D	1.72E+01	Y	8.03E-05	5.00E-02	1.08E-05
Cd-109	1.47E-02	D	1.14E-04	5.00E-02	1.31E-05

TABLE 2.2 (Cont.)

Radionuclide[c]	External DCFs (mrem/yr)/ (pCi/g)	Class[d]	Inhalation DCFs (mrem/pCi)	f_1[e]	Ingestion DCF (mrem/pCi)
Sn-113+D	1.46E-00	W	1.07E-05	2.00E-02	3.19E-06
Sb-124	1.17E+01	W	2.52E-05	1.00E-02	1.01E-05
Sb-125	2.45E-00	W	1.22E-05	1.00E-01	2.81E-06
Te-125m	1.51E-02	W	7.29E-06	2.00E-01	3.67E-06
I-125	1.66E-02	D	2.42E-05	1	3.85E-05
I-129	1.29E-02	D	1.74E-04	1	2.76E-04
Cs-134	9.47E-00	D	4.63E-05	1	7.33E-05
Cs-135	3.83E-05	D	4.55E-06	1	7.07E-06
Cs-137+D	3.41E-00	D	3.19E-05	1	5.00E-05
Ba-133	1.98	D	7.86E-06	1.00E-01	3.40E-06
Ce-141	3.18E-01	Y	8.95E-06	3.00E-04	2.90E-06
Ce-144+D	3.20E-01	Y	3.74E-04	3.00E-04	2.11E-05
Pm-147	5.01E-05	Y	3.92E-05	3.00E-04	1.05E-06
Sm-147	0.0	W	7.47E-02	3.00E-04	1.85E-04
Sm-151	9.84E-07	W	3.00E-05	3.00E-04	3.89E-07
Eu-152	7.01E-00	W	2.21E-04	1.00E-03	6.48E-06
Eu-154	7.68E-00	W	2.86E-04	1.00E-03	9.55E-06
Eu-155	1.82E-01	W	4.14E-05	1.00E-03	1.53E-06
Gd-152	0.0	D	2.43E-01	3.00E-04	1.61E-04
Gd-153	2.45E-01	D	2.38E-05	3.00E-04	1.17E-06
Ta-182	7.94E-00	Y	4.48E-05	1.00E-03	6.51E-06
Ir-192	4.61E-00	Y	2.82E-05	1.00E-02	5.74E-06
Au-195	2.07E-01	Y	1.30E-05	1.00E-01	1.06E-06
Tl-204	4.05E-03	D	2.41E-06	1	3.36E-06
Pb-210+D	6.05E-03	D	1.38E-02	2.00E-01	5.37E-03
Bi-207	9.38E-00	W	2.00E-05	5.00E-02	5.48E-06
Po-210	5.23E-05	W	9.40E-03	1.00E-01	1.90E-03
Ra-226+D	1.12E+01	W	8.60E-03	2.00E-01	1.33E-03
Ra-228+D	5.98E-00	W	5.08E-03	2.00E-01	1.44E-03
Ac-227+D	2.01E-00	D	6.72	1.00E-03	1.48E-02
Th-228+D	1.02E+01	Y	3.45E-01	2.00E-04	8.08E-04
Th-229+D	1.60E-00	W	2.16	2.00E-04	4.03E-03
Th-230	1.21E-03	W	3.26E-01	2.00E-04	5.48E-04
Th-232	5.21E-04	W	1.64	2.00E-04	2.73E-03

TABLE 2.2 (Cont.)

Radionuclide[c]	External DCFs (mrem/yr)/ (pCi/g)	Class[d]	Inhalation DCFs (mrem/pCi)	f_1[e]	Ingestion DCF (mrem/pCi)
Pa-231	1.91E-01	W	1.28	1.00E-03	1.06E-02
U-232	9.02E-04	Y	6.59E-01	5.00E-02	1.31E-03
U-233	1.40E-03	Y	1.35E-01	5.00E-02	2.89E-04
U-234	4.02E-04	Y	1.32E-01	5.00E-02	2.83E-04
U-235+D	7.57E-01	Y	1.23E-01	5.00E-02	2.67E-04
U-236	2.15E-04	Y	1.25E-01	5.00E-02	2.69E-04
U-238+D	1.37E-01	Y	1.18E-01	5.00E-02	2.69E-04
Np-237+D	1.10E-00	W	5.40E-01	1.00E-03	4.44E-03
Pu-238	1.51E-04	W	3.92E-01	1.00E-03	3.20E-03
Pu-239	2.95E-04	W	4.29E-01	1.00E-03	3.54E-03
Pu-240	1.47E-04	W	4.29E-01	1.00E-03	3.54E-03
Pu-241+D	1.89E-05	W	8.25E-03	1.00E-03	6.85E-05
Pu-242	1.28E-04	W	4.11E-01	1.00E-03	3.36E-03
Pu-244+D	7.73E-00	W	4.03E-01	1.00E-03	3.32E-03
Am-241	4.37E-02	W	4.44E-01	1.00E-03	3.64E-03
Am-243+D	8.95E-01	W	4.40E-01	1.00E-03	3.63E-03
Cm-243	5.83E-01	W	3.07E-01	1.00E-03	2.51E-03
Cm-244	1.26E-04	W	2.48E-01	1.00E-03	2.02E-03
Cm-245	3.40E-01	W	4.55E-01	1.00E-03	3.74E-03
Cm-246	1.16E-04	W	4.51E-01	1.00E-03	3.70E-03
Cm-247+D	1.86	W	4.14E-01	1.00E-03	3.42E-03
Cm-248	8.78E-05	W	1.65	1.00E-03	1.36E-02
Cf-252	1.76E-04	Y	1.57E-01	1.00E-03	1.08E-03

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

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

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

[d] The three inhalation classes D, W, and Y correspond to retention half-times of less than 10 days, 10 to 100 days, and greater than 100 days, respectively. (H_2O) indicates water; (ORGANIC) indicates an organic material; and (VAPOR) indicates a gaseous material.

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

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

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

TABLE 2.3 (Cont.)

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

TABLE 2.3 (Cont.)

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

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

[b] Calculated by using dose conversion factor and risk coefficient.

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

TABLE 2.4 Default Distribution Coefficients Used in RESRAD

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

TABLE 2.4 (Cont.)

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

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

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

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

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

TABLE 2.5 (Cont.)

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

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

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

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

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

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

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

TABLE 2.7 (Cont.)

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

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

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

[c] "–" indicates that the parameter is dimensionless.

[d] Value for this parameter will appear only if more than one room is selected in the "number of rooms" parameter.

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

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

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

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

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

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

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

Source: Eckerman and Ryman (1993).

3 TREATMENT OF SHORT-LIVED RADIONUCLIDES AND PARAMETER TYPES

3.1 TREATMENT OF SHORT-LIVED RADIONUCLIDES

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

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

3.2 PARAMETER TYPES AND DEFAULT VALUES

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

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

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

TABLE 3.1 (Cont.)

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

TABLE 3.1 (Cont.)

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

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

[b] "–" indicates that radionuclide is not available in the database.

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

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

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

TABLE 3.2 (Cont.)

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

TABLE 3.2 (Cont.)

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

TABLE 3.2 (Cont.)

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

TABLE 3.2 (Cont.)

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

TABLE 3.2 (Cont.)

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

TABLE 3.2 (Cont.)

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

[a] **Parameter types, P = physical, B = behavioral, M = metabolic.**

[b] Hyphen indicates that the parameter is dimensionless.

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

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

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

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

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

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

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

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

[k] The irrigation rate in DandD has the unit of L/m^2•day.

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

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

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

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

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

Footnotes continue on next page

TABLE 3.2 (Cont.)

Footnotes (continued)

[q] In the DandD code, floor dust, resuspension factor, indoor dust, outdoor dust, and gardening dust are used to calculate inhalation doses.

[r] In the DandD code this parameter is called indoor shielding factor. DandD also has a outdoor shielding factor for external exposure with the default set at 1.

[s] Instead of the indoor and outdoor time fractions, the DandD code uses time indoors, time outdoors, time gardening, exposure period, and garden period. Time indoors, time outdoors, and time gardening are behavioral parameters. Exposure period and garden period are behavioral parameters with constant value.

[t] The DandD code uses the fraction of human diet grown on-site. The default value for this parameter is 1, i.e., 100% is grown on-site.

[u] DandD uses separate animal feed intake rates for forage, grain, and hay for beef cattle, poultry, and layer hens. Default values listed in this table are for beef cattle.

[v] DandD uses separate animal feed intake rates for forage, grain, and hay for milk cows.

[w] DandD uses animal intake mass fraction of soil in dry fresh forage; the values are 0.02 for beef cattle and milk cows and 0.1 for layer hens and poultry.

[x] DandD uses plant mass loading (0.1 g/g) for leafy vegetables, other vegetables, fruit, grain, and also forage, grain, stored hay consumed by beef cattle, poultry, milk cows, and layer hens.

[y] In the DandD code this parameter is the weathering rate for activity removal of radionuclides from plants.

[z] The DandD code does not include the radon inhalation pathway in dose calculations.

[aa] This parameter is called the holdup period in the DandD code, and values are not provided for fish and water.

[bb] The DandD code has different carbon-model parameters. The parameters are mass fractions for beef, poultry, milk, eggs, forage, grain, hay, soil and animal activity. All parameters are physical with constant value.

[cc] The DandD code does not calculate risk.

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

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

TABLE 3.3 (Cont.)

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

See next page for footnotes.

TABLE 3.3 (Cont.)

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

[b] NA = not applicable (parameter is not required in the code).

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

[d] Time in building in DandD is related to total time and indoor fraction in RESRAD-BUILD

[e] Occupancy period in DandD is the same as total time in RESRAD-BUILD.

[f] Breathing rate in DandD and receptor inhalation rate in RESRAD-BUILD.

[g] DandD uses resuspension factor and RESRAD-BUILD uses resuspension rate.

[h] DandD uses the direct ingestion rate in m^2/h; whereas RESRAD-BUILD requires both direct and indirect ingestion rates. Direct ingestion rate has units of g/h or 1/h, and indirect ingestion rate has units of m^2/h.

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ATTACHMENT B

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

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NOTATION

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

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

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

UNITS OF MEASURE

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

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

1 INTRODUCTION

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

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

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

implementation of that strategy. It is the second of a series of letter reports for the first four subtasks discussed above. Results in this report will be used as the basis for prioritizing efforts in subtask 3[2] to conduct detailed analysis for parameter distributions.

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

2 RANKING STRATEGY FOR INPUT PARAMETERS

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

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

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

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

2.1 CRITERION 1: RELEVANCE OF PARAMETERS IN DOSE CALCULATIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The time at which the peak doses would occur in the future varied among the representative radionuclides. To observe the potential dose contributions from the groundwater-related pathways (which, for many contaminated sites, might be the critical pathways), the calculation time frame was extended to 3,000 years in the RESRAD code. Such an extension of the calculation time beyond 1,000 years (the time frame used in decontamination and decommissioning dose assessments) was necessary to fully explore the impact potential of the soil and water transport parameters on the radiation doses.

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

2.3 CRITERION 3: PARAMETER TYPE

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

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

2.4 CRITERION 4: DATA AVAILABILITY

The availability of data from the open literature varies, depending on the parameter being considered. Previous efforts resulted in the publication of several reports that compile and analyze probabilistic distributions for some input parameters. These reports include the ones published by the NRC for the DandD code (Beyeler et al. 1997 and 1998) and the one prepared by the Pacific Northwest National Laboratory for the soil/water distribution coefficient parameter (Kd) (Krupka et al. 1999). In addition, Argonne had compiled distribution information for some of the RESRAD parameters. Therefore, data for the parameters included in these reports are available, so less effort would be required to conduct further literature searches, and detailed analyses of probabilistic distributions could be undertaken in a shorter period of time. For the purpose of analyzing more parameters within the scope of this project, parameters included in the mentioned documents should be given a higher priority in the ranking process.

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

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

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

2.5 FINAL RANKING

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

3 DOSE VARIABILITY ANALYSES FOR CRITERION 2

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

3.1 Analyses for the RESRAD Parameters

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

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

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

3.2 Analyses for the RESRAD-BUILD Parameters

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

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

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

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

4 OVERALL RANKING RESULTS

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

4.1 Ranking Results for RESRAD

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

4.2 Ranking Results for RESRAD-BUILD

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

APPENDIX: CRITICAL PATHWAYS FOR THE REPRESENTATIVE RADIONUCLIDES

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

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

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

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

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

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

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

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

Table 3.1 Dose Variability Analysis Results for the RESRAD Input Parameters

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Source										
Nuclide concentration (pCi/g)	0.1	1	10	Base value corresponds to the default value used in the DandD code. Low and high values were 1/10 of and 10 times, respectively, the base value. They were selected to observe change in radiation doses.	Co-60	5.803E-01	5.803E+00	5.803E+01	990.00	990.00
					Sr-90	1.396E-01	1.396E+00	1.396E+01	990.00	
					Cs-137	1.465E-01	1.465E+00	1.465E+01	990.00	
					Ra-226	3.615E+00	3.615E+01	3.615E+02	990.00	
					Th-230	5.420E-02	5.420E-01	5.420E+00	990.00	
					U-238	1.736E-01	1.736E+00	1.736E+01	990.00	
					Pu-239	3.252E-01	3.252E+00	3.252E+01	990.00	
					Am-241	1.659E-02	1.659E-01	1.659E+00	990.00	
Transport Factors										
Distribution coefficients (contaminated zone, unsaturated zones, and saturated zone)(cm^3/g)	See Table 3.2	See Table3.2	See Table 3.2	See Table 3.2.	Co-60	5.752E+00	5.803E+00	5.803E+00	0.88	95.45
					Sr-90	1.372E+00	1.396E+00	1.414E+00	3.01	
					Cs-137	1.465E+00	1.465E+00	1.546E+00	5.53	
					Ra-226	3.611E+01	3.615E+01	3.615E+01	0.11	
					Th-230	5.032E-01	5.420E-01	7.814E-01	51.33	
					U-238	1.736E+00	1.736E+00	9.829E-02	94.34	
					Pu-239	3.252E+00	3.252E+00	1.480E-01	95.45	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Contaminated Zone Parameters										
Area of contaminated zone (m^2)	100	2400	10000	Base value corresponds to the default value used in the DandD code. Low and high values were selected to observe change in radiation doses.	Co-60	4.832E+00	5.803E+00	5.959E+00	19.42	117.48
					Sr-90	1.393E+00	1.396E+00	1.396E+00	0.21	
					Cs-137	1.254E+00	1.465E+00	1.496E+00	16.52	
					Ra-226	3.532E+01	3.615E+01	3.638E+01	2.93	
					Th-230	5.211E-01	5.420E-01	5.465E-01	4.69	
					U-238	7.234E-02	1.736E+00	2.098E+00	116.69	
					Pu-239	1.355E-01	3.252E+00	3.956E+00	117.48	
					Am-241	1.156E-01	1.659E-01	1.680E-01	31.59	
Thickness of contaminated zone (m)	0.15	0.15	4	Base value corresponds to the default value used in the DandD code. Low and high values were selected to observe change in radiation doses.	Co-60	5.803E+00	5.803E+00	7.029E+00	21.13	6156.46
					Sr-90	1.396E+00	1.396E+00	8.095E+00	479.87	
					Cs-137	1.465E+00	1.465E+00	2.147E+00	46.55	
					Ra-226	3.615E+01	3.615E+01	8.167E+01	125.92	
					Th-230	5.420E-01	5.420E-01	3.391E+01	6156.46	
					U-238	1.736E+00	1.736E+00	3.079E+01	1673.62	
					Pu-239	3.252E+00	3.252E+00	6.020E+01	1751.17	
					Am-241	1.659E-01	1.659E-01	5.706E-01	243.94	
Length parallel to aquifer flow (m)	10	48.99	100	Values correspond to square roots of the "area of contaminated zone" parameter.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	71.32
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	2.090E+00	1.736E+00	8.518E-01	71.32	
					Pu-239	3.914E+00	3.252E+00	1.600E+00	71.16	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Cover and Contaminated Zone Hydrological Data										
Cover depth (m)	0	0	0.3	High value was selected to observe potential reduction in radiation doses.	Co-60	5.803E+00	5.803E+00	2.568E-01	95.57	158.86
					Sr-90	1.396E+00	1.396E+00	1.314E+00	5.87	
					Cs-137	1.465E+00	1.465E+00	1.165E-01	92.05	
					Ra-226	3.615E+01	3.615E+01	3.212E+01	11.15	
					Th-230	5.420E-01	5.420E-01	1.403E+00	158.86	
					U-238	1.736E+00	1.736E+00	1.758E+00	1.27	
					Pu-239	3.252E+00	3.252E+00	3.548E+00	9.10	
					Am-241	1.659E-01	1.659E-01	8.132E-02	50.98	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Density of cover material (g/cm^3) [2]	0.86	1.4312	1.76	Low and high values are from Baes and Sharp (1983). Base value corresponds to the default value used in the DandD code.	Co-60	7.934E-01	2.568E-01	1.545E-01	248.79	248.79
					Sr-90	1.314E+00	1.314E+00	1.314E+00	0.00	
					Cs-137	2.023E-01	1.165E-01	1.037E-01	84.64	
					Ra-226	3.254E+01	3.212E+01	3.204E+01	1.56	
					Th-230	1.404E+00	1.403E+00	1.403E+00	0.07	
					U-238	1.758E+00	1.758E+00	1.758E+00	0.00	
					Pu-239	3.548E+00	3.548E+00	3.548E+00	0.00	
					Am-241	8.140E-02	8.132E-02	8.130E-02	0.12	
Cover erosion rate (m/yr) [2]	0	0.001	0.001	Judging from previously searched literature data, the RESRAD default value of 0.001 m/yr is the high end of the erosion rate. Therefore, it was used as the high value.	Co-60	2.558E-01	2.568E-01	2.568E-01	0.39	12.90
					Sr-90	1.314E+00	1.314E+00	1.314E+00	0.00	
					Cs-137	1.164E-01	1.165E-01	1.165E-01	0.09	
					Ra-226	3.208E+01	3.212E+01	3.212E+01	0.12	
					Th-230	1.222E+00	1.403E+00	1.403E+00	12.90	
					U-238	1.758E+00	1.758E+00	1.758E+00	0.00	
					Pu-239	3.548E+00	3.548E+00	3.548E+00	0.00	
					Am-241	8.078E-02	8.132E-02	8.132E-02	0.66	
Density of contaminated zone (g/cm^3)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60	4.664E+00	5.803E+00	6.185E+00	26.21	73.76
					Sr-90	1.380E+00	1.396E+00	1.400E+00	1.43	
					Cs-137	1.202E+00	1.465E+00	1.546E+00	23.48	
					Ra-226	2.324E+01	3.615E+01	4.337E+01	55.68	
					Th-230	2.899E-01	5.420E-01	6.897E-01	73.76	
					U-238	1.033E+00	1.736E+00	2.104E+00	61.69	
					Pu-239	2.027E+00	3.252E+00	3.915E+00	58.06	
					Am-241	1.656E-01	1.659E-01	1.660E-01	0.24	
Contaminated zone total porosity	0.34	0.4599	0.68	Low and high values were calculated by using the equation $\theta = 1 - \rho_b / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_b is the bulk soil density. Base value is the default value used in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	23.40
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.464E+00	1.465E+00	1.466E+00	0.14	
					Ra-226	3.971E+01	3.615E+01	3.125E+01	23.40	
					Th-230	5.739E-01	5.420E-01	4.944E-01	14.67	
					U-238	1.737E+00	1.736E+00	1.728E+00	0.52	
					Pu-239	3.253E+00	3.252E+00	3.250E+00	0.09	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Contaminated zone field capacity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.12
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.734E+00	0.12	
					Pu-239	3.252E+00	3.252E+00	3.251E+00	0.03	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Contaminated zone erosion rate (m/yr)	0	0.001	0.001	Judging from previously searched literature data, the RESRAD default value of 0.001 m/yr is at the high end of the erosion rate. Therefore, it was used as the high value.	Co-60	5.810E+00	5.803E+00	5.803E+00	0.12	159.04
					Sr-90	1.400E+00	1.396E+00	1.396E+00	0.29	
					Cs-137	1.467E+00	1.465E+00	1.465E+00	0.14	
					Ra-226	3.672E+01	3.615E+01	3.615E+01	1.58	
					Th-230	1.404E+00	5.420E-01	5.420E-01	159.04	
					U-238	1.758E+00	1.736E+00	1.736E+00	1.27	
					Pu-239	3.548E+00	3.252E+00	3.252E+00	9.10	
					Am-241	1.664E-01	1.659E-01	1.659E-01	0.30	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Contaminated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1e-5 to 1e+7. The high and low values were selected to observe the max. variation in potential radiation exposure.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.35
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.464E+00	0.07	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.421E-01	5.420E-01	5.419E-01	0.04	
					U-238	1.731E+00	1.736E+00	1.737E+00	0.35	
					Pu-239	3.250E+00	3.252E+00	3.253E+00	0.09	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Contaminated zone b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayey soil. Both limit values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.23
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.464E+00	1.465E+00	1.465E+00	0.07	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.418E-01	5.420E-01	5.420E-01	0.04	
					U-238	1.737E+00	1.736E+00	1.733E+00	0.23	
					Pu-239	3.254E+00	3.252E+00	3.251E+00	0.09	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Humidity in air (g/m^3)	3	8	16.5	Etnier (1980).	H-3	3.348E-03	3.348E-03	3.348E-03	0.00	0.00
Evapotranspiration coefficient	0.5	0.7	0.9	High value from Kamboj et al. (1997) for the Hanford site. Base value was selected, in conjunction with the value for the runoff coefficient, to approximate an infiltration rate of 0.2526 m/yr, the default value used in the DandD code.	Co-60	5.802E+00	5.803E+00	5.805E+00	0.05	44.19
					Sr-90	1.381E+00	1.396E+00	1.411E+00	2.15	
					Cs-137	1.414E+00	1.465E+00	1.518E+00	7.10	
					Ra-226	3.614E+01	3.615E+01	3.615E+01	0.03	
					Th-230	4.452E-01	5.420E-01	6.847E-01	44.19	
					U-238	1.744E+00	1.736E+00	1.676E+00	3.92	
					Pu-239	3.379E+00	3.252E+00	2.663E+00	22.02	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Wind speed (m/s)	1	2	4	Low and high values were taken to be 1/2 of and twice, respectively, the base value. The base value is the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	7.29
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.627E+01	3.615E+01	3.609E+01	0.50	
					Th-230	5.448E-01	5.420E-01	5.406E-01	0.77	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.743E-01	1.659E-01	1.622E-01	7.29	
Precipitation rate (m/yr)	0.161	1	1.617	High value from Bair (1992). Low value from Kamboj et al. (1997) for the Hanford site. The base value is the RESRAD default value.	Co-60	5.805E+00	5.803E+00	5.802E+00	0.05	43.84
					Sr-90	1.412E+00	1.396E+00	1.384E+00	2.01	
					Cs-137	1.523E+00	1.465E+00	1.424E+00	6.76	
					Ra-226	3.615E+01	3.615E+01	3.614E+01	0.03	
					Th-230	6.997E-01	5.420E-01	4.621E-01	43.84	
					U-238	1.651E+00	1.736E+00	1.743E+00	5.30	
					Pu-239	2.503E+00	3.252E+00	3.359E+00	26.32	
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06	
Irrigation rate (m/yr)	0.0396	0.1125	0.33	Data from Table 3.71 of Beyeler et al. (1998). The reported values in $L/m^2/d$ were converted to give values in m/yr with the assumption that duration for gardening activities was 90 days/yr.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	15.50
					Sr-90	1.398E+00	1.396E+00	1.390E+00	0.57	
					Cs-137	1.472E+00	1.465E+00	1.444E+00	1.91	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.580E-01	5.420E-01	4.989E-01	10.90	
					U-238	1.668E+00	1.736E+00	1.937E+00	15.50	
					Pu-239	3.128E+00	3.252E+00	3.605E+00	14.67	
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06	

Table 3.1 (Continued)

	Parameter Value					Corresponding Peak Dose (mrem/yr)				
Parameter	**Low**	**Base**	**High**	**Source**	**Nuclide**	**Low**	**Base**	**High**	**NDD[1]**	**Max. of NDD**
Runoff coefficient	0.03	0.3	0.7	High value from Gilbert et al. (1983). Low value from Kamboj et al. (1997). The base value was selected, in conjunction with the value for the evapotranspiration coefficient, to approximate an infiltration rate of 0.2526 m/yr, the default value used in the DandD code.	Co-60	5.802E+00	5.803E+00	5.804E+00	0.03	28.04
					Sr-90	1.388E+00	1.396E+00	1.407E+00	1.36	
					Cs-137	1.439E+00	1.465E+00	1.504E+00	4.44	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	4.894E-01	5.420E-01	6.414E-01	28.04	
					U-238	1.741E+00	1.736E+00	1.715E+00	1.50	
					Pu-239	3.329E+00	3.252E+00	2.958E+00	11.41	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Watershed area for nearby stream or pond (m^2)	10000	1,000,000	1,000,000	Low value set to be 1/100 of the base value. The base value is the default value used in the RESRAD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	40.25
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.985E+00	1.736E+00	1.736E+00	14.34	
					Pu-239	4.561E+00	3.252E+00	3.252E+00	40.25	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated Zone Hydrological Data										
Density of saturated zone (g/m3)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	82.32
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	2.598E+00	1.736E+00	1.449E+00	66.19	
					Pu-239	5.333E+00	3.252E+00	2.656E+00	82.32	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated zone total porosity	0.34	0.4599	0.68	Low and high values were calculated by using the equation $\theta = 1 - \rho_b / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_b is the bulk soil density. The base value is the default value used in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	71.96
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.332E+00	1.736E+00	2.368E+00	59.68	
					Pu-239	2.418E+00	3.252E+00	4.758E+00	71.96	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated zone effective porosity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	150.03
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	3.402E+00	1.736E+00	8.686E-01	145.93	
					Pu-239	6.505E+00	3.252E+00	1.626E+00	150.03	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated zone field capacity	0.1	0.2	0.4	Low and high values were taken to be 1/2 of and twice, respectively, the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	

Table 3.1 (Continued)

	Parameter Value					Corresponding Peak Dose (mrem/yr)				
Parameter	**Low**	**Base**	**High**	**Source**	**Nuclide**	**Low**	**Base**	**High**	**NDD'**	**Max. of NDD**
Saturated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1E-5 to 1E7. The high and low values were set to observe the max. variation in potential radiation exposure.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	116.93
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	7.746E-02	1.736E+00	2.053E+00	113.80	
					Pu-239	1.425E-01	3.252E+00	3.945E+00	116.93	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated zone hydraulic gradient	0.002	0.02	0.2	Low and high values taken to be 1/10 of and ten times, respectively, the base value, which is the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	110.27
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.759E-01	1.736E+00	2.052E+00	108.07	
					Pu-239	3.371E-01	3.252E+00	3.923E+00	110.27	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Saturated zone b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayey soil. Both the limit values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Water table drop rate (m/yr)	0.0005	0.001	0.002	Low and high values were taken to be 1/2 of and twice, respectively, the base value, which is the default value used in the RESRAD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Well pump intake depth (below water table) (m)	5	10	20	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	40.22
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.704E+00	1.736E+00	1.046E+00	37.90	
					Pu-239	3.265E+00	3.252E+00	1.957E+00	40.22	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Well pumping rate (m^3/yr)	54.884	118	276	Table 3.8.1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	77.55
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	2.090E+00	1.736E+00	7.437E-01	77.55	
					Pu-239	3.914E+00	3.252E+00	1.398E+00	77.37	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
	Low	Base	High			Low	Base	High		
Uncontaminated Unsaturated Zone Parameters										
Unsaturated zone thickness (m)	0.3	1.2288	316	The base value is the default value used in the DandD code. The low and high are from page 5.2-4, Beyeler et al. (1998)	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	95.71
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	7.746E-02	95.54	
					Pu-239	3.255E+00	3.252E+00	1.425E-01	95.71	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Unsaturated zone density (g/cm^3)	0.86	1.4312	1.76	Base value is the default value used in the DandD code. Low and high values were obtained from Baes and Sharp (1983).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.09
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.254E+00	3.252E+00	3.251E+00	0.09	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Unsaturated zone total porosity	0.34	0.4599	0.68	The low and high values were calculated by using the equation $\theta = 1 - \rho_b / 2.65$, where 2.65 is the soil particle density, θ is the total porosity, and ρ_b is the bulk soil density. The base value is the default value used in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.06
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.251E+00	3.252E+00	3.253E+00	0.06	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Unsaturated zone effective porosity	0.1	0.2	0.4	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.18
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.254E+00	3.252E+00	3.248E+00	0.18	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Unsaturated zone field capacity	0.1	0.2	0.4	Low and high values taken to be 1/2 of and twice, respectively, the base value, which is the RESRAD default value. Judging by the values listed in Table E.7 of Yu et al. (1993), these selections seem to be representative.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Unsaturated zone, soil-b parameter	0.998	5.3	14.2	The base value is the RESRAD default value. The low corresponds to the mean value for sand soil. The high value corresponds to the mean value for clayed soil. Both the limits values were obtained from Table 5.3.6 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Unsaturated zone hydraulic conductivity (m/yr)	0.001	10	200	The value can range several orders of magnitude from 1E-5 to 1E7. The high and low values were set to observe the maximal variation in potential radiation exposure.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Occupancy, Inhalation, and External Gamma Parameters										
Inhalation rate (m^3/yr)	4200	8578	16400	The base value was calculated by using the default inhalation rates (for outdoor, indoor, and gardening activities) and time fractions (for outdoor, indoor, and gardening activities) in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	5.91
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.413E-01	5.420E-01	5.432E-01	0.35	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.624E-01	1.659E-01	1.722E-01	5.91	
Mass loading for inhalation (g/m^3)	1E-7	3.014E-5	2.54E0-4	The base value was calculated by using the mass loading values (for outdoor and gardening activities) and time fractions (for outdoor and gardening activities) in the DandD code. The low value is from Beyeler et al. (1998). The high value is from Gilbert et al. (1989).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	34.90
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.406E-01	5.420E-01	5.521E-01	2.12	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.591E-01	1.659E-01	2.170E-01	34.90	
Indoor dust filtration factor	0.05	0.449	0.7	The low and high values are from Alzona et al. (1979). The base value was the ratio of dust loading factor indoors to dust loading factor outdoors in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	4.28
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.411E-01	5.420E-01	5.425E-01	0.26	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.616E-01	1.659E-01	1.687E-01	4.28	
Exposure duration (yr)	1	30	70	High value set to the average life span. The base value is the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.00
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
External gamma shielding factor	0.43	0.552	0.837	Figure 3.4.3 of Beyeler et al. (1998).	Co-60	4.857E+00	5.803E+00	8.014E+00	54.40	54.40
					Sr-90	1.394E+00	1.396E+00	1.400E+00	0.43	
					Cs-137	1.253E+00	1.465E+00	1.960E+00	48.26	
					Ra-226	3.544E+01	3.615E+01	3.781E+01	6.56	
					Th-230	5.304E-01	5.420E-01	5.691E-01	7.14	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.627E-01	1.659E-01	1.735E-01	6.51	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
	Low	Base	High			Low	Base	High		
Indoor time fraction	0.518	0.65	0.781	Beyeler et al. (1998).	Co-60	4.933E+00	5.803E+00	6.666E+00	29.86	37.51
					Sr-90	1.394E+00	1.396E+00	1.398E+00	0.29	
					Cs-137	1.270E+00	1.465E+00	1.658E+00	26.48	
					Ra-226	2.934E+01	3.615E+01	4.290E+01	37.51	
					Th-230	4.432E-01	5.420E-01	6.400E-01	36.31	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.533E-01	1.659E-01	1.785E-01	15.19	
Outdoor time fraction	0.055	0.12	0.2405	Beyeler et al. (1998).	Co-60	5.027E+00	5.803E+00	7.241E+00	38.15	38.15
					Sr-90	1.394E+00	1.396E+00	1.399E+00	0.36	
					Cs-137	1.291E+00	1.465E+00	1.787E+00	33.86	
					Ra-226	3.556E+01	3.615E+01	3.723E+01	4.62	
					Th-230	5.320E-01	5.420E-01	5.605E-01	5.26	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.579E-01	1.659E-01	1.808E-01	13.80	
Ingestion Pathway, Dietary Data										
Fruit, vegetables, and grain consumption (kg/yr)	56	111.8	844	The high value is from EPA (1997). The base value was calculated by using the default values in the DandD code. The low value is set to 1/2 of the base value.	Co-60	5.784E+00	5.803E+00	6.048E+00	4.55	418.32
					Sr-90	9.823E-01	1.396E+00	6.822E+00	418.32	
					Cs-137	1.447E+00	1.465E+00	1.693E+00	16.79	
					Ra-226	3.564E+01	3.615E+01	4.331E+01	21.22	
					Th-230	5.300E-01	5.420E-01	6.999E-01	31.35	
					U-238	1.721E+00	1.736E+00	1.936E+00	12.38	
					Pu-239	3.223E+00	3.252E+00	3.638E+00	12.76	
					Am-241	1.320E-01	1.659E-01	6.118E-01	289.21	
Leafy vegetable consumption	7	21.4	64	The low value is from Hoffman and Baes (1979) for children. The high value is from NRC (1977) for adults. The base value is the default value used in the DandD code.	Co-60	5.798E+00	5.803E+00	5.817E+00	0.33	30.23
					Sr-90	1.289E+00	1.396E+00	1.711E+00	30.23	
					Cs-137	1.460E+00	1.465E+00	1.478E+00	1.23	
					Ra-226	3.602E+01	3.615E+01	3.653E+01	1.41	
					Th-230	5.388E-01	5.420E-01	5.512E-01	2.29	
					U-238	1.706E+00	1.736E+00	1.711E+00	0.29	
					Pu-239	3.194E+00	3.252E+00	3.423E+00	7.04	
					Am-241	1.567E-01	1.659E-01	1.933E-01	22.06	
Milk consumption (L/yr)	112	233	778	The high value is from EPA (1997). The base value is the default value used in the DandD code. The low value is 1/2 of the base value.	Co-60	5.795E+00	5.803E+00	5.840E+00	0.78	51.93
					Sr-90	1.264E+00	1.396E+00	1.989E+00	51.93	
					Cs-137	1.423E+00	1.465E+00	1.653E+00	15.70	
					Ra-226	3.600E+01	3.615E+01	3.683E+01	2.30	
					Th-230	5.390E-01	5.420E-01	5.552E-01	2.99	
					U-238	1.709E+00	1.736E+00	1.860E+00	8.70	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.655E-01	1.659E-01	1.680E-01	1.51	
Meat and poultry consumption (kg/yr)	51	65.1	178	The low value is from the reported min. for meat consumption by the USDA (1992). The high value is from EPA (1997). The base value is the default value used in the DandD code.	Co-60	5.797E+00	5.803E+00	5.852E+00	0.95	19.91
					Sr-90	1.365E+00	1.396E+00	1.643E+00	19.91	
					Cs-137	1.451E+00	1.465E+00	1.573E+00	8.33	
					Ra-226	3.613E+01	3.615E+01	3.626E+01	0.36	
					Th-230	5.414E-01	5.420E-01	5.466E-01	0.96	
					U-238	1.735E+00	1.736E+00	1.745E+00	0.58	
					Pu-239	3.251E+00	3.252E+00	3.257E+00	0.18	
					Am-241	1.647E-01	1.659E-01	1.763E-01	6.99	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Fish consumption (kg/yr)	2.66	20.6	29.41	Low and high values are from Rupp et al. (1980) for the consumption rate of freshwater finfish. The base value is the default value used in the DandD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.46
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.734E+00	1.736E+00	1.737E+00	0.17	
					Pu-239	3.242E+00	3.252E+00	3.257E+00	0.46	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Other seafood consumption (kg/yr)	0	0.9	11.52	Low and high values are from Rupp et al. (1980) for the consumption of shellfish. The base value is the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.68
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.742E+00	0.35	
					Pu-239	3.250E+00	3.252E+00	3.272E+00	0.68	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Soil ingestion rate (g/yr)	0	18.25	36.5	Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.804E+00	0.02	61.42
					Sr-90	1.394E+00	1.396E+00	1.398E+00	0.29	
					Cs-137	1.464E+00	1.465E+00	1.465E+00	0.07	
					Ra-226	3.613E+01	3.615E+01	3.617E+01	0.11	
					Th-230	5.390E-01	5.420E-01	5.450E-01	1.11	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.150E-01	1.659E-01	2.169E-01	61.42	
Drinking water intake (L/yr)	154.45	478.5	1468	The base value is the mean value reported in Beyeler et al. (1998). The low and high values correspond to the values one standard deviation lower and higher, respectively, than the mean value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	260.92
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	6.523E-01	1.736E+00	5.046E+00	253.09	
					Pu-239	1.159E+00	3.252E+00	9.644E+00	260.92	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Aquatic food contaminated fraction	0	1	1	The base value is based on the assumption that all the ingested aquatic food is contaminated.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.40
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.734E+00	1.736E+00	1.736E+00	0.12	
					Pu-239	3.239E+00	3.252E+00	3.252E+00	0.40	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Ingestion Pathway, Non-dietary Data										
Livestock fodder intake for meat (kg/d)	13.4	26.81	53.6	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated fodder that is ingested.	Co-60	5.797E+00	5.803E+00	5.815E+00	0.31	11.17
					Sr-90	1.344E+00	1.396E+00	1.500E+00	11.17	
					Cs-137	1.456E+00	1.465E+00	1.481E+00	1.71	
					Ra-226	3.614E+01	3.615E+01	3.616E+01	0.06	
					Th-230	5.418E-01	5.420E-01	5.423E-01	0.09	
					U-238	1.735E+00	1.736E+00	1.738E+00	0.17	
					Pu-239	3.252E+00	3.252E+00	3.253E+00	0.03	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD'	Max. of NDD
	Low	Base	High			Low	Base	High		
Livestock fodder intake for milk (kg/d)	31.6	63.22	126	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated fodder that is ingested.	Co-60	5.798E+00	5.803E+00	5.813E+00	0.26	23.42
					Sr-90	1.286E+00	1.396E+00	1.613E+00	23.42	
					Cs-137	1.446E+00	1.465E+00	1.502E+00	3.82	
					Ra-226	3.608E+01	3.615E+01	3.628E+01	0.55	
					Th-230	5.410E-01	5.420E-01	5.439E-01	0.54	
					U-238	1.724E+00	1.736E+00	1.761E+00	2.13	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Livestock water intake for meat (L/d)	25	50	100	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated water that is ingested.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.35
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.734E+00	1.736E+00	1.740E+00	0.35	
					Pu-239	3.251E+00	3.252E+00	3.254E+00	0.09	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Livestock water intake for milk (L/d)	30	60	120	The low and high values are 1/2 of and 2 times, respectively, the base value, which is the default value used in the DandD code. They account for the amount of contaminated water that is ingested.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	2.42
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.722E+00	1.736E+00	1.764E+00	2.42	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Livestock intake of soil (kg/d)	0.25	0.5	1	The low and high values are 1/2 of and 2 times, respectively, the RESRAD base value, which is the default value used in the DandD code.	Co-60	5.792E+00	5.803E+00	5.825E+00	0.57	9.15
					Sr-90	1.359E+00	1.396E+00	1.469E+00	7.88	
					Cs-137	1.420E+00	1.465E+00	1.554E+00	9.15	
					Ra-226	3.605E+01	3.615E+01	3.635E+01	0.83	
					Th-230	5.389E-01	5.420E-01	5.481E-01	1.70	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.626E-01	1.659E-01	1.727E-01	6.09	
Mass loading for foliar deposition (g/m3)	1E-7	4E-4	7E-4	Base value and high value are from page 5.4-7 of Beyeler et al. (1998). The low value was set to the low value for the "dust loading for inhalation" parameter to observe potential variation in radiation dose.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	1.45
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.419E-01	5.420E-01	5.420E-01	0.02	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.646E-01	1.659E-01	1.670E-01	1.45	
Depth of soil mixing layer (m)	0.075	0.15	0.3	The low value is 1/2 of the RESRAD default value and the high value is twice the RESRAD default value.	Co-60	5.803E+00	5.803E+00	5.792E+00	0.19	20.01
					Sr-90	1.396E+00	1.396E+00	1.358E+00	2.72	
					Cs-137	1.465E+00	1.465E+00	1.420E+00	3.07	
					Ra-226	3.615E+01	3.615E+01	3.603E+01	0.33	
					Th-230	5.516E-01	5.420E-01	5.367E-01	2.75	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.662E-01	1.659E-01	1.330E-01	20.01	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Depth of roots (m)	0.3	0.9	3	Based on previously collected data.	Co-60	5.936E+00	5.803E+00	5.757E+00	3.08	253.37
					Sr-90	4.016E+00	1.396E+00	4.789E-01	253.37	
					Cs-137	1.655E+00	1.465E+00	1.398E+00	17.54	
					Ra-226	3.885E+01	3.615E+01	3.520E+01	10.10	
					Th-230	6.037E-01	5.420E-01	5.204E-01	15.37	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	3.270E-01	1.659E-01	1.096E-01	131.04	
Wet-weight crop yields for non-leafy vegetables (kg/m^2)	0.31	2.4	3	USDA (1997) is the source for the low value, which corresponds approximately to the average yields of asparagus, lima beans, and peas. The high value is the upper limit set in the RESRAD code and is close to the reported max. value (4) in USDA (1997) for the average yields of onions, carrots, strawberries, and grapefruits. The base value is from Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	12.58
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.422E-01	5.420E-01	5.420E-01	0.04	
					U-238	1.941E+00	1.736E+00	1.730E+00	12.15	
					Pu-239	3.649E+00	3.252E+00	3.240E+00	12.58	
					Am-241	1.696E-01	1.659E-01	1.658E-01	2.29	
Wet-weight crop yields for leafy vegetables (kg/m^2)	2.7	2.9	3.0	Low and base values are from Table 5.5.1.5 of Beyeler et al. (1998). The high value is the upper limit that can be accepted by the RESRAD code.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.28
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.739E+00	1.736E+00	1.735E+00	0.23	
					Pu-239	3.258E+00	3.252E+00	3.249E+00	0.28	
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06	
Wet-weight crop yields for fodder (kg/m^2)	1.259	1.8868	2.36	Table 5.5.2.2 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	1.04
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.749E+00	1.736E+00	1.731E+00	1.04	
					Pu-239	3.253E+00	3.252E+00	3.252E+00	0.03	
					Am-241	1.660E-01	1.659E-01	1.659E-01	0.06	
Length of growing season for non-leafy vegetables (yr)	0.085	0.2466	0.4932	Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.34
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.731E+00	1.736E+00	1.736E+00	0.29	
					Pu-239	3.242E+00	3.252E+00	3.253E+00	0.34	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Length of growing season for leafy vegetables (yr)	0.062	0.123	0.246	Base value is from Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.81
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.419E-01	5.420E-01	5.420E-01	0.02	
					U-238	1.726E+00	1.736E+00	1.740E+00	0.81	
					Pu-239	3.233E+00	3.252E+00	3.259E+00	0.80	
					Am-241	1.658E-01	1.659E-01	1.660E-01	0.12	

Table 3.1 (Continued)

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

Table 3.1 (Continued)

	Parameter Value					Corresponding Peak Dose (mrem/yr)				
Parameter	Low	Base	High	Source	Nuclide	Low	Base	High	NDD[1]	Max. of NDD
Wet foliar interception fraction for leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	3.75
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.704E+00	1.736E+00	1.768E+00	3.69	
					Pu-239	3.191E+00	3.252E+00	3.313E+00	3.75	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Wet foliar interception fraction for fodder	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	2.19
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.717E+00	1.736E+00	1.755E+00	2.19	
					Pu-239	3.251E+00	3.252E+00	3.253E+00	0.06	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Dry foliar interception fraction for non-leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.42
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.419E-01	5.420E-01	5.420E-01	0.02	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.656E-01	1.659E-01	1.663E-01	0.42	
Dry foliar interception fraction for leafy vegetables	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.66
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.419E-01	5.420E-01	5.420E-01	0.02	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.654E-01	1.659E-01	1.665E-01	0.66	
Dry foliar interception fraction for fodder	0.1	0.35	0.6	Table 5.8-1 of Beyeler et al. (1998).	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.06
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.736E+00	0.00	
					Pu-239	3.252E+00	3.252E+00	3.252E+00	0.00	
					Am-241	1.659E-01	1.659E-01	1.660E-01	0.06	
Storage Times for Fruits, Non-leafy Vegetables, and Grain[3]										
Storage times for fruits, non-leafy vegetables, and grain (d)	0	14	28	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.26
					Ra-228	4.907E+00	4.914E+00	4.920E+00	0.26	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for leafy vegetables (d)	0	1	7	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD¹	Max. of NDD
	Low	Base	High			Low	Base	High		
Storage times for milk (d)	0	1	7	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for meat (d)	7	20	30	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.02
					Ra-228	4.913E+00	4.914E+00	4.914E+00	0.02	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for fish (d)	1	7	14	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for crustacea	1	7	14	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for well water (d)	0.5	1	2	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for surface water (d)	0.5	1	2	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Storage times for livestock fodder (d)	15	45	90	The low and high values were selected to observe potential changes. The base value is the default value of the DandD code.	Ca-45	2.470E-02	2.470E-02	2.470E-02	0.00	0.00
					Ra-228	4.914E+00	4.914E+00	4.914E+00	0.00	
					Cf-252	3.870E-02	3.870E-02	3.870E-02	0.00	
Carbon-Model Parameters										
C-12 concentration in local water (g/cm³)	0.000002	0.00002	0.0002	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.327E-02	5.327E-02	5.326E-02	0.02	0.02
C-12 concentration in contamination soil (g/g)	0.003	0.03	0.3	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.383E-02	5.327E-02	5.310E-02	1.37	1.37
Fraction of vegetation carbon absorbed from soil	0.002	0.02	0.2	The low and high are 1/10 of and 10 times, respectively, the RESRAD default value.	C-14	5.321E-02	5.327E-02	5.382E-02	1.15	1.15
Fraction of vegetation carbon adsorbed from air	0.8	0.98	0.998	The low and high were determined by using the high and low values, respectively, of the previous parameter.	C-14	5.293E-02	5.327E-02	5.330E-02	0.69	0.69
C-14 evasion layer thickness in soil (m)	0.2	0.3	1	Values were selected to observe potential variation in doses.	C-14	5.265E-02	5.327E-02	1.254E-01	136.57	136.57
C-14 evasion flux rate from soil (1/s)	0.00000035	0.0000007	0.0000014	Values were selected to observe potential variation in doses.	C-14	5.235E-02	5.327E-02	5.510E-02	5.16	5.16
C-12 evasion flux rate from soil (1/s)	5E-11	1E-10	0.0000000002	Values were selected to observe potential variation in doses.	C-14	5.327E-02	5.327E-02	5.327E-02	0.00	0.00
Grain fraction in livestock feed for beef cattle	0.125	0.25	0.5	Base value from page 5.6-5 of Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.	C-14	5.397E-02	5.327E-02	5.252E-02	2.72	2.72
Grain fraction in livestock feed for milk cow	0.05	0.1	0.2	Base value from page 5.6-5 of Beyeler et al. (1998). The low and high values were set to 1/2 of and twice the base value.	C-14	5.352E-02	5.327E-02	5.291E-02	1.15	1.15

Table 3.1 (Continued)

Parameter	Parameter Value			Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD[1]	Max. of NDD
	Low	Base	High			Low	Base	High		
Transfer Factors										
Transfer factors for plants	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.738E+00	5.803E+00	5.803E+00	1.12	480.55
					Sr-90	1.602E-01	1.396E+00	1.396E+00	88.52	
					Cs-137	1.371E+00	1.465E+00	1.555E+00	12.56	
					Ra-226	3.493E+01	3.615E+01	5.001E+01	41.72	
					Th-230	5.143E-01	5.420E-01	8.202E-01	56.44	
					U-238	1.736E+00	1.736E+00	1.737E+00	0.06	
					Pu-239	3.252E+00	3.252E+00	3.253E+00	0.03	
					Am-241	9.347E-02	1.659E-01	8.907E-01	480.55	
Transfer factors for meat [(pCi/kg)/(pCi/d)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.778E+00	5.803E+00	6.056E+00	4.79	101.22
					Sr-90	1.267E+00	1.396E+00	2.680E+00	101.22	
					Cs-137	1.409E+00	1.465E+00	2.026E+00	42.12	
					Ra-226	3.609E+01	3.615E+01	3.671E+01	1.72	
					Th-230	5.396E-01	5.420E-01	5.660E-01	4.87	
					U-238	1.731E+00	1.736E+00	1.784E+00	3.05	
					Pu-239	3.249E+00	3.252E+00	3.279E+00	0.92	
					Am-241	1.606E-01	1.659E-01	2.196E-01	35.56	
Transfer factors for milk [(pCi/L)/(pCi/d)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.789E+00	5.803E+00	5.945E+00	2.69	179.80
					Sr-90	1.168E+00	1.396E+00	3.678E+00	179.80	
					Cs-137	1.392E+00	1.465E+00	2.191E+00	54.54	
					Ra-226	3.589E+01	3.615E+01	3.876E+01	7.94	
					Th-230	5.369E-01	5.420E-01	5.926E-01	10.28	
					U-238	1.689E+00	1.736E+00	2.212E+00	30.13	
					Pu-239	3.252E+00	3.252E+00	3.254E+00	0.06	
					Am-241	1.652E-01	1.659E-01	1.737E-01	5.12	
Bioaccumulation Factors										
Bioaccumulation factors for fish [(pCi/kg)/(pCi/L)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	3.51
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.734E+00	1.736E+00	1.754E+00	1.15	
					Pu-239	3.242E+00	3.252E+00	3.356E+00	3.51	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	
Bioaccumulation factors for crustacea and mollusks [(pCi/kg)/(pCi/L)]	See Table 3.2	See Table 3.2	See Table 3.2	See Table 3.2	Co-60	5.803E+00	5.803E+00	5.803E+00	0.00	0.49
					Sr-90	1.396E+00	1.396E+00	1.396E+00	0.00	
					Cs-137	1.465E+00	1.465E+00	1.465E+00	0.00	
					Ra-226	3.615E+01	3.615E+01	3.615E+01	0.00	
					Th-230	5.420E-01	5.420E-01	5.420E-01	0.00	
					U-238	1.736E+00	1.736E+00	1.741E+00	0.29	
					Pu-239	3.251E+00	3.252E+00	3.267E+00	0.49	
					Am-241	1.659E-01	1.659E-01	1.659E-01	0.00	

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

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

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

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

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

Table 3.2 (Continued)

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

Table 3.2 (Continued)

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

Table 3.2 (Continued)

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

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

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

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Indoor fraction	0.205	0.267	0.383	The base value is the default value used in the DandD code. The low and high values are from Fig. 5.1 of Beyeler et al. (1997).	Volume	Co-60	1.910E+00	2.490E+00	3.570E+00	66.67	67.25
						Sr-90	3.150E-03	4.100E-03	5.880E-03	66.59	
						Cs-137	4.460E-01	5.810E-01	8.330E-01	66.61	
						Ra-226	2.360E+00	3.070E+00	4.400E+00	66.45	
						Th-230	1.640E-03	2.134E-03	3.053E-03	66.21	
						U-238	1.740E-02	2.260E-02	3.250E-02	66.81	
						Pu-239	1.390E-03	1.810E-03	2.600E-03	66.85	
						Am-241	5.810E-03	7.570E-03	1.090E-02	67.24	
					Surface	Co-60	1.160E-05	1.510E-05	2.160E-05	66.23	
						Sr-90	2.880E-06	3.750E-06	5.380E-06	66.67	
						Cs-137	3.230E-06	4.210E-06	6.040E-06	66.75	
						Ra-226	3.394E-05	4.420E-05	6.110E-05	61.45	
						Th-230	4.720E-04	6.150E-04	8.820E-04	66.67	
						U-238	1.720E-04	2.240E-04	3.210E-04	66.52	
						Pu-239	6.440E-04	8.380E-04	1.200E-03	66.35	
						Am-241	6.610E-04	8.610E-04	1.240E-03	67.25	
Deposition velocity (m/s)	0	0.01	0.01	The low value was selected for considering radionuclides in the gas form.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	206.19
						Sr-90	4.100E-03	4.100E-03	4.100E-03	0.00	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	9.400E+00	3.070E+00	3.070E+00	206.19	
						Th-230	3.490E-03	2.134E-03	2.134E-03	63.54	
						U-238	2.260E-02	2.260E-02	2.260E-02	0.00	
						Pu-239	1.740E-03	1.810E-03	1.810E-03	3.87	
						Am-241	7.500E-03	7.570E-03	7.570E-03	0.92	
					Surface	Co-60	1.460E-05	1.510E-05	1.510E-05	3.31	
						Sr-90	2.530E-06	3.750E-06	3.750E-06	32.53	
						Cs-137	3.610E-06	4.210E-06	4.210E-06	14.25	
						Ra-226	3.750E-05	4.420E-05	4.420E-05	15.16	
						Th-230	6.090E-04	6.150E-04	6.150E-04	0.98	
						U-238	2.210E-04	2.240E-04	2.240E-04	1.34	
						Pu-239	8.020E-04	8.380E-04	8.380E-04	4.30	
						Am-241	8.290E-04	8.610E-04	8.610E-04	3.72	
Resuspension rate (1/s)	1.2E-10	1.42E-07	4.00E-04	The base value was obtained by multiplying the DandD resuspension factor by the base value of the deposition velocity. The low and high values are from the reported data for resuspension factor/rate listed in Table 5.10 of Beyeler et al. (1997).	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	11969.23
						Sr-90	4.130E-03	4.100E-03	4.100E-03	0.73	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.080E+00	3.070E+00	3.410E+00	10.75	
						Th-230	1.557E-02	2.134E-03	2.187E-03	627.13	
						U-238	2.960E-02	2.260E-02	2.260E-02	30.97	
						Pu-239	8.110E-02	1.810E-03	1.740E-03	4384.53	
						Am-241	1.640E-02	7.570E-03	7.500E-03	117.57	
					Surface	Co-60	1.580E-05	1.510E-05	1.460E-05	7.95	
						Sr-90	1.570E-05	3.750E-06	2.530E-06	351.20	
						Cs-137	1.030E-05	4.210E-06	3.610E-06	158.91	
						Ra-226	5.320E-03	4.420E-05	2.960E-05	11969.23	
						Th-230	7.000E-03	6.150E-04	6.090E-04	1039.19	
						U-238	3.520E-03	2.240E-04	2.210E-04	1472.77	
						Pu-239	3.860E-02	8.380E-04	8.020E-04	4510.50	
						Am-241	5.050E-03	8.610E-04	8.290E-04	490.24	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Room height (m)	1.67	2.5	3.75	The low and high values are 2/3 of and 1.5 times, respectively, the base value, which is the default value used in the RESRAD code.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	83.09
						Sr-90	4.110E-03	4.100E-03	4.100E-03	0.24	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.250E+00	3.070E+00	2.910E+00	11.07	
						Th-230	2.810E-03	2.134E-03	1.669E-03	53.47	
						U-238	2.290E-02	2.260E-02	2.250E-02	1.77	
						Pu-239	2.690E-03	1.810E-03	1.230E-03	80.66	
						Am-241	8.460E-03	7.570E-03	6.970E-03	19.68	
					Surface	Co-60	1.530E-05	1.510E-05	1.490E-05	2.65	
						Sr-90	5.330E-06	3.750E-06	2.610E-06	72.53	
						Cs-137	4.500E-06	4.210E-06	4.000E-06	11.88	
						Ra-226	6.010E-05	4.420E-05	3.340E-05	60.41	
						Th-230	9.210E-04	6.150E-04	4.100E-04	83.09	
						U-238	3.350E-04	2.240E-04	1.490E-04	83.04	
						Pu-239	1.250E-03	8.380E-04	5.590E-04	82.46	
						Am-241	1.290E-03	8.610E-04	5.760E-04	82.93	
Room area (m^2)	3.6	36	360	The low and high values are 1/10 of and 10 times, respectively, the RESRAD default value.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	990.00
						Sr-90	4.170E-03	4.100E-03	4.090E-03	1.95	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	1.400E+01	3.070E+00	1.980E+00	391.53	
						Th-230	1.610E-02	2.134E-03	7.310E-04	720.20	
						U-238	2.690E-02	2.260E-02	2.220E-02	20.80	
						Pu-239	1.770E-02	1.810E-03	2.270E-04	965.36	
						Am-241	2.390E-02	7.570E-03	5.940E-03	237.25	
					Surface	Co-60	1.970E-05	1.510E-05	1.440E-05	35.10	
						Sr-90	3.640E-05	3.750E-06	4.780E-07	957.92	
						Cs-137	9.170E-06	4.210E-06	3.630E-06	131.59	
						Ra-226	3.420E-04	4.420E-05	1.420E-05	741.63	
						Th-230	6.150E-03	6.150E-04	6.150E-05	990.00	
						U-238	2.230E-03	2.240E-04	2.250E-05	985.49	
						Pu-239	8.380E-03	8.380E-04	8.380E-05	990.00	
						Am-241	8.610E-03	8.610E-04	8.640E-05	989.97	
Air exchange rate for building and room (1/h)	0.18	0.8	1.5	The high value is from Mueller Associates (1986); the low value is from EPA (1997). The base value is the RESRAD default value.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	390.57
						Sr-90	4.120E-03	4.100E-03	4.100E-03	0.49	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	7.240E+00	3.070E+00	2.480E+00	155.05	
						Th-230	7.490E-03	2.134E-03	1.401E-04	344.42	
						U-238	2.420E-02	2.260E-02	2.240E-02	7.96	
						Pu-239	7.880E-03	1.810E-03	9.910E-04	380.61	
						Am-241	1.360E-02	7.570E-03	6.730E-03	90.75	
					Surface	Co-60	1.590E-05	1.510E-05	1.480E-05	7.28	
						Sr-90	1.250E-05	3.750E-06	2.130E-06	276.53	
						Cs-137	5.820E-06	4.210E-06	3.910E-06	45.37	
						Ra-226	1.560E-04	4.420E-05	2.870E-05	288.01	
						Th-230	2.730E-03	6.150E-04	3.280E-04	390.57	
						U-238	9.930E-04	2.240E-04	1.190E-04	390.18	
						Pu-239	3.720E-03	8.380E-04	4.470E-04	390.57	
						Am-241	3.750E-03	8.610E-04	4.610E-04	382.00	

Table 3.3 (Continued)

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

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Source length or area (m or m^2)	3.6	36	360	The low and high values were set to 1/10 of and 10 times, respectively, the RESRAD default value.	Volume	Co-60	4.610E-01	2.490E+00	3.480E+00	121.24	990.00
						Sr-90	7.880E-04	4.100E-03	4.990E-03	102.49	
						Cs-137	1.080E-01	5.810E-01	7.950E-01	118.24	
						Ra-226	4.660E-01	3.070E+00	1.470E+01	463.65	
						Th-230	2.630E-04	2.134E-03	1.638E-02	755.25	
						U-238	4.180E-03	2.260E-02	3.490E-02	135.93	
						Pu-239	1.860E-04	1.810E-03	1.770E-02	967.62	
						Am-241	1.270E-03	7.570E-03	2.560E-02	321.40	
					Surface	Co-60	2.470E-06	1.510E-05	3.660E-05	226.03	
						Sr-90	3.840E-07	3.750E-06	3.650E-05	963.09	
						Cs-137	6.610E-07	4.210E-06	1.370E-05	309.71	
						Ra-226	5.150E-06	4.420E-05	3.560E-04	793.78	
						Th-230	6.150E-05	6.150E-04	6.150E-03	990.00	
						U-238	2.240E-05	2.240E-04	2.230E-03	985.54	
						Pu-239	8.380E-05	8.380E-04	8.380E-03	990.00	
						Am-241	8.620E-05	8.610E-04	8.610E-03	989.99	
Air release fraction	0.01	0.1	1	The low and high values were set to 1/10 of and 10 times, respectively, the default value.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	990.00
						Sr-90	4.090E-03	4.100E-03	4.170E-03	1.95	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.070E+00	3.070E+00	3.070E+00	0.00	
						Th-230	9.670E-04	2.134E-03	1.370E-02	596.67	
						U-238	2.220E-02	2.260E-02	2.690E-02	20.80	
						Pu-239	2.270E-04	1.810E-03	1.770E-02	965.36	
						Am-241	5.940E-03	7.570E-03	2.390E-02	237.25	
					Surface	Co-60	1.430E-05	1.510E-05	2.240E-05	53.64	
						Sr-90	4.770E-07	3.750E-06	3.650E-05	960.61	
						Cs-137	3.610E-06	4.210E-06	1.020E-05	156.53	
						Ra-226	1.560E-05	4.420E-05	3.310E-04	713.57	
						Th-230	6.150E-05	6.150E-04	6.150E-03	990.00	
						U-238	2.250E-05	2.240E-04	2.230E-03	985.49	
						Pu-239	8.380E-05	8.380E-04	8.380E-03	990.00	
						Am-241	8.640E-05	8.610E-04	8.610E-03	989.97	
Direct ingestion rate (g/h for volume source and 1/h for all other sources)	0	0	0.0025	The low/high value was obtained by using 1/10 of the upper/lower limit of the ingestion rate (0/200 mg/d) in the DandD code and the assumption that the exposure time was 8 hr/d.	Volume	Co-60	2.490E+00	2.490E+00	2.490E+00	0.00	1143.09
						Sr-90	4.100E-03	4.100E-03	4.990E-03	21.71	
						Cs-137	5.810E-01	5.810E-01	5.810E-01	0.00	
						Ra-226	3.070E+00	3.070E+00	3.080E+00	0.33	
						Th-230	2.134E-03	2.134E-03	5.136E-03	140.67	
						U-238	2.260E-02	2.260E-02	2.420E-02	7.08	
						Pu-239	1.810E-03	1.810E-03	2.250E-02	1143.09	
						Am-241	7.570E-03	7.570E-03	2.880E-02	280.45	
	0	3.08E-07	0.00005	The high value corresponds to an ingestion rate that would consume the entire source in 10 years, assuming an exposure time of 8 hours per day and 250 days per year. It was selected to observe variation in radiation doses.	Surface	Co-60	1.510E-05	1.510E-05	1.510E-05	0.00	
						Sr-90	3.750E-06	3.750E-06	3.750E-06	0.00	
						Cs-137	4.210E-06	4.210E-06	4.210E-06	0.00	
						Ra-226	4.420E-05	4.420E-05	4.420E-05	0.00	
						Th-230	6.150E-04	6.150E-04	6.150E-04	0.00	
						U-238	2.240E-04	2.240E-04	2.240E-04	0.00	
						Pu-239	8.380E-04	8.380E-04	8.380E-04	0.00	
						Am-241	8.610E-04	8.610E-04	8.610E-04	0.00	

Table 3.3 (Continued)

Parameters	Parameter Value			Data Source	Radiation Source	Nuclide	Corresponding Peak Dose (mrem/yr)			NDD	Max. of NDD
	Low	Base	High				Low	Base	High		
Removable fraction	0.01	0.1	0.5	The base value was set to the assumed value used in the DandD code. The low value and high value were selected to observe variation in radiation doses.	Surface	Co-60	1.500E-05	1.510E-05	1.530E-05	1.99	490.55
						Sr-90	4.830E-07	3.750E-06	1.830E-05	475.12	
						Cs-137	3.780E-06	4.210E-06	6.110E-06	55.34	
						Ra-226	1.620E-05	4.420E-05	1.690E-04	345.70	
						Th-230	6.150E-05	6.150E-04	3.070E-03	489.19	
						U-238	2.250E-05	2.240E-04	1.120E-03	489.96	
						Pu-239	8.380E-05	8.380E-04	4.190E-03	490.00	
						Am-241	8.640E-05	8.610E-04	4.310E-03	490.55	
Time for source removal or source lifetime (d)	365	365	36500	The low and high values were set to 1/10 of and 10 times, respectively, the RESRAD default value.	Surface	Co-60	1.510E-05	1.510E-05	1.500E-05	0.66	99.00
						Sr-90	3.750E-06	3.750E-06	1.560E-07	95.84	
						Cs-137	4.210E-06	4.210E-06	3.740E-06	11.16	
						Ra-226	4.420E-05	4.420E-05	1.340E-05	69.68	
						Th-230	6.150E-04	6.150E-04	6.190E-06	98.99	
						U-238	2.240E-04	2.240E-04	2.430E-06	98.92	
						Pu-239	8.380E-04	8.380E-04	8.390E-06	99.00	
						Am-241	8.610E-04	8.610E-04	8.880E-06	98.97	
Radionuclide concentration (pCi/g for volume source, pCi/m^2 for surface source)	0.1	1	10	Values were varied to observe change in radiation doses.	Volume	Co-60	2.490E-01	2.490E+00	2.490E+01	990.00	990.00
						Sr-90	4.100E-04	4.100E-03	4.100E-02	990.00	
						Cs-137	5.810E-02	5.810E-01	5.810E+00	990.00	
						Ra-226	3.070E-01	3.070E+00	3.070E+01	990.00	
						Th-230	2.134E-04	2.134E-03	2.134E-02	990.00	
						U-238	2.260E-03	2.260E-02	2.260E-01	990.00	
						Pu-239	1.810E-04	1.810E-03	1.810E-02	990.00	
						Am-241	7.570E-04	7.570E-03	7.570E-02	990.00	
	0.1	1	10	Values were varied to observe change in radiation doses.	Surface	Co-60	1.510E-06	1.510E-05	1.510E-04	990.00	
						Sr-90	3.750E-07	3.750E-06	3.750E-05	990.00	
						Cs-137	4.210E-07	4.210E-06	4.210E-05	990.00	
						Ra-226	4.420E-06	4.420E-05	4.420E-04	990.00	
						Th-230	6.150E-05	6.150E-04	6.150E-03	990.00	
						U-238	2.240E-05	2.240E-04	2.240E-03	990.00	
						Pu-239	8.380E-05	8.380E-04	8.380E-03	990.00	
						Am-241	8.610E-05	8.610E-04	8.610E-03	990.00	
Source thickness, volume source (cm)	5	15	30	The low and high values were selected to observe change in radiation doses.	Volume	Co-60	1.390E+00	2.490E+00	2.650E+00	50.60	94.46
						Sr-90	3.260E-03	4.100E-03	4.150E-03	21.71	
						Cs-137	3.570E-01	5.810E-01	5.920E-01	40.45	
						Ra-226	1.480E+00	3.070E+00	4.380E+00	94.46	
						Th-230	1.770E-03	2.134E-03	2.417E-03	30.32	
						U-238	1.490E-02	2.260E-02	2.340E-02	37.61	
						Pu-239	1.800E-03	1.810E-03	1.810E-03	0.55	
						Am-241	7.680E-03	7.570E-03	7.570E-03	1.45	
Source density, volume source (g/cm^3)	2	2.4	4	The low and high values were varied from the RESRAD default value, which is the average value for concrete, to observe change in radiation doses.	Volume	Co-60	2.350E+00	2.490E+00	2.680E+00	13.25	81.22
						Sr-90	4.050E-03	4.100E-03	4.150E-03	2.44	
						Cs-137	5.580E-01	5.810E-01	6.020E-01	7.57	
						Ra-226	2.770E+00	3.070E+00	3.990E+00	39.74	
						Th-230	1.850E-03	2.134E-03	3.195E-03	63.03	
						U-238	2.170E-02	2.260E-02	2.400E-02	10.18	
						Pu-239	1.520E-03	1.810E-03	2.990E-03	81.22	
						Am-241	7.260E-03	7.570E-03	8.780E-03	20.08	

Table 3.3 (Continued)

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

Table 3.3 (Continued)

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

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

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

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

Table 4.1 Ranking Results for the RESRAD Parameters

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

Table 4.1 (Continued)

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

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

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

[3] 0 = relevant, 9 = irrelevant.

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

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

[6] Type + Relevance + Data Availability + Dose Variability.

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

Table 4.2 Summary of the Overall Ranking Results for RESRAD

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

Table 4.2 (Continued)

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

Table 4.3 Overall Ranking Results for the RESRAD-BUILD Parameters

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

Table 4.3 (Continued)

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

Table 4.3 (Continued)

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

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

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

[3] 0 = relevant, 9 = irrelevant.

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

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

[6] Type + Relevance + Data Availability + Dose Variability.

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

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

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

Table A.1 Peak Radiation Doses for the Base Case[1] in the RESRAD Code

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

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

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

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

Table A.1 (Continued)

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

Table A.3 Maximum Radiation Doses for the Base Case of Surface Contamination[1] in the RESRAD-BUILD Code

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

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

ATTACHMENT C

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

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ABBREVIATIONS AND ACRONYMS

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

USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project

1 INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has taken steps to ensure that residual radioactive contamination remaining after licensed nuclear facilities are decontaminated and decommissioned meets established standards (Subpart E to Title 10, *Code of Federal Regulations*, Part 20 [10 CFR Part 20]) and that risks to the exposed "critical group" of the public will be within prescribed limits (10 CFR 20.1402 and 20.1403) (NRC, 1998a,b).

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

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

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

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

The effect of these parameter distributions on the distribution of estimated doses will be assessed in Subtask 1.4[3]. Parallel development of the probabilistic interface for the RESRAD and RESRAD-BUILD codes (Subtask 1.6)[4] is underway, taking into account parameter correlations as they are identified. As experience is gained in the use of the parameter distributions and application of the codes to decontamination and decommissioning efforts, more information will become available for the future refinement of the parameter distributions. These refinements can be achieved, through an iterative process, by investigation of sensitivity and uncertainty when the codes are fully developed.

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

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

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

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

2 METHODOLOGY FOR PARAMETER DISTRIBUTION ASSIGNMENT

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

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

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

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

2.1 Selection of Parameters To Be Assigned Distributions

In Subtask 1.2, parameters were ranked and placed in one of three priority categories — Priorities 1 through 3. Priority 1 was assigned to the most relevant (high priority) parameters and Priority 3 to the least relevant (low priority). Argonne and the NRC Dose Modeling Working Group agreed that Priority 3 parameters would be excluded from distribution analysis at the present time because parameters of this category had already been determined to be of low priority and had insignificant impact on the overall results. This letter report for Subtask 1.3 includes the assignment of distributions to all Priority 1 and Priority 2 (i.e., medium priority) parameters. However, a few directly measurable, site-input parameters, such as nuclide concentration, area of contamination, and thickness of contaminated zone, will not be assigned distributions in the supplement. Table 2.1-1 lists the parameters considered.

2.2 Parameters Not Assigned Distributions

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

2.3 Data Collection

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

2.4 Assignment of Parameter Distributions

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

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

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

Table 2.1-1 (Cont.)

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

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

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

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

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

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

2.4.1 Parameters with Well-Characterized Distributions

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

2.4.2 Parameters with Sufficient Data

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

2.4.3 Parameters with Some Data

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

2.4.4 Parameters with Insufficient Data

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

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

2.4.5 Multiple Distributions

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

2.4.6 Parameter Correlations

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

2.5 Presentation of Results

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

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

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

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

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

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

Table 2.5-1 (Cont.)

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

Table 2.5-1 (Cont.)

Parameter	Section[b]	Data Source		Comment
		RESRAD / RESRAD-BUILD	DandD	
Inhalation rate	5.1	RESRAD - Most likely value same as recommended for DandD RESRAD-BUILD - Most likely value same as recommended for DandD	Beyeler et al. (1998b) for the residential scenario; Beyeler et al. (1998a) for the building occupancy scenario	
Drinking water intake	5.2	Same as DandD	Lognormal distribution for adults in Roseberry and Burmaster (1992)	
Milk consumption rate	5.3	EPA (1997), most likely value of 102 L/yr	NUREG/CR-5512 Draft Vol.2 cites 233 kg/yr (Table D.5) and references Vol.1 (Table 6.23) which lists 100 L/yr	The milk consumption information used for RESRAD is the most recent and comprehensive data set directly applicable to the input parameter.
Fruit, vegetable, and grain consumption rate	5.4	EPA (1997); Putnam (1999)	Not directly applicable, has separate categories for food ingestion	
Aquatic food contaminated fraction	5.5	EPA (1997), assumes most likely value of 0.39	Assumes a value of 1	The RESRAD value was chosen in an effort to remove the conservatism associated with the arbitrary assumption of 1 for the value.
Soil ingestion rate	5.6	Same as DandD	Beyeler et al. (1998b)	
Direct ingestion rate	5.7	None recommended	Not applicable	
Indirect ingestion rate	5.8	Same as DandD, uses the lower estimate in Beyeler et al. (1998a)	Beyeler et al. (1998a)	
Depth of roots	6.1	Various sources	Not applicable	
Transfer factors for plants	6.2	Primarily NCRP (1999); Yu et al. (1993a)	Not applicable, has separate groupings for plants	
Transfer factors for meat	6.3	Primarily NCRP (1999); Hoffman et al. (1982)	NUREG/CR-5512 (Kennedy and Strenge, 1992)	The transfer factor information used for RESRAD is the most recent and widely accepted data set.

Table 2.5-1 (Cont.)

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

Table 2.5-1 (Cont.)

		Data Source		
Parameter	Section[b]	RESRAD / RESRAD-BUILD	DandD	Comment
Indoor fraction	7.6	RESRAD - EPA (1997), same as DandD RESRAD-BUILD - EPA (1997)	Beyeler et al. (1998b) for the residential farmer scenario (used same source of data as used in EPA [1997]); Beyeler et al. (1998a) for the building occupancy scenario;	A large, consistent set of data for adults at both residences and at work was used for RESRAD and RESRAD-BUILD.
Room area	7.7	Professional judgment	Not applicable	
Room height	7.8	EPA (1997); NAHB (1998)	Not applicable	
Shielding thickness	7.9	Ayers et al. (1999)	Not applicable	
External gamma shielding factor	7.10	Derived using statistics on current construction practices (Dept. of Housing and Urban Development, 1996,1999)	Beyeler et al. (1998b), derived shielding factors for three different floor types (non-continuous distribution)	In light of the range in floor and wall materials and thicknesses, a continuous distribution attempting to represent this variability was considered the best approach for RESRAD.
Source density, volume source	8.1	Various sources for concrete	Not applicable	
Source erosion rate, volume source	8.2	Based on conservative assumptions	Not applicable	
Removable fraction	8.3	DOE (1994a); NRC (1974)	Assumed value of 10%	Most likely value for RESRAD-BUILD (20%) based on maximum allowed removable concentration limits.
Source porosity	8.4	Various sources for concrete	Not applicable	
Volumetric water content	8.5	Various sources for concrete	Not applicable	
Air release fraction	8.6	DOE (1994b)	Not applicable	
Wet + dry zone thickness	8.7	Based on various sources with data for concrete	Not applicable	
Time for source removal or source lifetime	8.8	Derived from data in ANS (1998)	Not applicable	

Table 2.5-1 (Cont.)

		Data Source		
Parameter	Section[b]	RESRAD / RESRAD-BUILD	DandD	Comment
Source thickness, volume source	8.9	Ayers et al. (1999)	Not applicable	
Water fraction available for evaporation	8.10	Various sources	Not applicable	
C-14 evasion layer thickness in soil	8.11	Sheppard et al. (1991); Amiro et al. (1991)	Not applicable	

[a] For parameters selected for distributional analysis.

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

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

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

3 HYDROGEOLOGICAL PARAMETER DISTRIBUTIONS

3.1 Density of Soil

Applicable Code: RESRAD

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

Units: grams per cubic centimeter (g/cm^3)

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

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

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

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

$$\rho_b = (1 - p_t)\,\rho_s \ . \qquad (3.1\text{-}1)$$

From the above definition, it is obvious that the value of the dry bulk density is always smaller than the value of the soil particle density. The soil particle density represents the density of the soil particles collectively and is expressed as the ratio of the solid phase mass to the volume of the solid phase of the soil. In most mineral soils, the soil particle density has a narrow range of 2.6 to 2.7 g/cm^3 (Hillel, 1980). This density is close to that of quartz, which is usually the predominant constituent of sandy soils. Aluminosilicate clay minerals have particle density variations in the same range. The presence of iron oxides and other heavy minerals increases the value of the soil particle density. The presence of solid organic materials in the soil decreases the density. A typical value of 2.65 g/cm^3 has been suggested to characterize the soil particle density of a general mineral soil (Freeze and Cherry, 1979; Beyeler et al., 1998b). With that, the bulk density becomes:

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

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

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

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

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

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

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

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

Table 3.1-2 CONUS-SOIL Texture Summary

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

Source: Beyeler et al. (1998b).

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

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

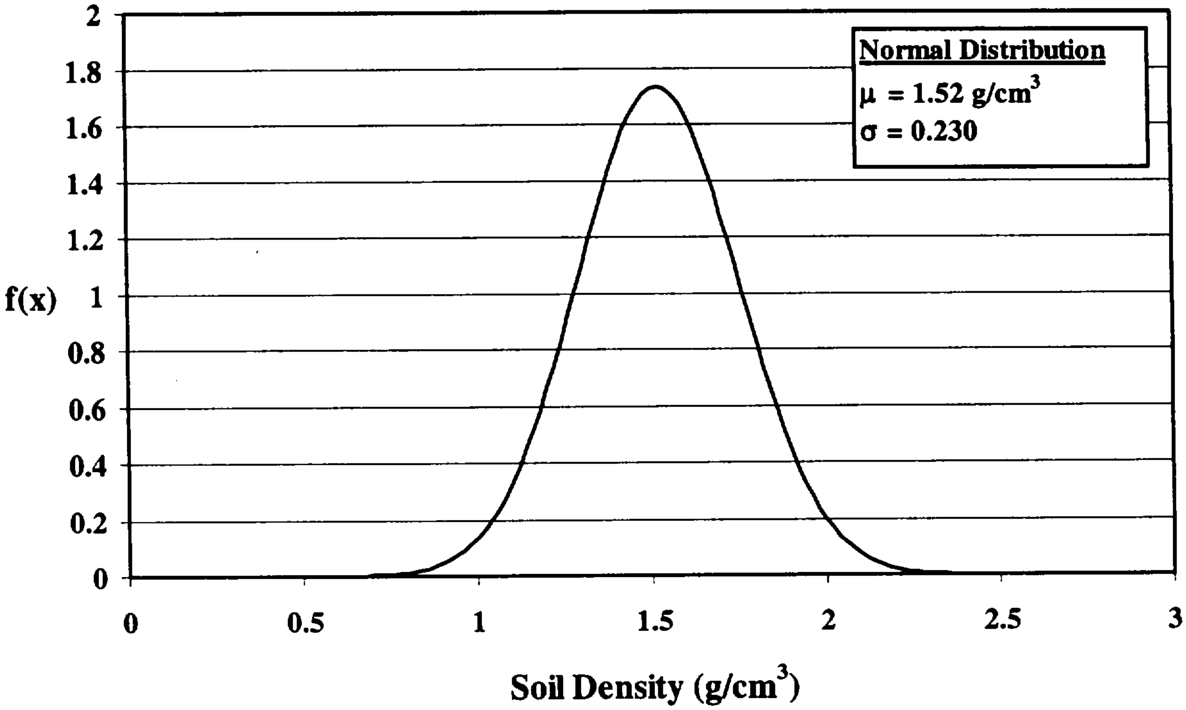

Figure 3.1-1 Soil Density Probability Density Function for the Generic Soil Type

3.2 Total Porosity

Applicable Code: RESRAD

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

Units: unitless

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

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

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

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

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

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

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

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

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

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

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

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

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

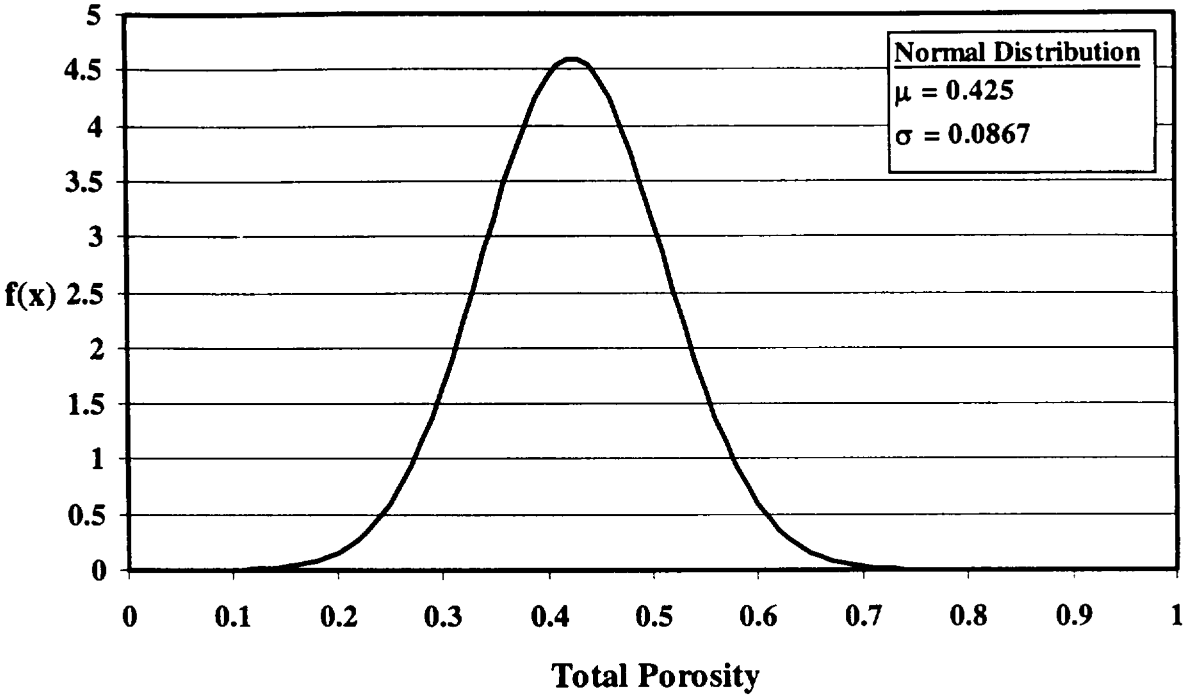

Figure 3.2-1 Total Porosity Probability Density Function for the Generic Soil Type

3.3 Effective Porosity

Applicable Code: RESRAD

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

Units: unitless

Probabilistic Input:

Distribution: truncated normal

Defining Values for Distribution:

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

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

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

$$p_e = p_t - \theta_r . \tag{3.3-1}$$

Carsel and Parrish (1988) used data on bulk density to infer the saturated water content. They then applied the data on sand and clay contents and the inferred saturated water content to the multiple regression model developed by Rawls and Brakensiek (1985) to generate estimates of residual water content for the 12 USDA soil textural classifications. The estimates were fitted by either a normal distribution or a transformed normal distribution by using methods in Johnson (1987) and Johnson and Kotz (1970). Meyer et al. (1997) then used the data generated by Carsel and Parish (1988) for saturated water content and residual water content to develop distributions for effective porosity by subtraction. Table 3.3-1 gives the distributions and the defining parameters for effective porosity for the 12 soil textural classes and for the generic soil type.

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

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

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

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

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

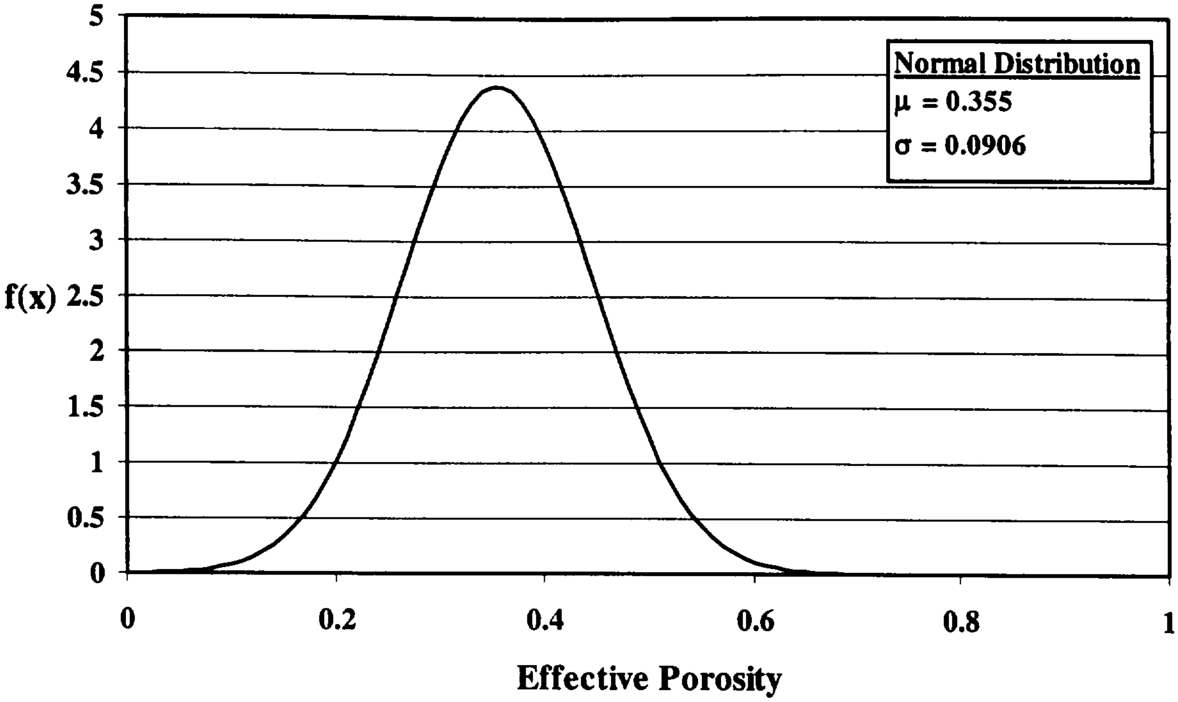

Figure 3.3-1 Effective Porosity Probability Density Function for the Generic Soil Type

3.4 Hydraulic Conductivity

Applicable Code: RESRAD

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

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

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

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

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

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

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

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

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

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

- Generate realizations of the parameters using Latin Hypercube Sampling and the distributions from Carsel and Parrish (1988).

- Calculate the Kolmogorov D-statistic for a fit of each simulated parameter distribution to normal, lognormal, and beta distributions.

- Select the recommended distribution based on the D-statistic values.

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

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

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

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

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

[c] Correspond to lower and upper observed values.

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

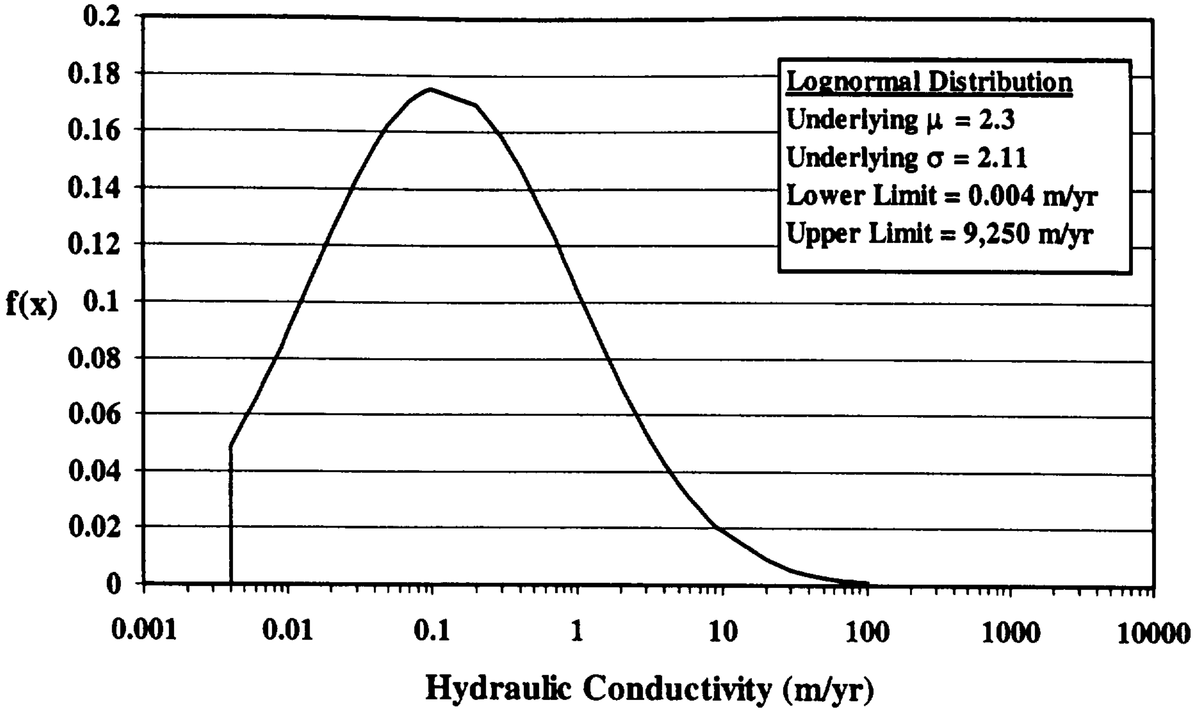

Figure 3.4-1 Hydraulic Conductivity Probability Density Function for the Generic Soil Type

3.5 Soil b Parameter

Applicable Code: RESRAD

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

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

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

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

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

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

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

Meyer et al. (1997) derived a relationship for b by using the soil water retention parameters considered in Carsel and Parrish (1988). Using the derived relationship, Meyer et al. (1997) then constructed distributions for the soil-b parameter for the 12 USDA soil textural classifications. The distribution type and the parameters for the 12 soil types and for the generic soil type are provided in Table 3.5-1. The distribution to be used for cases where the type of soil is not known (generic soil type) was obtained as the weighted average of the distributions for the individual soil classes. The distribution for the generic soil type is the RESRAD default. The probability density function for the soil-b parameter for this generic soil type is shown in Figure 3.5-1. When a site-specific analysis is being conducted, the distribution for the soil type present at the site should be used. For consistency, distributions corresponding to the same soil type selected for this parameter should also be selected for the following parameters: soil density, total porosity, effective porosity, and hydraulic conductivity.

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

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

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

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

[c] Correspond to lower and upper observed values.

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

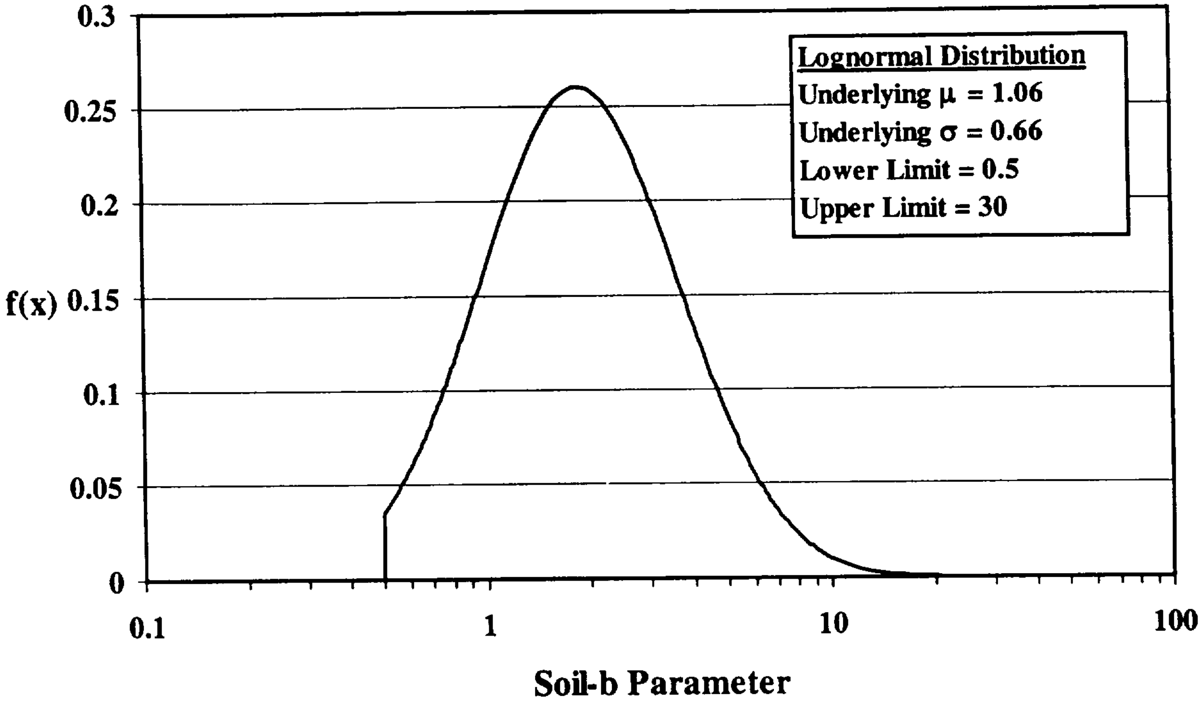

Figure 3.5-1 Soil-b Parameter Probability Density Function for the Generic Soil Type

3.6 Hydraulic Gradient

Applicable Code: RESRAD

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

Units: unitless

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

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

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

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

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

In an unconfined (water table) aquifer, the horizontal hydraulic gradient of groundwater flow is approximately the slope of the water table. In a confined aquifer, it represents the difference in potentiometric surfaces over a unit distance. The potentiometric surface is the elevation to which water rises in a well that taps a confined aquifer. It is an imaginary surface analogous to a water table. In general, the hydraulic gradient of groundwater flow in a highly permeable geological material, such as sand or gravel, is far less than that in a geological material with a low permeability, such as silt and clay (Yu et al., 1993b). Groundwater moves through an aquifer in a direction generally parallel to the hydraulic gradient. The movement generally is perpendicular to the lines of equal altitude of the potentiometric surface. The altitude of the potentiometric surface of different aquifer systems can be obtained from the *Ground Water Atlas of the United States* at http://wwwcapp.er.usgs.gov/publicdocs/gwa/.

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

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

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

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

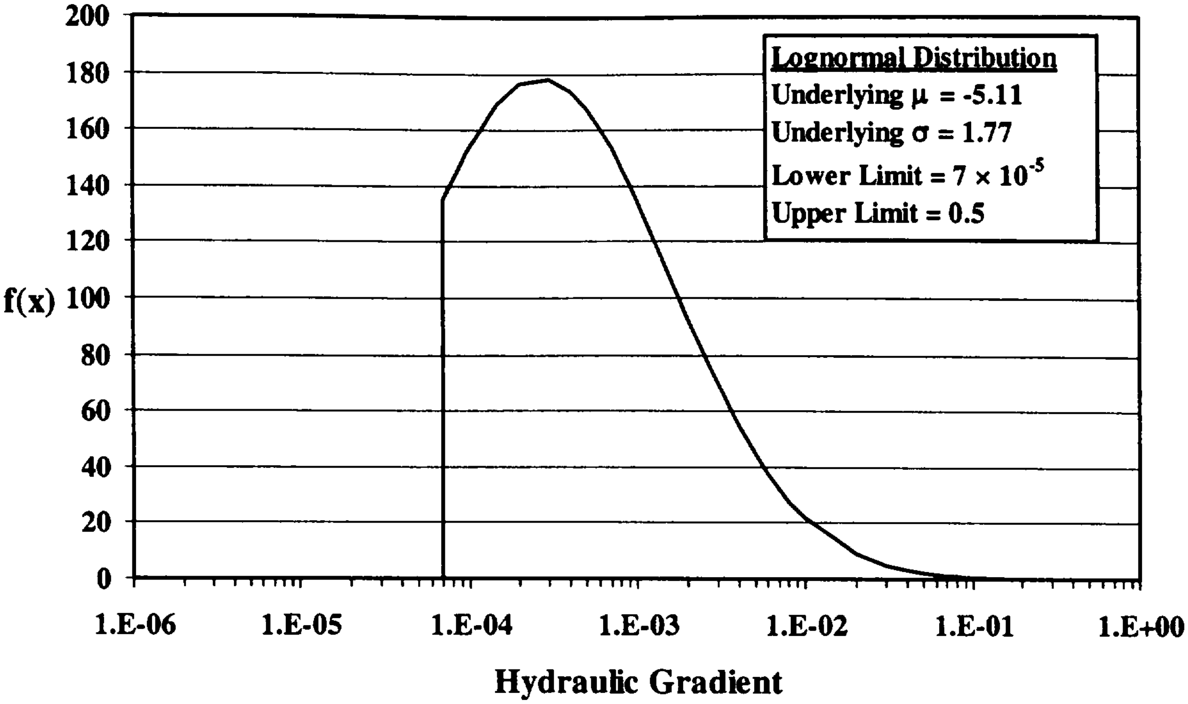

Figure 3.6-1 Hydraulic Gradient Probability Density Function

3.7 Unsaturated Zone Thickness

Applicable Code: RESRAD

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

Units: meters (m)

Probabilistic Input:

Distribution: bounded lognormal-n

Defining Values for Distribution:

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

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

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

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

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[1] Corresponds to the cumulative probability of 0.1%.

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

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

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

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

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

Source: Beyeler et al. (1998a).

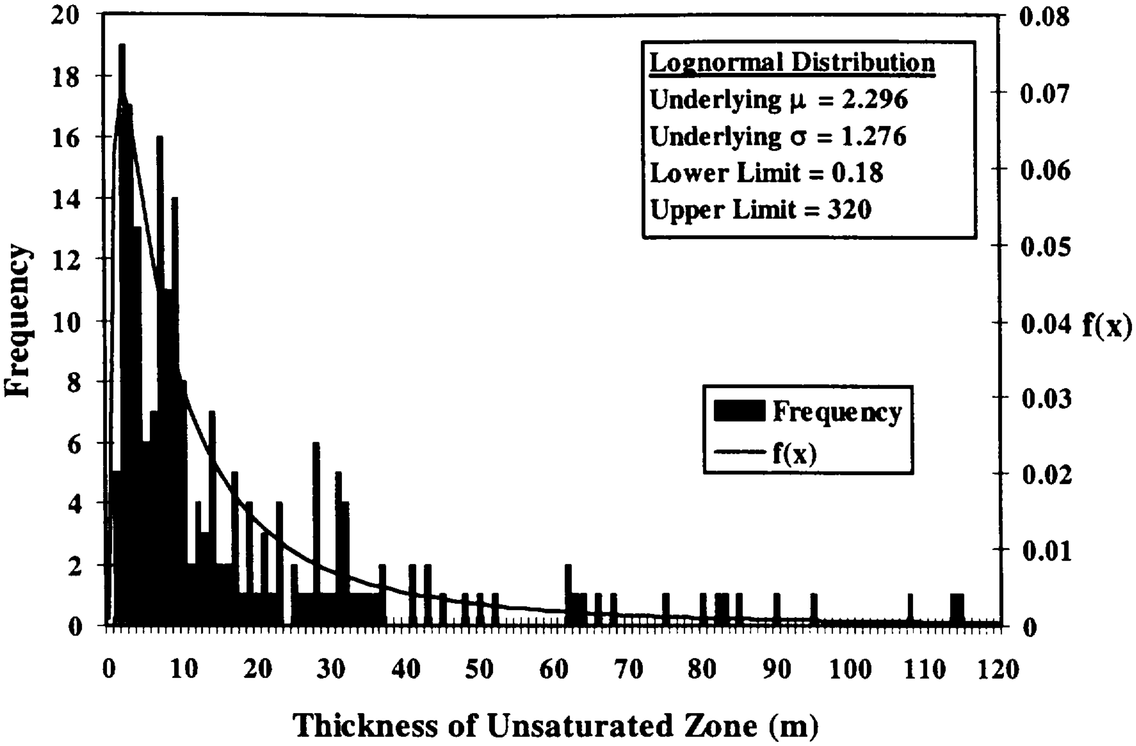

Figure 3.7-1 Probability Density Function for Unsaturated Zone Thickness

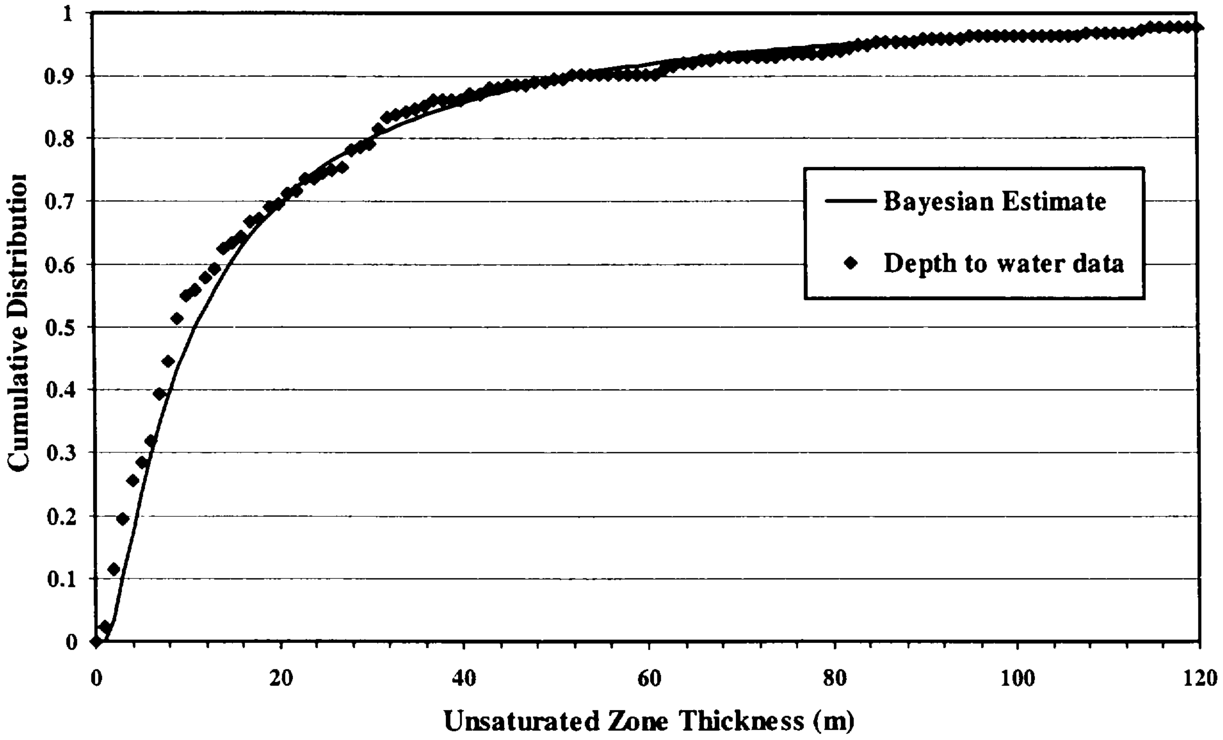

Figure 3.7-2 Cumulative Distribution Function for Unsaturated Zone Thickness

3.8 Cover and Contaminated Zone Erosion Rate

Applicable Code: RESRAD

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

Units: meters per year (m/yr)

Probabilistic Input:

Distribution: User defined with continuous logarithmic interpolation

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

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

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

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

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

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

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

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

Baffault et al. (1998) analyzed frequency distributions of measured daily soil loss values and determined if the Water Erosion Prediction Project (WEPP) model accurately reproduced statistical distributions of the measured daily erosion rate. They fitted a log Pearson type III distribution to measured and WEPP-predicted soil loss values from six sites for periods ranging from 6 to 10 years. Cumulative soil loss results indicated that large storms contributed a major portion of the erosion under conditions where cover was high, but not necessarily under conditions of low cover. They found the maximum erosion rates of between 3 and 30 kg/m^2 for a given day for the six sites studied.

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

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

[a] Estimated soil erosion assuming average soil density of 1.54 g/cm^3.

[b] NA = data not available.

Source: Pimentel et al. (1976).

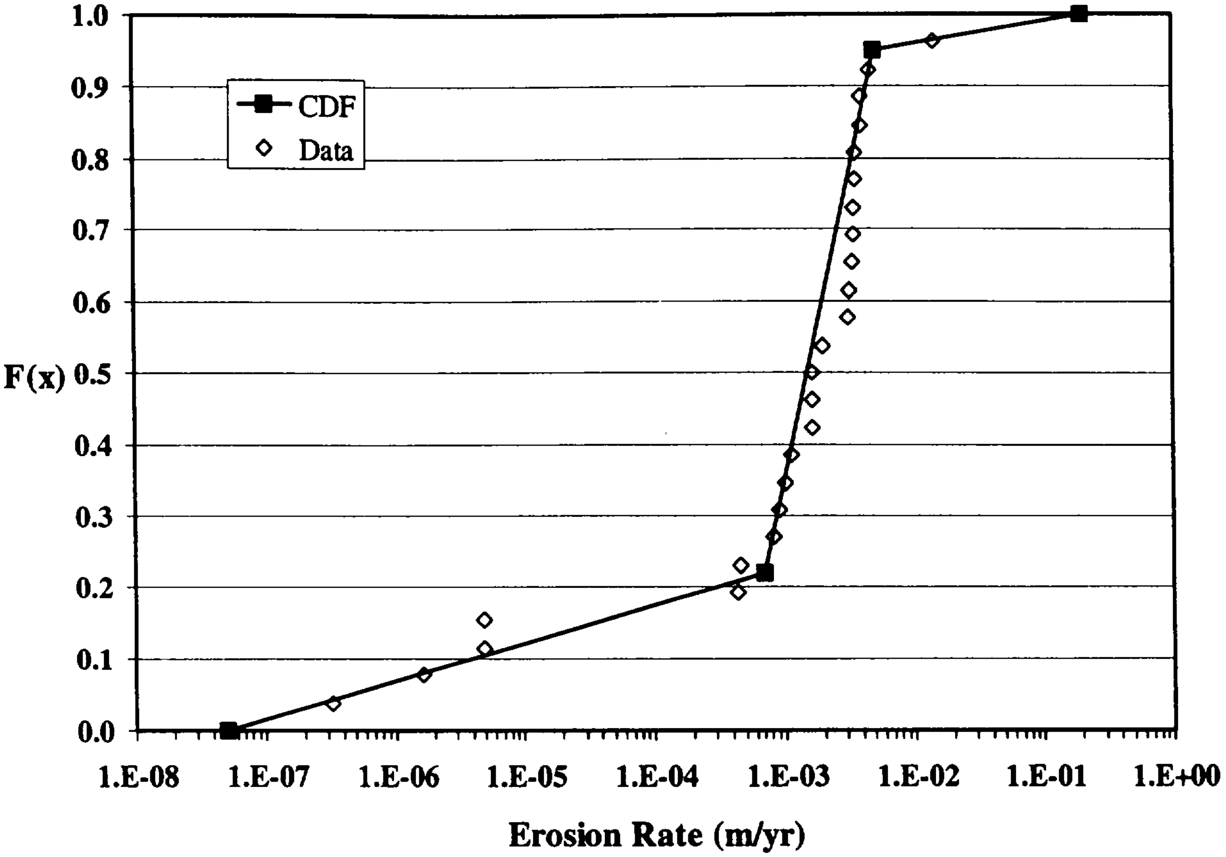

Figure 3.8-1 Cumulative Distribution for Input to RESRAD for Erosion Rate

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

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

[a] For estimating average erosion, bulk density is assumed to be ~1 g/cm^3.

Source: Zuzel et al. (1993).

3.9 Distribution Coefficients

Applicable Code: RESRAD

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

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

Probabilistic Input:

Distribution: truncated lognormal-n

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

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

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

$$R_d = 1 + \rho_b K_d / \theta , \tag{3.9-1}$$

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

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

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

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

Table 3.9-1 (Cont.)

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

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

1 - Developed by Beyeler et al. (1998b) by fitting available literature data.

2 - Developed by using the RESRAD default root uptake transfer factor and the correlation between K_d and CR for loamy soil as suggested by Baes et al. (1984).

3 - Developed by using the experimental data compiled by Thibault et al. (1990).

4 - Developed by Baes and Sharp (1983) by fitting experimental data.

5 - Developed on the basis of consideration that tritiated water (HTO) travels with the same speed as water. The mean value for K_d should be very small, and the range of distribution should be narrow.

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

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

[d] Exponential of the mean value.

[e] NA = not available.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table 3.9-2 (Cont.)

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

[a] NA = not applicable.

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

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

Table 3.9-3 (Cont.)

Element	Table 3.9-1 Value	Baes and Sharp (1983)	Sheppard and Thibault (1990)				McKinley and Scholtis (1991)	EPA (1999b)
			Sand	Loam	Clay	Organic		
Ra	3,533	NA	57 to 21,000	1,262 to 530,000	696 to 56,000	NA	NA	NA
Ru	1,588	48 to 1,000	5 to 490	NA	NA	39,000 to 87,000	NA	NA
S	38	NA	NA	NA	NA	NA	NA	NA
Sb	380	NA	NA	NA	NA	NA	NA	NA
Sc	935	NA	NA	NA	NA	NA	0 to 17	NA
Se	113	NA	NA	NA	NA	NA	1 to 50	NA
Se(IV)	NA	1.2 to 8.6	NA	NA	NA	NA	NA	NA
Sm	825	NA	NA	NA	NA	NA	1 to 5,011	NA
Sn	825	NA	NA	NA	NA	NA	50 to 794	NA
Sr	32	0.15 to 3,300	0.05 to 190	0.01 to 300	3.6 to 32,000	8 to 4,800	10 to 100	1 to 1,700
Ta	257	NA		NA	NA	NA	NA	NA
Tc	0.51	0.0029 to 0.28	0.01 to 16	0.01 to 0.4	1.16 to 1.32	0.02 to 340	0 to 5	NA
Te	38	NA	NA	NA	NA	NA	0 to 15.8	NA
Th	5,884	2,000 to 510,000	207 to 150,000	NA	244 to 160,000	1,579 to 13,000,000	794 to 63,100	20 to 30,000
Tl	71	NA	NA	NA	NA	NA	NA	NA
U	126	2,000 to 510,000	0.03 to 2,200	0.2 to 4,500	46 to 395,100	33 to 7,350	20 to 1,584	0.4 to 1,000,000
Zn	1,075	0.1 to 8,000	0.1 to 8,000	3.6 to 11,000	200 to 100,000	70 to 13,000	NA	NA
Zr	1,378	NA	NA	NA	NA	NA	10 to 7,943	NA

[a] NA = not applicable.

3.10 Well Pumping Rate

Applicable Code: RESRAD

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

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

Probabilistic Input:

Distribution: none recommended

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

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

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

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

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

3.11 Well Pump Intake Depth

Applicable Code: RESRAD

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

Units: meters (m)

Probabilistic Input:

Distribution: triangular

Defining Values for Distribution:

Minimum: 6 Maximum: 30 Most likely: 10

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

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

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

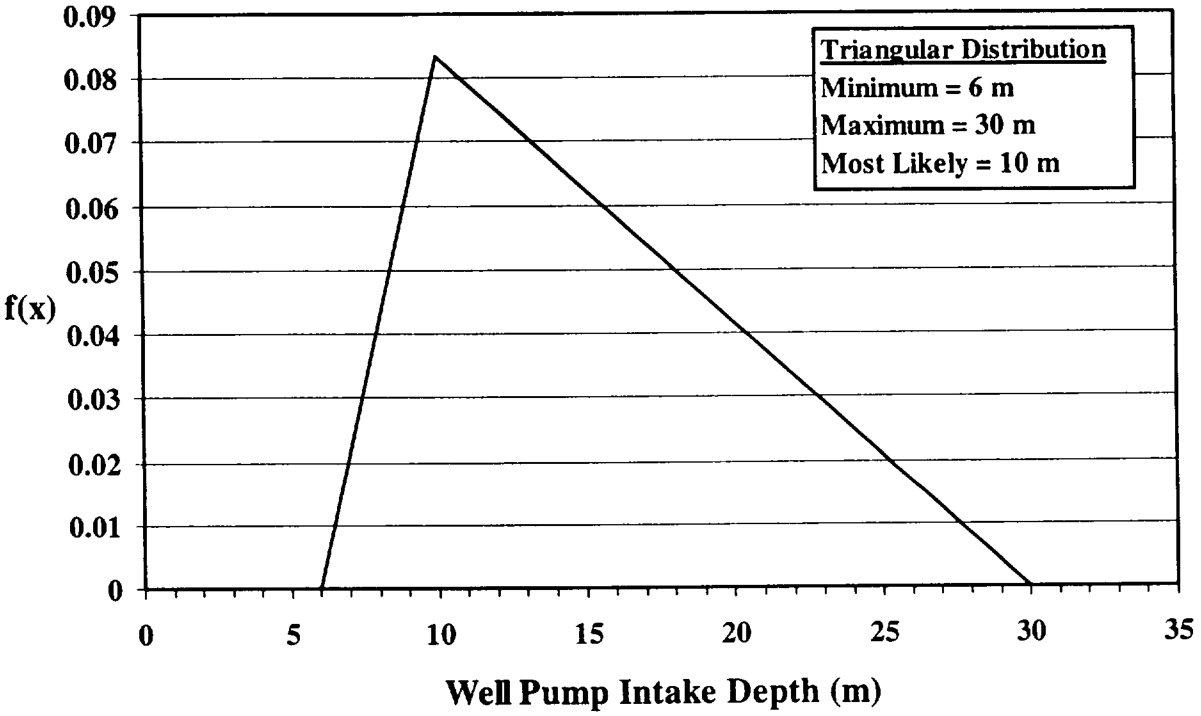

Figure 3.11-1 Well Pump Intake Depth Probability Density Function

3.12 Depth of Soil Mixing Layer

Applicable Code: RESRAD

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

Units: meters (m)

Probabilistic Input

Distribution: triangular

Defining Values for Distribution:

Minimum: 0.0 Maximum: 0.6 Most likely: 0.15

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

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

Tillage of the soil for crop production should be as shallow as possible and still meet the objectives of aerating the soil, removing stubble, controlling weeds, incorporating fertilizer, controlling erosion, and providing a suitable seedbed and rootbed (Buckingham, 1984). Typical plow depths are on the order of 0.15 to 0.20 m (6 to 8 in.). However, a plow sole, or hardpan (compacted soil layer), can form when a field is plowed to the same depth each year (Buckingham, 1984). This compacted layer should be broken up periodically by plowing to a deeper depth so as not to restrict air and water movement. Deeper tillage of this type, down to approximately 0.6 m (23 in.), can be routinely achieved with commercially available equipment. Thus, the soil mixing layer depth is expected to range from 0 to 0.6 m for the residential farmer scenario. A triangular distribution for the soil mixing layer between these two values, with 0.15 m (6 in.) as a most likely value, was selected for use in RESRAD as an approximation, because knowledge of the percentage of land used for crops and the crop types affect the amount of land and depth of plowing required, respectively. The probability density function for the soil mixing layer depth is shown in Figure 3.12-1.

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

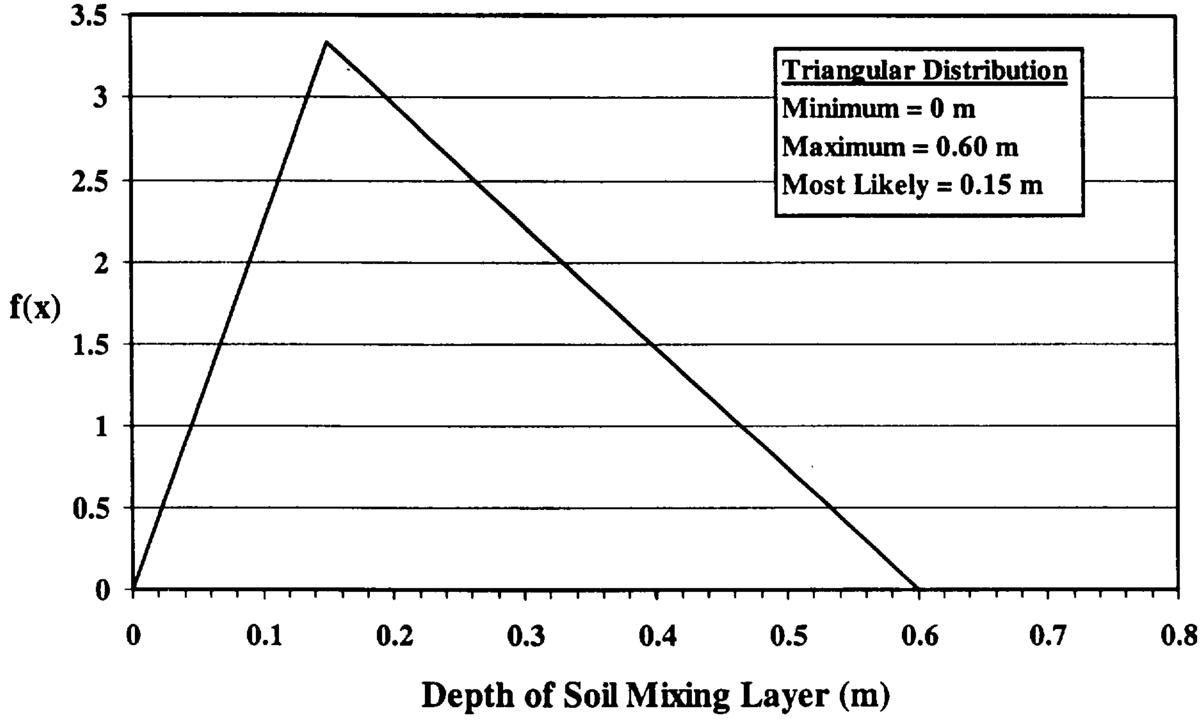

Figure 3.12-1 Depth of Soil Mixing Layer Probability Density Function

3.13 Cover Depth

Applicable Code: RESRAD

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

Units: meters (m)

Probabilistic Input:

Distribution: none recommended

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